Updated Analysis of Circuit Reliability Test Results

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Abstract

The downhole oil and gas market is continually pushing for higher reliability at higher temperatures. Satisfying this need requires continuous improvement, driven by failure analysis of both internal testing and field returns. This paper discusses recent lessons learned from on-going tests. Results of unpowered circuit assembly tests are reviewed. Also, a detailed analysis of separate powered life testing is presented. The internal testing results are further discussed in the context of field return data.

Keywords: High Temperature Electronics, Reliability, Life Testing

Introduction

Quartzdyne manufacturers pressure transducers and hybrid circuits for down-hole oil and gas exploration and monitoring. This market is continually pushing for higher reliability at higher temperatures. Satisfying this need requires continuous improvement, driven by failure analysis of both internal testing and field returns.

We have presented several papers on our internal unpowered life/cycle testing [1] [2]. This paper discusses recent lessons learned from this on-going test, as well as a more detailed analysis of a powered life test than has been previously presented. Finally, we compare results of the internal tests to field return data.

Test Description

We routinely sample production units and put them into one of two tests. The first test which we call Life/Cycle is an unpowered test of circuit assemblies where units are exposed to temperature, thermal cycling and mechanical shock until failure [1]. Typical test temperature is 250°C, but other temperatures have also been tested. We have several hundred units in this test at any time.

The second test (Powered Life) is of completed pressure transducers. Transducers are placed in an oven, powered continuously, and monitored daily for functionality. Test temperatures range from 150°C to 250°C depending on circuit type. We have 15 to 20 units in this test at any given time.

These on-going tests provide the dual function of monitoring the process for process drift as well as exposing wear-out mechanisms. As we address weak links exposed by these tests, the bar by which we judge "acceptable" performance is continually moving.

Recent Life/Cycle Results

As product life improves, the test time required to demonstrate wear-out mechanisms increases. If the test takes too long, the results cannot be acted upon in a timely fashion. We have historically considered a 1-year mean-time-to-failure (MTTF) as the threshold for increasing our test temperature. That threshold was met with the introduction of our ASIC circuit in 2007. This circuit eliminated multiple troublesome components and reduced component count significantly [3].

In response to increased life at 250°C we initiated a pilot test at 265°C two years ago. To date, 29 units have been placed in the test, 14 of which were removed after 1000 hours for shear testing [4]. The remaining 15 units, representing 6 different lots over a two year period continue to survive. Nine units have now exceeded 16,400 hours (nearly 2 years). These results are unexpectedly good, and create a conundrum as we compare them to results at 250°C as shown in Figure 1.

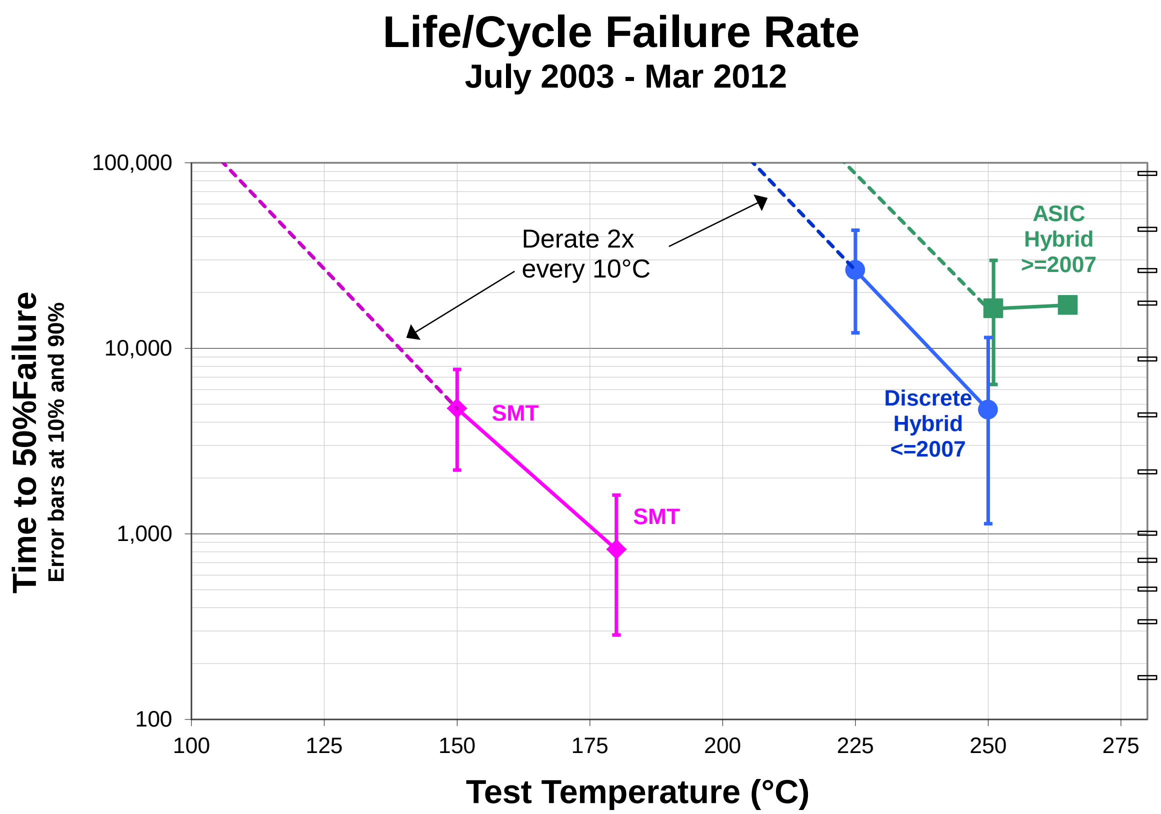

Figure 1: Life/Cycle test predictions for SMT circuits, hybrids based on discrete component designs, and more recent hybrids based on ASICs.

Visually, the graph would suggest that the parts are more reliable at 265°C than they are at 250°C. Using the results to calculate an activation energy, or simple extrapolating the line back to lower temperatures would suggest that the longer the circuit survives at 265°C, the worse the performance would be at lower temperatures. This conclusion defies logic.

Looking at the 250°C data we can show that the problem likely lies in the fact that both the sample size and test time for the 265°C tests are insufficient. Figure 2 shows the 250°C data set back-truncated to three different periods. The 2.5 year truncation is consistent with the last major circuit revision and with all units in the 265°C data set. The survival function projects 50% survival at 20 years. Adding just 6 months of data projects 3 years and opening the data set to the full 5 years yields 1.9 years to 50% survival, the same result we get if we assume that half of the surviving units at 265°C were to fail tomorrow.

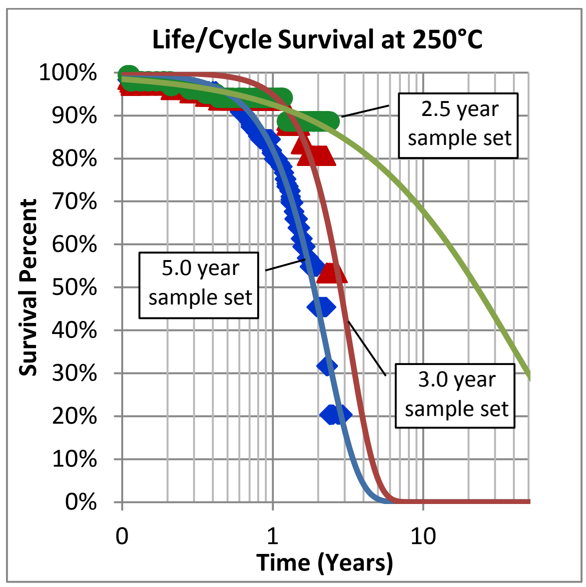

Figure 2: Comparison of Kaplan-Meier survival functions for 3 back-truncated versions of the same data set. If the sample set is insufficient to show wear-out mechanisms the end-of-life predictions will not be accurate.

It is obvious that the truncated data set is simply insufficient to make life predictions from. The data set must include a significant number of samples which have demonstrated the wear-out mechanism before it can accurately predict when wear-out will occur.

The original ASIC hybrid was introduced in July 2007. In October 2009 a second ASIC was added to the circuit to replace problematic components and reduce circuit sensitivity to resistor drift [5]. Failure modes at 250°C were compared for the two versions of the circuit to see if improved test results could be explained by circuit changes.

We have observed seven failures on the newer circuit. These are listed in Table 1. The first 4 are considered infantile failures and the root causes have been addressed. A damaged drop tester was implicated in several of these. The remaining three are clearly wear-out mechanisms.

Table 1: Failure times and modes for circuits built since October 2009. Four infantile failures and three wear-out failures have been observed.

Time (hours @ 250°C)	Failure Mode
340	Component Detach
479	Substrate Detach
479	Substrate Detach
987	Substrate Detach
10,902	Resistor drift
13,591	Resistor drift
14,930	Shorted capacitor

Looking at the entire data set for this technology, we see similar wear-out mechanisms with a mean-time-to-failure of 8600 hours. This is lower than the new data set and can be explained by design improvements which reduced component count and circuit sensitivity to resistor drift. The data would suggest an improvement of a factor of 1.5 for the onset of wear-out which would predict an MTTF closer to the 3 years at 250°C that the 2.5-year truncated data predicts.

Getting back to the stellar performance of the 265°C units, if we assume 3 years at 250°C, our normal de-rating would predict failure closer to 9 months at 265°C. We still should have seen multiple failures by now. Two theories have been considered as to why the 265°C units are performing so well. The first is that the wear-out mechanism is somehow suppressed at the higher temperature. For example, if stress in bond joints was a driver for the failure mechanism, remaining at temperatures close to the temperature where the joints were cured may be a less severe test than aging parts at a cooler temperature. The materials may also be softer as their Tg is approached.

Another possible theory is that the higher soak temperatures have somehow weakened the joints sufficiently to relieve stress over the whole temperature range while leaving the materials malleable enough to continue to hold together. This would be comparable to an annealing process which provides improved material properties through heat-treating.

Alas, these are just speculations that will require further time and study to resolve.

Powered Life

The results cited above are from unpowered tests of self-contained circuit assemblies designed for use with quartz pressure transducers. The pressure transducer includes sensors, wiring and mechanical parts which affect the reliability of the transducer. The transducer is ultimately combined with additional electronics and hardware to create a deployable down-hole tool. A failure in any subcomponent has the same result – bad or missing data. Powered Life test is designed to move one step closer to the end-use environment.

Prior to this paper we had not published comprehensive results from our Powered Life test for several reasons. Chief among these is the limited number of samples that we have tested. Our test system is capacity limited to 20 units. Lower test temperatures are often imposed by circuit functional limits not applicable in the unpowered tests, resulting in longer test times. Further, we sell, and consequently feel constrained to test many different configurations of our product. This leads to fragmentation, resulting in statistically insignificant sample sizes.

That said; there is much that we have learned. To date we have tested 197 units, recording 175 failures. The difference represents units still living, or which have been removed from the test before failures were observed. The results are grouped by the system-level component that resulted in transducer failure. The discussion is also grouped by these components.

Solder is the dominant wear-out mechanism for transducers in Powered Life Test (43 failures). Failure times are plotted in Figure 3. We generally use HMP solder for connecting wires to our components. This solder degrades with time at temperature. Failures are aggravated by handling and thermal cycles – stress that is not of part of the test by design, but happens on occasion. Average failure time at 250°C is 2100 hours (6 units); at 225°C the average is 8500 hours (31 units), increasing to 24,000 hours at 200°C (6 units).

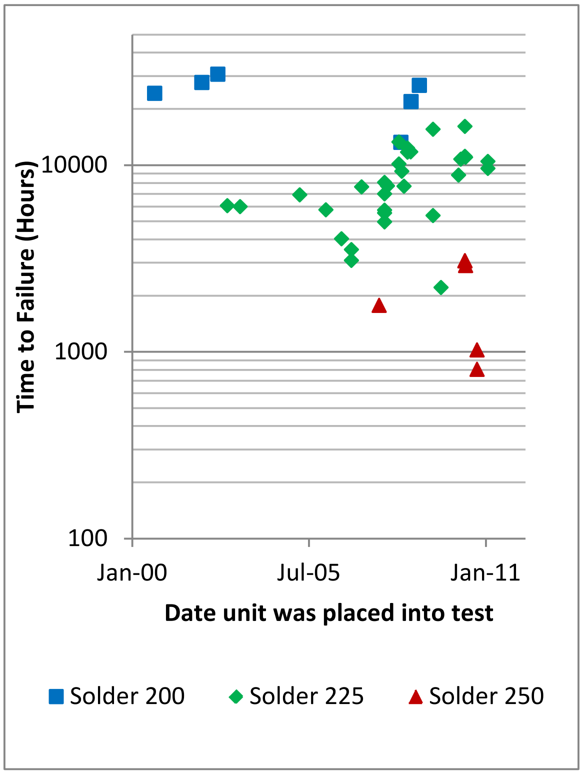

Figure 3: Time to solder failure in Powered Life Test. Test temperatures range from 150°C to 250°C. No solder failures have been observed below 200°C.

Pressure crystals account for 31 test failures over the last 12 years. This is a higher than expected rate given the low field return rates for this part (Figure 8). As shown in Figure 4, there are several infantile pressure crystal failures - 7 with less than 2000 hours. Initially, we had been allocating units that failed our pressure performance screens to this test. In retrospect, these units had latent defects that had already been identified, and were thus not representative of product we were likely to ship. Another way of saying this is “Garbage in, garbage out.” We also realized that many of the pressure crystal failures were low-temperature products being tested at higher temperatures, even though we knew that the oil used in our low-temperature products damages the pressure crystal at the test temperatures. We have since switched all products to high-temperature compatible oil which eliminates this problem.

Of the remaining pressure crystal failures, the majority are related to lead attach. We have made some progress in this arena, but recognize that more opportunities for improvement remain. Since 2008, the average time to failure in powered life for a pressure crystal is 10,000 hours at 225°C.

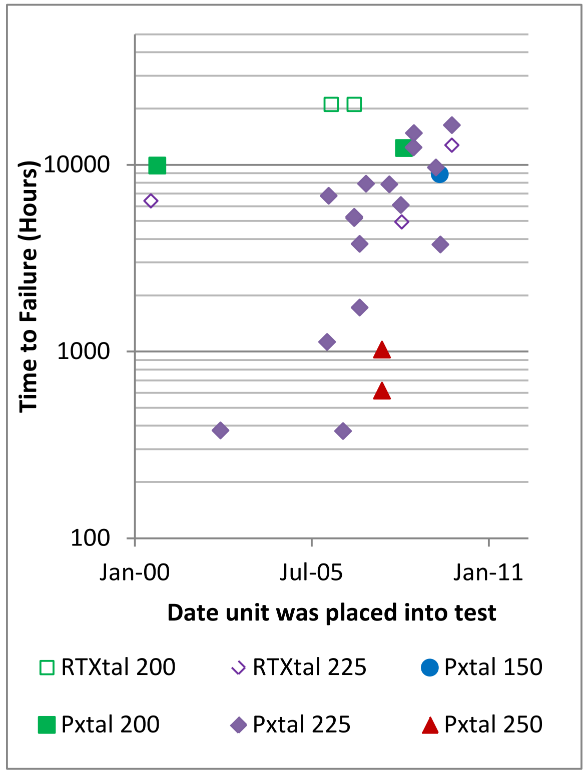

Figure 4: Pressure (Pxtal) and Reference or Temperature crystal (RTXtal) failures in Powered Life Test. Early pressure crystal failures are the result of a poorly designed test.

Temperature and Reference Crystals account for only 4 failures in the Powered Life test (Figure 4). When compared to field returns, this is much lower than expected. The primary cause of field failure in this category is excess shock and vibration, which this test does not address.

Circuit Failures

The test includes three classes of circuit assemblies: Through-hole (Thru-hole), surface mount (SMT) and hybrid (bare die on ceramic). Results at the various test temperatures for these three categories are shown in Figure 5.

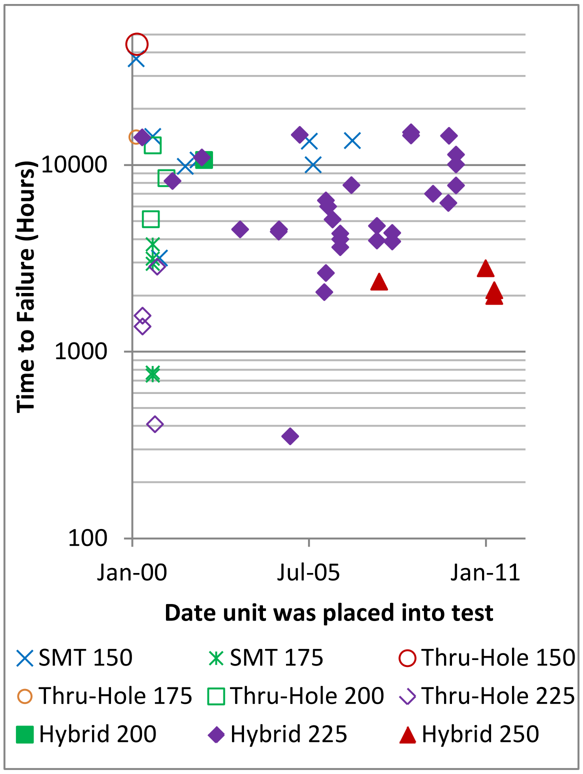

Figure 5: Powered life failure times attributed to various circuit technologies.

Thru-hole: We discontinued our thru-hole product in 2001 after the release of the hybrid circuit. Of 9 boards tested prior to this time, 5 failed for degradation of the polyimide PC board (Figure 4). Four test temperatures were included in the sample. Results are summarized in Table 2.

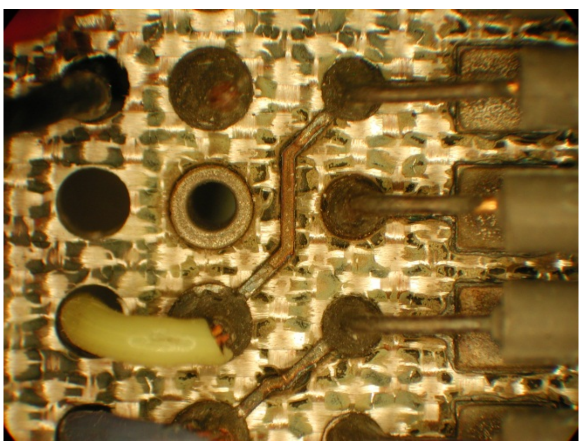

Figure 6: Polyimide Thru-hole PCB after extended exposure to 225°C. The polyimide resin has mostly evaporated leaving a fragile mesh of fiberglass and copper.

Table 2: Average life for Thru-hole circuits built prior to 2001. Primary failure mode was breakdown of the polyimide substrate material.

Samples	Test Temperature	Average Life
4	225°C	1500 hours
3	200°C	8700 hours
1	175°C	14,000 hours
1	150°C	45,000 hours

Surface Mount: We have built and tested SMT boards with both Sn63 and SAC solder. Results for both board types are similar. Thirteen failures are classified as SMT with an average life at 150°C of 14,000 hours, reducing to 2200 hours at 175°C. The primary failure for all SMT boards is high-impedance Au-to Al wire bonds in plastic packages. This failure mode has been discussed at length in previous papers [1] [6]. Life times are better than those shown in Figure 1 primarily because the Powered Life samples are representative of older models which had a more favourable plastic formulation.

Hybrids account for 35 failures. The high ratio relative to other circuit categories is due to the high ratio of hybrid circuits in the test (139 hybrids vs. 36 for all others combined). Average failure time at 250°C is 2300 hours (4 units), increasing to 7500 hours at 225°C (30 units). Remember that this data set covers 11 years and two different manufacturers of hybrid circuits.

Within this failure category, shorted or partially shunted capacitors are responsible for 21 failures with degraded component attach material and bond wires responsible for the remaining. The majority of capacitor failures were diagnosed as shorts through pinholes in BME-class capacitors [7] [8]. Since we switched to PME-class capacitors the pin-hole shorting failure rate has been reduced, but a different failure mode of moderate shunting only at elevated temperatures has been observed. We are presently engaged in a study of this failure mode.

Field Returns

As part of our commitment to quality, openness and continuous improvement, we routinely publish failure statistics on our website [9]. However uncomfortable this may be at times, we recognize that it is a powerful step in keeping us focused on the right problems. Figure 7 shows overall return rates for our transducers and demonstrates a trend of continuous improvement, but with plenty of opportunity for additional work.

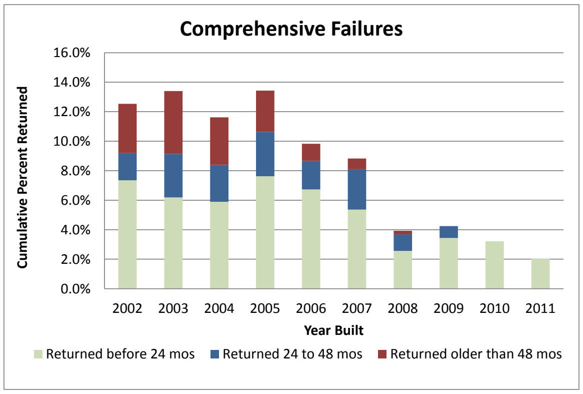

Figure 7: Comprehensive field returns rate based on year built. Colour bands represent the time between shipping the product and when it was returned.

We further break the returns into component categories allowing us to focus on the most significant opportunities. In this section we will talk about two of those categories which we believe are relevant to this conference. Note that the bulk of the failures are now mechanical in nature and we encourage the interested reader to refer to the reference for further discussion.

We consider the overall reliability of **hybrids** to be very good. Field return rates for hybrid circuit faults are less than 1% after 5 years as shown in Figure 8. Any field failure is taken seriously. Field-failure analysis is a prime driver for continuous improvement. The step-wise improvements shown on the graph are evidence of the success of this strategy.

When hybrids were first released in 2001, the field return rates were dismal at >12% (not shown). The high initial rate is attributable in part to the fact that most units sold that year were placed into accelerated qualification tests. The more significant reason was that in our pre-release qualifications we had not anticipated all possible failure modes. As these became apparent, processes and qualification tests were changed. Prior to 2003 component and substrate attach problems dominated the failure modes. Changes in attach methods tailored to specific components resulted in significant improvement in field reliability [10].

In 2007 we made additional improvements that impacted field returns. These changes included bringing the process in-house where we could more closely monitor it, and introducing ASIC technology which allowed for more robust designs with lower component count [3].

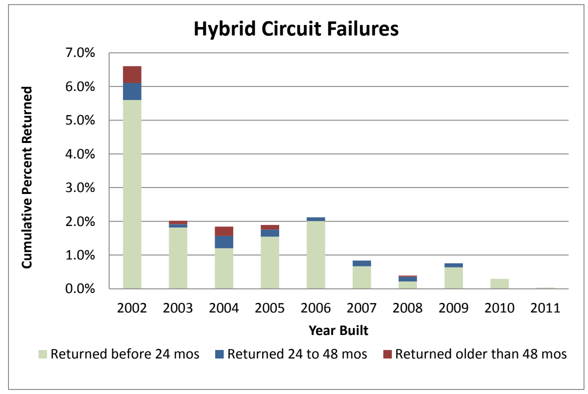

Figure 8: Return rates for Quartzdyne transducers attributable to hybrid circuits. Return rates are less than 1% over the last 5 years.

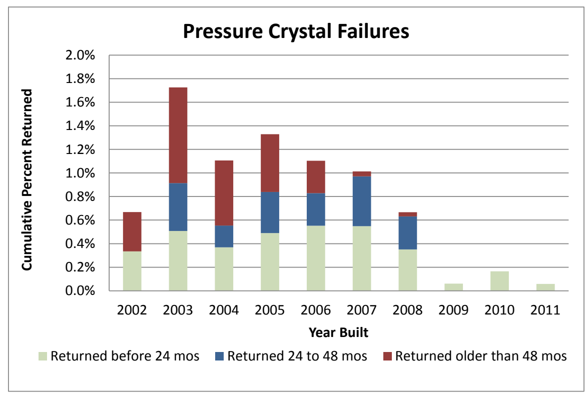

Figure 9: Return rates for Quartzdyne transducers attributable to pressure crystals. Return rates are less than 0.2% since 2009.

Pressure crystal failures are the category with the lowest failure rate. Even so, an improving trend can be seen in Figure 9. The failure mechanisms, if not quantity, are consistent with those observed in our Powered Life testing. 2003 shows a misstep where a change intended to improve the product made it worse. This change was withdrawn as soon as the negative impact was discovered. Changes introduced in 2008, addressing the same failure mode, were subject to a much more rigorous qualification process. We have clearly demonstrated a positive return on this change with 24 month warranty return rates below 0.2%.

Conclusions

Maintaining high reliability in the harsh down-hole environment requires continuous vigilance. Processes must be monitored closely, changes must be qualified carefully, and field failure must be tracked and analysed. The trend towards hotter and deeper oil wells combined with a dramatic increase in the number of permanently instrumented wells has resulted in ever-increasing expectations for system reliability under harsh conditions. Satisfying this market place requires continuous improvement driven by exhaustive testing and real-world failure analysis.

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