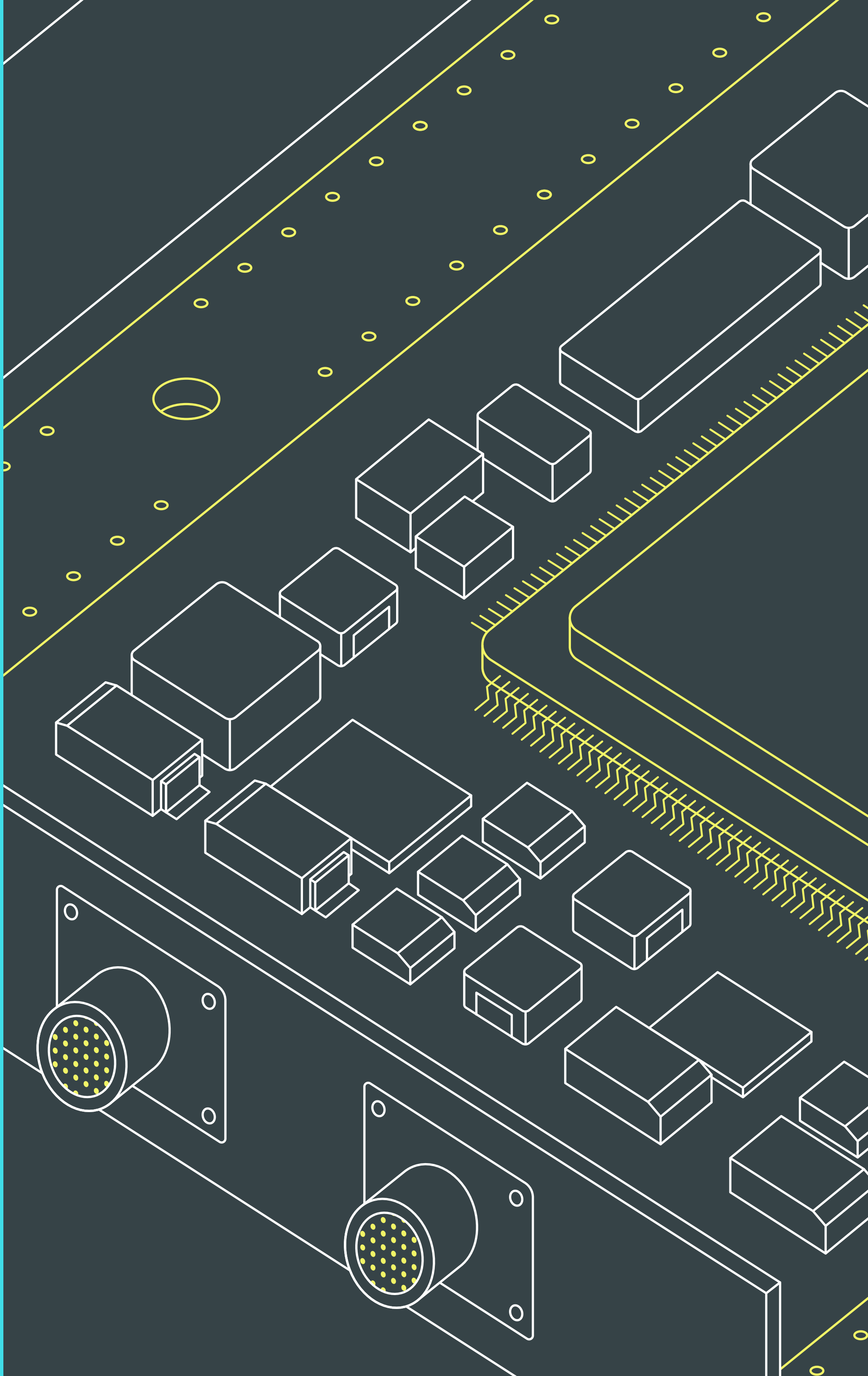
TEMPO

PART 1 OF 2

PCBA Manufacturing for Extreme Environments

Temperature, Pressure, Corrosion



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Introduction

THE PCBAS THAT ARE USED IN MOST EQUIPMENT ARE DESIGNED WITH VERY BENIGN ENVIRONMENTS IN MIND. TYPICALLY THIS MEANS TEMPERATURE-CONTROLLED BUILDINGS THAT ARE DRY, STATIONARY AND AT ATMOSPHERIC PRESSURE.

Just putting electronics outside presents challenges of wide temperature ranges, moisture, and possibly even rodents. High mountains, deserts, and arctic environments makes these challenges worse. Then at the extreme end are the abyssal plane at the bottom of the ocean, oil wells deep under the earth and the vacuum of outer space. Cars and trucks, industrial machinery, aircraft, and rocket engines present their own unique challenges. Each of these environments presents unique challenges that can only be met by specialized techniques. This ebook series will cover the effects extreme environments have on electronics and how manufacturing can help mitigate those effects.

EMI and ESD appear in extreme environments but they are covered in many existing resources so they will not be included in this discussion.

PART 1 WILL COVER:

- High and Low DRASD Temperature
- High Pressure and Vacuum
- Humidity and Corrosion

AND PART 2 WILL COVER:

- Vibration and Shock
- Particle Radiation

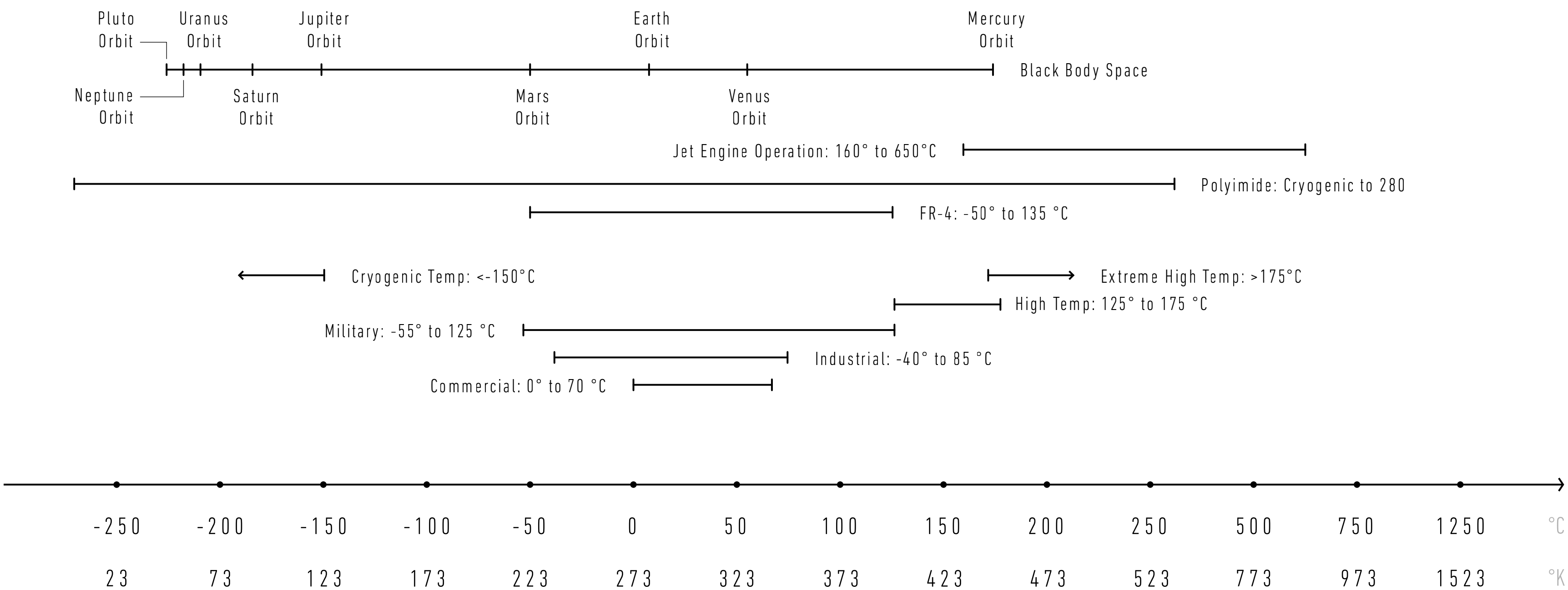
This ebook will also not cover design techniques or techniques that involve environmentally controlled chambers such as temperature chambers, pressure vessels, etc. These techniques are very successful but they rely on system level design beyond the PCBA and therefore they are out of scope.

DISCLAIMER: Components and PCBAs vary significantly by manufacturer so it is necessary to do extensive testing in a controlled environment to validate proper functionality under the target environmental conditions.

Temperature

EXTREME TEMPERATURES ARE ONE OF THE ENVIRONMENTAL FACTORS THAT ELECTRONICS EXPERIENCE MOST OFTEN.

Temperature has dramatic effects not only on material properties but also the geometry of the PCBA. These effects are true for the entire temperature range but their impact on PCBAs changes whether it is high or low temperature.



Effects

MATERIAL BREAKDOWN

At both the high and low end of the temperature range materials used for PCBAs can begin to fail. At high temperatures this failure is characterized first by the weakening of the chemical bonds within materials and an increase in their CTE (see below). This is known as the glass transition temperature (T_g). At even higher temperatures the chemical bonds actually begin to break at what is known as the decomposition temperature (T_d). All materials that make up a PCBA have a T_g and a T_d including IC packages and dielectric materials. At very low temperatures PCBA materials become brittle and cracks begin to form, making the board extremely weak.

MATERIAL BREAKDOWN

Another effect is that chemical reactions such as metal migration, void formation, corrosion in water, intermetallic growth, and dielectric breakdown speed up at higher temperatures.

THE INCREASE RATE IS DESCRIBED BY THE ARRHENIUS LAW:

$$t_f = Ae\left(\frac{-E_a}{kT}\right)$$

Where A is a constant related to reaction, E_A is the activation energy associated with the reaction, k is the Boltzmann constant (8.617×10−5 eV/K) and T is the absolute temperature.

A USEFUL REARRANGEMENT OF THIS IS AS AN ACCELERATION FACTOR (AF) COMPARED TO THE BASE RATE:

$$AF = \left(\frac{Time_{use}}{Time_{test}}\right) = e\left(\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)\right)$$

Arrhenius effects forms the basis of the “doubling” rule of thumb which states, **“For every increase of 10°C, component life is reduced by half.”**

This rule of thumb does model lifetime impact, but only under certain temperature and even then they may not be the dominant factor so be sure to consider other factors as well.

THERMAL CYCLING

All materials have a coefficient of thermal expansion (CTE). This measures the amount that the material physically expands or contracts per degree °C. CTE becomes an issue when two materials have different CTEs rates. This differential expansion causes stress between materials. So, though CTE is a temperature effect, the actual impact on the PCBA is physical. CTE affects everything from the component packages and copper-dielectric bond, to the lead-solder bond. In applications where the device goes through multiple thermal cycles, stress causes fatigue and can ultimately break the bond or the material itself. Satellites are an extreme example of this, where internal temperatures can range ±100°C(K) depending on whether the satellite is in sunshine or in shadow. Temperature cycling also affects aircraft, automobile engines, and telecom installations.

THERMAL SHOCK

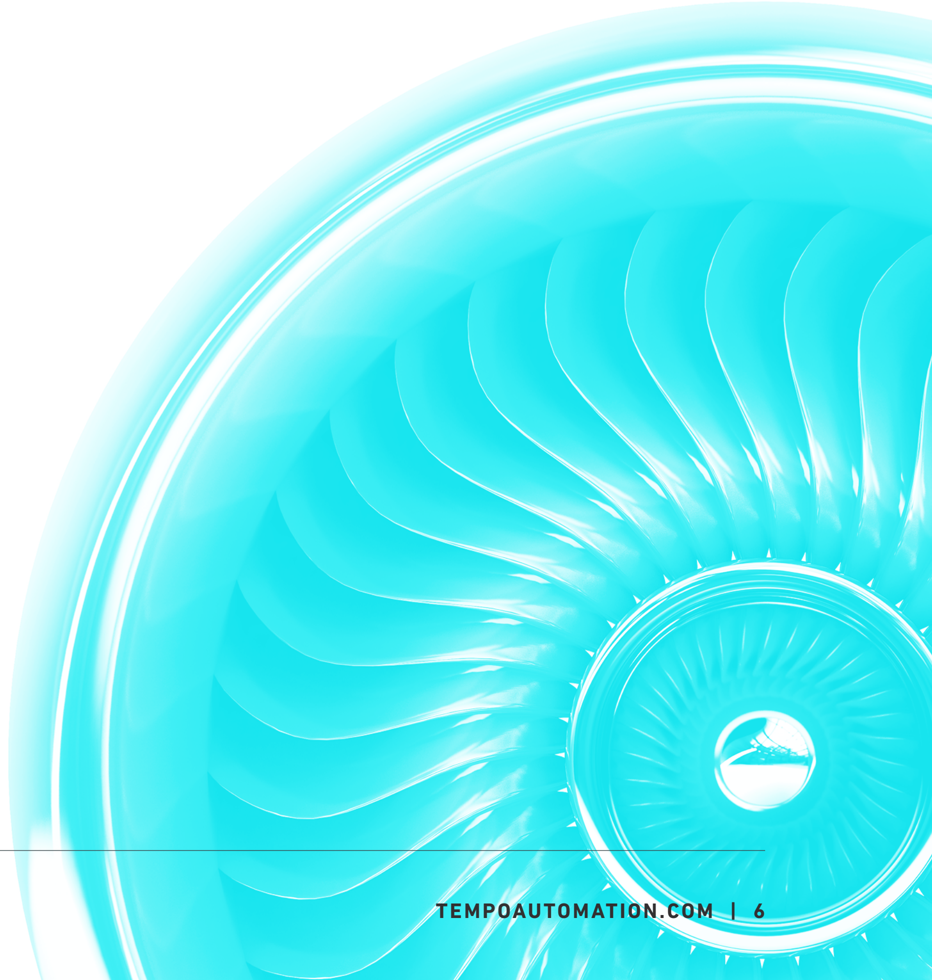
Thermal shock is also a CTE effect, but the difference is that in thermal shock events the rate of change in the temperature is much higher. Typically, shock happens at rates of 30°C/min or higher. At these rates the surface of the material can be at a much higher temperature than the core. This temperature gradient creates a differential expansion which exerts large stresses on the board and, if they are greater than the strength of the board, will cause cracking. The classic example is reflow in assembly, but thermal shock can also occur under environmental conditions especially in motors, jet and rocket engines, or even unloading from a temperature controlled environment to the atmosphere.

THERMAL COEFFICIENTS

Beyond physical and chemical degradation of the board, all parts of the PCBA have parameters that drift with temperature. The capacitance of capacitors, the resistance of resistors, the gain of transistors, the D_k of dielectric materials, et cetera, all show a temperature dependence. Circuits operation can fail if these parameters drift too much.

OUTGASSING

High temperatures can cause package or PCB material outgas into the PCBA enclosure. These can then condense onto the board, where it can cause corrosion or interfere with circuit operation. Also, trapped substances, such as water, can put high forces on PCB interfaces potentially causing delamination.



Manufacturing Considerations

High Temperature Applications

COMPONENTS

High static temperatures affect PCBAs mainly through weakening of the physical material, coefficient effects, and accelerated chemical reactions. Physical weakening is defined by the glass transition temperature (T_g). For plastic packages T_g max is around 175°C (448°K) but ceramic packages can go to much higher temperatures. Component thermal coefficients vary a lot but, in general, resistors are affected less and capacitors are affected more. Semiconductors generally lose gain and have higher leakage as temperature increases.

COMPONENT	EXTREME TEMPERATURE	HIGH TEMPERATURE	HIGH TEMPERATURE NOT RECOMMENDED
Connectors	Nickel Alloy, Stainless Steel Contacts PTFE, PEEK, Ceramic Housing	Phosphor Bronze, Brass Terminals Polyamide, Aluminum Housing	Polyester, Polyethylene, A.B.S, PVC Housings
Resistors	Wirewound, Metal Film	Thin Film, Thick Film	Carbon Composition
Capacitors	Ceramic NP0, PTFE	Ceramic X7R	Electrolytic
Semiconductors	Silicon on Insulator (Sol, Silicon Carbide (SiC), LTCC Packages	Silicon	—
Oscillators	MEMs, VXO, LTCC Packages	Ovenized Crystal	Uncompensated Crystal, Temperature Compensated Crystal

PCB MATERIALS

Dielectric materials should have a T_g that is 25°C greater than the maximum operating temperature. Dielectric material parameters, such as D_k and D_r are also highly temperature dependent and may not be stable at higher temperatures. High temperatures can also cause outgassing so select for materials that have a low Total Mass Loss (TML) and a low Collected Volatile Condensable Materials (CVCM) parameters. RT/Duroid and TMM materials are good examples. For solder, general rule is the maximum temperature the solder is exposed to is 25°C less than the eutectic temperature. This means that most solder will work at high temperatures. It is only the extreme end, such as downhole applications, where different solder chemistry is required.

MATERIAL	EXTREME TEMPERATURE	HIGH TEMPERATURE	HIGH TEMPERATURE NOT RECOMMENDED
Dielectric	LTCC, Polyimide, Rogers 3000	High Temp FR-4	FR-4, High Speed Laminates
Solder	High Lead Content Solder	Lead Free63Sn-37Pb	—
Surface Finish	—	—	—

Low Temperature Applications

COMPONENTS

Low temperature applications show different effects. For passive components, resistance rises and capacitance falls. Another example is that some semiconductors can exhibit what is known as carrier "freeze out" and cease to function.

MATERIAL	CRYOGENIC TEMPERATURE	LOW TEMPERATURE	NOT RECOMMENDED
Connectors	Gold Contacts, Metal Housing	Gold Contacts, Metal Housing	Tin Contact, Plastic Housing
Resistors	Thin FIlm, Wire Wound, Metal Film	Thick Film	Carbon Composition
Capacitors	PTFE Capacitor, Ceramic NP0	Ceramic X7R	Electrolytic
Semiconductors	MOSFET	Bipolar, JFET	—
Oscillators	MEMs	Si	—

PCB MATERIALS

Dielectric materials and packages become brittle at low temperatures. For example FR-4 can be used down to -50°C but below that cracks begin to form.

MATERIAL	CRYOGENIC TEMPERATURE	LOW TEMPERATURE	NOT RECOMMENDED
Dielectric	Polyimide, Aluminum	FR-4	—
Solder	Indium Based	Indium Based	Sn Based Solder
Surface Finish	ENIG	ENIG	HASL

APPLICATIONS WITH TEMPERATURE CYCLING

PCBAs in applications where the temperature cycles not only have to withstand the temperature extremes, but also have to withstand the stress caused by differential CTE rates. The key is to match the CTE of the ICs, copper and dielectric material together. Some dielectric materials have intrinsically low Z-CTE. A metal core can also reduce the effective CTE of the dielectric material. Another option is to increase dielectric and copper thickness which will increase the total fatigue the PCBA can endure.

APPLICATIONS WITH THERMAL SHOCK

Thermal shock is driven by absolute CTE of the material rather than how well it matches with the other materials around it. Selecting low CTE materials such as polyimide will help reduce the effects of thermal shock. Increasing thermal conductivity can also help lessen the thermal gradient and reduce stress to the board.

SOME REPRESENTATIVE CTES ARE SHOWN BELOW:

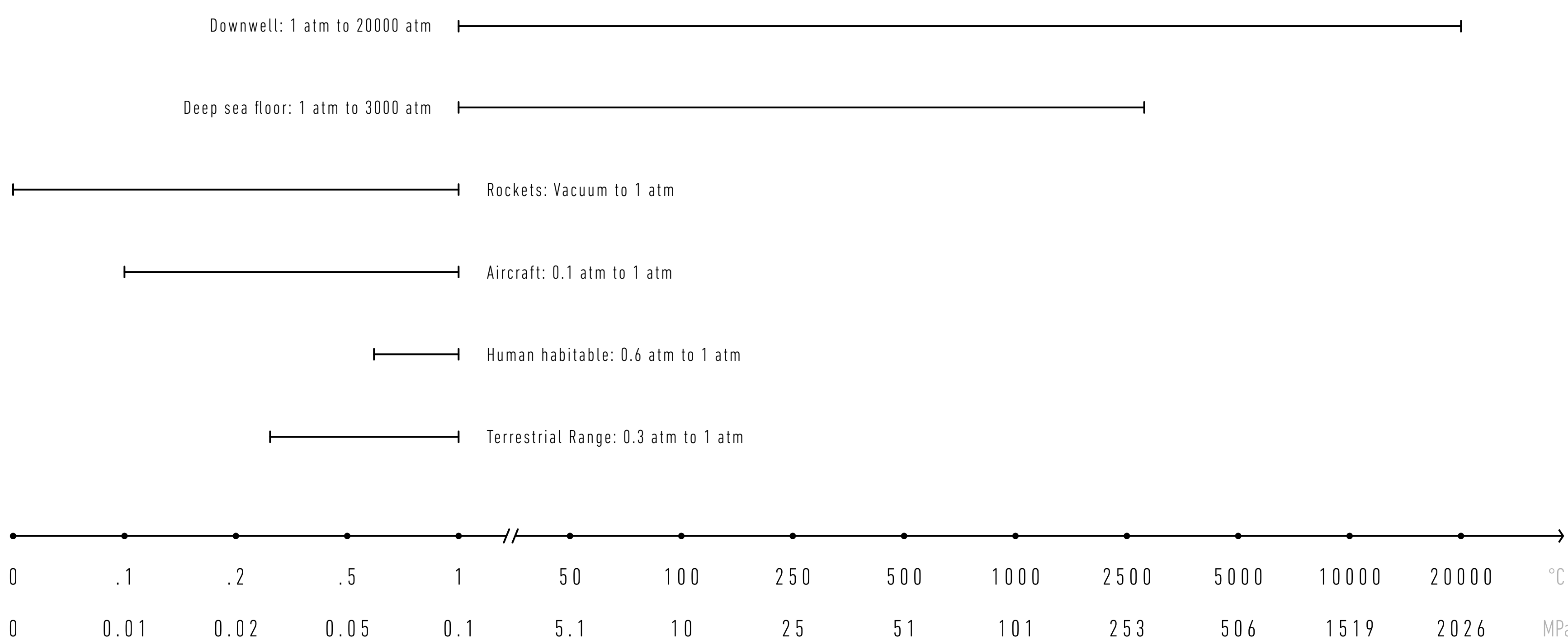
MATERIAL CTE

MATERIAL	CTE (PPM/°C)
Copper	17
Large IC Packages	6
FR-4	14
FR-4 with Copper-Invar-Copper (CIC) Core	12
FR-4 with Copper-Molybdenum-Copper (CMC) Core	9
PTFE	200
Polyimide	55
LTCC	4-8

Pressure

PRESSURE EXERTS AN EVEN FORCE OVER THE ENTIRE CIRCUIT BOARD ASSEMBLY.

In general, pressure differentials put physical stress on the PCBA. Pressure can also speed up diffusion effects where material is either absorbed from or outgassed into the environment. Vacuum testing is done by many manufacturers for space rated component but unfortunately, there are not many who will test their components at high pressure so validation has to be done by the designer.



Effects

VOID RUPTURE

Voids are created during the manufacture of many components and they are filled with gases (most often air) at atmospheric pressure. As ambient pressure increases or decreases, the differential pressures can create high enough forces that can cause failure of the component or board.

OUTGASSING

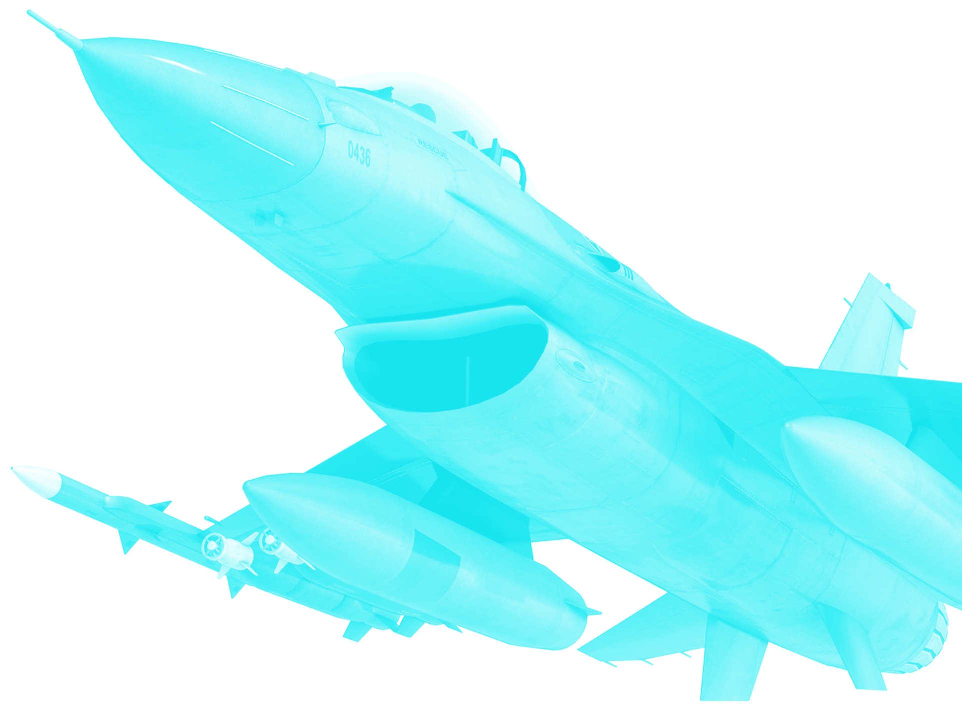
At low pressures gases or liquids trapped in the PCBA can outgas. This can even happen with the PCBA materials themselves. Outgassing can cause physical damage or potential corrosion the outgassed material condenses on the PCB. Examples of this are electrolyte leaks in batteries and electrolytic capacitors.

INCREASED ABSORPTION

The inverse of outgassing is adsorption. Absorption happens at any pressure if there are fluids or gases surrounding the PCBA (see the **Relative Humidity** section). This is most often water moisture but can be anything the PCBA is in contact with (for example, dielectric oil in a deep ocean application). The gas or fluid will penetrate component packages or PCB dielectric and can cause parameter changes, swelling, or delamination. Higher pressures exacerbate this effect.

PRESSURE CYCLING

Cycling between high and low pressure puts PCBAs under the same sort of physical stress that temperature cycling can though, in this case the fatigue mechanism is absorption and outgassing or pressure differentials in the materials rather than CTE. This is another case where overall fatigue capacity of the PCBA materials is the key parameter.



Manufacturing Considerations

High Pressure Applications

COMPONENTS

For systems that do not use a pressure vessel the electronics are surrounded by a dielectric fluid such as oil. However, this means that the components must be able to withstand the pressure differences involved. Many COTS components are inherently pressure tolerant because they are manufactured without voids. For components with voids it may be possible to pierce them so dielectric fluid can fill them. If that is not possible then these components should be potted in an encapsulant that can act as a shield and prevent implosion.

PCB MATERIALS

Absorption is a greater issue at high pressure. Selecting PCB materials that are resistant to intrusion or compensating for parameter changes are possible mitigations. Another option is coating or potting in a hermetic compound.

COMPONENT	HIGH PRESSURE TOLERANCE	NOT RECOMMENDED
Connectors	All	None
Resistors	Carbon Film, Metal Film, Wire Wound, Tin Oxide	Carbon Comp.
Capacitors	Ceramic, Film, Solid Tantalum	Aluminum Electrolytic, Wet-Slug Tantalum, Paper
Semiconductors	Epoxy Enclosed	Metal Can
Oscillators	Surface Mount or Epoxy Coated Resonators	Surface Mount or Metal Can Crystals

Low Pressure Applications

COMPONENTS

Low pressure can cause the same pressure differentials as high pressure so the same types of components can be used. Outgassing can happen if pressure differentials are high enough. See the **Temperature Outgassing** section for mitigation options. It can also increases the likelihood of ESD events.

PCB MATERIALS

Outgassing is also an issue in low pressure and vacuum applications. Use the same recommendations described in the **High Temperature** section.

MATERIAL	VACUUM	LOW PRESSURE	NOT RECOMMENDED
Connectors	Hermetically Sealed Metal	Hermetically Sealed	Exposed Pins
Resistors	Sealed to Prevent Outgassing	Most COTs, Sealed to Prevent Outgassing	Plastic Packages
Capacitors	Ceramic, Some Tantalum	—	Vented Electrolytic, Paper
Semiconductors	Hermetically Package, Ceramic	Hermetically Package	—
Oscillators	MEMs, TXO, VXO, Vacuum Sealed	MEMs, TXO, VXO	Housings with Gas Voids

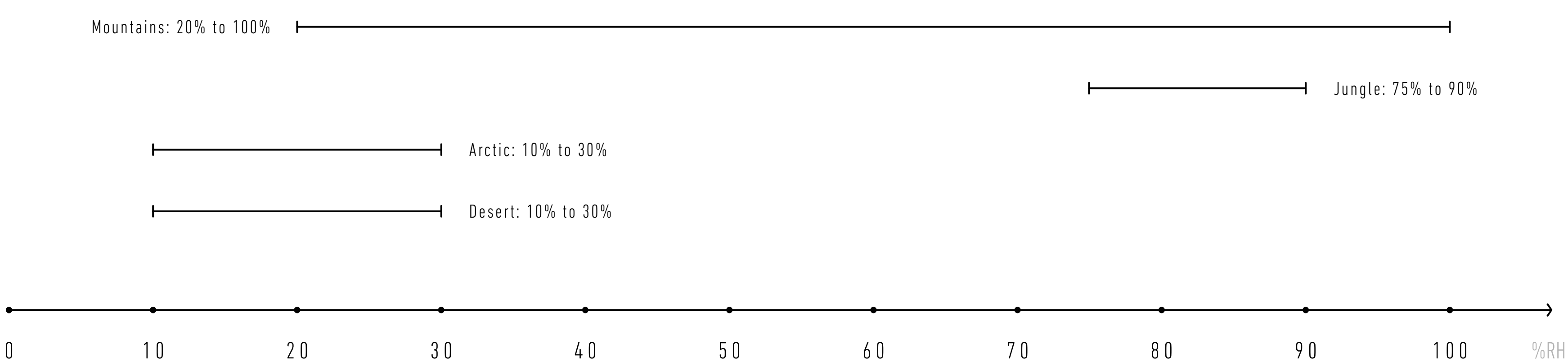
Environmental Corrosion

CORROSION IS A CHEMICAL EFFECT THAT IS CAUSED BY CONTAMINANTS THAT COME IN CONTACT WITH EXPOSED METALS. OUTDOOR, MARINE, AND INDUSTRIAL APPLICATIONS ARE TYPICALLY WHERE CORROSION IS A RISK BUT IT CAN ALSO SHOW UP IN AEROSPACE APPLICATIONS.

One of the most common causes of corrosion is when environmental conditions cause water vapor to condense on the PCBA. This is driven by the relative humidity (RH) of the environment.

The atmosphere can hold a specific mass of water vapor depending on the temperature and pressure. RH is a ratio of the current water vapor mass to the maximum water vapor mass the air can hold. If the temperature increases and pressure decreases the holding capacity increases. If the temperature decreases and pressure increases then the vapor holding capacity decreases. Condensation will form if the maximum capacity approaches the amount of water vapor in the air or visa versa. This condensation can then mix with any contaminants on the board and start corrosion.

RELATIVE HUMIDITY



Condensation is not the only source of moisture for PCBAs. Water can also intrude into the PCBA enclosure from many sources including rain, oceans spray, or equipment washing. Water intrusion can also carry with them additional contaminants such as salt or dirt that can accelerate corrosive processes.

In addition, many industrial environments expose the PCBA to chemicals including H_2S, SO_2, Cl_2 which are highly reactive to PCBA materials.
The ISA has produced the Environmental Conditions for Process Measurement and Control Systems: Airborne Contaminants (ISA-S71.04) standard which contains the following classification system.

SEVERITY LEVEL	ENVIRONMENT	DESCRIPTION
G1	Mild	An environment sufficiently well-controlled such that corrosion is not a factor in determining equipment reliability.
G2	Moderate	An environment in which the effects of corrosion are measurable and corrosion may be a factor in determining equipment reliability.
G3	Harsh	An environment is which there is a high probability that corrosive attack will occur. These harsh levels should prompt further evaluation resulting in environmental controls or specially designed and packaged equipment.
GX	Severe	An environment in which only specially designed and packaged equipment would be expected to survive. Specifications for equipment in this class are a matter of negotiation between user and supplier.

Effects

GALVANIC CORROSION

Galvanic corrosion happens anytime dissimilar metals are immersed in an electrolyte. These metals develop a voltage difference between them which causes an oxidation reaction.

The electrolyte can be many liquids but many times it is water condensing out of the air. The speed of corrosion depends on how far apart the metals are on the galvanic series.

GALVANIC SERIES

	MAGNESIUM	ALUMINUM	ZINC	IRON	CADMIUM	NICKEL	TIN	LEAD	COPPER	SILVER	PALLADIUM	GOLD
MAGNESIUM	0.00	-0.71	-1.61	-1.93	-1.93	-2.12	-2.23	-2.24	-.271	-3.17	-3.36	-3.87
ALUMINUM	0.71	0.00	-.90	-1.22	-1.26	-1.41	-1.52	-1.53	-2.00	-2.46	-2.65	-3.16
ZINC	1.61	0.9	0.00	-0.32	-0.36	-0.51	-0.63	-0.64	-1.10	-1.56	-1.75	-2.26
IRON	1.93	1.22	0.32	0.00	-0.04	-0.019	-0.30	-0.31	-0.78	-1.24	-1.43	-1.94
CADMIUM	1.93	1.26	0.36	0.04	0.00	-0.15	-0.27	-0.28	-0.74	-1.20	-1.39	-1.90
NICKEL	2.12	1.41	0.51	0.019	0.15	0.00	-0.11	-0.12	-0.59	-1.05	-1.24	-.175
TIN	2.23	1.52	0.63	0.3	0.27	0.11	0.00	-0.01	-0.47	-0.93	-1.12	-1.64
LEAD	2.24	1.53	0.64	0.31	0.28	0.12	0.01	0.00	-0.46	-0.93	-1.11	-1.63
COPPER	0.271	2	1.1	0.78	0.74	0.59	0.47	0.46	0.00	-0.46	-0.65	-1.16
SILVER	3.17	2.46	1.56	1.24	1.2	1.05	0.93	0.93	0.46	0.00	-0.19	-0.70
PALLADIUM	3.36	2.65	1.75	1.43	1.39	1.24	1.12	1.11	0.65	0.19	0.00	-0.51
GOLD	3.87	3.16	2.26	1.94	1.9	0.175	1.64	1.63	1.16	0.7	0.51	0.00

ELECTROLYTIC CORROSION

Electrolytic corrosion oxidation process but in this case the voltage difference comes circuit, most often a PCBA. This accelerates the oxidation process. One of the most damaging examples of this is Conductive Anodic Filament (CAF) growth.

GASEOUS CORROSION

Gases in the air, mostly oxygen, can also corrode PCBAs through oxidation. This is even a problem in space vacuums where atomic oxygen can exist and is extremely corrosive to some metals, especially silver.

MOISTURE ABSORPTION

Gas or liquid can enter many dielectric materials through micro-cracks in the surface. Then through wicking and capillary action enter the body of the PCBA. After moisture penetration, delamination and blistering can occur especially if the board is subject to thermal cycles. This effect is accelerated under high pressure.

ESD

As temperature and pressure rise, the RH drops and the resistance of the air increases. At below 30% charge can dissipate into the atmosphere quickly enough and electrostatic charge can begin to build up on surfaces. This can increase ESD damage risk to unacceptable levels. ESD control is well understood during manufacturing but charging can also occur in the environment. In applications where there are now moving parts ESD risk is minimized since there is there is no triboelectric charging. Applications with moving parts have a greater risk, especially if there is a combination of conductors and insulators in the device. One unexpected place where charging occurs is in satellites. Enclosures can be charged directly by plasma or particle radiation and are at 0% RH, of course, so there is no dissipation path. Eventually this can result in an ESD event, either within the satellite itself or into surrounding plasma. If the ESD is in the wrong place it can damage the PCBA.

Manufacturing Considerations

High Humidity Applications

COMPONENTS

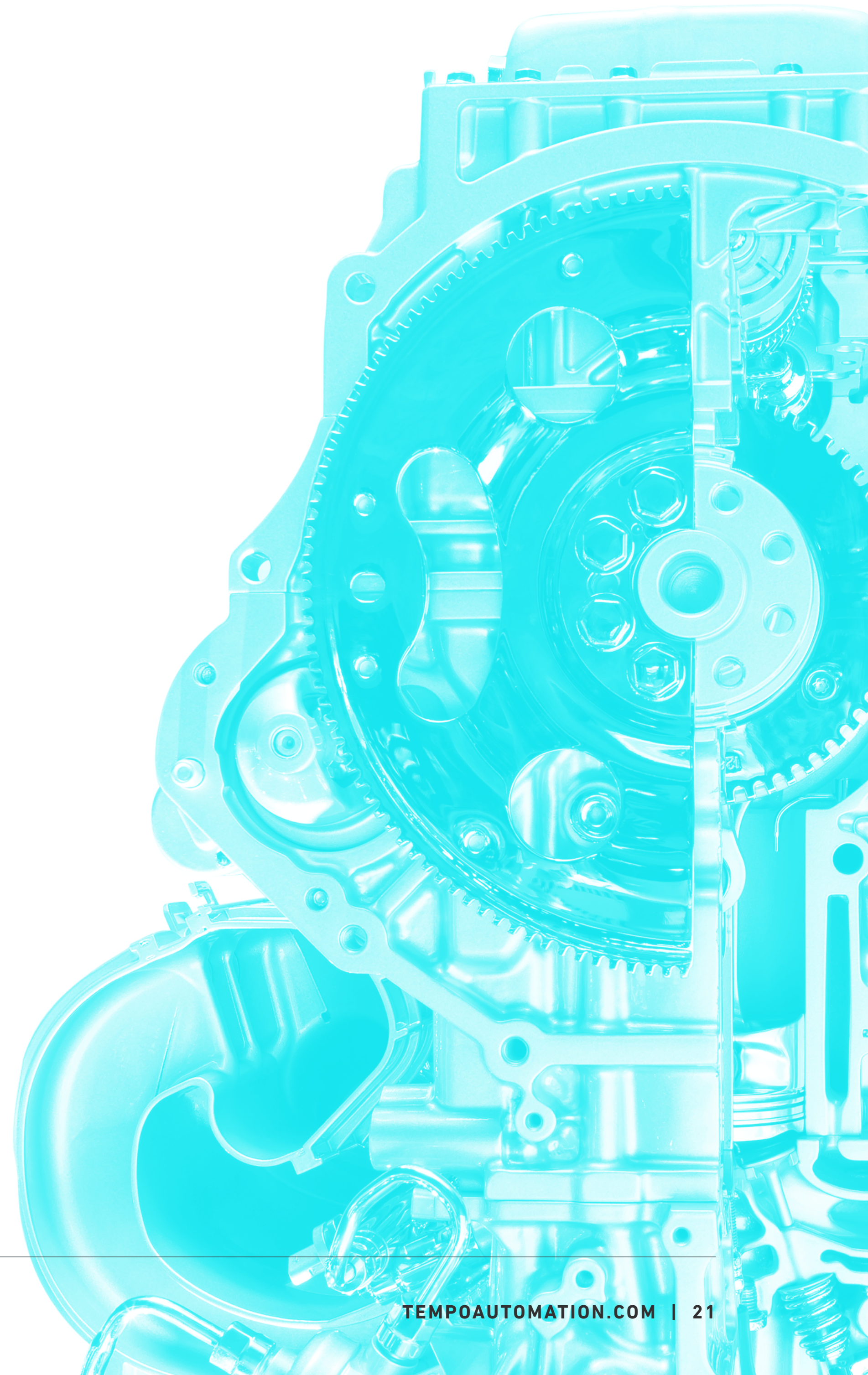
Humidity can cause issues all by itself if it is absorbed into packages or the PCB. Water content affects component parameters and can also cause structural damage if it outgasses under higher temperatures or low pressures. Hermetically sealed components are ideal for these applications. Conformal coating (see below) and potting are also potential solutions if the package cannot be sealed.

COMPONENT	DIFFUSION RESISTANT	NOT RECOMMENDED
Connectors	Hermetically Sealed, Metal Housing, Matched Contact Metals	Tin Plated
Resistors	Sealed, Nichrome	Metal Foil, Unsealed, Carbon Composition
Capacitors	Glass, Ceramic	Paper
Semiconductors	Glass, Ceramic, Epoxy Packages	Plastic Packages
Oscillators	AT Cut	SC Cut

PCB MATERIALS

Metallic materials (solder, surface finish, etc) are not moisture absorbent, but many dielectric materials are. FR-4 is generally resistant but polyimide, which has so many other good characteristics, is not.

MATERIAL	DIFFUSION RESISTANT	NOT RECOMMENDED
Dielectric	LTCC, FR-4	Polyimide
Solder	All	—
Surface Finish	All	—



Corrosive Applications

COMPONENTS

Corrosive environments vary over a wide range from water vapor condensation to salt spray and corrosive chemicals. Selecting materials that are not reactive is the key to surviving in these environments so be sure to understand the chemicals that will be in the operating environment. One non-environmental source of contamination is the no-clean flux used during assembly. This will not corrode the board by itself but can accelerate other corrosion processes. Instructing the manufacturer to wash the PCBA is a good way to ensure this does not contribute to any corrosion during operation. For corrosive environments that directly attack copper, conformal coating may be the only option.

COMPONENT	CORROSION RESISTANT	NOT RECOMMENDED
Connectors	Hermetically Sealed, Matched Contact Metals	Tin Plated, Plastic Package
Resistors	Sulfur Resistant, Nichrome	Silver Terminated, Plastic Package
Capacitors	Glass, Ceramic	Plastic Package
Semiconductors	Ceramic	Plastic Package
Oscillators	Sealed	Plastic package

PCB MATERIALS

Electronics are highly susceptible to corrosion since many of the compounds, including copper, silver, and tin, are highly reactive. To reduce the chances of corrosion it is importance to insure a clean board. Any contaminants on the surface of the PCB will reduce the resistance to electrolytic current flow and increase the rate of corrosion.

AN OVERVIEW OF MATERIALS IS SHOWN BELOW:

MATERIAL	CORROSION RESISTANT	NOT RECOMMENDED
Dielectric	Polyimide, PEEK, PTFE	—
Solder	Lead Free	—
Surface Finish	Immersion Tin, High Phosphorus ENIG, ENEPIG	Immersion Silver, OSP, Poor Wetting Characteristics

Another way to protect electronics from humid and corrosive environments is to conformal coat the PCBA with a thin layer of material. These coatings are very effective and allow more freedom when choosing components and PCB material, but they add additional process steps with increased lead time and cost. It is also possible for moisture to penetrate the coating and still cause corrosion. Selecting hermetically sealed coating can mitigate this issue.

CONFORMAL COATING	APPLICATION	ADVANTAGES	DISADVANTAGES
Acrylic Resin (AR)	One part application	• Reworkable	• Low corrosion resistance
Urethane Resin (UR)	One part or two part application	• High corrosion resistance • Low moisture absorption	• Long cure time • Cannot rework
Epoxy Resin (ER)	Two part application	• High corrosion resistance • Hermetic seal	• Cannot rework
Silicone Resin (SR)	One part application	• High corrosion resistance • Low moisture absorption • High temperature tolerant	• Cannot rework • Difficult to remove
Parylene (XY)	Vapor deposition	• Best corrosion resistance • High temperature tolerant • High dielectric strength	• Very difficult to remove

Conclusion

THE EFFECTS OF TEMPERATURE, PRESSURE, HUMIDITY, AND CORROSION ON PCBAS PRESENT MANY CHALLENGES WHEN CREATING ELECTRONICS THAT CAN OPERATE FOR EXTREME ENVIRONMENTS.

These effects can be broken down into chemical, mechanical, and parameter effects.

EFFECT	CHEMICAL	MECHANICAL	PARAMETER
High Temperature	Weakens materials	Outgassing stress	Yes
Low Temperature	Embrittles materials	—	Yes
Temperature Cycling	—	Inter-material stress	Yes
Temperature Shock	—	Intra-material stress	Yes
High Pressure	—	Pressure differential stress	Yes — moisture adsorption
Vacuum	—	Pressure differential stress, Outgassing stress	—
Pressure Cycling	—	Pressure differential stress	—
Galvanic Corrosion	Chemical reaction	—	—
Electric Corrosion	Chemical reaction	—	—
Gaseous Corrosion	Chemical reaction	—	—

Each of these environmental factors is a challenge all on its own but in most environments, electronics will experience multiple factors that compound on each other.

And this is not even covering the effects from vibration, shock, and particle radiation (see Part 2). Treating these effects independently can help clarify design decision. Unfortunately, sometimes the manufacturing options to mitigate the effects of one factor of the operating environment can conflict with another factor. Some examples include polyimide which can survive in extreme high temperature but easily absorbs water vapor or PTFE which is corrosion resistant but has a high CTE. When managing these complex requirements it is important to work with a CM that has the capabilities and the knowledge to meet these challenges and to create successful products.

BELOW ARE SOME EXAMPLES OF THE COMBINATIONS THAT SHOW UP IN VARIOUS OPERATING ENVIRONMENTS:

- **TEMPERATE OUTDOORS:** High temperature, temperature cycling, high humidity, moisture intrusion from rain, dust contamination
- **DESERT OUTDOORS:** High temperatures, temperature cycling, low humidity
- **ARCTIC OUTDOORS:** Low temperatures, temperature cycling, high humidity
- **MARINE:** High temperature, temperature cycling, humidity, moisture intrusion from rain, salt corrosion
- **INDUSTRIAL:** High temperature, corrosive atmosphere, high humidity, contamination
- **AUTOMOTIVE ENGINE:** Extreme high temperature, temperature cycles, humidity, moisture intrusion from rain, salt corrosion
- **AIRCRAFT:** Low temperature, temperature cycling, low pressure, pressure cycling, humidity, moisture intrusion
- **OCEAN ABYSSAL PLANE:** Extreme pressure, pressure cycling, low temperatures, absorption
- **DOWNHOLE:** Extreme pressure, extreme temperature, corrosive atmosphere
- **OUTER SPACE:** Vacuum, cryogenic temperature, extreme high temperatures, temperature cycling, gaseous corrosion

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TEMPO AUTOMATION

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