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Reliability Statistics of Quartzdyne® Pressure Transducers

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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 crystals are the most reliable components of the transducer. Additionally, it discusses initiatives to improve product reliability in the future.

To better understand how Quartzdyne reliability has changed over the years, the year 2000 and 2005 are used as reference points. The data reflects field-failure returns up to December 31, 2019.

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”, ½”), 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 pressure. 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.

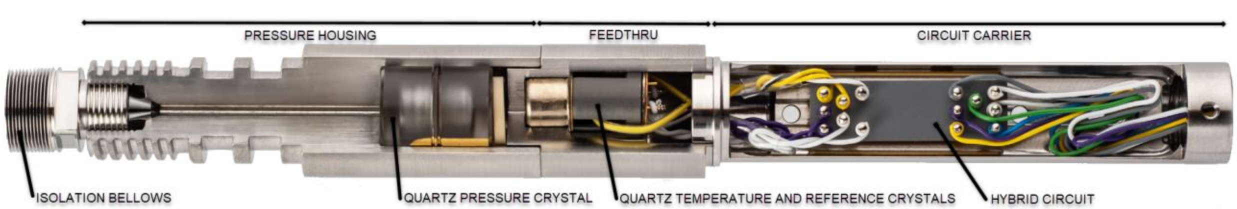

Figure 1: Cross-Section of Typical Quartzdyne Pressure Transducer with Key Elements Identified

Overall Reliability

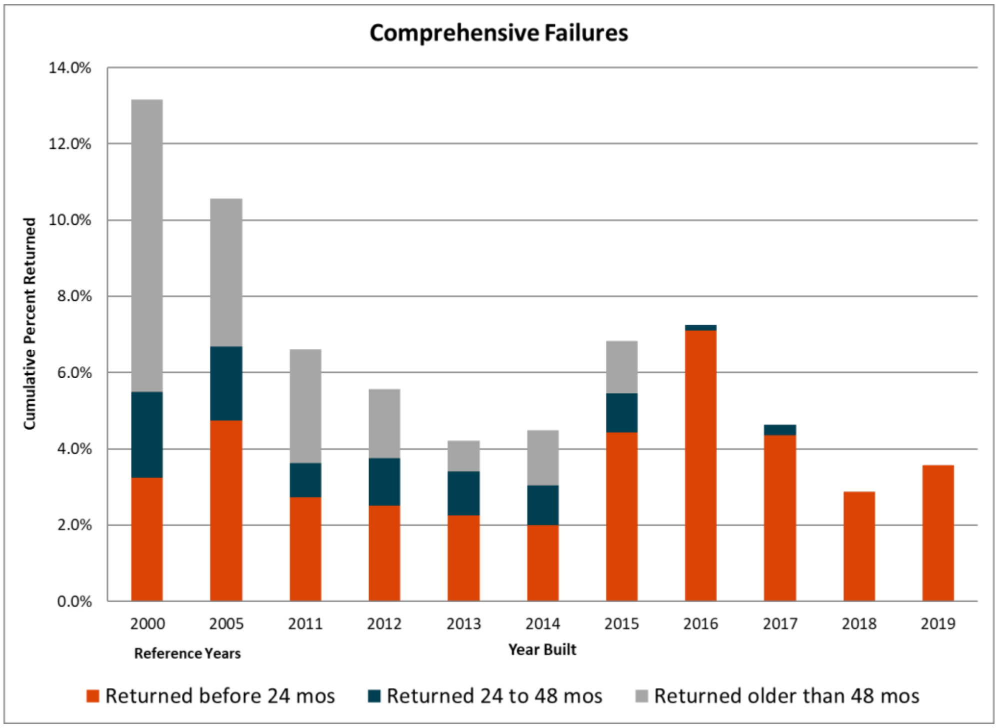

Figure 2: Overall Reliability

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 this data and then focusing on the "weakest link" has led to significant improvements over the past twenty years. For Quartzdyne, continuous improvement has increased 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.

Quartzdyne sells transducers into three primary markets: completions, drilling, and production logging. Since transducers sold to completions applications 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:

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

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 2000 had a 3.2% failure rate after two years in the field, while the "average" 2005 transducer had a 4.7% failure rate after two years in the field. This chart does NOT provide any information concerning the actual time at temperature and pressure. Most of these transducers have been placed downhole in many different locations, and our customers do not provide us a log.

The overall reliability chart 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 due to mishandling (dropped downhole, crushed, flooded, etc.)
- returned for recalibration
- returned for a circuit or model upgrade without any failure symptom noted

To focus our improvement efforts, the comprehensive failures are split into categories: pressure crystals (QP), temperature crystals (QT) and reference crystals (QR), circuits (surface-mount or hybrid), bellows, and miscellaneous (dimensional, wires, screws, incorrect documentation, packaging, etc.)

Pressure Crystals

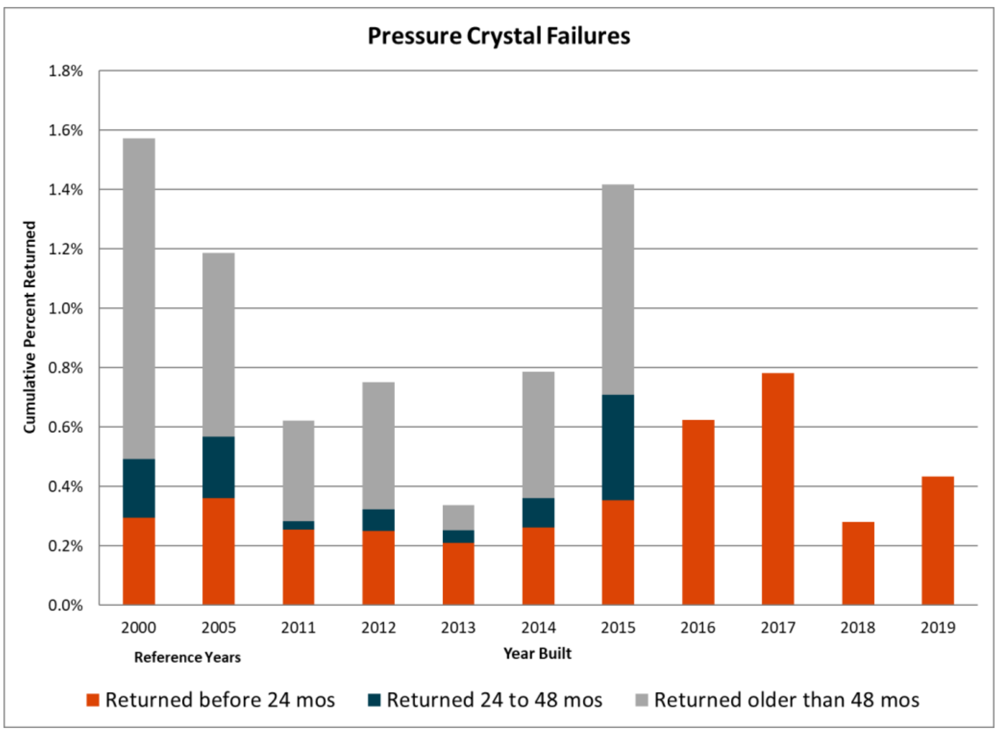

Figure 3: Pressure Crystal Reliability

Historically, quartz pressure (QP) crystal failure rates were around one percent returned. Drive Level Sensitivity (DLS) accounts for most of the 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 a 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 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 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 in 1998, not shown in these charts. (For reference, 11% of pressure crystals manufactured in 1997 failed after four years in the field; current failure rates are less than 0.5%.) We attribute this marked improvement to a more repeatable process and an improved high-temperature design. The lead-attach process changes implemented in 2008 were thoroughly qualified, and in conjunction with the ASIC release (discussed below) 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 the higher probability of experiencing a future 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 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.

The 2019 increase is largely attributed to transducers that were testing outside of the published specifications (i.e., DLS, Hi-Z, accuracy drift, etc.) Occasionally we also see returns for completely unresponsive pressure crystals due to detached connections.

Temperature and Reference Crystals

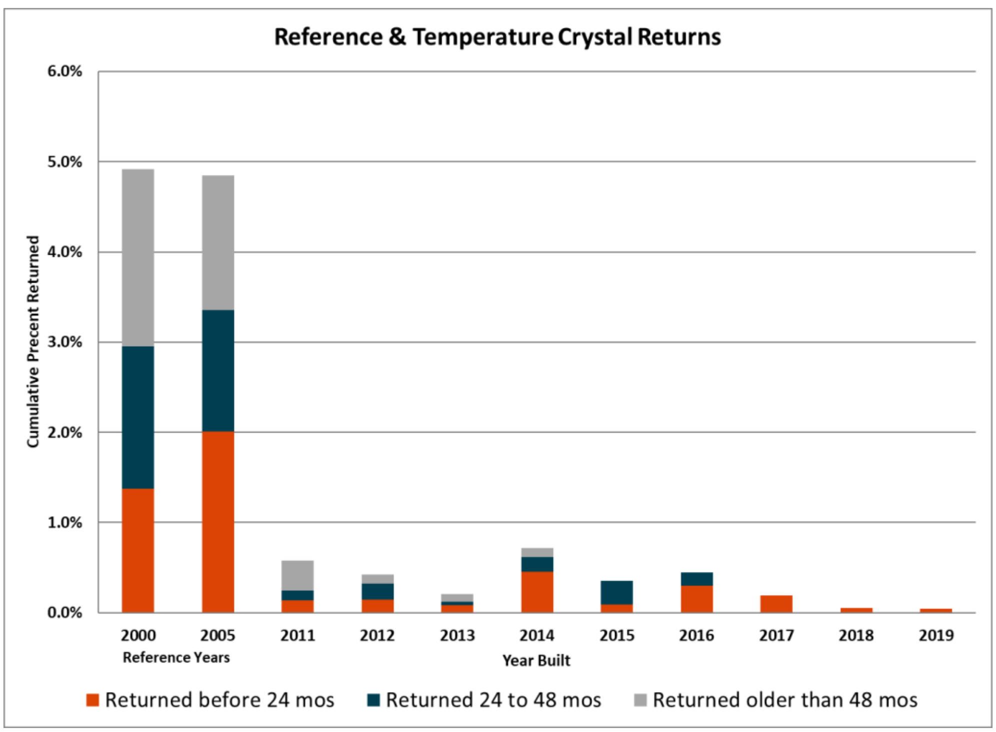

Figure 4: Reference and Temperature Crystal Reliability

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. 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.) To make 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 subsequently 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. Process Automation & Improvement. We introduced process automation initiatives during 2007 that have reduced batch variability and crystal handling. Automated systems remove variability and human interaction from the process. In 2010, we implemented cleaning schedules within the cleanroom to remove stray particles. Two years later, in 2012, we increased the scheduled maintenance frequency for the fixturing. The same year, several superfluous steps were removed from the process requiring less handling resulting in fewer particles. At the beginning of 2014, we also replaced some of the screwdriver-driven screws with thumb screws to avoid creating metal particles with the screwdriver in fixtures. In conjunction with Lean manufacturing, we continue to evaluate process changes that facilitate further reliability improvements.

2. Automatic Gain Control. 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 have 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.)

Electronic Circuits

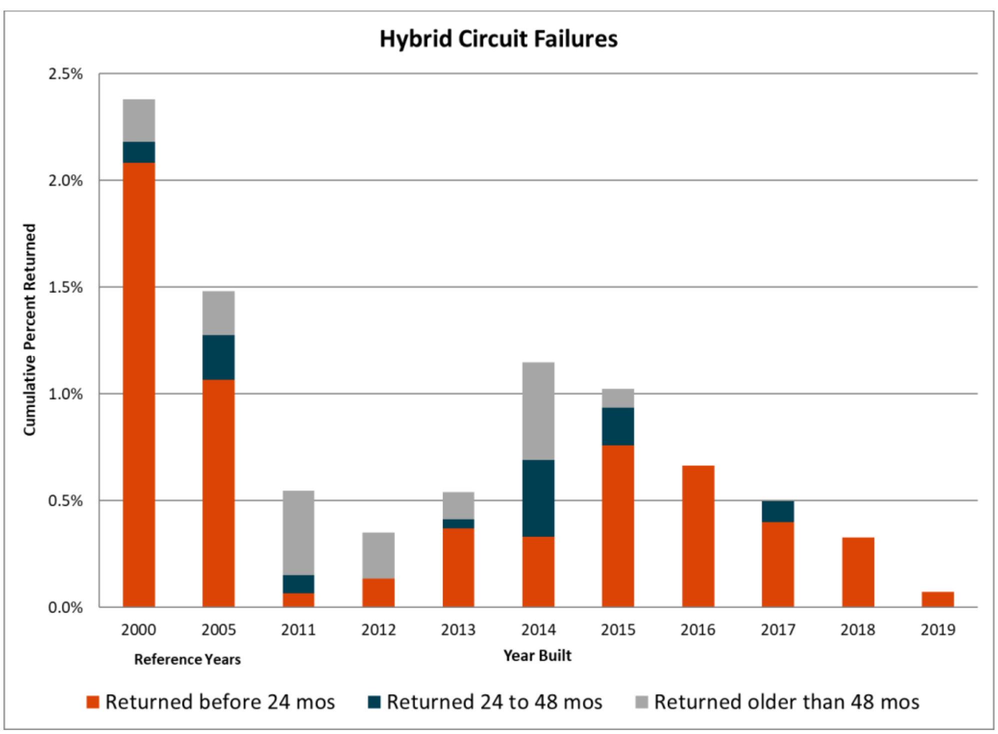

Figure 5: Hybrid Circuit Reliability

Circuit life varies with electronic component packaging and the downhole environment (mainly temperature). Surface-mount (SMT) circuits can be used reliably 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 circuit reliability is based upon our internal testing and field failures. Field failures generally corroborate with failure modes from our internal circuit-life tests. Since surface-mount and hybrid circuits are markedly different technologies, we split out the field-failures of these circuits. Figure 5 shows hybrid circuit reliability for Quartzdyne's in-house designed and manufactured circuits. In 2019 Quartzdyne concluded reporting on SMT circuit reliability primarily due to lower sales volume. Quartzdyne has written numerous papers on circuit technologies and test methods which are available on our website.

200°C-rated Hybrid Circuit

Quartzdyne introduced its hybrid circuit to the market in mid-2000. Our internal tests indicate that the hybrid circuit lasts 100 times longer than an 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 the 177°C SMT and 200°C through-hole circuits.

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 input and output (I/O) bond wires 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 of weakening 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 nearly vanished from customer returns.

To minimize the number of infantile field failures, Quartzdyne screens each hybrid circuit before 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 tests 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.

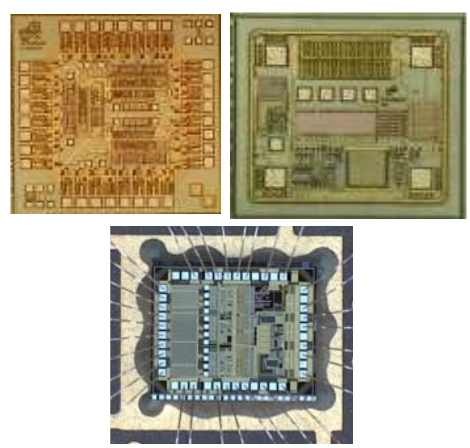

Figure 6: Oscillator, Voltage Regulator and Frequency Counting ASICs improved circuit and sensor reliability.

To further reduce component count inside the hybrid, newer ASICs were developed during 2009: a voltage regulator (Vreg) and a frequency counter. The Vreg 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 5thbyte checksum for data integrity. These two ASICs do the combined functions of 16 discrete components.

We continue to improve our products by developing application-specific integrated circuits (ASIC) that make our electronics more reliable, higher temperature, and smaller. Our latest ASIC combines three ICs and 23 passives into one chip, reducing the total component count inside the frequency-output ("analog") hybrid from 29 to 4. This breakthrough took several years to engineer, with a few "re-spins" to fine-tune the ESD protection and crystal oscillation. Due to the reduced component count, the analog circuit has shrunk to one-third of its prior length. The reduced component count and improved packaging also reduced the number of gold wire bonds, a known weak point in the hybrid. The analog ASIC (See Figure 7) has survived over 20,000 hours at 275°C, and the accompanying transducers have passed our standard environmental qualification tests.

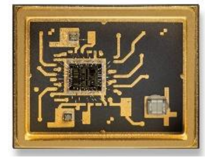

Figure 7: Next generation "analog" hybrid circuit. ASIC eliminates 23 additional parts.

Similar results were accomplished for the I2C-output ("digital") hybrid (See Figure 8). The latest ASIC helped reduce the component count and size by 50% combined with the elimination of I/O wire bonds.

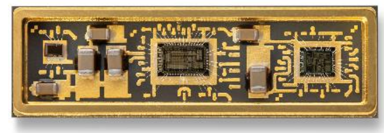

Figure 8: Next generation "digital" hybrid circuit.

Isolation Bellows

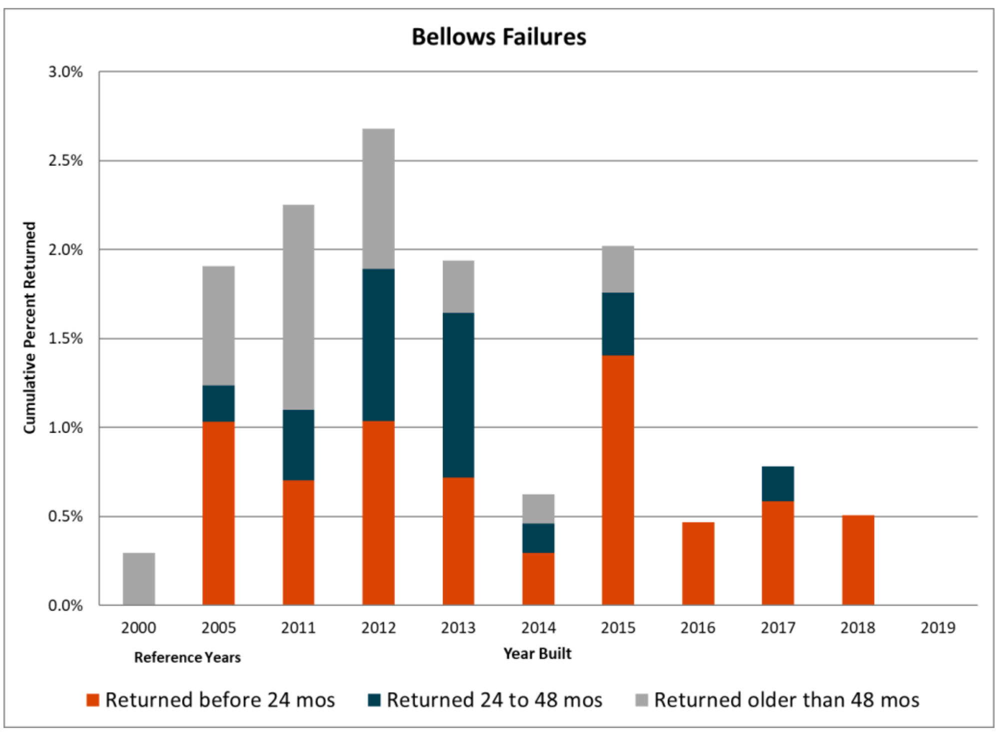

Figure 9: Bellows Reliability

In 2013 we launched a major initiative to reduce returns for bellows problems. The goal was to eliminate high-pressure readings (+5 psi over normal) at ambient pressures. While accurate barometric pressure is not within our specified operating range of > 200psi to full scale, the phenomenon creates concerns for our customers who verify performance at the surface before deploying a tool. The results of this effort were a success. We were able, through process improvement during the bellows backfill process, to bring these readings back in-line with expectations.

In 2013 / 2014, due to feedback from the field, Quartzdyne studied incidences of loosened QMB (7/8") bellows. Because of this information, we increased the installation torque of the bellows from 40 to 70 ft-lbs. So far, internal testing and customer feedback have confirmed that this action corrected the problem.

The 2015 / 2016 increase was largely due to returns for high or low-pressure readings when measuring at ambient conditions. We discovered that products exposed to a high temperature without pressure could result in plastic deformation of the bellows. Heating the bellows expands the backfill fluid beyond the elastic range of the metal. When the bellows cool the initial bellows setpoint or height is different, causing a shift in the pressure reading. This method of testing a product goes beyond Quartzdyne's recommended usage. For more information on testing conditions, contact the Quartzdyne sales department.

In 2018 several transducers were returned after developing pin hole leaks within the bellows. Shortly after the investigation concluded process steps were implemented to address the root cause of the issue. Countermeasures were adopted at supplier and internal levels. As of December 31, 2019, we have had zero returns for bellows leaks or any of the other typical failure modes.

Miscellaneous Failures

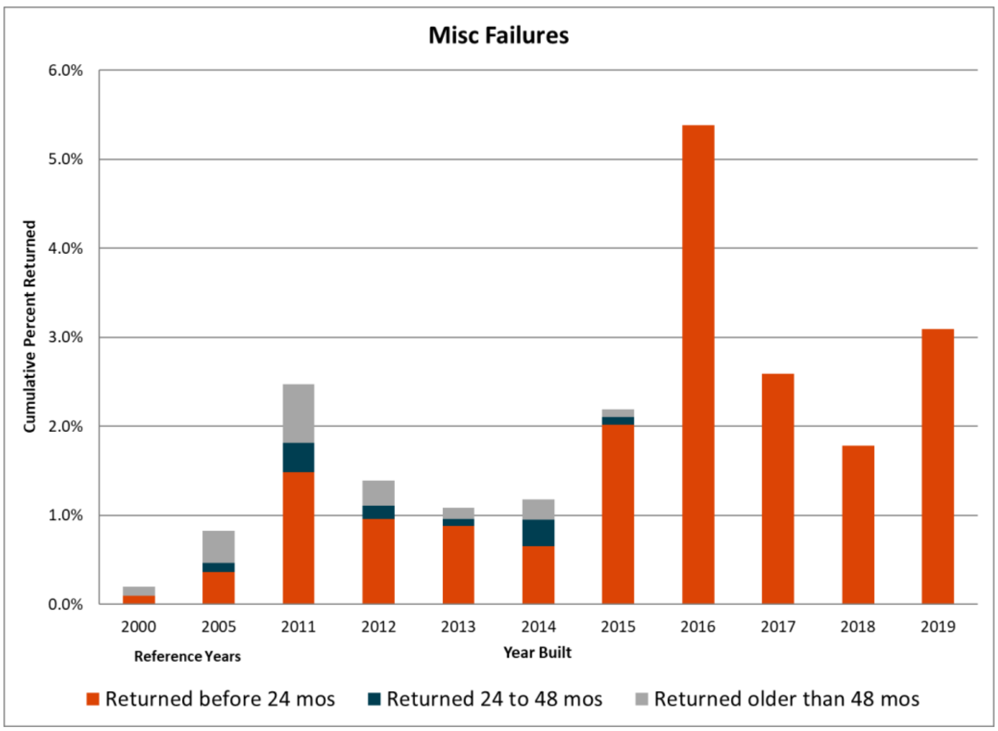

Figure 10: Miscellaneous Failures

The 2016 increase in miscellaneous returns was a combination of documentation and process issues, i.e., dimensional flaws, contamination, and connector issues. Several improvements were implemented in 2017 that directly addressed the uptick in miscellaneous failures. For dimensional returns, the method of identifying critical items was revised. Most critical parts now have part specific inspection guidelines, and some have custom supplier quality plans that explain all critical to quality requirements to suppliers. We have also purchased new inspection instruments and equipment including an automated inspection machine. Overall, Quartzdyne has adopted a more focused approach to inspection. In addition to the incoming inspection improvements Quartzdyne launched product specific final inspection standards, a dedicated resource focusing on final inspection of product.

Concerning contamination returns, improvements were made to the cleaning procedure for soldered connections. All solder connections are peer inspected using a 100X magnification microscope. In addition, Quartzdyne has launched wire welded connections for most product types.

The 2019 increase is attributed to two failure modes associated with new products (over 80% of the combined returns). One was a one-time product marking issue and the other was related to deficient standards around the newly adopted wire weld process.

Quartzdyne acknowledges the impact infantile failures have on our customers, the disruption, and delays to production, along with occasional repeat issues are not acceptable. In 2020 we began our quality initiative of “Drive to Zero Defects,” the companywide program is focused on implementing Shingo Principles, specifically Assure Quality at the Source. Our journey began with the foundation of implementing Successive Checks for critical processes and risk areas based on final inspection rejects and customer returns. The end goal is Source Inspection with mistake proofing, catching errors before they develop into defects.