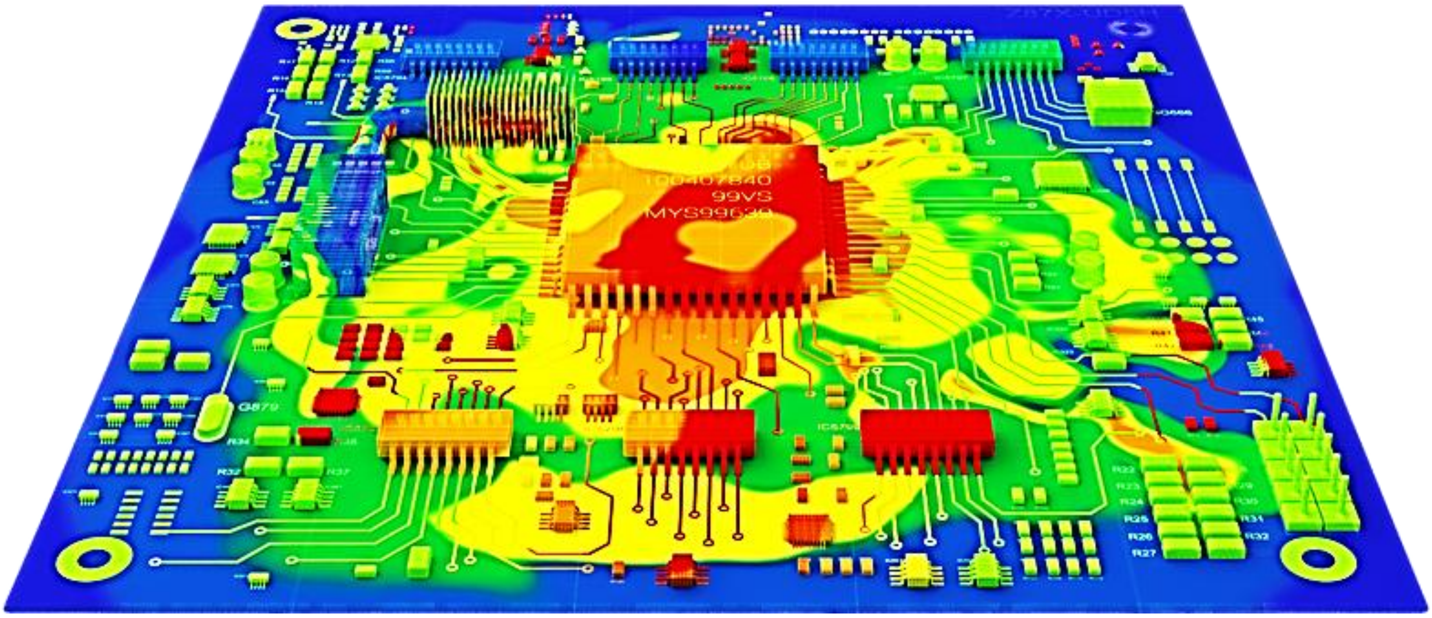
Hardware Engineer's Guide

THERMAL

MANAGEMENT



By Shimi Cohen

HEAT EFFECT

1.1 Why Thermal Management Matters

RELIABILITY IMPACT

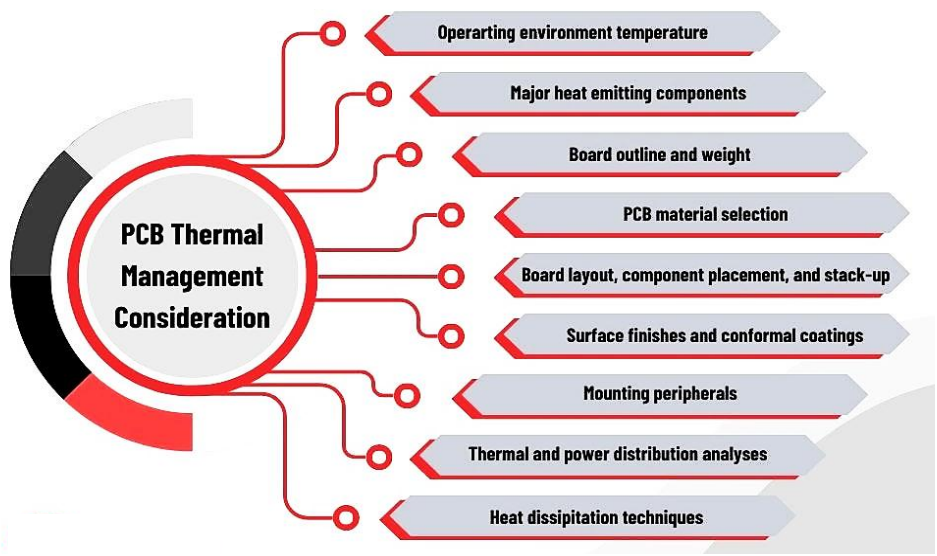
Every 10°C temperature increase reduces component life by 50%. This fundamental relationship drives all thermal design decisions.

PERFORMANCE DEGRADATION

- Semiconductors: Leakage current doubles every 8-10°C
- Resistors: Drift increases with temperature coefficient
- Capacitors: ESR increases, capacity decreases
- Crystals: Frequency drift affects timing accuracy

DESIGN TEMPERATURE TARGETS

COMPONENT TYPE	TARGET JUNCTION TEMP	AMBIENT +
MCU	≤ 85°C	25°C + 60°C
MOSFETS	≤ 125°C	25°C + 100°C
LDO	≤ 100°C	25°C + 75°C
ELEC CAPS	≤ 85°C	25°C + 60°C



1.2 Effects of Heat on Reliability

ARRHENIUS RELATIONSHIP

Component failure rate increases exponentially with temperature. Arrhenius equation:

$$Failure\ Rate\ = A \times e^{\wedge}(-Ea/kT)$$

Where:

A = Pre-exponential factor

Ea = Activation energy

K = Boltzmann constant

T = Absolute temperature

PRACTICAL APPLICATION

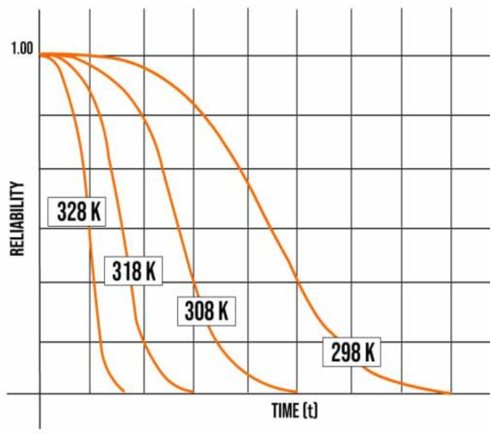
For every 10°C reduction in operating temperature, component life approximately doubles.

Repeated Thermal Cycling Outcome:

- Solder joint fatigue
- Wire bond failures
- Package cracking
- Delamination

CRITICAL TEMPERATURE THRESHOLDS:

MATERIAL	THRESHOLD	FAILURE MODE
SOLDER (SAC305)	217°C	MELTING
FR-4 SUBSTRATE	130°C	GLASS TRANSITION
BOND WIRE	175°C	INTERMETALLIC GROWTH
DIE ATTACH	150°C	DELAMINATION



1.3 Common Heat Sources in PCBs

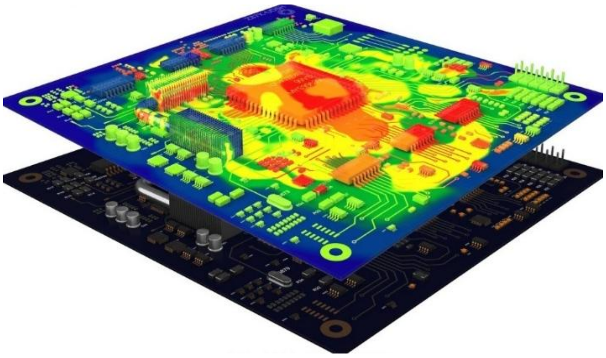
PRIMARY HEAT GENERATORS

POWER MANAGEMENT:

- Switching regulators: 5-15% power loss
- Linear regulators: (VIN-VOUT)/VIN loss percentage
- Battery chargers: 10-20% loss typical

PROCESSING COMPONENTS:

- Microprocessors: 0.5-50W depending on performance
- FPGAs: 1-100W based on utilization
- DSPs: 0.1-10W typical range



POWER DEVICES:

- MOSFETs: I^2R losses + switching losses
- Diodes: VF × IF continuous
- LEDs: 60-80% electrical power as heat

PASSIVE COMPONENTS:

- Resistors: I^2R heating, especially current sensing
- Inductors: Core and copper losses
- Transformers: Primary and secondary losses

HEAT DENSITY DISTRIBUTION:

COMPONENT TYPE	TYPICAL W/CM²	COOLING CHALLENGE
CPU/GPU	50-200	VERY HIGH
POWER MOSFET	10-50	HIGH
LINEAR REGULATOR	5-25	MEDIUM
LED ARRAY	1-10	MEDIUM
RESISTORS	0.5-5	LOW

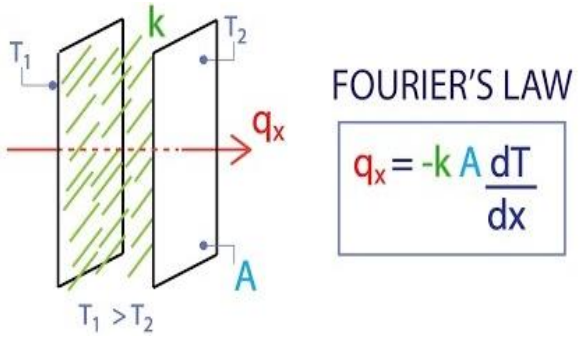
HEAT TRANSFER FUNDAMENTALS

2.1 Conduction Principles

FOURIER'S LAW & RESISTNACE MODEL

$$Q = -k \times A \times (dT/dx)$$

$$Rt = L / (k \times A)$$



Where:

Q = Heat flow rate (watts)

Rt = Resistance Model

k = Thermal conductivity (W/m·K)

A = Cross-sectional area (m^2)

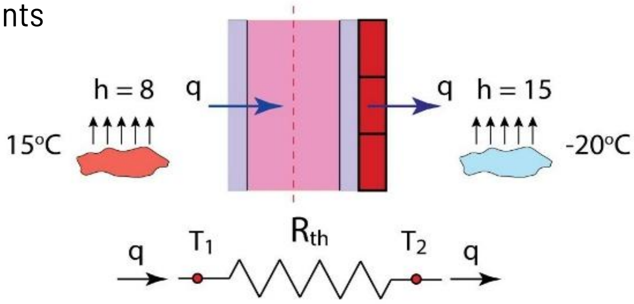
dT/dx = Temperature gradient (K/m)

MATERIAL THERMAL CONDUCTIVITIES:

MATERIAL	THERMAL CONDUCTIVITY	PCB APPLICATION
COPPER	400	TRACES, PLANES, VIAS
ALUMINUM	237	HEAT SINKS, SUBSTRATES
FR-4	0.3	STANDARD SUBSTRATE
POLYIMIDE	0.2	FLEXIBLE CIRCUITS
THERMAL EPOXY	1-3	DIE ATTACH, TIM

PCB CONDUCTION PATHS

- Copper traces: Primary horizontal heat flow
- Copper planes: Large area heat spreading
- Thermal vias: Vertical heat transfer
- Component leads: Heat input/output points



2.2 Convection Mechanisms

NEWTON'S LAW OF COOLING

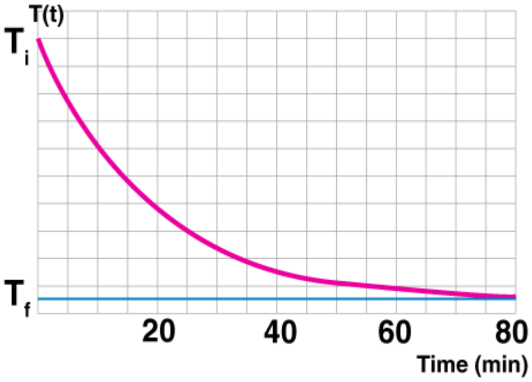
$$Q = h \times A \times (Tsurface - Tambient)$$

Where:

h = Convection coefficient (W/m^2·K)

A = Surface area (m^2)

T = Temperature (K)



Newton's Law of Cooling – Temperature vs Time

CONVECTION TYPES

NATURAL CONVECTION:

- Buoyancy-driven air movement
- Typical h = 5-25 W/m^2·K
- Orientation dependent
- Limited cooling capacity

FORCED CONVECTION:

- Fan or blower driven
- Typical h = 25-250 W/m^2·K
- Velocity dependent
- Higher cooling capacity

CONVECTION COEFFICIENTS:

CONDITION	H (W/M^2·K)	APPLICATION
NATURAL AIR, VERTICAL	5-25	PASSIVE COOLING
NATURAL AIR, HORIZONTAL	2-10	POOR ORIENTATION
FORCED AIR, 2 M/S	50-100	FAN COOLING
FORCED AIR, 10 M/S	100-300	HIGH-SPEED FANS

2.3 Radiation Effects

STEFAN-BOLTZMANN LAW

$$Q = \varepsilon \times \sigma \times A \times (T_1^{\,4} - T_2^{\,4})$$

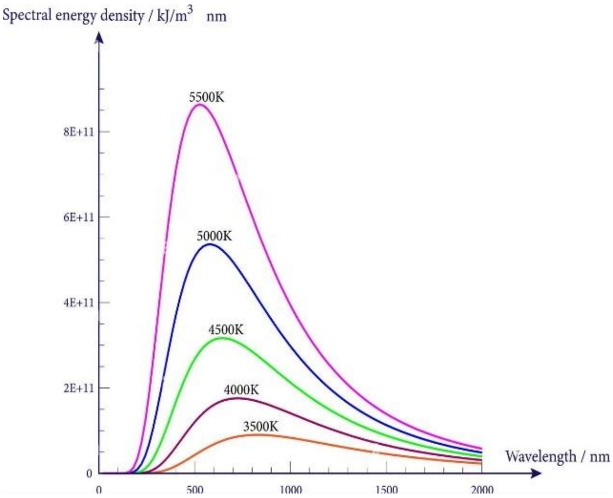
Where:

ε = Emissivity (0-1)

σ = SB constant (5.67×10^{-8} W/m²·K⁴)

A = Surface area (m²)

T = Absolute temperature (K)



SURFACE EMISSIVITY VALUES:

SURFACE	EMISSIVITY	RADIATION EFFECTIVENESS
BLACK ANODIZED ALUMINUM	0.9	EXCELLENT
GREEN SOLDER MASK	0.8	GOOD
BARE COPPER	0.1	POOR
POLISHED METAL	0.05	VERY POOR

RADIATION CONTRIBUTION

At typical PCB temperatures (60-80°C), radiation accounts for 20-40% of total heat transfer in natural convection environments.

DESIGN IMPLICATIONS:

- Increase surface area for radiation
- Use high-emissivity finishes
- Avoid shiny metal surfaces
- Consider radiation in thermal budget

THERMAL PROPERTIES

3.1 Standard FR-4 Performance

FR-4 THERAL PROPERTIES:

PROPERTY	VALUE	UNIT	IMPACT
THERMAL CONDUCTIVITY	0.3	W/M·K	HEAT SPREADING
GLASS TRANSITION (TG)	130-180	°C	MAX OPERATING TEMP
DECOMPOSITION (TD)	300+	°C	ABSOLUTE LIMIT
CTE Z-AXIS	50-70	PPM/°C	VIA RELIABILITY

FR-4 LIMITATIONS

- Low thermal conductivity limits heat spreading
- CTE mismatch causes via stress
- Tg limits high-temperature operation
- Moisture absorption affects properties

ENHANCED FR-4 OPTIONS

HIGH TG FR-4:

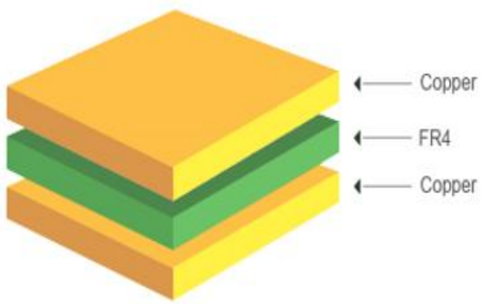
- Tg: 170-180°C vs 130°C standard
- Better high-temperature stability
- 15-20% cost premium
- Same processing requirements

LOW CTE FR-4:

- Reduced Z-axis expansion
- Better via reliability
- Improved thermal cycling performance
- 25-30% cost increase

THERMAL DESIGN WITH FR-4:

- Rely on copper for heat conduction
- Minimize through-substrate heat paths
- Use thermal vias extensively
- Consider heat spreading planes



3.2 Metal-Core PCB Applications

METAL-CORE PCB (MCPCB)

- Metal base (aluminum/copper)
- Dielectric layer (thermally conductive)
- Copper circuit layer
- Solder mask and silkscreen

THERMAL PERFORMANCE:

MCPCB TYPE	THERMAL [W/M·K]	APPLICATION
STANDARD ALUMINUM	1.5-3.0	LED LIGHTING
HIGH PERFORMANCE	5.0-8.0	POWER ELECTRONICS
COPPER CORE	15-25	RF POWER AMPS
CERAMIC FILLED	3.0-12	HYBRID SOLUTIONS

DESIGN CONSIDERATIONS

ADVANTAGES:

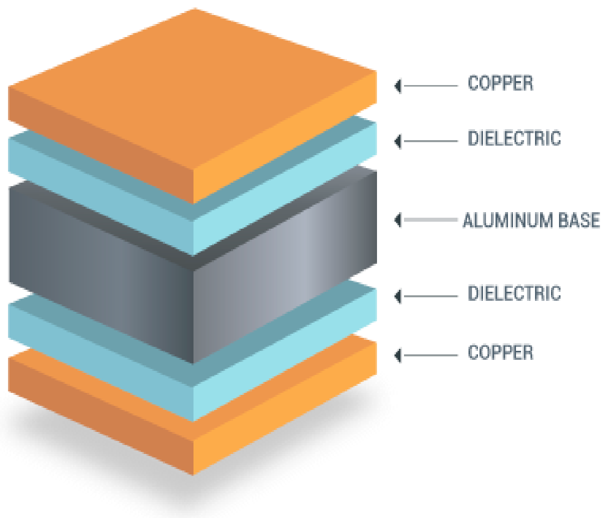
- Excellent heat dissipation
- Reduced thermal interface layers
- Direct mounting to heat sink
- Lower overall thermal resistance

LIMITATIONS:

- Single-sided circuits only
- Higher cost than FR-4
- Limited via options
- Special manufacturing process

POWER ELECTRONICS:

- Linear regulators > 5W
- Switching regulators > 20W
- Motor controllers
- Power amplifiers

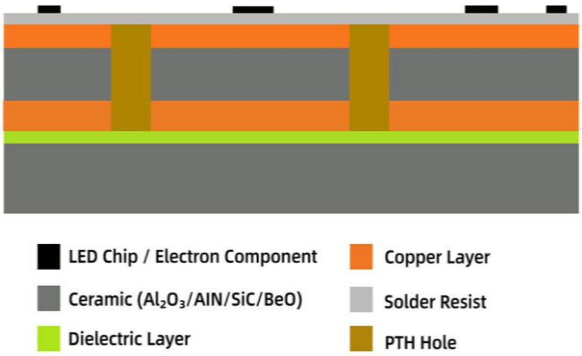


3.3 Advanced Substrate Options

CERAMIC SUBSTRATES

ALUMINUM NITRIDE (ALN):

- Thermal conductivity: 170-200 W/m·K
- Electrical isolation
- Low CTE match to silicon



BERYLLIUM OXIDE (BEO):

- Thermal conductivity: 250-300 W/m·K
- Excellent electrical properties
- Toxic material, handling issues
- Specialized applications only

FLEXIBLE SUBSTRATES

POLYIMIDE WITH THERMAL FILLERS:

- Enhanced thermal conductivity: 1-3 W/m·K
- Maintains flexibility
- Higher cost than standard
- Specialized applications

LIQUID CRYSTAL POLYMER (LCP):

- Low loss at high frequencies
- Good thermal stability
- Moderate thermal conductivity
- RF/microwave applications

APPLICATION	PRIMARY NEED	RECOMMENDED SUBSTRATE
HIGH-POWER LED	HEAT DISSIPATION	ALUMINUM MCPCB
RF POWER AMP	HEAT + RF PERFORMANCE	COPPER MCPCB
PRECISION ANALOG	THERMAL STABILITY	HIGH TG FR-4
POWER MODULE	MAXIMUM HEAT REMOVAL	ALN CERAMIC

COMPONENT HANDLING

4.1 Heat-Generating Components

POWER DISSIPATION CALCULATION

LINEAR REGULATORS:

$$PD = (VIN - VOUT) \times IOUT + (VIN \times IQ)$$

Example LM1117-3.3:

- Input: 5V, Output: 3.3V, Current: 1A
- PD = (5V - 3.3V) × 1A + (5V × 5mA) = 1.725W

SWITCHING REGULATORS:

$$PD = POUT \times (1 - \eta) / \eta + PSWITCHING$$

MOSFETs**:**

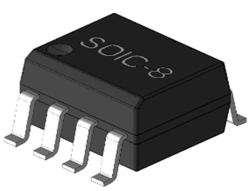
- Conduction loss: $I^2RMS \times RDS(on)$
- Switching loss: $½ \times VDS \times IDS \times (tr + tf) \times fsw$

MICRO-CONTROLLER:

$$PD = VCC \times ICC + Dynamic\ power$$

COMPONENT POWER RATINGS:

PACKAGE TYPE	TYPICAL POWER	THERMAL RESISTANCE
SOT-23	0.2W	250°C/W
SOIC-8	0.5W	150°C/W
QFN-16	1.0W	50°C/W
TO-220	15W	60°C/W
D2PAK	25W	3°C/W

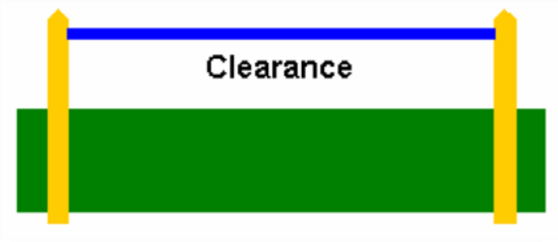


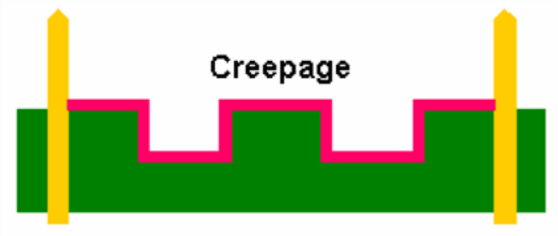
4.2 Optimal Placement Strategies

HEAT SOURCE DISTRIBUTION

SPACING REQUIREMENTS:

- Minimum 5mm between HP components
- Consider airflow patterns





PLACEMENT PRIORITY:

1. **Highest Power Components:**
   - Center of board for heat spreading
   - Access to maximum copper area
   - Direct thermal path to heat sink
2. **Medium Power Components:**
   - Distribute around high-power devices
   - Consider cooling airflow
3. **Low Power Components:**
   - Fill remaining areas
   - Normal placement rules apply

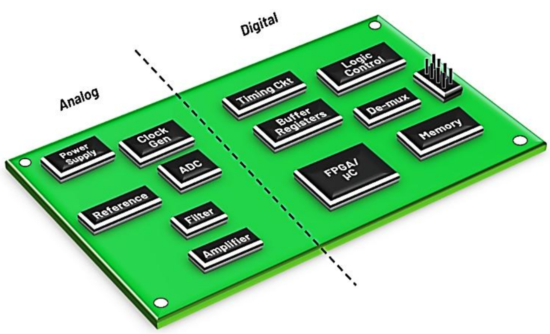
BOARD ZONES

ZONE TYPE	TEMPERATURE	SUITABLE COMPONENTS
HOT ZONE	>70°C	POWER DEVICES ONLY
WARM ZONE	40-70°C	DIGITAL LOGIC, DRIVERS
COOL ZONE	<40°C	PRECISION ANALOG, REFERENCES

PLACEMENT RULES

POWER MANAGEMENT:

- Place switching regulators away from sensitive analog
- Linear regulators need heat sinking above 1W
- Keep feedback components cool
- Minimize input/output ripple coupling

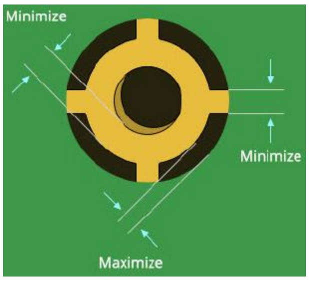


PROCESSING UNITS:

- Center placement for heat spreading
- Direct thermal path to system cooling
- Consider package orientation for airflow
- Separate power and I/O connections

4.3 Layout for Heat Dispersion

COPPER POUR STRATEGY



GROUND PLANE UTILIZATION:

- Connect hot components directly to ground plane
- Maximize copper area under components
- Use plane cutouts only when necessary

THERMAL RELIEF CONSIDERATIONS

Standard thermal reliefs reduce heat conduction by 80-90%. Use direct connections for thermal management.

TRACE WIDTH FOR THERMAL CONDUCTION:

CURRENT	STD WIDTH	THR WIDTH	IMPROVEMENT
1A	0.5MM	2.0MM	4X HEAT CONDUCTION
3A	1.5MM	4.0MM	2.7X HEAT CONDUCTION
5A	2.5MM	6.0MM	2.4X HEAT CONDUCTION

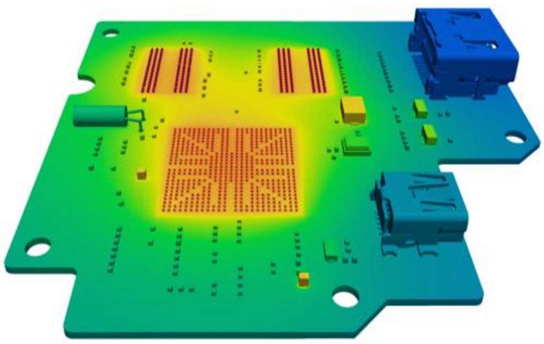
HEAT SPREADING TECHNIQUES

COPPER FLOODING:

- Fill unused areas with copper
- Maintain electrical isolation where required
- Provide stitching vias between layers

THERMAL PADS:

- Large copper areas under components
- Multiple via connections to planes
- Solder mask opening for heat sink contact



LAYER ASSIGNMENT:

- Dedicate inner layers to heat spreading
- Use thick copper (2oz/70μm minimum)
- Provide cross-layer thermal connections

LAYER STACK-UP

5.1 Layer Count Impact

THERMAL PERFORMANCE VS LAYER COUNT

LAYER COUNT	THERMAL IMPROVEMENT	COST IMPACT	APPLICATION
2-LAYER	BASELINE	1X	SIMPLE, LOW POWER
4-LAYER	2-3X	1.5X	MODERATE COMPLEXITY
6-LAYER	3-4X	2X	HIGH PERFORMANCE
8+ LAYER	4-5X	3X+	COMPLEX SYSTEMS

HEAT CONDUCTION PATHS

2-LAYER BOARDS:

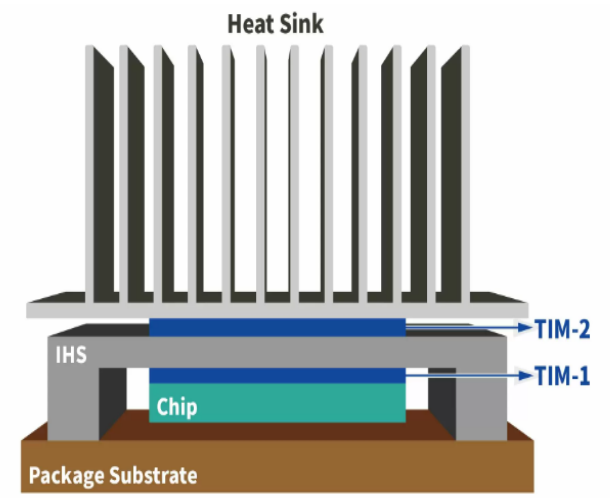
- Limited to top and bottom copper
- Thermal vias essential
- Component placement critical
- External heat sinking often required

4-LAYER BOARDS:

- Internal power/ground planes
- Better heat spreading
- Reduced thermal resistance
- Standard for moderate power

6+ LAYER BOARDS:

- Dedicated thermal planes possible
- Multiple heat spreading paths
- Lower overall thermal resistance
- Required for high-power density



5.2 Copper Thickness Optimization

STANDARD COPPER WEIGHTS

COPPER WEIGHT	THICKNESS	RESISTANCE	THERMAL BENEFIT
0.5OZ	17µM	HIGH	LIMITED
1OZ	35µM	STANDARD	GOOD
2OZ	70µM	LOW	VERY GOOD
3OZ	105µM	VERY LOW	EXCELLENT

THERMAL CONDUCTANCE SCALING

Thermal conductance increases linearly with copper thickness. 2oz copper provides 2x thermal performance vs 1oz.

PERFORMANCE

1OZ COPPER (STANDARD):

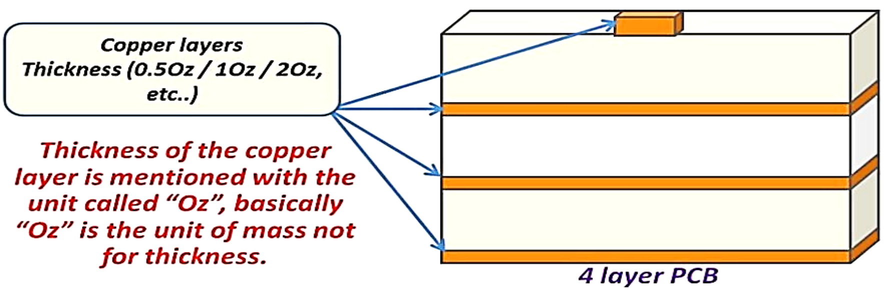
- Adequate for <2W/cm^2
- Most common choice

2OZ COPPER:

- 2x thermal performance
- Good for 2-5W/cm^2

3OZ COPPER:

- 3x thermal performance
- Required for >5W/cm^2



5.3 Power/Ground Plane Design

THERMAL STRATEGY

DEDICATED THERMAL PLANES:

- Separate layer for heat spreading
- Not used for electrical connections
- Maximum copper retention
- Connected via thermal vias

POWER PLANE UTILIZATION:

- VCC planes conduct heat
- Multiple power domains create thermal barriers
- Ground planes typically best thermal conductors
- Consider plane assignment for thermal management

PLANE CONNECTION METHODS

CONNECTION TYPE	THERMAL RESISTANCE	ELECTRICAL FUNCTION
DIRECT CONNECT	LOWEST	POWER/GROUND
THERMAL VIA	LOW	ISOLATION
THERMAL RELIEF	HIGH	STANDARD ELECTRICAL
NO CONNECTION	INFINITE	ISOLATION

PLANE SPLITS

THERMAL IMPACT OF SPLITS:

- Plane splits block heat flow
- Create thermal barriers
- Force heat through limited paths
- Should be minimized in hot areas

DESIGN RULES:

- Avoid splits under hot components
- Provide thermal bridges across splits
- Use multiple narrow splits vs single wide
- Consider thermal via arrays at splits

THERMAL VIAS

6.1 Thermal Via Design

VIA THERMAL RESISTANCE

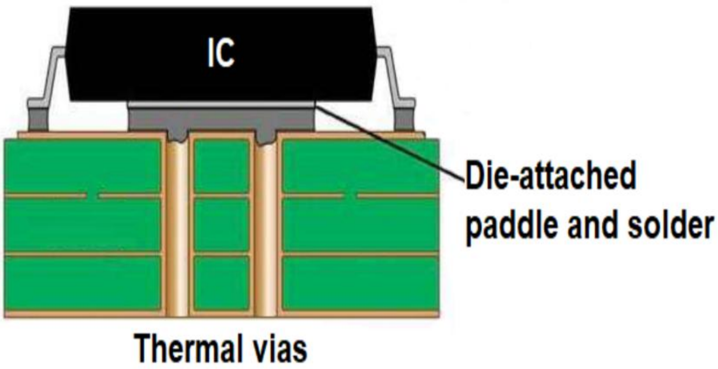
$$Rth\_Via = L / (k \times A) + Contact\ resistances$$

Where:

L = Via length (board thickness)

k = Copper thermal conductivity

A = Via barrel area



STANDARD VIA THERMAL PERFORMANCE:

VIA SIZE	DRILL/PAD	THERMAL RESISTANCE	CURRENT CAPACITY
0.2MM	0.2/0.4MM	100°C/W	1A
0.3MM	0.3/0.5MM	70°C/W	2A
0.5MM	0.5/0.8MM	40°C/W	4A
0.8MM	0.8/1.2MM	25°C/W	8A

VIA ARRAY DESIGN

$$N = Rtotal / Rvia$$

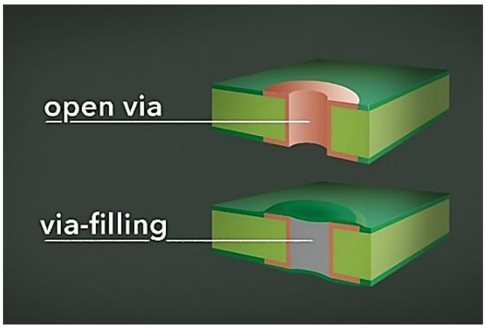
EXAMPLE:

- Required thermal resistance: 5°C/W
- Single via resistance: 50°C/W
- Required vias: 50/5 = 10 vias minimum

VIA SPACING:

- Minimum: 3x drill diameter
- Optimal: 5x drill diameter for manufacturing
- Maximum: Constrained by component size
- Pattern: Regular grid preferred

VIA FILL OPTIONS



UNFILLED VIAS:

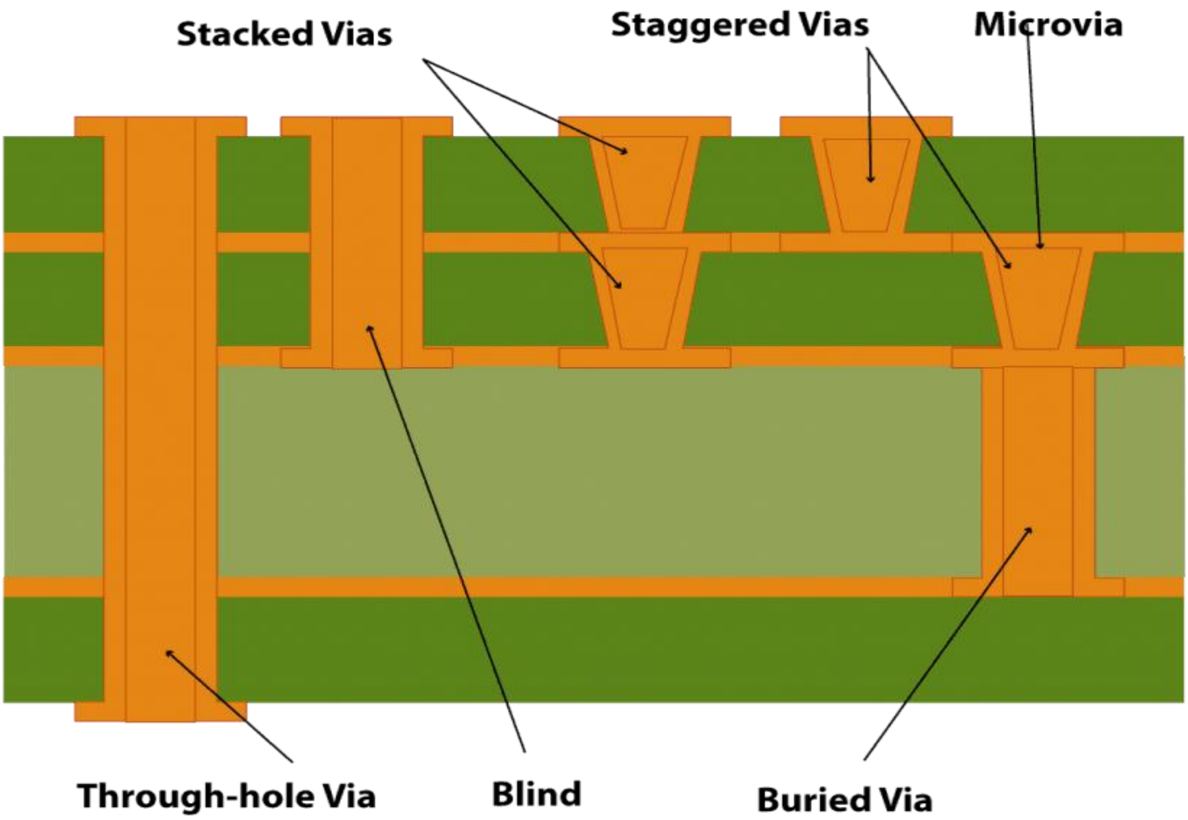
- Lowest cost
- Good thermal performance
- Potential solder wicking
- Standard manufacturing

FILLED VIAS:

- Prevent solder wicking
- Slightly better thermal performance
- Higher manufacturing cost
- Required for via-in-pad

CAPPED VIAS:

- Plugged with soldermask
- Lowest cost fill option
- Good for most applications
- Standard capability



6.2 Via-in-Pad Implementation

VIA-IN-PAD BENEFITS

- Maximum thermal efficiency
- Shortest thermal path
- Reduced PCB area
- Better electrical performance

MANUFACTURING REQUIREMENTS

- Via filling mandatory
- Planarization required
- Higher cost process
- Extended lead times

DESIGN GUIDELINES

VIA SIZE SELECTION:

- Smaller vias preferred for filling
- 0.1-0.2mm typical for via-in-pad
- Aspect ratio <8:1 recommended
- Consider manufacturing capabilities

PAD DESIGN:

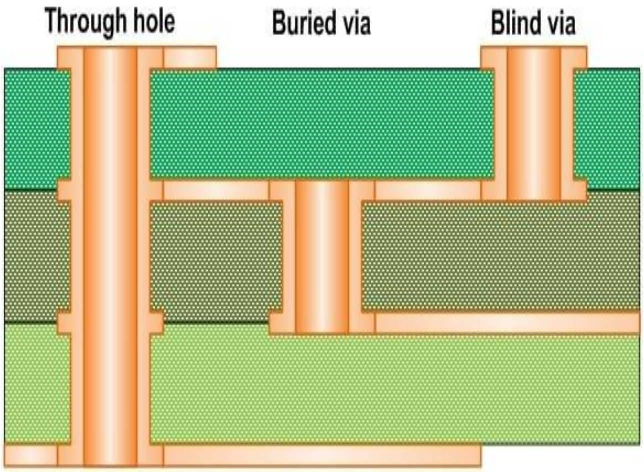
- Pad size accommodates via and tolerances
- Via centered in pad
- Multiple vias per pad if size allows
- Maintain solder joint integrity

PROCESS COMPATIBILITY:

FILL METHOD	COST	THERMAL PERFORMANCE	RELIABILITY
CONDUCTIVE EPOXY	MEDIUM	GOOD	GOOD
ELECTROPLATED COPPER	HIGH	EXCELLENT	EXCELLENT
SOLDERMASK PLUG	LOW	FAIR	FAIR

6.3 Advanced Via Techniques

MICRO-VIAS



BURIED THERMAL VIAS:

- Connect internal layers only
- Lower thermal resistance
- Higher manufacturing complexity

STACKED MICRO-VIAS:

- Sequential build-up
- Very low thermal resistance
- Advanced HDI capability required

VIA PATTERNING STRATEGIES

THERMAL VIA ARRAYS:

- Regular grid pattern
- Uniform heat distribution
- Predictable thermal performance

VIA WALLS:

- Linear via arrangements
- Thermal barriers or channels
- Direct heat flow control

HYBRID VIA STRATEGIES:

- Combine different via types
- Optimize cost vs performance
- Match thermal requirements

THERMAL VIA PLACEMENT

COMPONENT-CENTRIC:

- Radial pattern from heat source
- Shortest thermal path
- Maximum effectiveness

SYSTEM-LEVEL:

- Board-wide thermal network
- Heat spreading and collection
- Multiple heat sources

HEATSINK MATERIALS

7.1 Heat Sink Selection

HEAT SINK THERMAL RESISTANCE

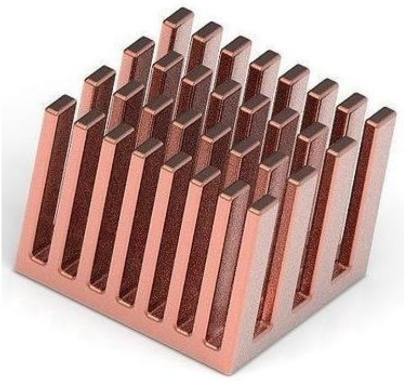
$$Rth = (Tj - Ta) / P - Rth\_jc - Rth\_interface$$

HEAT SINK TYPES

TYPE	THERMAL RESISTANCE	COST	APPLICATION
STAMPED ALUMINUM	15-50°C/W	LOW	<5W COMPONENTS
EXTRUDED ALUMINUM	5-20°C/W	MEDIUM	5-25W COMPONENTS
BONDED FIN	2-10°C/W	HIGH	25-100W COMPONENTS
VAPOR CHAMBER	0.5-3°C/W	VERY HIGH	>100W COMPONENTS

HEAT SINK SIZING

$$Required\ area \approx Power / (h \times \Delta T)$$



EXAMPLE:

- Power dissipation: 10W
- Temperature rise limit: 40°C
- Natural convection h = 10 W/m^2·K
- Required area: 10W / (10 × 40) = 0.025m^2 = 250cm^2

FIN EFFICIENCY:

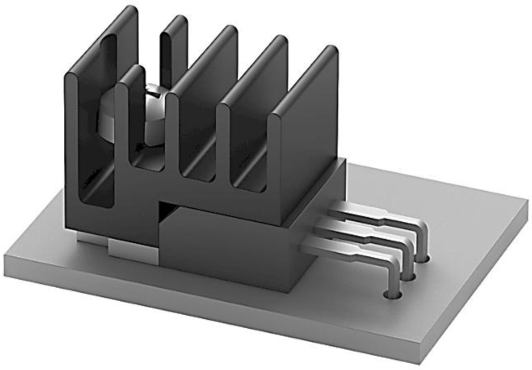
Longer, thinner fins have reduced efficiency due to thermal resistance along the fin length.

OPTIMAL FIN SPACING:

CONVECTION TYPE	FIN SPACING	OPTIMIZATION
NATURAL	8-12MM	MINIMIZE INTERFERENCE
LOW SPEED FORCED	4-8MM	BALANCE AREA/FLOW
HIGH SPEED FORCED	2-4MM	MAXIMUM AREA

7.2 Integration Methods

COMPONENT-LEVEL INTEGRATION:



TO-220 PACKAGES:

- Thermal interface required
- Electrical isolation considerations
- Multiple mounting options

SURFACE MOUNT PACKAGES:

- Heat sink attachment to PCB
- Thermal pad connections
- Assembly complexity

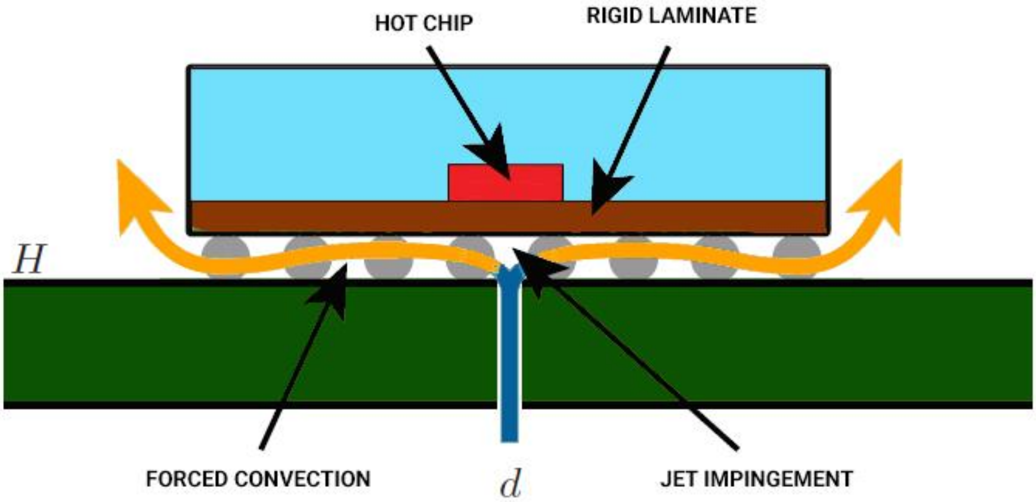
SYSTEM-LEVEL INTEGRATION:

CHASSIS INTEGRATION:

- PCB mounted to chassis
- Component thermal pads contact chassis
- Maximum heat dissipation

DEDICATED COOLING SYSTEMS:

- Separate heat sink assemblies
- Heat pipes for heat transport
- Liquid cooling for extreme cases



ACTIVE & PASSIVE COOLING

8.1 Natural Convection Design

BUOYANCY-DRIVEN FLOW

Natural convection relies on density differences in heated air to create airflow.

HEAT TRANSFER COEFFICIENT

$$h = C \times (\Delta T/L)^n$$

Where:

C = Constant based on geometry

ΔT = Temperature difference

L = Characteristic length

n = Exponent (typically 0.25)

BOARD ORIENTATION EFFECTS:

VERTICAL ORIENTATION:

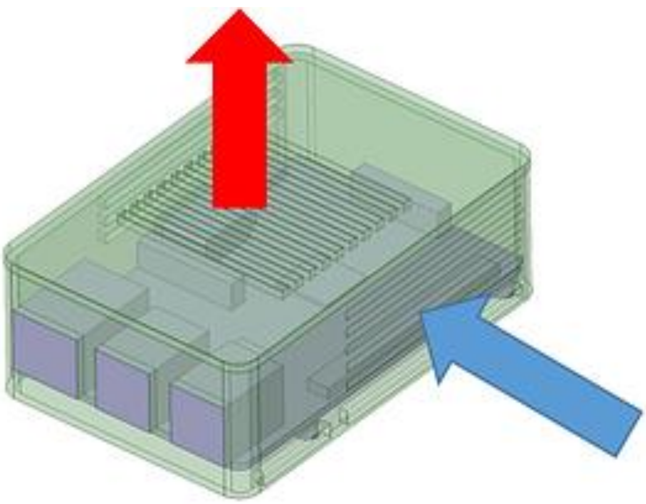
- Best natural convection
- Unobstructed airflow
- 25-30% better than horizontal
- Recommended when possible

HORIZONTAL (COMPONENTS UP):

- Moderate convection
- Component interference
- Hot air pooling
- Standard orientation

HORIZONTAL (COMPONENTS DOWN):

- Poor convection
- Heat trapped
- Worst case scenario
- Avoid if possible



8.2 Forced Air Systems

FAN SELECTION CRITERIA:

AIRFLOW VS STATIC PRESSURE:

- High airflow: Open systems, low restriction
- High static pressure: Restricted systems, heat sinks

FAN CURVES

Every fan has a characteristic curve relating airflow to static pressure.

TYPICAL FAN PERFORMANCE:

FAN SIZE	FREE AIR FLOW	MAX STATIC PRESSURE	NOISE LEVEL
40MM	10-20 CFM	5-15 MMH2O	25-40 DBA
60MM	25-50 CFM	8-20 MMH2O	20-35 DBA
80MM	40-80 CFM	10-25 MMH2O	18-30 DBA
120MM	80-150 CFM	12-30 MMH2O	15-25 DBA

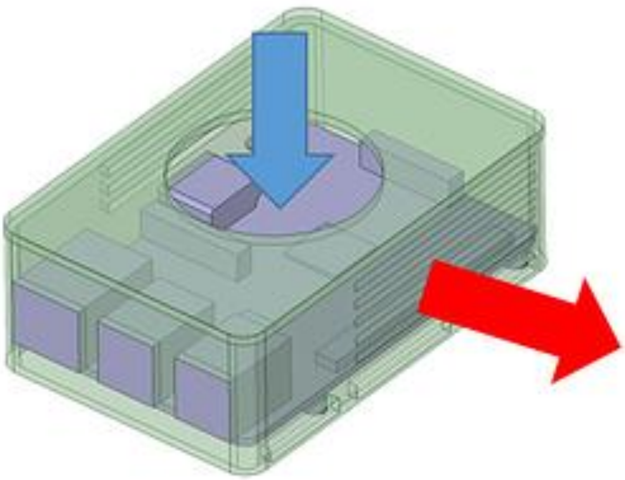
FAN PLACEMENT STRATEGIES

EXHAUST CONFIGURATION:

- Fan pulls air through system
- Negative pressure inside enclosure
- Slightly better cooling efficiency

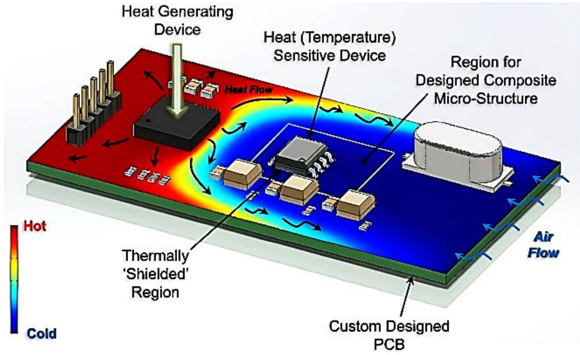
INLET CONFIGURATION:

- Fan pushes air through system
- Positive pressure inside enclosure
- Direct component cooling



8.3 System-Level Integration

THERMAL ARCHITECTURE PLANNING



HEAT SOURCE MAPPING:

- Identify all significant heat sources
- Calculate individual power dissipation
- Map thermal interaction zones
- Plan heat removal paths

SYSTEM THERMAL BUDGET:

COMPONENT	POWER (W)	LOCAL TEMP RISE (°C)	COOLING METHOD
CPU	25	45	HEAT SINK + FAN
POWER SUPPLY	15	35	NATURAL CONVECTION
LED ARRAY	8	30	MCPCB + HEAT SINK
LINEAR REGULATOR	3	25	COPPER PLANE
TOTAL	51	-	SYSTEM FAN

LIQUID COOLING INTEGRATION

WHEN TO CONSIDER LIQUID COOLING:

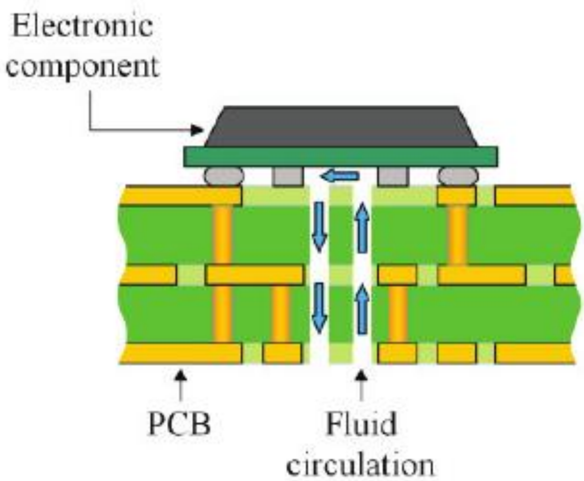
- Power density >200W/L
- Quiet operation required
- Remote heat rejection needed

LIQUID COOLING TYPES:

- Closed loop systems
- Custom loops
- Phase change cooling

IMPLEMENTATION CHALLENGES:

- Leak prevention critical
- Pump reliability
- Maintenance requirements



8.4 Simulation Tools and Methods

THERMAL SIMULATION CATEGORIES

COMPONENT-LEVEL:

- Package thermal models
- Junction-to-case resistance
- Thermal test chip data
- JEDEC standard models

BOARD-LEVEL:

- PCB layer stack-up modeling
- Component placement optimization
- Via thermal network analysis
- Airflow interaction

SYSTEM-LEVEL:

- Enclosure thermal modeling
- Fan curve integration
- Multi-board interactions
- Environmental conditions

POPULAR SIMULATION TOOLS:

TOOL	CAPABILITY	COST	APPLICATION
ANSYS ICEPAK	FULL 3D CFD	HIGH	PROFESSIONAL
MENTOR FLOTHERM	ELEC FOCUSED	HIGH	PROFESSIONAL
SIWAVE	SI/PI/THERMAL	MEDIUM	BOARD LEVEL
OPENFOAM	OPEN SOURCE CFD	FREE	ACADEMIC

8.5 Measurement and Validation

TEMPERATURE MEASUREMENT METHODS

THERMOCOUPLES:

- Wide temperature range
- Good accuracy (±1-2°C)
- Multiple point monitoring

INFRARED CAMERAS:

- Full surface temperature map
- Real-time monitoring
- Emissivity compensation required

THERMAL TEST POINTS:

- PCB-mounted temperature sensors
- Specific location monitoring
- Continuous operation data

MEASUREMENT ACCURACY FACTORS:

FACTOR	IMPACT	MITIGATION
THERMAL MASS	MEASUREMENT DELAY	SMALL SENSORS
CONTACT RESISTANCE	LOWER READINGS	THERMAL INTERFACE
AIR CURRENTS	FLUCTUATING READINGS	SHIELD SENSORS
EMISSIVITY VARIATION	IR CAMERA ERRORS	CALIBRATION

VALIDATION PROCESS

THERMAL TEST PROTOCOL:

- Power-up sequence documentation
- Steady-state temperature recording
- Transient response measurement

CORRELATION WITH SIMULATION:

- Compare measured vs predicted
- Update simulation models
- Refine design parameters

ADVANCED TOPICS

9.1 Thermal Reliability Engineering

ACCELERATED TESTING

TEMP CYCLING:

- -40°C to +125°C typical
- 1000+ cycles standard
- Solder joint reliability
- Package stress analysis

POWER CYCLING:

- On/off thermal stress
- Bond wire fatigue
- Die attach reliability
- Real-world simulation

LIFE PREDICTION MODELS

ARRHENIUS MODEL:

$$h = C \times (\Delta T/L)^n$$

COFFIN-MANSON MODEL:

$$Nf = A \times (\Delta T)^{-n}$$

Where:

Nf = Cycles to failure

ΔT = Temperature swing

n = Material constant

A = Material constant

DESIGN FOR RELIABILITY

- 20°C margin from limits
- Conservative design approach
- Extended operational life
- Reduced warranty costs

9.2 Future Trends and Technologies

ADVANCED PCB TECHNOLOGIES

EMBEDDED COMPONENTS:

- Components inside PCB
- Improved thermal paths
- Reduced assembly height
- Manufacturing complexity

3D PRINTED HEAT EXCHANGERS:

- Complex geometries
- Optimized heat transfer
- Custom solutions
- Rapid prototyping

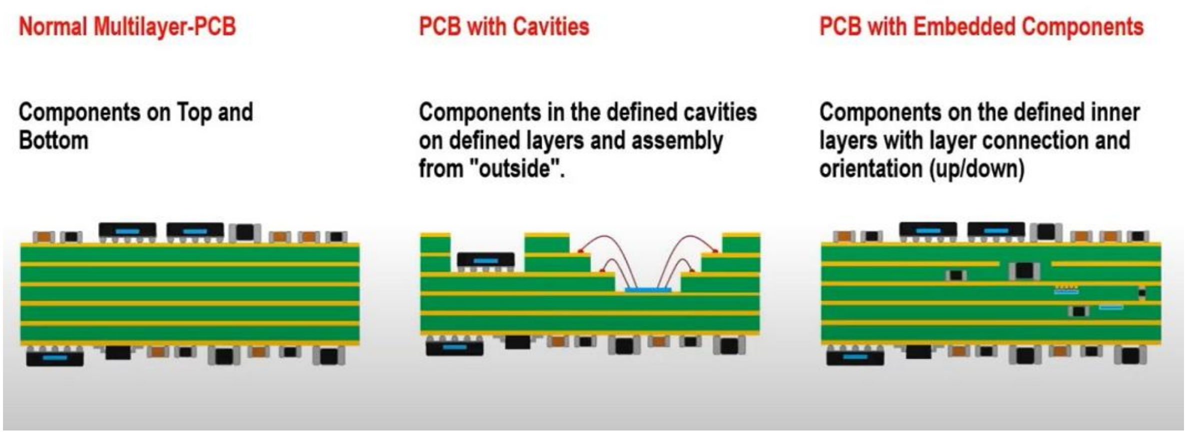
SMART THERMAL MANAGEMENT

ADAPTIVE COOLING:

- Temperature-based fan control
- Dynamic power management
- Predictive thermal control
- System optimization

THERMAL MONITORING NETWORKS:

- Distributed sensors
- Real-time monitoring
- Predictive maintenance
- System health assessment



DESIGN GUIDELINES SUMMARY

Material Selection Guide

DENSITY	PCB MATERIAL	COPPER	COOLING METHOD
<1W/CM^2	STANDARD FR-4	1OZ	NATURAL CONVECTION
1-5W/CM^2	HIGH TG FR-4	2OZ	HEAT SINK + NATURAL
5-15W/CM^2	MCPCB	3OZ	FORCED AIR
>15W/CM^2	CERAMIC	HEAVY	LIQUID COOLING

Thermal Via Guidelines

POWER	VIA COUNT	VIA SIZE	SPACING
<1W	4	0.2MM	1.5MM
1-5W	9	0.3MM	2.0MM
5-15W	16	0.5MM	2.5MM
>15W	25+	0.8MM	3.0MM

Heat Sink Selection

POWER	HEAT SINK TYPE	TH RESISTANCE	TYPICAL COST
1-5W	STAMPED ALUMINUM	20-50°C/W	$0.50-2.00
5-25W	EXTRUDED ALUMINUM	5-20°C/W	$2.00-10.00
25-100W	BONDED FIN	2-10°C/W	$10.00-50.00
>100W	VAPOR CHAMBER	0.5-3°C/W	$50.00-200.00

Design Checklist

THERMAL ANALYSIS:

- [ ] Power dissipation calculated for all components
- [ ] Junction temperatures verified within limits
- [ ] Thermal resistance paths analyzed
- [ ] Worst-case scenarios considered

PCB DESIGN:

- [ ] Appropriate PCB material selected
- [ ] Copper weight optimized for thermal performance
- [ ] Thermal vias properly designed and placed
- [ ] Component placement optimized for heat flow

COOLING SYSTEM:

- [ ] Heat sinks properly sized and selected
- [ ] Thermal interface materials specified
- [ ] Airflow requirements calculated
- [ ] Fan selection and placement optimized

VALIDATION:

- [ ] Thermal simulation completed
- [ ] Temperature measurements planned
- [ ] Reliability analysis performed
- [ ] Design margins verified