Quartzdyne, Inc.
4334 W. Links Drive
Salt Lake City, Utah 84120 USA
Tel: 801-839-1000
www.quartzdyne.com

Reliability Statistics of Quartzdyne® Pressure Transducers

May 2012

Introduction

This report describes the general design of a Quartzdyne® Pressure Transducer, and provides updated reliability statistics and common failure modes for each of the major components, based on field-failure returns. Our statistics suggest that the pressure crystal is the most reliable component of the transducer, and we discuss initiatives to improve crystal and circuit reliability by incorporating ASICs (Application-Specific Integrated Circuits) into surface-mount and hybrid circuits.

Transducer Design

All Quartzdyne Pressure Transducers share three common elements: a set of three quartz crystals, an oscillator circuit, and an isolation bellows. Although various models offer different packaging options (i.e., 1", 7/8", 3/4"), a straightforward analysis of customer returns indicates that the ultimate reliability of our products lies in the performance of these core elements.

The quartz pressure and temperature crystals change frequency to measure pressure and temperature; the quartz reference crystal is used as a clock. All three crystals are temperature-sensitive in varying degrees, but only the pressure crystal is hydrostatically exposed to the pressurized medium. As depicted in Figure 1, the temperature and reference crystals are of similar construction (packaged in metal TO-5 cans), while the pressure crystal is a monolithic quartz crystal, capable of withstanding high compressive stresses induced by pressure.

Overall Reliability

Quartzdyne utilizes two data sources to track product reliability: internal testing and customer returns/feedback. Internal tests are designed to test a specific element (crystal, circuit, bellows) over a range of operating conditions. This requires several customized tests, each optimized to probe the element in question for specific failure criteria. Customer returns provide valuable feedback, revealing which areas need the most improvement and where internal testing should be improved.

We maintain an extensive database containing measurements from all internal tests and customer returns. Continuous analysis of these data, and then focusing on the "weakest link" has led to significant improvements over the past fifteen years. For Quartzdyne, continuous improvement lies in increasing the working life of each transducer.

Therefore, a thorough review of the field performance of Quartzdyne Pressure Transducers helps us chart our progress towards this goal. Publishing field reliability data, both the good and the bad, is rare in our industry. We do it to establish customer confidence in our ongoing work of continuous improvement.

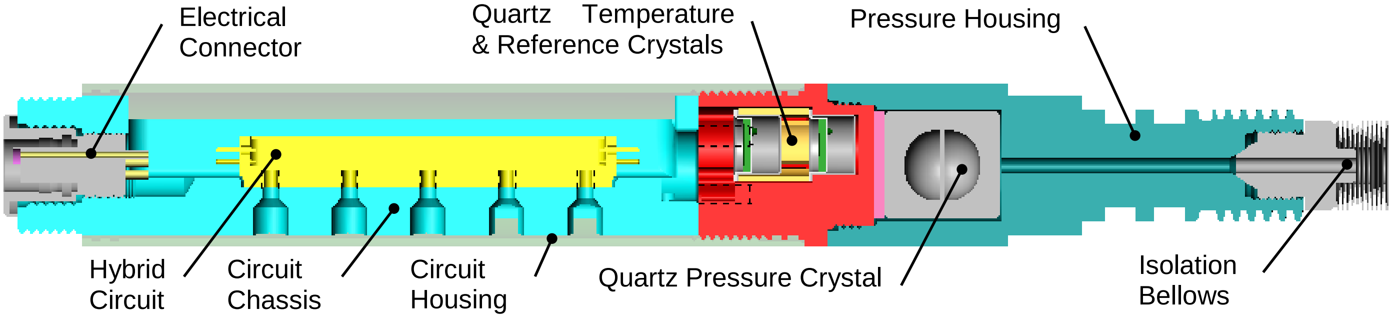


Figure 1: Cross-Section of Typical Quartzdyne Pressure Transducer with Key Elements Identified

Quartzdyne sells transducers into three primary markets: logging (wireline), drilling, and permanent monitoring. Since transducers sold to our permanent monitoring customers rarely return to Quartzdyne, we do not include transducers sold to this market in the denominator. Consider Figure 2, where the cumulative percent returned is defined as:

$$\frac{\text{Number returned from a given year (Logging, Drilling, and Permanent)}}{\text{Number of New units shipped in a given year (Logging and Drilling)}}$$

These percentages are charted versus the age (at return) of the transducer, and sorted by the year built. For example, as shown in Figure 2 the "average" transducer built in 2005 had a 7.8% failure rate after two years in the field, while the "average" 2006 transducer had a 6.7% failure rate after two years in the field. This graph does NOT provide any information concerning the actual time at temperature and pressure. Most of these transducers have made trips down many different holes, and our customers do not provide us a log.

The overall reliability graph shown in Figure 2 includes all failures traced to a Quartzdyne component (crystals, circuit, bellows, etc.) We excluded all returned transducers that qualified for one of the following criteria:

- failed for mishandling (dropped downhole, crushed, flooded, etc.)
- returned for recalibration
- returned for a circuit or model upgrade without any failure symptom noted

In order to focus our improvement efforts we split the failures up into various categories: pressure crystals (QP), temperature crystals (QT), reference crystals (QR), circuits (surface-mount or hybrid), and miscellaneous (bellows, packaging).

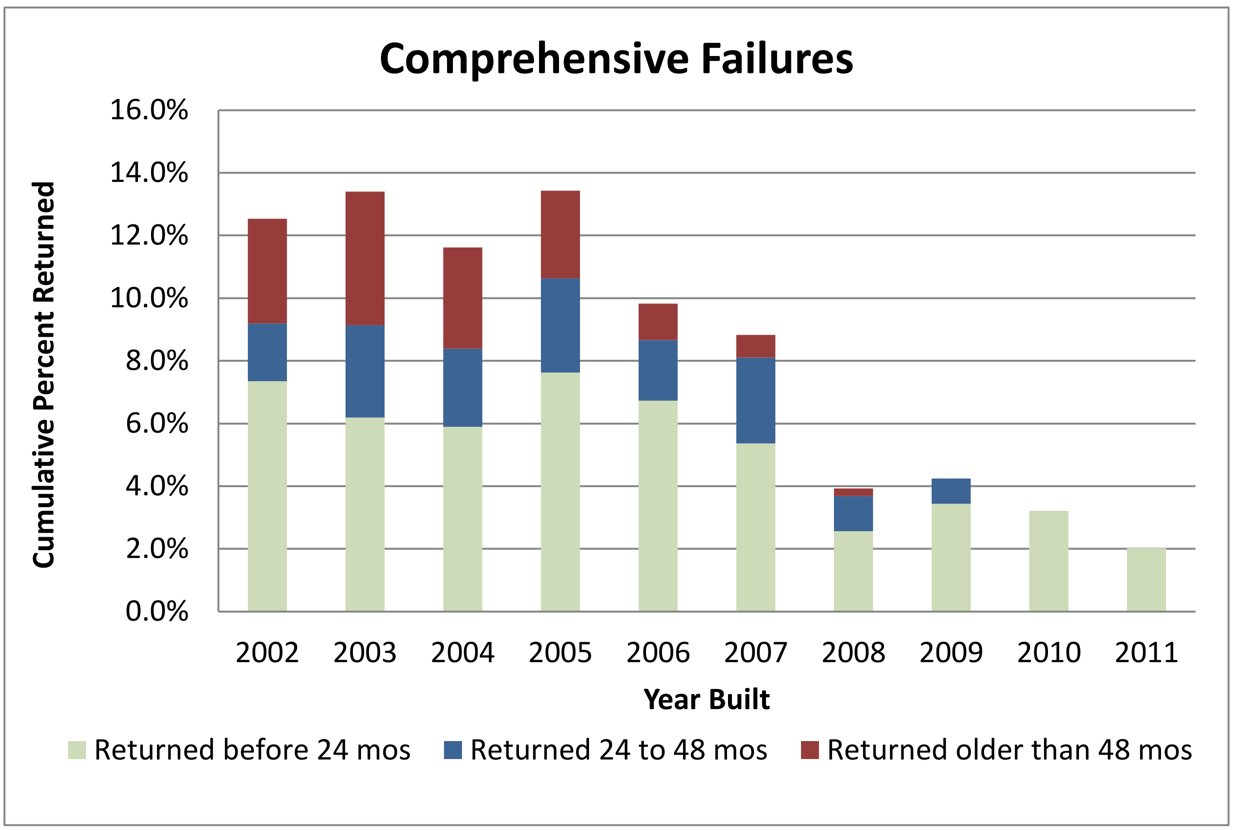


Figure 2: Overall Reliability

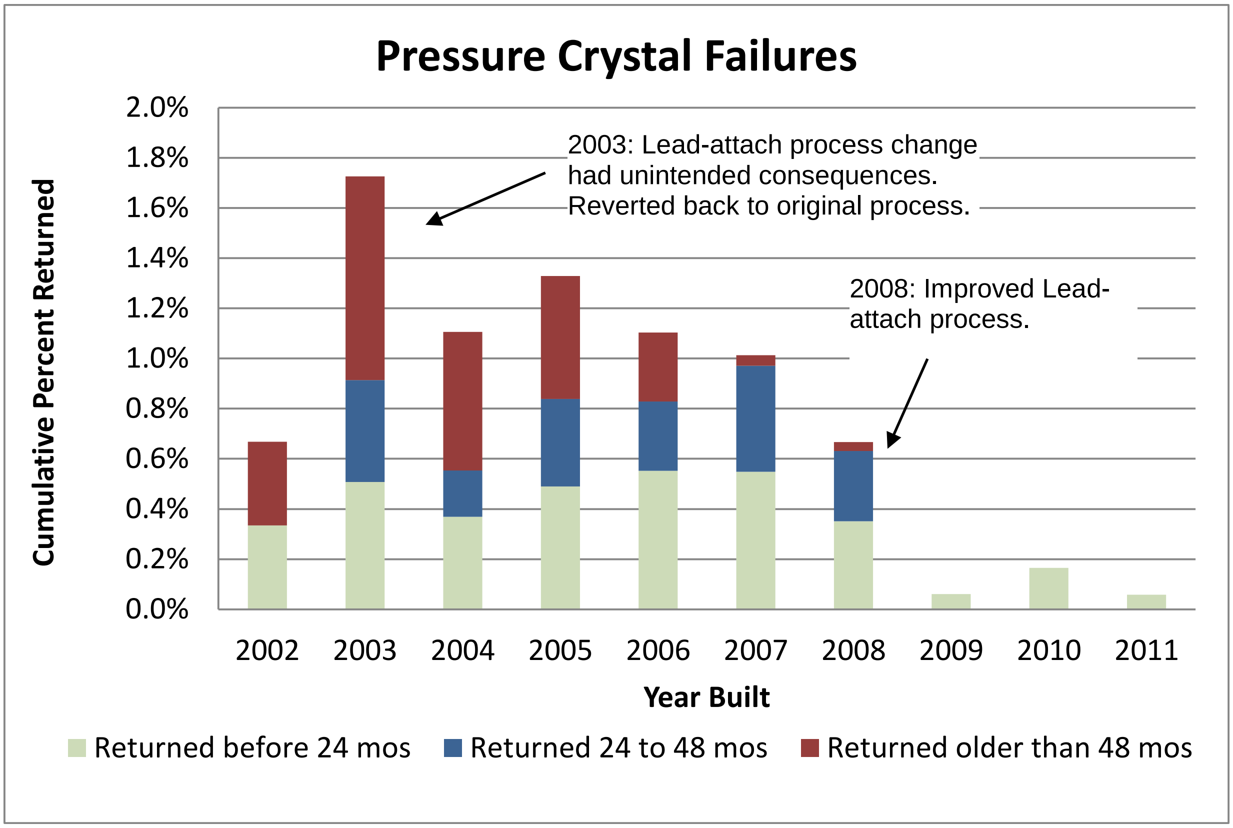


Figure 3: Pressure Crystal Reliability Curves

Pressure Crystals

Historically, quartz pressure (QP) crystal failure rates were around one percent returned. Drive Level Sensitivity (DLS) accounts for roughly 50% of pressure crystal failures. DLS is quantified by measuring the impedance of the resonant frequency at various drive (energy) levels. A set of stable impedance measurements over the drive level set is an indication of an electrically "good" pressure crystal. DLS crystals may exhibit slow or non-startup. DLS may be exacerbated by mechanical shock which could result in a marginal but functioning crystal going intermittent or completely “dead” in the field.

The second most frequent failure mode of pressure crystals (~40%) is high impedance (Hi-Z). Since the oscillator circuit is designed to drive pressure crystals with a specific range of impedances, a Hi-Z crystal simply will not start to oscillate. Hi-Z is often the result of a detached or broken electrical connection from the feed-through to the crystal.

A dramatic decrease in pressure crystal failures occurred during the 1998-1999 period. (11% of pressure crystals manufactured in 1997 failed after five years in the field; current failure rates are < 0.6%.) We attribute this marked improvement to a more repeatable process and to an improved high-temperature (> 180°C) design. The small jump in 2003 was due to a process change in lead-attach that had a negative impact on reliability. Exposed in internal testing, this process change was reversed within the same year. The lead-attach process change implemented in 2008 was more thoroughly qualified and has resulted in a step improvement.

Transducers returned for repair are diagnosed; if the pressure crystal is not within the current specifications, Quartzdyne will not repair the transducer. Since circuit and crystal specifications are subject to change, the crystal must be compatible with circuits available for repair. Scrapping an out-of-spec pressure crystal protects customers from using a questionable transducer, which is more likely to experience a field failure.

Because a pressure crystal failure results in a scrapped transducer, it is the most expensive failure mode (circuits, temperature, and reference crystals can be replaced). Accordingly, if a transducer is returned with a faulty circuit, but the pressure crystal is also scanned as Hi-Z, for example, the failure mode is assigned to the pressure crystal. As such, some of the transducers in Figure 3 may have failed initially for another symptom.

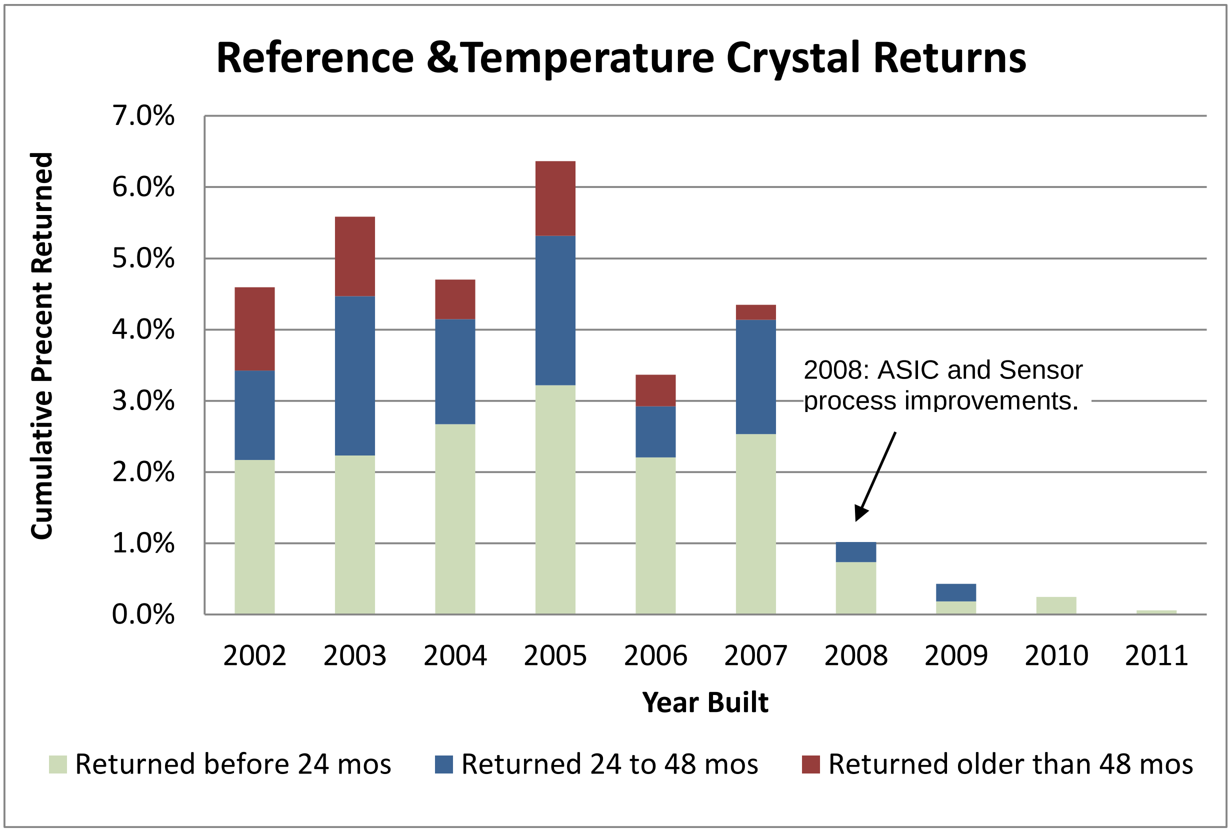


Figure 4. Temperature and Reference Crystal Reliability

Temperature and Reference Crystals

When discussing failures of the quartz temperature (QT) and reference (QR) crystals, the same terminology discussed in the Pressure Crystal section applies, namely DLS and Hi-Z. Over 75% of QT/QR failures are attributed to DLS, followed by Hi-Z failures. DLS and Hi-Z failures are often caused by severe shocks, where contaminants become dislodged, or the epoxy joints completely fracture. (The conductive epoxy is both the electrical and mechanical attachment of the crystal disc to the metal pins of the TO-5 can.)

In order to fabricate QT/QR crystals that survive drilling vibration, we stiffened the mounting joints inside the TO-5 can in 1999. This improvement has nearly eliminated Hi-Z failures since that time.

Through 2007, DLS remained the primary failure mode of our quartz crystals, we acquired a scanning-electron microscope (SEM) to help us better understand the source(s) of DLS. It is widely accepted that particle damping is a cause of DLS, and the SEM has helped us identify sources of microscopic particulates. We have attacked DLS failures in two ways:

1. <u>Process Automation & Improvement</u>. We introduced process automation initiatives during 2007 that have reduced batch variability and crystal handling. In conjunction with LEAN manufacturing, we continue to evaluate process changes that will facilitate further reliability improvements.

2. <u>Automatic Gain Control</u>. In 2007, we developed a new ASIC circuit that “kick-starts” marginally DLS crystals. This feature is termed automatic gain control (AGC). Our customized AGC works in this manner: if the crystal impedance is normal, the AGC remains off. If the crystal impedance becomes unstable (DLS), the AGC turns on and overdrives the crystal to maintain oscillation. After a DLS episode is over, the AGC shuts off. We believed that the AGC feature would cut the number of DLS crystal returns in half. We’ve seen a 90% reduction of failures due to DLS QT/QR crystals on units shipped with ASIC hybrids since 2007. (2008 included shipments of both types of circuits.)

The 2-year return rate for QT and QR crystals combined has stayed below 0.2% since the above changes were made.

Circuits

Circuit life varies with electronic component packaging and test temperature. Surface-mount (SMT) circuits can be used at 125°C for one year, or at 100°C for five years. With properly constructed hybrid circuit assemblies (multi-chip modules), we expect more than five years at 200°C, or more than 30 years at 175°C.

Our ongoing circuit evaluation is based upon our internal circuit-life tests and field failures. Field failures generally corroborate with failure modes from internal circuit-life tests. Since surface-mount and hybrid circuits are markedly different technologies, we split out the field-failures of these circuits in Figure 5 and Figure 7. Quartzdyne has written numerous papers on circuit technologies and test methods which are available on our website.

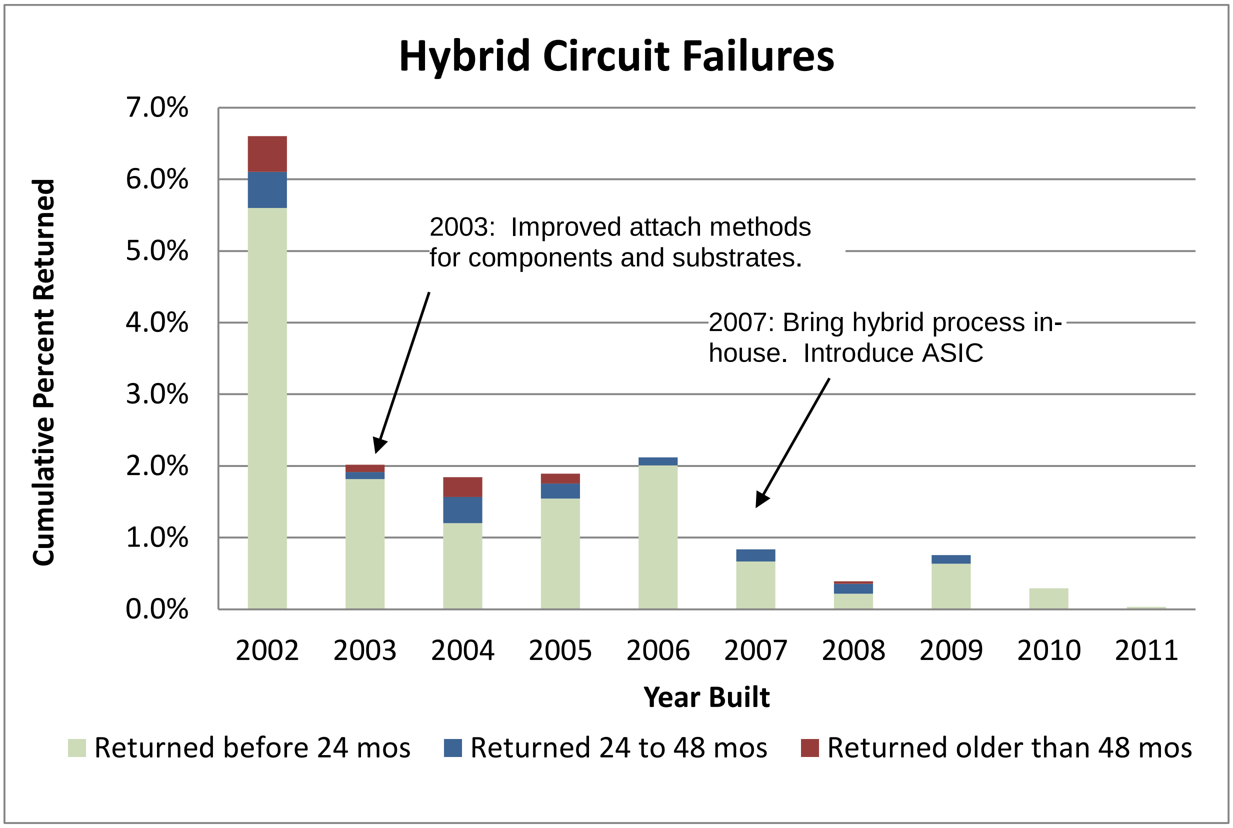


Figure 5: Hybrid Circuit Reliability

200°C-rated Hybrid Circuit (Figure 5)

Quartzdyne introduced its hybrid circuit to the market in mid-2000. Our internal tests indicate that the hybrid circuit will last 100 times longer than a SMT circuit, and over six times longer than a through-hole circuit. Due to its long-term reliability and robust design, the hybrid rapidly displaced purchases of the 177°C SMT and 200°C through-hole circuits.

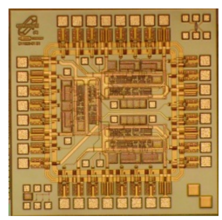
Many early failures of hybrid circuits were caused by electrostatic discharge (ESD), over-voltage, and customer miswiring with unlimited power supplies. ESD failures were addressed by customer notification and by using more robust components. Over-voltage and miswiring with unlimited supply current cause the I/O bondwires to melt; these failures require ongoing customer caution.

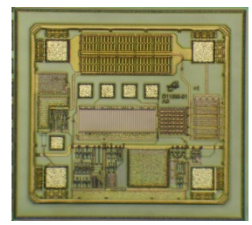
Mechanical integrity was another early source of hybrid circuit field failures. Thermal cycling coupled with vibration was suspected to weaken the substrate-to-package bond. Although the number of units returned for this symptom was few, we worked to improve the hybrid assembly in mid-2002. We also implemented the screening procedure described below on all hybrids. Since this time, this failure mode has vanished from customer returns.

To minimize the number of infantile field failures, Quartzdyne screens each hybrid circuit prior to its usage in a product. The screen consists of fifteen (15) ½-hour thermal cycles between 25 and 225°C plus 72 hours aging at 225°C. Following the temperature cycling and aging, each hybrid is subjected to 10 mechanical shocks in a metal-to-metal drop fixture, which was designed for testing the robustness of the package and components under high-shock loads. These test are in addition to our lot-qualification test and the full-scale pressure/temperature calibration.

As mentioned in the QT/QR reliability section, all hybrids now include an AGC. Since an AGC would normally add dozens of components inside the hybrid (for which we had no room), we accomplished it by designing an Application Specific Integrated Circuit (ASIC). ASIC technology allows us to incorporate an AGC without increasing the size of the hybrid circuit. In fact, the oscillator ASIC has improved the reliability of the hybrid circuit as it reduces the total component count inside the hybrid by 50%. Since the ASIC operates on low voltage, it requires a 2.7 – 5.5 VDC supply.

To further reduce component count inside the hybrid, two new ASICs were developed during 2009 at Quartzdyne: a voltage regulator (V_{reg}) and a frequency counter. The V_{reg} ASIC enables our hybrids to operate down to a 2.7 VDC minimum supply, and the FC ASIC reduces current draw in digital-output hybrids and allowed us more functionality, such as a 5^{th} byte checksum for data integrity. These two ASICs do the combined functions of 16 discrete components.





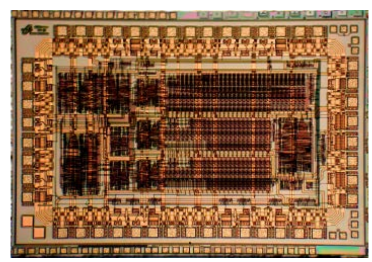


Figure 6. Oscillator, Voltage Regulator and Frequency Counting ASICs improved circuit and sensor reliability.

Figure 5 shows the Hybrid circuit's reliability. Hybrids generally operate in harsher environments and at higher temperatures than SMT circuits, and their reliability surpasses that of the SMT. Hybrid returns are less than 1% since 2007 when the ASIC oscillator was introduced.

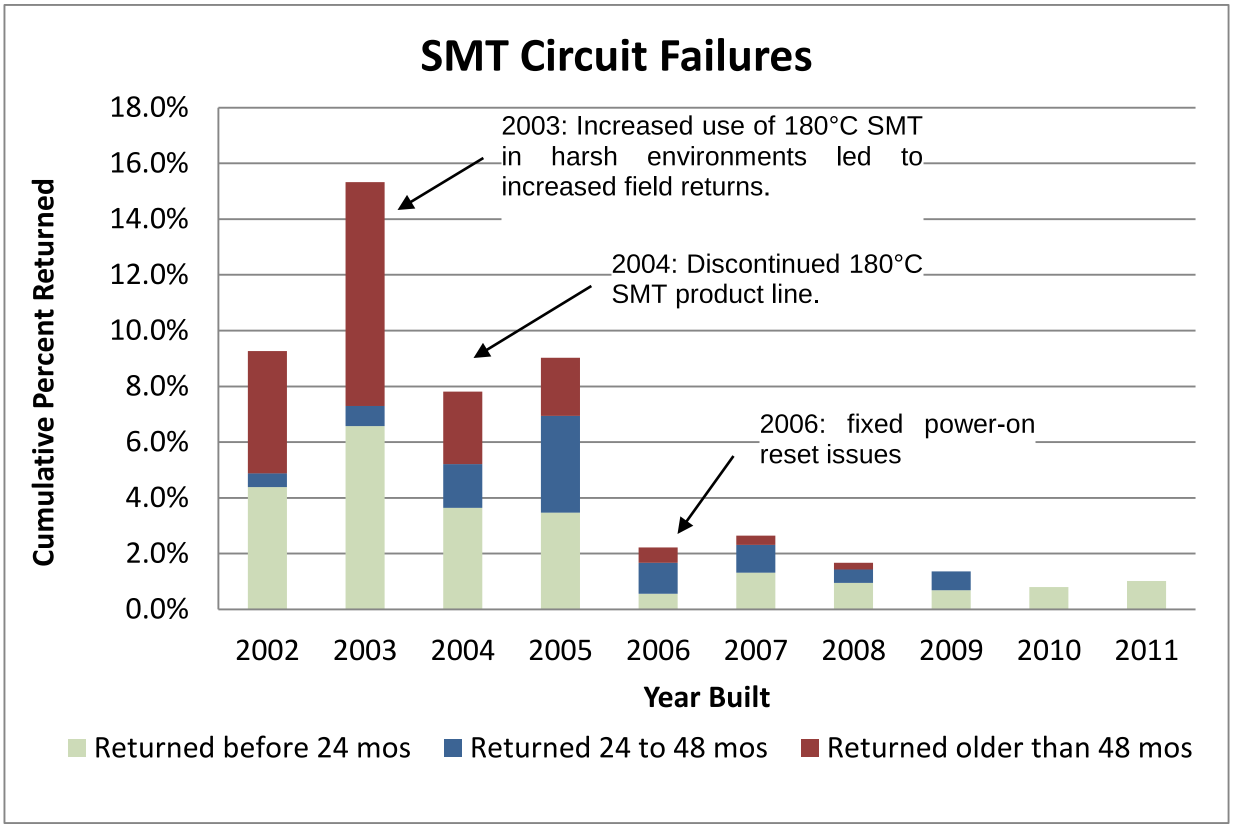


Figure 7: SMT Circuit Reliability

150°C-rated Surface-Mount (SMT) Circuit (Figure 7)

The Sn63Pb37 (183°C eutectic) solder limits the operating temperature of this design. Prior to 2004 we also offered a pb-free SAC solder version of our circuit. While this circuit was rated to 180°C, its lifetime at temperature was only a few months. In 2002, hybrid circuits began to replace the 180°C SMT in most high temperature applications and a step improvement in our returns data was observed. We expect to be re-introducing RoHS compliant SAC solder to our SMT products in the coming year, but the temperature rating will remain at 150°C.

Commercial plastic packages are used in the SMT designs. The primary failure mode in these designs is wirebond degradation at the Au-Al interface on the chip. The failure rate is accelerated by the formulation of the plastic package which has changed over the years. In 1998 we saw failures at about 2400 hours at 180°C. This decreased to 600 hours by 2004 as smaller particle size and more active Bromine flame retardants were incorporated. New Halide-free plastic formulations have been introduced in response to the higher soldering temperatures required to satisfy the RoHS directive. These packages are showing increase in life back to the lifetimes seen prior to 1998.

In 2005 the majority of SMT returns were digital-output circuits that demonstrated a problem in the reset logic during startup. Some circuits did not startup properly which could result in a hung bus depending upon the customer's software. We did not discover the problem since our test systems were designed to detect the problem, reset the bus, and try again (according to our manual and Phillips I^2C recommendations). We revised the digital FPGA firmware in 2006 to eliminate the startup problem. Total SMT returns have been below 2.5% since 2006.

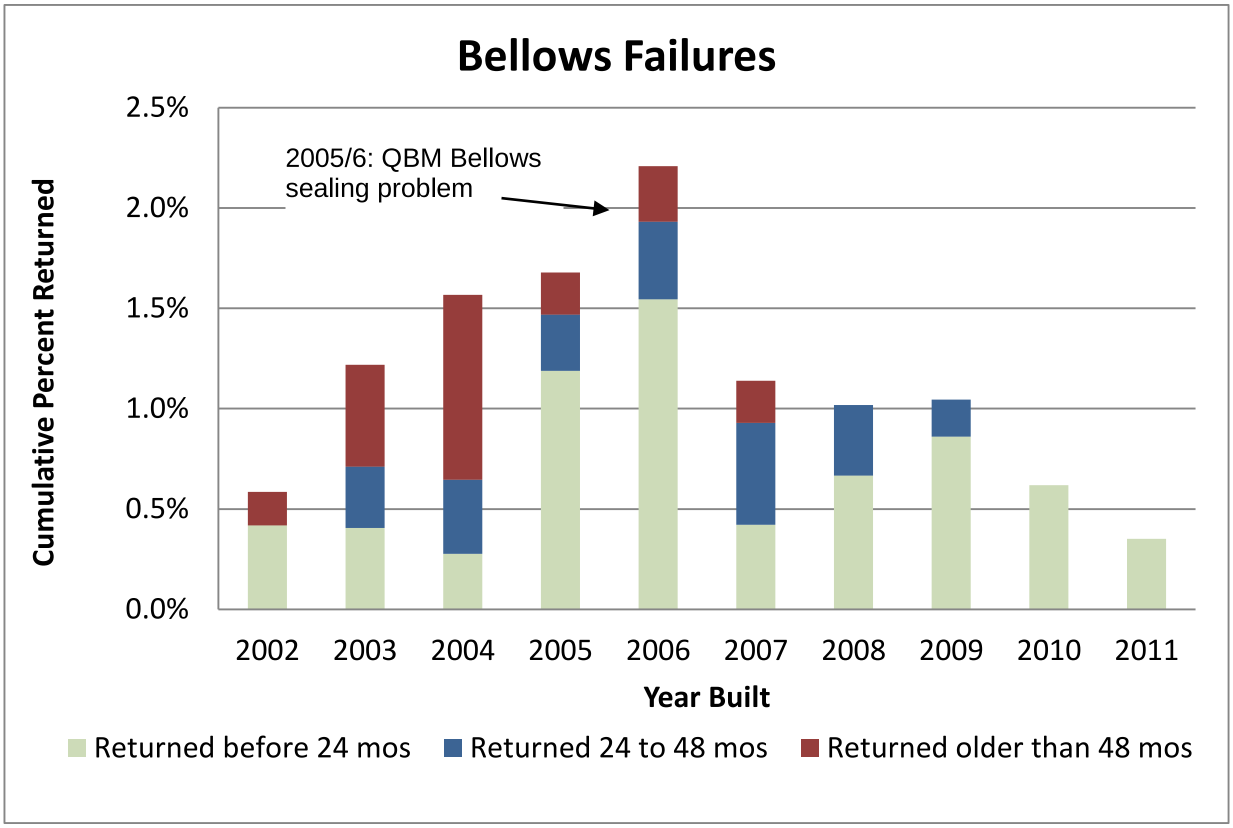


Figure 8. Bellows Reliability

Bellows Failures (Figure 8)

For the first time, we are separating bellows failures from the miscellaneous category. As circuit and crystal reliability has improved, the miscellaneous category has begun to dominate. Separating this category into actionable subcategories enables us to focus our attentions on more meaningful improvements.

In 2005 we became aware of sealing issues in our QBM bellows. This problem was addressed by moving to a larger thread which allowed more torque to provide a better seal. This improvement was implemented in April 2007. Bellows failures dropped in half with this change and remain around 1%.

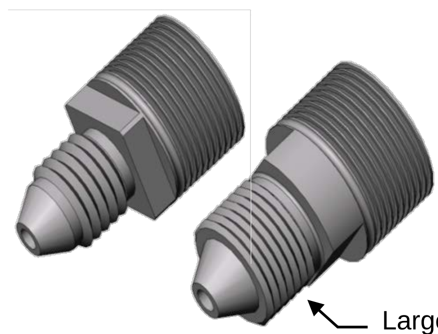


Figure 9. Thread change provided increased reliability for bellows.

Another bellows failure mode is damage caused by particulate, particularly in drilling applications (Figure 10). We have made advances on diaphragm designs which may alleviate this problem. Consult with our sales department to see if a diaphragm may be a good alternative to the traditional bellows in your application.

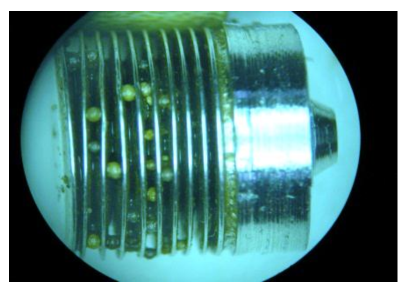


Figure 10. Bellows damage caused by particulates trapped between convolutions.

This year we have launched a major initiative to deal with zero-return problems in our bellows design. This problem is manifest by high pressure readings (+5 psi over normal) at ambient pressures. While not within our specified operating range of >200psi, the phenomenon creates concerns for our customers who verify performance at the surface before deploying a tool. We expect to make major improvements in this area before the end of the year.

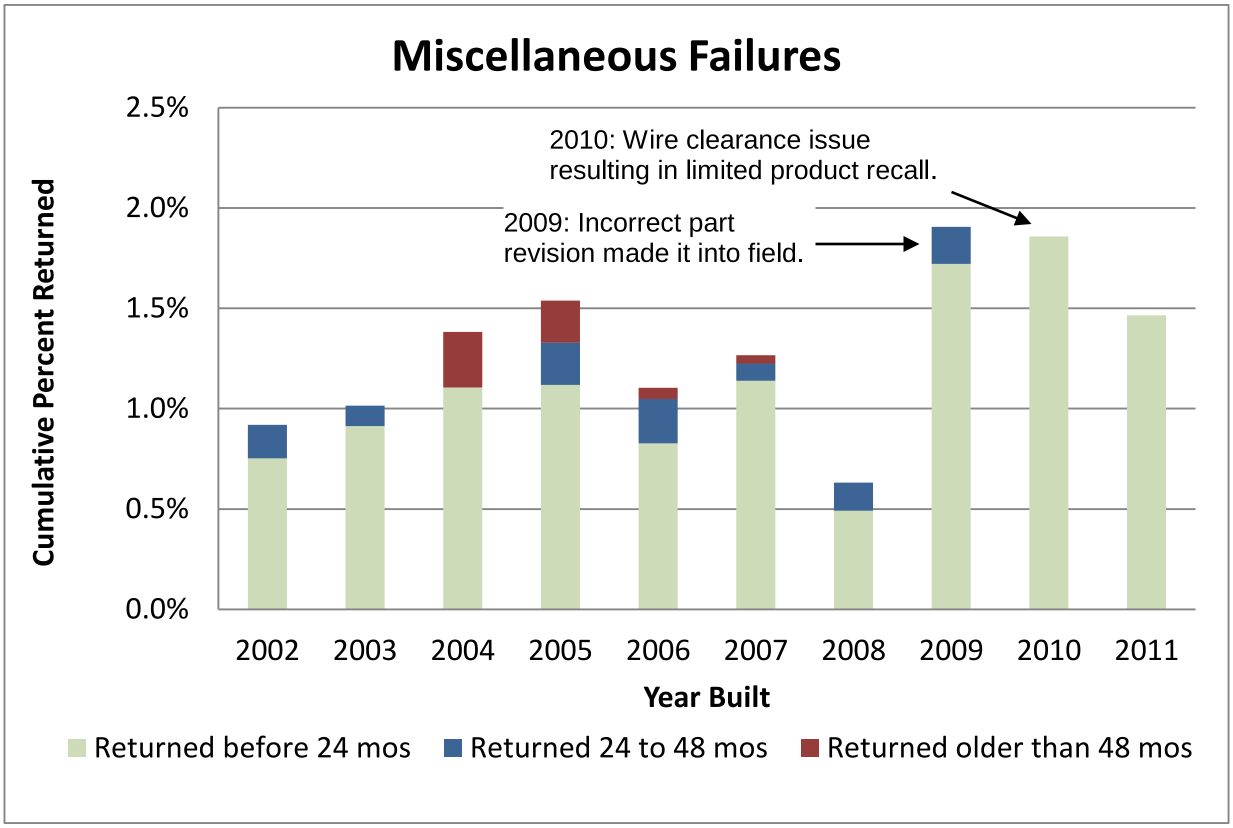


Figure 11: Miscellaneous Failures

Miscellaneous Failures (Figure 9)

Even with bellows removed, Miscellaneous remains the dominant category for field returns.

Most of the miscellaneous returns in 2009 were dimensional issues relating to the wrong revision of a part that made it to the field. The other failures were evenly spread over a mix of issues including wires, screws, contamination, and software.

2010 miscellaneous failures include a wire-clearance problem that resulted in a limited recall. The remaining failures were again primarily cosmetic and/or minor mechanical in nature. Issues include threads, screws, electrical connectors and incorrect labels.

The largest miscellaneous failure for 2011 is an incorrect build due to a documentation error. Mechanical issues such as burrs, scratches and thread damage follow. Increased attention has been given to our final visual inspection process to help catch these problems before they leave the facility.