

Exhibit D

High-Temperature Electronics Pose Design and Reliability Challenges

By Jeff Watson and Gustavo Castro

Introduction

Many industries are calling for electronics that can operate reliably in harsh environments, including extremely high temperatures. Traditionally, engineers had to rely on active or passive cooling when designing electronics that must function outside of normal temperature ranges, but in some applications, cooling may not be possible—or it may be more appealing for the electronics to operate hot to improve system reliability or reduce cost. This choice presents challenges that affect many aspects of the electronic system, including the silicon, packaging, qualification methodology, and design techniques.

High-Temperature Applications

The oldest, and currently largest, user of high-temperature electronics ($>150^{\circ}\text{C}$) is the *downhole* oil and gas industry (Figure 1). In this application, the operating temperature is a function of the underground depth of the well. Worldwide, the typical geothermal gradient is $25^{\circ}\text{C}/\text{km}$ depth, but in some areas, it is greater.

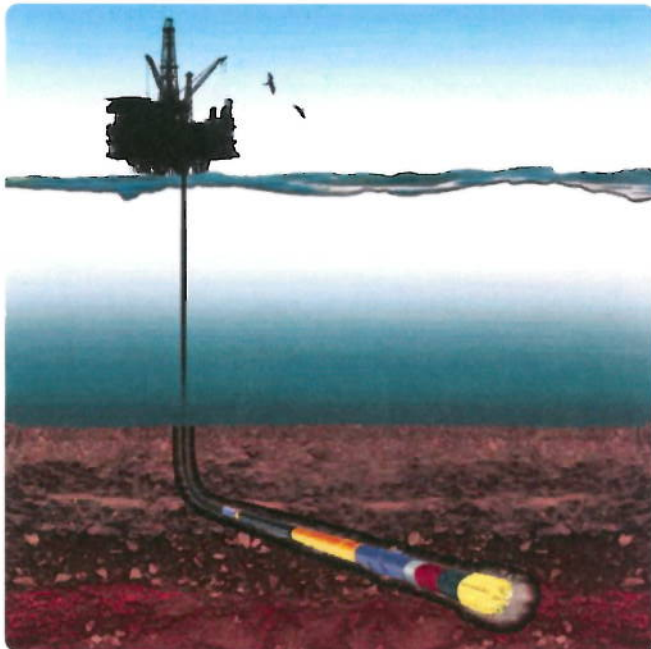


Figure 1. Downhole drilling operation.

In the past, drilling operations have maxed out at temperatures of 150°C to 175°C , but declining reserves of easily accessible natural resources coupled with advances in technology have motivated the industry to drill deeper, as well as in regions of the world with a higher geothermal gradient. Temperatures in these *hostile* wells can exceed 200°C , with pressures greater than 25 kpsi. Active cooling is not practical in this harsh environment, and passive cooling techniques are not effective when the heating is not confined to the electronics.

The applications for high-temperature electronics in the downhole industry can be quite complex. First, during a drilling operation, electronics and sensors steer the drilling equipment and monitor

its health. With the advent of directional drilling technology, high-performance geosteering instrumentation must guide the borehole position to an exact geologic target.

While drilling, or soon thereafter, sophisticated downhole instruments acquire data about the surrounding geologic formations. This practice, known as *well logging*, measures resistivity, radioactivity, acoustic travel time, magnetic resonance, and other properties to determine characteristics of the formation, such as lithology, porosity, permeability, and water/hydrocarbon saturation. This data allows the geologist to make judgments about the types of rock in the formation, the types of fluids present and their location, and whether adequate amounts of hydrocarbons can actually be extracted from fluid-bearing zones.

Finally, during the completion and production phases, electronic systems monitor pressure, temperature, vibration, and multiphase flow—and actively control valves. Meeting these needs requires a complete signal chain of high-performance components (Figure 2). System reliability is of utmost importance, as the cost of downtime due to equipment failure can be quite severe. A failed electronics assembly on a drill string operating miles underground can take more than a day to retrieve and replace—and the rate for operating a complex deep-water offshore rig is of the order of \$1M per day!

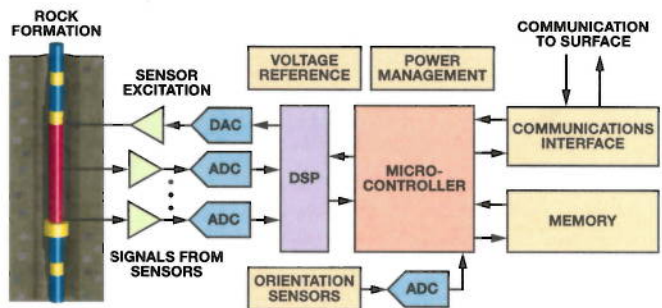


Figure 2. Simplified downhole logging instrumentation signal chain.

Other users: Besides the oil and gas industries, other applications, such as *avionics*, are emerging for high-temperature electronics. The aviation industry now has a growing movement toward the “more electric aircraft” (MEA). Part of this initiative seeks to replace traditional centralized engine controllers with distributed control systems.¹ Centralized control requires large, heavy wire harnesses with hundreds of conductors and multiple connector interfaces. Moving to a distributed control scheme places the engine controls closer to the engine (Figure 3), reducing the complexity of the interconnections by a factor of 10, saving hundreds of pounds of aircraft weight,² and increasing the reliability of the system (estimated in part as a function of *connector pin count* (per MIL-HDBK-217F)).³

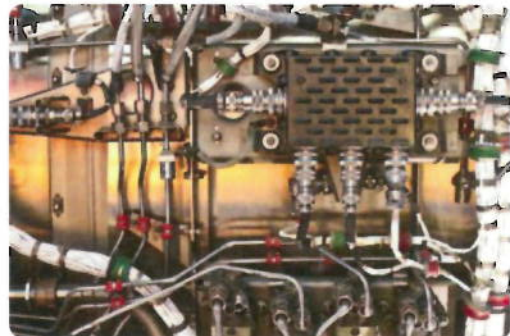


Figure 3. Controls mounted on aircraft engine.

The trade off, however, is that the ambient temperature, in close proximity to the engine, ranges from -55°C to $+200^{\circ}\text{C}$. Although electronics can be cooled in this application, it is undesirable for two reasons: cooling adds cost and weight to the aircraft, and, most importantly, failure of the cooling system could lead to failure of the electronics that control critical systems.

Another aspect of the MEA initiative is to replace hydraulic systems with power electronics and electronic controls to improve reliability and reduce maintenance costs. The control electronics ideally need to be very close to the actuators, which again produce a high-ambient-temperature environment.

The *automotive industry* provides another emerging application for use of high-temperature electronics. As with avionics, the auto industry is migrating from purely mechanical and hydraulic systems to electromechanical or *mechatronic* systems.⁴ This requires locating sensors, signal conditioning, and control electronics closer to heat sources.

The maximum temperature and exposure time varies by vehicle type and location of the electronics on the vehicle (Figure 4). For example, higher integration of electrical and mechanical systems, such as collocation of the transmission and transmission controller, could simplify the manufacture, test, and maintenance of automotive subsystems.⁵ Electric vehicles and hybrid-electrics require power electronics with high energy density for converters, motor controls, and charging circuits that are also associated with high temperatures.



Figure 4. Typical automotive maximum temperature ranges.⁵

Using ICs Beyond Data Sheet Temperature Specifications

In the past, high-temperature electronics designers, such as those in the oil and gas industry, were compelled to use standard-temperature components well above their rated specification due to the unavailability of high-temperature ICs. Some standard-temperature ICs will indeed work at elevated temperatures, but it is an arduous and risky endeavor to use them. For example, engineers must identify potential candidates, completely test and characterize performance over temperature, and qualify the reliability of the part over a long period of time. Performance and lifetime of the part are often substantially derated. This is a challenging, expensive, and time-consuming process:

- Qualifying components requires testing in a lab oven with a high-temperature printed-circuit board (PCB) and fixtures, for at least as long as the mission profile requires. It is difficult to accelerate testing because new failure mechanisms may be encountered. Failures during testing require another iteration of component selection and long-term test, delaying project timelines.
- Operation outside of data sheet specifications is not guaranteed, and performance may vary between component lots. In particular, IC process changes can result in unexpected failures at temperature extremes.

- Plastic packages are only robust up to about 175°C —with reduced operating life. Near this temperature limit, it can be difficult to distinguish between a packaging-related failure and silicon-related failure without costly and time-consuming laboratory failure analysis. Availability of standard components in ceramic packages is scarce.
- Often, components used in harsh environments must survive not only high temperature but also severe shock and vibration. Many engineers prefer to use packages with leads, such as a DIP or a gull-wing SMT, because they provide a more robust attachment to the PCB. This further limits device selection, as other industries trend toward smaller, leadless packages.
- It could be desirable to obtain parts in die form, especially if a component is otherwise only available in a plastic package. The die can then be repackaged in a high-temperature compliant hermetic package or multichip module. However, of the few components that will work at elevated temperature, yet a smaller subset is readily available as *tested* dice.
- Due to time constraints and test-equipment limitations, engineers in the industry may tend to restrict qualification of a device to a specific application circuit, without covering all key device parameters, thus limiting component reuse for other projects without further testing.
- Key non-data-sheet IC properties, such as *electromigration* in metal interconnects, could lead to failures at high temperatures.

ICs Designed and Qualified for High Temperature

Fortunately, recent IC technology has produced devices that can operate reliably at elevated temperature with guaranteed data sheet specifications. Advances have been made in process technology, circuit design, and layout techniques.

Managing many key device characteristics is crucial for successful, high-performance operation at elevated temperatures. One of the most important and well-known challenges is posed by increased *substrate leakage current*. Some others are decreased *carrier mobility*, variation in device parameters, such as V_T , β , and V_{SAT} , increased *electromigration* of metal interconnects, and decreased *dielectric breakdown strength*.⁶ Although standard silicon can operate well beyond the military requirement of 125°C ,⁷ leakage in standard silicon processes doubles for every 10°C increase, making it unacceptable for many precision applications.

Trench isolation, *silicon-on-insulator* (SOI), and other variations on the standard silicon process greatly decrease leakage and enable high-performance operation to well above 200°C . Figure 5 illustrates how an SOI bipolar process reduces the leakage area. Wide-band-gap materials, such as silicon carbide (SiC), raise the bar even higher; silicon carbide ICs have operated at up to 600°C in laboratory investigations. However, SiC is an emerging process technology, and, currently, only simple devices such as power switches are commercially available.

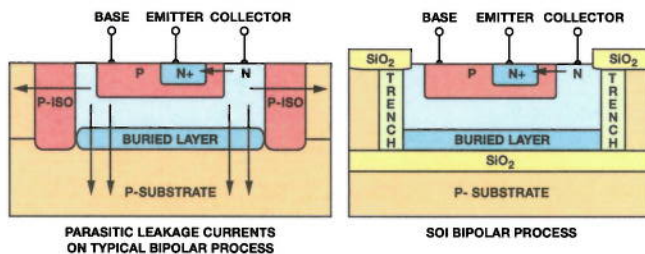


Figure 5. Junction leakage mechanisms in bulk silicon and SOI compared.

Instrumentation amplifier: Instrumentation amplifiers require high precision in downhole drilling applications to amplify very weak signals in the noisy environments commonly present. This specialty amplifier type is generally the first component at the measurement front-end, so its performance is critical to performance of the entire signal chain.

The Analog Devices development team targeted the AD8229 instrumentation amplifier for high-temperature operation from its inception and designed it for this purpose from the ground up. To meet its unique performance requirements, a proprietary SOI bipolar process was the technology of choice. The designers implemented special circuit techniques to guarantee operation over a wide variation of device parameters, such as base-emitter voltage and forward current gain.

The IC layout also critically affects the AD8229's performance and reliability. To maintain low offset and high CMRR over the entire temperature range, the layout compensates for variations in interconnect and temperature coefficient. In addition, careful analysis of the current flow densities in key sections mitigated the effects of electromigration, contributing to increased reliability under extreme conditions. Likewise, the designers anticipated fault conditions to prevent premature breakdown.

The combination of robust process, circuit-design, and layout techniques enables the device to meet the most stringent precision and reliability requirements over temperature.

Packaging Considerations

Once high-temperature functional silicon is in hand, the battle is only half won. Packaging the die, and then attaching the package to the PCB, is not trivial at high temperatures. Many factors affect package integrity at temperature (Figure 6).

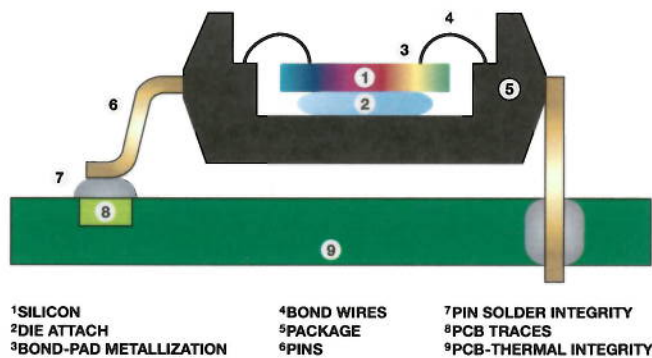


Figure 6. Elements of IC packaging and mounting.

The *die-attach* material secures the silicon to the package or substrate. Many materials proven for use in standard temperature ranges have a low glass transition temperature (T_G) and are not suitable for high-temperature operation. Particular attention needs to be paid to matching the *coefficient of thermal expansion* (CTE) between the die, die-attach, and substrate—so that the die is not stressed or fractured over cycles of wide temperature span. Even slight mechanical stress on the die can cause electrical parameters to shift to unacceptable levels for precision applications. For power devices that require thermal and electrical connection to the package substrate, metallic die-attach materials may be necessary.

Wire bonding is a method for interconnecting the die to the pins by attaching metallic wires from the lead frame to bond pads on the die surface. When considering wire bond reliability at elevated temperatures, the compatibility of the metals used for the wire

and bond-pad metallization is of major concern. Failures related to poor compatibility of bonding metals are twofold: *intermetallic compound* (IMC) growth at the boundary interface, which creates a brittle bond; and *diffusion* (Kirkendall effect), which creates voids at the interface, weakening the bond's strength and increasing its resistance. Unfortunately, one of the most popular metal combinations in industry—gold wire and aluminum bond-pad metallization—is prone to these phenomena at elevated temperatures. Figure 7, a section through an Au/Al bond, shows IMC growth, which is compromising bond integrity after 500 hours at high temperature.

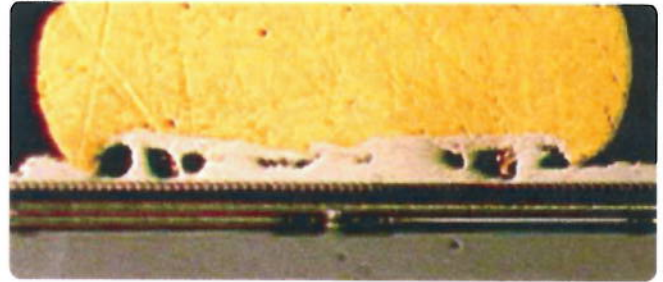


Figure 7. Au/Al bond after 500 hours at 195°C.

Figure 8 shows substantial Au/Al intermetallic growth and Kirkendall voids after bond failure at high temperature. To make matters worse, halogens such as bromine and chlorine—sometimes found in molding compounds—can cause corrosion at the boundary interface at elevated temperature, accelerating the time to failure (although fortunately, the industry is shifting to “green” halogen-free molding compounds). Thus, there is a strong incentive to use the same metal for the bond wire and bond pad (a *monometallic* bond) to avoid these negative effects. If this is not possible, engineers should select metals that have slow enough IMC growth and diffusion rates to be reliable over the required lifetime.

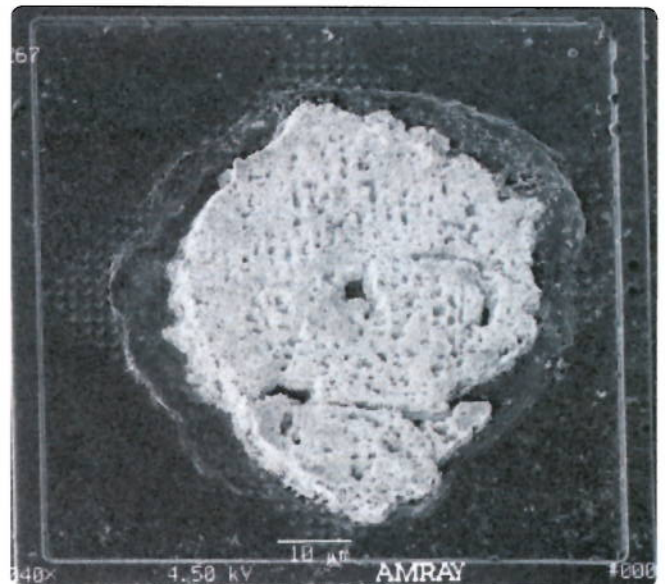


Figure 8. Intermetallic growth with voids.

Figure 9 illustrates the robustness of the monometallic bond at elevated temperature. The bond section shows no sign of IMC growth after 3000 hours at 195°C.

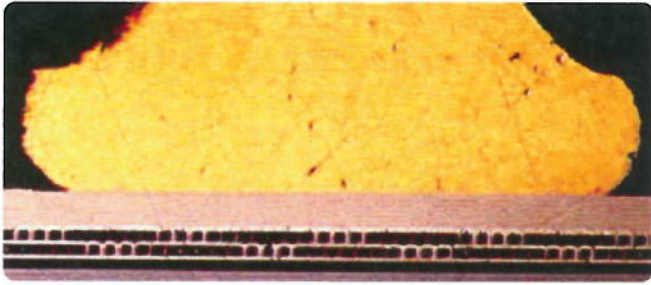


Figure 9. Monometallic bond after 3000 hours at 195°C.

The IC package must also withstand stresses imposed by harsh environments. Plastic packages, although the industry standard, have historically only been rated to 150°C for sustained use. With recent interest in high-temperature applications, investigations have shown that this rating can stretch to 175°C but only for relatively short durations. Depending on package construction, 175°C is the point at which some materials, such as the molding compound, exceed the glass-transition temperature. Operating above T_G can cause significant mechanical changes in key parameters, such as CTE and flexural modulus, and lead to failures such as delamination and cracking from the increased thermal strain.⁸

For this reason, hermetic ceramic packages are preferred for high-temperature applications (Figure 10). The hermetic seal provides a barrier to the moisture and contamination ingresses that cause corrosion. Unfortunately, hermetic packages are normally larger, heavier, and significantly more expensive than their plastic counterparts. In applications with less extreme temperature requirements (<175°C), plastic packages may be preferred to conserve PCB area, reduce cost, or provide better vibration compliance. For systems requiring hermetic packaging and high component density, high-temperature multichip modules may be an appropriate solution. However, this solution requires that known good dice be available.

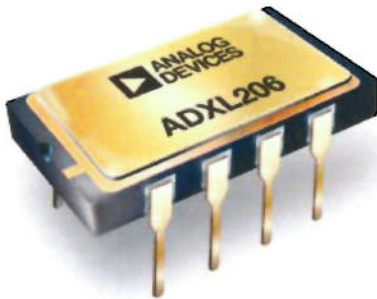


Figure 10. Hermetically sealed side-brazed ceramic DIP package.

Package lead configuration and metallization must also be evaluated. Surface-mount components depend solely on the bond pad area and quality of the adhesive between the copper layer and the prepreg. On the other hand, the through-hole DIP configuration, one of the most proven and reliable packages in industry, also provides robust shock and vibration performance. In extreme cases, attachment strength can be improved further by bending the pins on the bottom side of the board to “staple” it to the PCB, but the through-hole pinout does not allow component population of the bottom side of the board—possibly a major concern for applications such as downhole instruments, which have tight space constraints.

Gull-wing SMT lead configuration is a viable alternative in many cases, but leadless SMT may not be robust enough under high shock and vibration conditions encountered in many high temperature environments. When using SMT components, the designer should consider their height and mass. The application of high-temperature epoxies will improve attachment robustness but increase manufacturing costs and limit the ability to perform repairs. In all cases, the lead metallization must be compatible with high-temperature solders.

The most popular standard solder alloys have melting points below 200°C. However, there are some readily available alloys that fall within the category of “high melting point” (HMP), with melting points well above 250°C. Even in such cases, the maximum recommended operating temperature for any solder subjected to stress is about 40°C below its melting point. For example, the standard HMP solder alloy composition of 5% tin, 93.5% lead, and 1.5% silver has a melting point of 294°C but is recommended for use only up to about 255°C.⁹ Note that BGA (ball-grid array) packages have solder balls attached by the factory that may not have a high melting point.

Finally, the PCB itself is a potential source of failure. Standard FR4 reaches glass transition anywhere from 130°C to 180°C, depending on the specific composition. If used above this temperature—for even short time durations—it can expand and delaminate. A good proven alternative is polyimide, the same material used in Kapton, which has T_G as high as 250°C, depending on composition. However, polyimide suffers from very high moisture absorption, which can quickly lead to failure of the PCB by a variety of mechanisms, so it is important to control moisture exposure. In recent years, industry has introduced exotic laminates that absorb less moisture and maintain integrity at high temperatures.

Verification, Qualification, and Test

Verification of high-temperature components in the laboratory is not a trivial task, as it requires engineers to incorporate all the previously mentioned techniques to test performance at temperature extremes. In addition to using special materials in the construction of the test jig, test engineers must operate the environmental chambers carefully, allowing the system to adjust to the required temperature changes. Due to the mismatch in expansion coefficients, fast temperature changes can result in damage to the solder joints on the PC board, warping, and ultimately, premature system failure. A guideline employed in the industry is to maintain the temperature rate of change below 3°C per minute.

To accelerate testing of life and reliability, an accepted practice for electronic components is to perform the tests at an elevated temperature. This introduces an acceleration factor, α , defined by the Arrhenius equation:

$$\alpha = e^{\frac{E_a}{k} \left(\frac{1}{T_a} - \frac{1}{T_s} \right)}$$

where E_a is the activation energy, k is the Boltzmann’s constant, T_a is the expected operating temperature during use, and T_s is the stress temperature. Although accelerated aging works well for standard products, increasing the stress temperature well above the rated temperature may introduce new failure mechanisms and yield inaccurate results. Therefore, to guarantee the lifetime reliability of high-temperature devices like the AD8229, the high-temperature operating life test (HTOL) was run at the maximum rated temperature of 210°C for 1000 hours (approximately six

weeks). For lower temperatures, the expected lifetime can be predicted using the acceleration relationship shown in Figure 11.

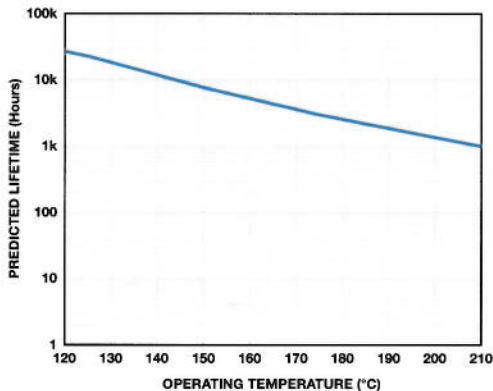


Figure 11. AD8229 lifetime vs. operating temperature, 1000 hours @ 210°C.¹¹

There are additional hindrances to reliable characterization of high-temperature ICs. For example, the test and measurement system used is only as reliable as its weakest link. This means that every element exposed to elevated temperatures over a long period must be inherently more reliable than the IC itself. An unreliable system will yield data that does not represent the long-term reliability of the component and will result in costly and time-consuming repetitions of the process. Statistical techniques for increasing the success rate include accurately *oversizing* the test sample to add a margin of error for premature system failures not caused by a DUT (device under test) failure.

Another hurdle is imposed by production steps required to guarantee performance parameters at the extremes, such as test, probing, and trimming. The development team needs to customize these steps for high-temperature products.

High-Temperature System Design Considerations

The designer of circuits that operate at high temperature must account for changes in IC parameters and passive components over a wide temperature range, paying close attention to their behavior at the temperature extremes to ensure circuit operation within the target limits. Examples include offset and input bias drift, gain errors, temperature coefficients, voltage ratings, power dissipation, board leakage, and intrinsic leakage of other discrete devices—such as those used in ESD and overvoltage protection devices. For example, in situations where high source impedance is in series with an amplifier input terminal, undesired leakage currents (other

than the amplifier’s own bias current) can create offsets that will induce bias-current measurement error (Figure 12).

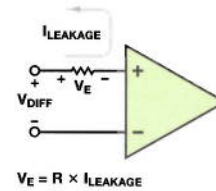


Figure 12. How bias and leakage induce offset errors.

In all cases, high-temperature operation exacerbates board leakages introduced by contaminants such as solder flux, dust, and condensation. Proper layout can help minimize these effects by providing adequate spacing between sensitive nodes—separating amplifier inputs from noisy power rails, for example.

The standard pinout for operational amplifiers and instrumentation amplifiers places one of the input terminals next to the negative supply terminal. This dramatically reduces the tolerance for post-assembly PCB flux residues that can produce increased leakage. To reduce leakage and increase high-frequency CMRR, the AD8229 employs the same high-performance pinout as other precision instrumentation amplifiers built by Analog Devices (Figure 13).

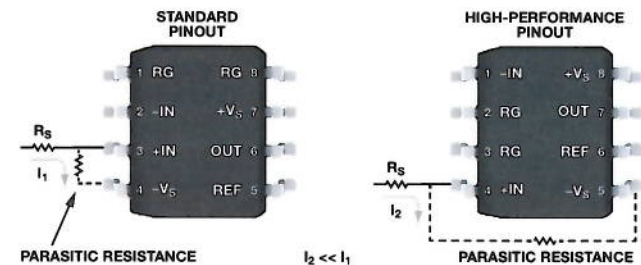


Figure 13. Modification of device pinout helps minimize parasitic leakage.

The leakage of diodes, transient-voltage suppressors (TVS), and other semiconductor devices increases exponentially with temperature, and, in many cases, can be many orders of magnitude larger than the input bias current of the amplifier. In such cases, the designer must ensure that the leakage at extreme temperatures will not degrade the circuit specifications beyond the desired limits.

Nowadays, several passive components are available for high-temperature operation. Resistors and capacitors are ubiquitous in any circuit design. Some commercially available options are shown in Table 1.

Table 1. Examples of High-Temperature Resistors and Capacitors

Capacitors	Max Rated Temperature	Comments
MLCC (ceramic) C0G/NP0	200°C	Low values, low TC, available in SMT or throughhole
MLCC (ceramic) X7R	200°C	Higher TC than C0G/NP0, lower cost
Electrolytic Wet Tantalum	200°C	High capacitance values, mostly throughhole
Electrolytic Tantalum	175°C	High capacitance values, SMT packages available
Resistors	Max Rated Temperature	Comments
Wire-Wound	275°C	High surge capability, stable
Metal Film	230°C	High precision
Metal Oxide	230°C	General purpose
Thick Film	275°C	General purpose, wide resistance range
Thin Film	215°C	Compact, low TC, high stability, resistor arrays available
Ceramic Composition	220°C	High-temperature replacement for carbon composition

Note that surface-mount components are prone to leakage between terminals if their bodies sit against the PC board, as flux residues tend to remain trapped underneath after the assembly process. Such residues wick moisture, which, at high temperature, increases their conductivity. In this situation, a parasitic resistor (with rather unpredictable behavior) will appear across the surface-mount component, potentially introducing additional circuit errors. To overcome this problem, consider selecting larger chip sizes, gull-wing lead-forming, or through-hole components in areas of the circuit that are particularly sensitive. Ultimately, this undesired residue can be all but eliminated by adding an effective board wash step, typically employing ultrasound or a saponifier, at the end of the assembly process.

The designer of systems that will operate in harsh environments must keep thermal management in mind. Even with components designed for high ambient temperature, consider the self-heating associated with their power dissipation. In the case of the AD8229, its guaranteed operation up to 210°C assumes a small output current load. Additional power dissipation caused by driving heavy loads or permanent fault conditions (such as an output short circuit), will increase the junction temperature beyond the maximum ratings of the part, greatly reducing the operating life of the amplifier. It is important to follow the recommended guidelines for heat dissipation and to be aware of adjacent heat sources, such as power regulators.

Even high-temperature resistors have derated power ratings above 70°C. Pay special attention to resistor temperature ratings at the intended operating temperature, especially if they will dissipate a considerable amount of power. For example, if a 200°C-rated resistor is operating in an ambient temperature of 190°C, but if its self-heating due to power dissipation is 20°C, it will be exceeding its rating.

While many passive components can withstand high temperatures, their construction may not be suitable for long-term exposure to environments that may combine high temperature with shock and vibration. In addition, manufacturers of high-temperature resistors and capacitors specify the operating life at a given temperature. Matching the operating life specifications of all the components is important to obtain a high reliability system. Finally, do not overlook that many components rated for high temperature may need additional derating to achieve lasting operation.

Case Study: Mapping the Thermal Gradient in an Oven

As a demonstration of two suitable devices in a high-temperature application, the AD8229 and ADXL206 (dual-axis accelerometer) were operated in a high-temperature environment that was both portable and safe to use. The demonstration utilizes a small electric oven with a rotating assembly on which a high temperature PCB is mounted and continuously operated. The heating element inside the oven is located near the top. This arrangement creates a large temperature gradient inside the volume of the oven. The rotating mechanism lends itself to an experiment that can combine temperature and position measurements.

The AD8229 conditions the signal coming from a K-type thermocouple, which is constantly rotating inside the oven. The thermocouple probe extends about 6" beyond the PCB—the better to measure variation of the oven temperature. At the same

time, the ADXL206 measures the angle of rotation. Three signals (temperature gradient, x-acceleration, and y-acceleration) are sent through a slip ring (rotary connector) rated for high-temperature operation. The slip ring maintains connection to the nonrotating harness, which connects to the data-acquisition board outside the oven. Since the “cold junction” is located inside the oven, a second thermocouple provides a static reference to the internal temperature. The AD8495 thermocouple amplifier (also *outside* the oven) uses its integrated cold-junction compensation to condition the signal of the additional thermocouple.

The board inside the oven is located near the center on the rotating assembly, where the approximate temperature is 175°C. The board's construction uses polyimide material. The tracks on the copper layers use a minimum width of 0.020" to improve copper adhesion to the prepreg material (Figure 14). The components were attached using standard HMP solder (5/93.5/1.5 Sn/Pb/Ag), and Teflon-coated wires were used to connect the board and the slip ring.

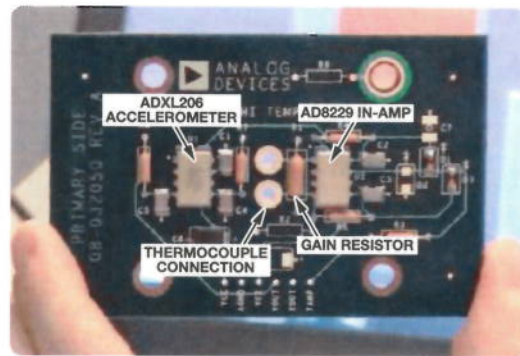


Figure 14. High temperature PCB with components mounted.

All precision components use through-hole mounting. A 25 ppm/°C metal-film resistor sets the gain of the instrumentation amplifier. The amplifier operates at high gain, so the trace length from the amplifier to the gain resistor is as short as possible to minimize copper resistance (4000 ppm/°C TC). The interface between the thermocouple and the amplifier is located at the center of the board, in order to maintain a constant temperature during rotation. The thermocouple terminals are as close together as possible to cancel undesired thermal EMF effects at the junction.

High-temperature tantalum capacitors and C0G/NP0 capacitors decouple the power supply and serve as filters for the output of the accelerometer.

A computer processes data from four different sources: the angle of rotation (the rectangular x and y components), the internal temperature gradient, and the reference temperature. All these measurements are combined together to map the temperature gradient (Figure 15). The analysis results show that the temperature variation can be as wide as 25°C. As expected, the highest temperature is near the heating element, which is located near the top of the back wall of the oven. Due to natural convection, the top portion of the oven is the second hottest area inside the oven. The lowest temperature is sensed when the thermocouple is opposite to the heating element.

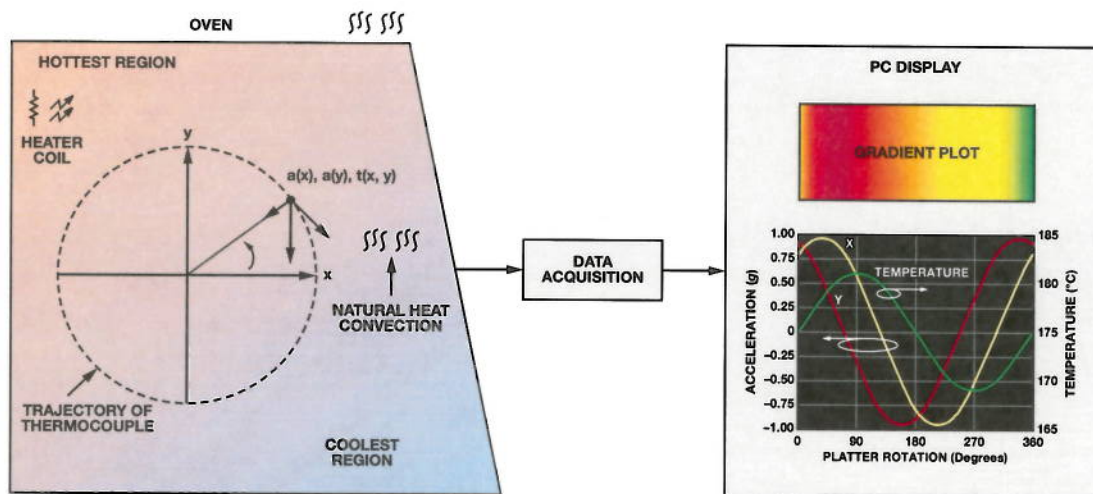


Figure 15. High temperature demo diagram.

This experiment suggests, in a simple way, how high-temperature components, integrated into a logging system, can extract valuable information while operating in a harsh environment.

Conclusion

Many applications, both established and emerging, require components that function in very high-temperature environments. In the past, it was challenging to design such systems reliably due to the lack of devices rated for these kinds of harsh environments. Now, ICs and supporting components designed and qualified to operate in these environments are available, saving engineering time and lowering the risk of failure. Leveraging this new technology and following high-temperature design practices will enable high-performance systems to operate reliably in even more extreme environments than were previously feasible.

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