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CIRCUIT LIFE AT TEMPERATURE

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INTRODUCTION

Much has been reported about the reliability of electronics in downhole applications. As a manufacturer of pressure transducers designed for high temperature use, we have found that circuit life varies with the circuit technology and the test temperature. Quartzdyne currently employs three circuit technologies in its products: surface-mount, through-hole, and hybrid. All circuits are essentially the same circuit, varying only by the construction technology. We have found that component packaging is the weak link in the surface-mount and through-hole technologies, while hybrid technology has eliminated this weakness.

In Figure 1, Quartzdyne is releasing test data gathered since 1994 of high-temperature circuit testing from over 400 production circuit assemblies. We have determined that while the specific failure mechanisms vary with circuit technology and test temperature, the mean time before failure (MTBF) of any given technology closely follows a de-rating curve of a factor of two for every 10°C. Based on the test results, it can be concluded that surface-mount technology can be used reliably at 150°C for one year, or 125°C for five years. With properly constructed hybrid assemblies, more than three years at 200°C, or more than 15 years at 175°C, can be expected.

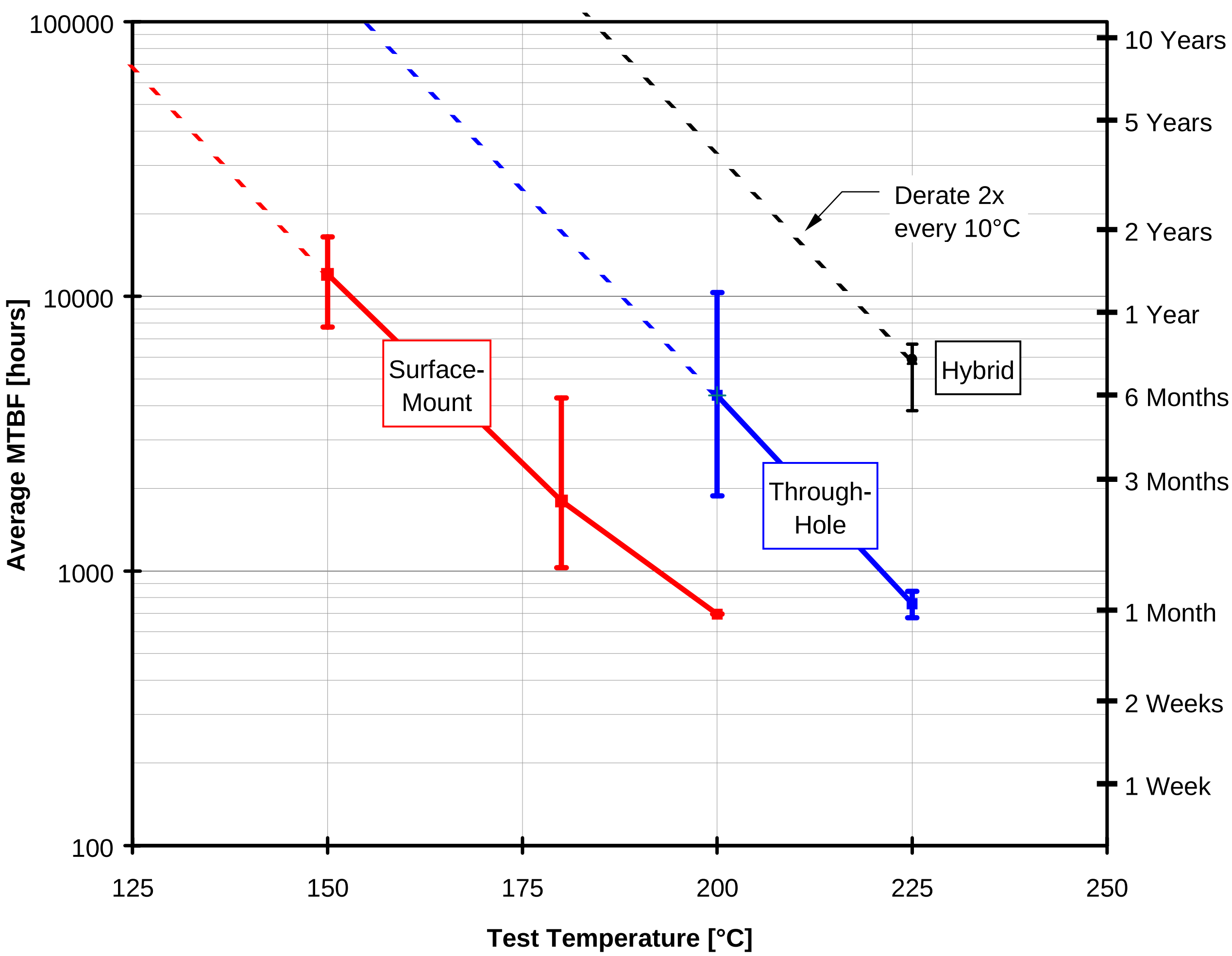

Figure 1: Quartzdyne circuit life, grouped by technology. MTBF error bars represent real test data. Solid lines are drawn through MTBF averages, while dashed lines represent a theoretical 2X per 10°C de-rating curve.

QUARTZDYNE CIRCUIT TECHNOLOGIES

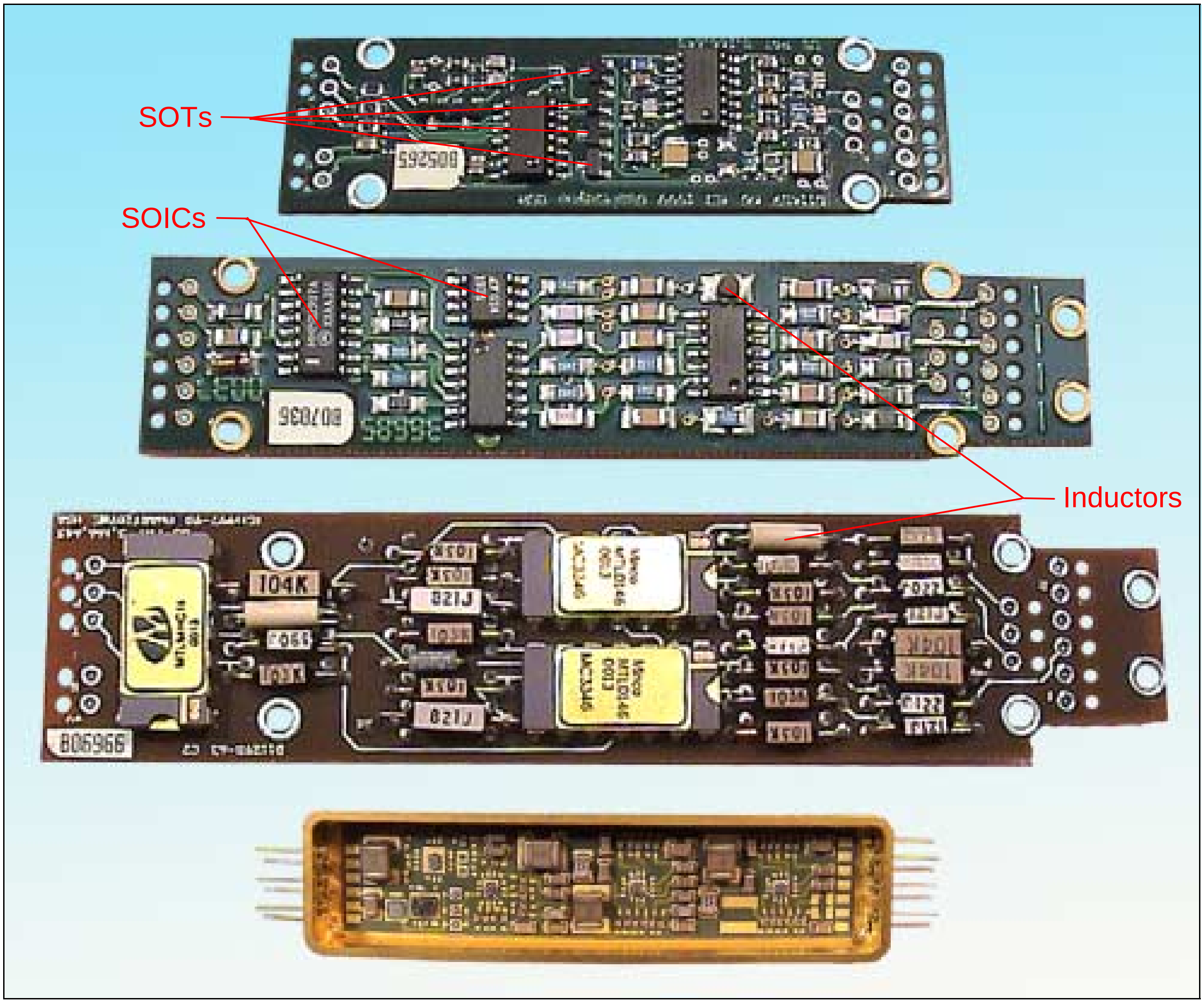

Figure 2: Quartzdyne Circuit Technologies, (listed from top to bottom) 150°C-rated surface-mount, 177°C-rated surface mount, 200°C-rated through-hole, and 200°C-rated hybrid.

Surface-Mount Circuit, 150°C-rated

The Sn63Pb37 (183°C eutectic) solder limits the operating temperature of this surface-mount (SMT) design to 150°C. However, our in-house circuit board thermal-cycle tests show that the long-term primary failure mechanism at 150°C is the plastic-encapsulated SOTs (Small Outline Transistor) or SOICs (Small Outline Integrated Circuit), where the plastic breaks down, and the internal wirebonds fail (see Figure 2.)

The few field failures (of Sn63 boards) we see are rarely due to solder. Nearly all of the field failures are infantile component failures, caused by inductors, diodes, and capacitors. Inductors are heat sensitive: they tolerate the standard belt-furnace solder reflow, but can be damaged by hand-rework of solder joints. Glass-encapsulated diodes and multi-layer surface-mount capacitors can also be damaged by rework or other mechanical stresses. Exposure to temperatures greater than 150°C is likely to damage circuit components and will shorten the life of the solder. The epoxy-coated inductors will be damaged by temperatures greater than 150°C.

We have found that the best method to control reliability of 150°C circuit board assemblies is consistent on-site audits and inspections of our vendor(s), and 100% inspection of all solder joints. We saw a 400% improvement in field returns by switching vendors in 1996. Silicone conformal coatings provide a marginal improvement above 125°C, but provide a more valuable physical protection during handling and assembly.

Surface-Mount Circuit, 177°C-rated

Until 2001, we produced this circuit in the greatest volume, primarily for Series QU transducers. The solder limits the operating temperature of this design. CASTIN™ solder (non-eutectic melting point approximately 210°C) is a variant of Sn96, with traces of Sb and Cu added to improve ductility and to reduce scavenging.

In 1994, our 177°C SMT boards were build by an outside vendor, using oven-reflowed eutectic Sn96Ag4. A 500% improvement in field returns was achieved in 1995 due to a major change in the soldering procedure and materials: we now build these boards in-house, by hand.

In late 1996, we further improved the QU circuit by replacing the SOTs with similar transistors in SOIC packages. This decision was based upon observed failures of SOTs in the field and in our board cycle tests: when testing older circuits to failure (in our 180°C cycle tests), we found that 30% of the failures were attributable to SOTs. Since the SOTs have been eliminated from this circuit, the average life of the circuit in our cycle tests has increased by about 30%. (Note that we continue to use SOTs in 150°C-rated circuits. When using the standard Sn63 oven-reflow process for 150°C-rated boards, SOTs are as reliable as SOICs.)

We can see the limitations of the 177°C circuit design in our thermal-cycle test, where we observe failures in solder joints, or integrated circuit failures due to the plastic packages breaking down. Outgassing of bromides used as the fire-retardant causes purple plague in wire bond connections. The fundamental limits of 177°C-rated SMT QU circuit lie in the Sn96 solder and the plastic packages: any improvement requires eliminating these two items.

Through-Hole Circuit, 200°C-rated

This circuit uses HMP solder (Sn05Pb93.5Ag1.5) with axial-leaded through-hole components. The melting point (296°C - 301°C) of this solder is too high to be used with SMT components. Leaded components can withstand the solder temperatures because the lead isolates the component body from the solder joint.

Up until mid-1999, the 200°C circuit was functionally limited: it did not have an internal voltage regulator, and the output drivers couldn't drive more than a few inches of cable. This was because the leaded circuit was designed to fit into the same volume as the SMT circuits. The 200°C circuit also had some reliability problems related to forcing "too much circuit into too little space." The components were tightly spaced, which required tight lead bends and component "stacking". This hampered assembly, and created mechanical stress on components. The circuit was also vulnerable by the limited supply of obsolete metal-canned transistors and the mechanical strength of the leaded passive components (particularly glass-encapsulated diodes and capacitors). To improve our reliability, we changed our selection criteria for transistors, capacitors, and resistors.

In mid-1999, we decided to eliminate the need for the obsolete metal-canned transistors. We re-designed the circuit around the same transistor arrays which we have used in the 177°C circuit. Since these arrays are not available in a high-temperature package, we had them custom-packaged in a ceramic dual-in-line package (DIP or DIL). The glass-encapsulated passives were also replaced with epoxy-coated capacitors and resistors rated for 200°C service. With the space-savings produced by the transistors' repackaging, we were able to add a 74HC14 output driver to the circuit, powerful enough to drive a 10 foot cable. The 200°C circuit still lacks an internal voltage regulator, requiring a 5.00 ± 0.25 VDC supply.

We specify only qualified manufacturers for electrical components. Moreover, for each purchased lot of components, our incoming inspection procedures and customized mechanical testing helps ensure that the component meets our requirements.

We noted a marginal decrease in the 200°C circuit life in 1999. In late 1999, we discovered that the inductor manufacturer had reformulated these devices for 150°C maximum operation! We were forced to revert back to our previous supplier of high-temperature leaded inductors, which proved to be a less reliable. We concluded that the only long-term solution is to "design-out" inductors in future circuits (see hybrid below.)

In spite of this limitation, the 200°C circuit doesn’t have the solder and plastic package limits of the SMT circuits. It will survive long periods at high temperature (i.e., permanent installations), and it can be used continuously at 200°C. The 200°C circuit is still a good choice for high temperature environments (>150°C) that are NOT subjected to extreme shock and vibration. However, the best circuit choice for high temperature, rugged, and high reliability applications is the hybrid circuit (see below.)

Hybrid Circuit, 200°C-rated

The hybrid is an emerging and maturing circuit technology for Quartzdyne. It represents a perfect union of reliability (long life at high temperatures) and ruggedness. "Hybrid" indicates a mix of technologies: all die connections (on transistors and metal-film resistors) are wire bonds; the wire type is selected for compatibility with the individual die's bonding pad metallization. Hybrids are also called MCM (Multi-Chip Modules) or "chip and wire" circuits.

For long life, stresses are minimized by selecting a substrate (alumina ceramic) with a low coefficient of thermal expansion. Plastic packages and inductors have all been eliminated. To protect the circuitry from oxidation, it is sealed inside a custom hermetic enclosure backfilled with an inert atmosphere. Although the rated operating temperature of the hybrid is 200°C, we are able to perform accelerated testing at 225°C.

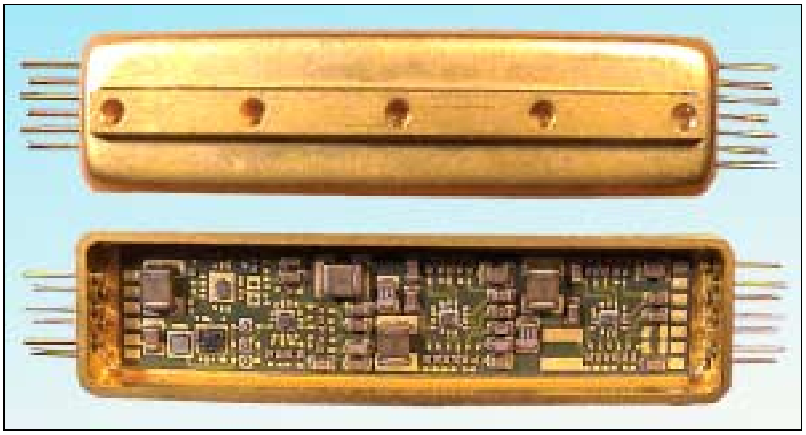

Figure 3: 200°C-rated hybrid circuit, capable of 225°C testing

We understand that the market for high-temperature electronics is small; however the need for accelerated testing at high temperatures is crucial for reliability assessment. Hence, the hybrid offers greater dependability than "conventional" electronics do, based on its notable performance at test temperatures of 225°C. Its application is not limited to high temperatures: we recommend it for all high reliability applications, including those below 150°C.

TEST METHODS

Our circuit evaluation is based upon field failures, our internal board-lot thermal-cycle tests, and our internal Powered LifeTest. Since field failures don't provide us any time and temperature history, the thermal-cycle test is a repeatable "standard" which monitors any variations in the quality of components and assembly processes on each production lot of circuits. We determine the expected life of finished transducers in Powered LifeTest.

Thermal-Cycle Test

The thermal-cycle test exposes a small sample of circuit boards to hundreds of thermal-cycles from room temperature to the maximum rated temperature of the board. The circuits are cycled every 12 hours from the maximum temperature to ambient. Since the rapid thermal-cycle to room temperature lasts ½ hour, most of the exposure time is at maximum temperature. These tests take place in forced-air convection ovens. At regular intervals, SMT circuits are subjected to ultrasonic vibration, while some hybrid circuits undergo high-frequency impact shocks.

Circuits remain unpowered during oven testing, but we periodically test them at room temperature. This electronic diagnostic test measures 26 performance parameters (i.e., current draw, startup time, V_{p-p}, frequency jitter, duty cycle, rise and fall times). Since the test provides much more data than a simple hard failure, we are able to monitor the onset of soft failures.

We monitor the life of the circuits, log the time to failure, and determine the cause of failure. We know that all circuits will fail if tested long enough; we want to verify uniform quality of each circuit lot (of a given model), and expect circuits to fail for known limiting factors, not for new random causes. We have been qualifying our board lots with this process since 1994, and find that our manufacturing lots are very uniform.

Powered LifeTest

In light of the increasing focus on permanent installations and intelligent well activity, Quartzdyne has begun a new in-house test using complete transducers. A permanent application is vastly different from a retrievable wireline application. A wireline application generally involves one thermal cycle per downhole trip, and if batteries are employed, the circuit may be switched on/off many times. On the other hand, a permanent installation is exposed to a constant pressure and temperature while the circuit is continuously powered.

In April 2000, Quartzdyne started pulling finished transducers from production for Powered LifeTest. LifeTest is primarily designed to test to failure at a constant temperature, but we also monitor for "soft" failures like high current draw and frequency jitter.

One technical note on the test procedure: at temperatures above 180°C, we use a resistor divider to attenuate the V_{p-p} of the output frequencies. This is done to simulate a (typical) short wire length leading from our oscillator circuit to our customer's frequency counter. From past experience, we produced premature failures at 1000 hours by driving a 10 foot cable at high temperature. The silicon CMOS output driver produces too much self-heating from high capacitance switching (too much cable length), particularly at the 7.20 MHz reference frequency.

TEST RESULTS and DISCUSSION

In the table below, we're providing a summary of test results from both thermal-cycle tests and Powered LifeTest. Note that many of the Powered LifeTests are ongoing, so the final value for the MTBF has not been determined.

Circuit Type	Temperature	Thermal-Cycle Test	Powered LifeTest
150°C Sn63 Surface-Mount	150°C	12000 hours (1000 cycles) limit: plastic-packaged SOTs or SOICs	3300+ hours*
177°C Sn96 Surface-Mount		12000 hours (1000 cycles) limit: plastic-packaged SOICs	7700+ hours*
200°C HMP Through-Hole		-	7700+ hours*
200°C Hybrid		-	-
177°C Sn96 Surface-Mount	177°C	2000 hours (166 cycles) limit: plastic-packaged SOICs	2250 hours limit: plastic-packaged SOICs
200°C HMP Through-Hole		-	7700+ hours*
200°C Hybrid		-	-
200°C HMP Through-Hole	200°C	4000 hours (333 cycles) limit: inductors, capacitors	4900+ hours*
200°C Hybrid		-	2800+ hours*
200°C HMP Through-Hole	225°C	750 hours (60 cycles) limit: polyimide substrate	1500 hours limit: polyimide substrate
200°C Hybrid		5850+ hours* (490 cycles)	6200+ hours*

*Ongoing test

A summary of the thermal-cycle test results are shown graphically in Figure 1. Note that Figure 1 shows only one line for surface-mount circuits. Although we have tested Sn63 and Sn96 SMT circuits, upon graphing both sets of SMT lines, we observed that the lines were nearly coincident. This is predicable, since both circuits share the same fundamental limit of the technology: plastic-packaged SOICs. "Pushing" the SMT technology beyond 150°C doesn't make sense. Changing the solder type in a SMT circuit may provide higher temperature operation, but at significantly reduced life (based on our tests of using Sn63, Sn96, and HMP.)

These results underscore the fact that for temperatures of 125°C or less, SMT technology can provide 5+ year reliable operation. Above 125°C, hybrid, or properly designed through-hole, technology is required for acceptable lifetimes. As noted previously, hybrid circuits can withstand much higher levels of shock and vibration.