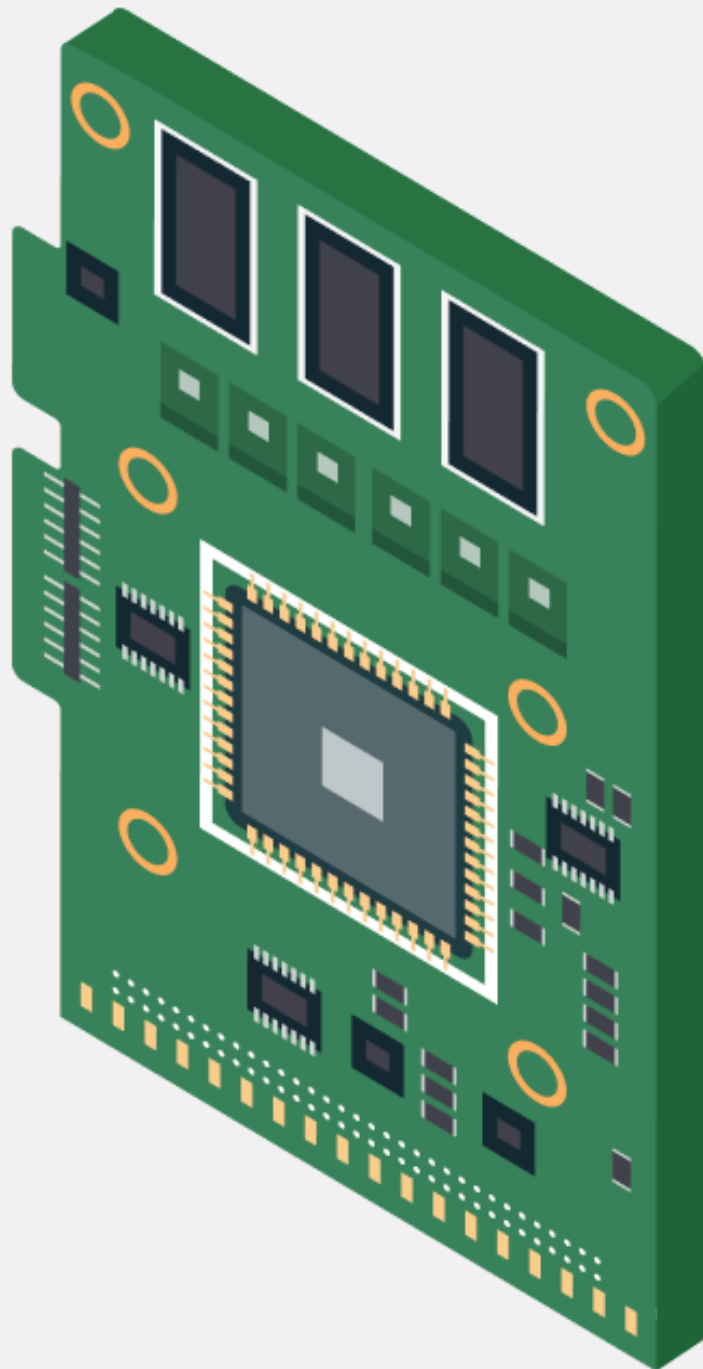


Designing PCBs for Harsh Environments

A guide to building boards that survive vibration, moisture, heat, and EMI



Moisture, Humidity, Corrosion

Protection Strategies:

- **Sealed Enclosures:** Full mechanical barrier against water ingress, rated to IP67/IP68 depending on design. General idea is for PCB to be housed inside a physical shell and sealed using gaskets, ultrasonic welding, or adhesives.
 - Advantages: Full immersion protection, excellent physical durability, no impact on reworkability or board-level design.
 - Tradeoffs: Adds thermal management complexity (trapped heat), mechanical seals must withstand thermal cycling.
- **Conformal Coating:** Thin polymer film (25–250 μm) applied directly to PCB surfaces to protect against moisture, dust, chemicals, and temperature swings. Covers components, solder joints, and traces with a moisture-resistant film.
 - The coating “conforms” to the board contours, covering components, solder joints, traces, and exposed metal surfaces.
 - Advantages: Lightweight, allows airflow, preserves board accessibility, useful for splash or high-humidity environments.
 - Tradeoffs: Not rated for immersion; edge coverage and sharp corners are potential failure points if coating isn’t uniform.
- **Hydrophobic Nanocoatings:** Creates a surface with a high water contact angle that causes droplets to bead and roll off instead of wetting the surface.
 - Advantages: Ultra-thin (1–2 μm), no impact on weight, reworkable; ideal for splash resistance or condensation protection.
 - Tradeoffs: Not suitable for full immersion or pressurized moisture; wears off over time without reapplication.
- **Potting:** Encase the PCB in epoxy, polyurethane, or silicone resin to create a permanent waterproof block.
 - Liquid resin is poured into a mold or housing around the PCB, then cured to form a solid mass that excludes water and air.
 - Advantages: Highest level of environmental protection (IP68+), excellent resistance to pressure, vibration, chemicals, and physical abuse.
 - Tradeoffs: Adds weight and volume, raises thermal resistance (poor heat dissipation), and makes rework or inspection nearly impossible.



Potting a PCB



UV inspection of a conformal coated PCB

Moisture, Humidity, Corrosion

Conformal Coating

Applications: Common in aerospace (avionics, mission-critical boards), automotive (ECUs, underhood electronics), wearables (waterproofing), and medical devices (corrosion prevention in implants).

Application Methods:

- **Spraying:** Manual or automated. Good for high-mix, low-volume runs. Requires masking to protect connectors and no-coat zones.
- **Brushing:** Used for rework or small batches. Precise but inconsistent; not suitable for production.
- **Dipping:** Full immersion offers uniform coverage, including under components. High throughput but needs extensive masking.
- **Selective Coating:** Robotic systems apply coating only where needed, reducing waste and eliminating masking. Scales well for medium to high-volume production.

Conformal Coating Types

Type	Strengths	Tradeoffs	Use Cases
Acrylic	Cheap, fast to apply, easy to rework	Limited chemical resistance	Consumer, light industrial
Silicone	Wide temp range (-65 °C to +200 °C), flexible under stress	Lower abrasion resistance	Automotive, aerospace
Polyurethane	Excellent chemical and abrasion resistance	Harder to remove, slower cure	Fuel/chemical exposure environments
Epoxy	Strong, durable, moisture-proof	Rigid, not reworkable	Industrial, sealed systems
Parylene	Ultra-thin, uniform, pinhole-free (via vacuum CVD)	Expensive, slow, can't be reworked	Medical, aerospace, high-reliability

Vibration & Shock

Vibration and shock are responsible for roughly 20% of PCB assembly field failures, typically at mechanical weak points like solder joints and component leads.

Common Failures Mechanisms:

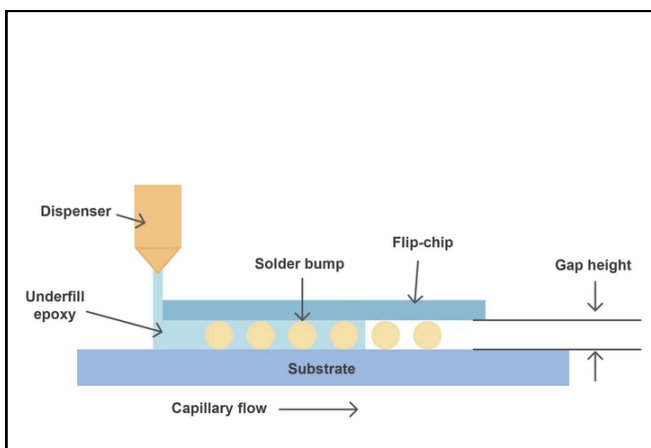
- **Solder Joint Fatigue:** Caused by cyclic mechanical stress, especially in surface-mounted devices (SMDs) and ball grid arrays (BGAs).
 - Cracks often initiate at solder fillets (SMDs) and the top of solder balls (BGAs), and can be exacerbated by coefficient of thermal expansion (CTE) mismatch or high package mass.
- **Board Flexure:** Vibration & shock events cause bending, concentrating stress at mounting points and unsupported board spans.
 - Effects can include cracked solder joints, pad delamination (more pronounced on rigid substrates like FR-4), or damaged components.
- **Shock Events:** Mechanical shock can produce accelerations of 20–100g over a short duration of time.
 - Typical shock levels include 100g during missile launch (defense), 40g during crash landings (aerospace), and 30g from pipeline strikes (oil & gas).

Design Considerations:

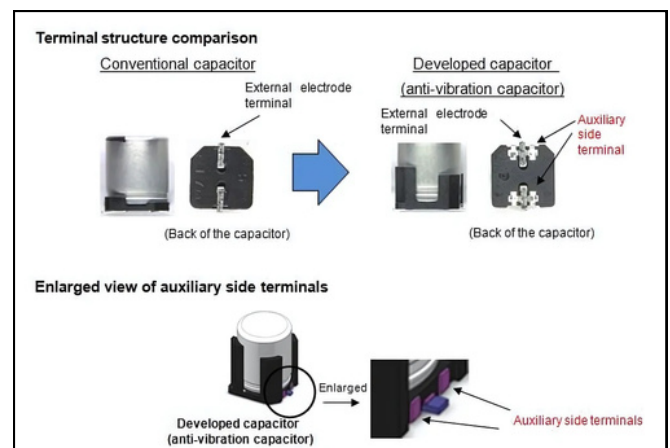
- **Underfill Epoxy:** Epoxy flows beneath the package, then cures to reinforce solder joints and improve shock resistance. Can significantly strengthen SMD components.
- **Anti-Vibration Components:** Use capacitors and other passives specifically designed with ruggedized terminations or flexible leads.
- **Board Stiffening:** Increase PCB thickness (especially beneficial in high-mass component regions or where the board spans large mounting distances) or add metal stiffeners (e.g. aluminum backing plates)
- **Mounting:** Use multiple mounting points with wedge-locks, metal standoffs, or Nyloc nuts for vibration damping.
- **Shock-Absorbing Enclosures:** Use vibration isolators or compliant gaskets to decouple the board from enclosure shocks.

Testing Standards:

- Designs should be validated using environmental standards that simulate real-world vibration and shock loads. Common benchmarks include MIL-STD-810H (defense/aerospace) and IEC 60068-2-64 (automotive/industrial), which define profiles for random vibration, mechanical shock, and combined stress testing.



Underfill Epoxy Process



Comparison of standard and anti-vibration capacitors

Thermal Stress & Management

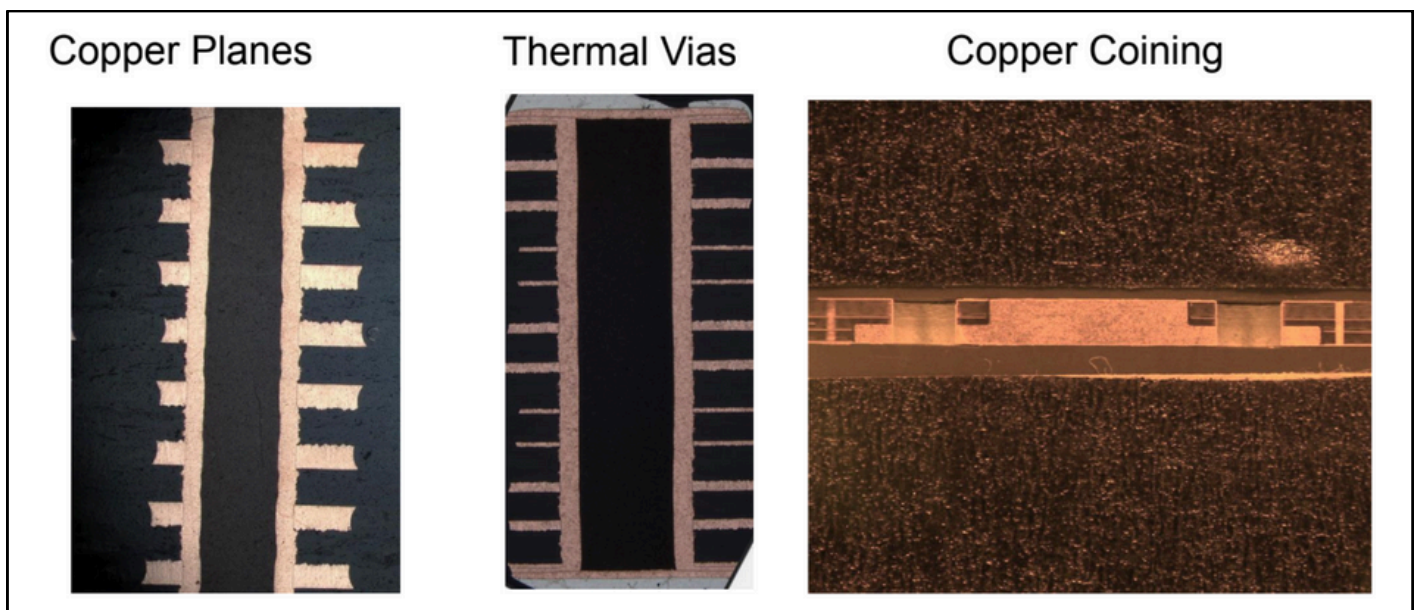
Environments like aerospace, defense, downhole drilling, and mining expose electronics to **-55 °C** to **+150 °C** during operation. Broader non-operating conditions can also occur during transport or storage.

Design Considerations:

- **Component Selection:** Use mil-temp (-55 °C to +125 °C) or AEC-Q100 Grade 0 ICs rated to +150 °C.
 - Mil-temp components follow military standards for extreme temperature and reliability.
 - AEC-Q100 is an automotive qualification standard; Grade 0 is the highest tier, designed for under-hood conditions and harsh thermal cycling.
- **Materials:** Standard FR-4 degrades above 130 °C. Use high-Tg FR-4 (Tg >170 °C) or polyimide for sustained high-temp applications.
 - For >150 °C or high thermal loads, metal-core PCBs or IMS (Insulated Metal Substrate) improve heat conduction and CTE matching.
- **Assembly & Interconnects:** Use high-temp solder alloys to maintain joint integrity above 125 °C.
 - For example, transient liquid phase sintering paste (TLPS) melts once during reflow, then forms stable intermetallics that behave like solid metal. It cannot re-melt under normal operating conditions, making it ideal where reflow, creep, or thermal fatigue must be permanently eliminated.

PCB Thermal Management Techniques

- Thermal vias beneath hot components help spread heat to internal copper planes or external heat sinks.
- Copper planes (large continuous copper layers) help spread heat laterally and into connected thermal vias.
- Copper coining embeds thick copper slugs beneath high-power parts for direct conduction through the PCB.



Cross-Section of Internal PCB Heat Dissipation Methods

Electromagnetic Interference (EMI)

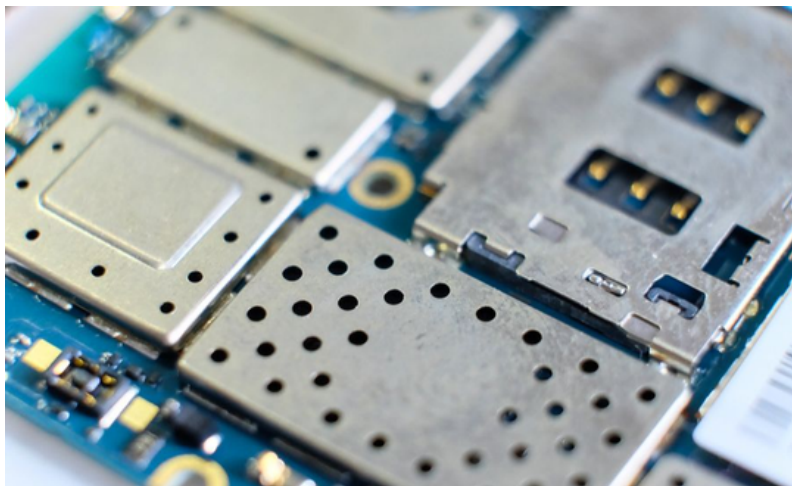
Harsh environments often involve high levels of electromagnetic interference (EMI) from sources like motors, relays, or RF systems. EMI protections ensure the system neither emits nor absorbs unwanted signals that could disrupt operation or damage sensitive components.

Design Considerations:

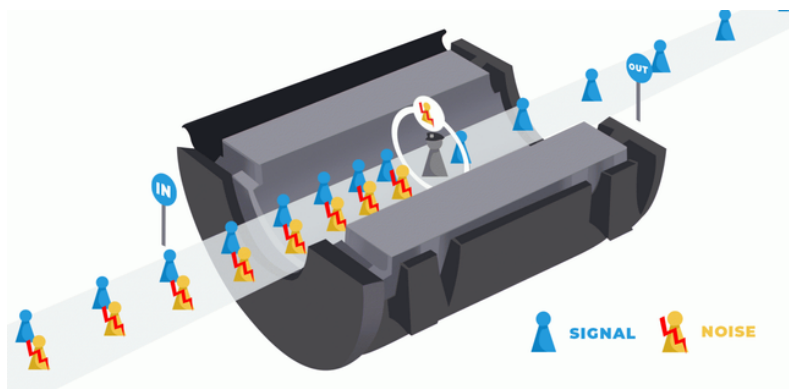
- **Shielding Cans and Enclosures:** Enclose noisy or sensitive circuitry in metal cans or conductive housings. Acts as a Faraday cage to block external RF sources.
- **Cable Shielding and Routing:** Use shielded cables for I/O, power, and high-speed lines.
- **Chassis Grounding:** Tie cable shields and enclosure grounds to a low-impedance chassis ground. Avoid ground loops by controlling return paths.

Board-Level Considerations:

- **Solid Ground Planes:** Use continuous, low-impedance planes to minimize loop area and provide clean return paths for high-speed signals. Reduces both radiated and conducted emissions.
- **Differential Pair Routing:** Keep differential pairs tightly coupled with consistent spacing and controlled impedance. Reduces EMI and limits coupling to nearby traces.
- Ferrite beads at power entry points and local decoupling capacitors near high-speed ICs suppress high-frequency noise and isolate noisy subsystems.



PCB Shielding Can



Internal structure of a ferrite bead used to block high-frequency noise