

Comparative Reliability Prediction Using Physics of Failure Models

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Abstract

Quartzdyne Electronics has invested millions of device test hours in life testing of circuits in both powered and un-powered tests. In addition to time at temperature, these tests include thermal cycling and high impact drop testing. Recent projects have required the use of larger packages and components as we have expanded the variety of circuits that we build. It is desirable to predict the effects of these changes on long-term reliability before investing in tooling. In this study we will compare a new design which contains these larger components to the simpler, smaller designs for which we have extensive life-test data. Using a physics-of-failure approach, component mounting stresses will be analyzed using finite element modeling. These results will be compared to pre and post-aging shear strengths of actual components of varying sizes. Aging models will then be developed to predict the reliability of the new design based on the comparative stress margins of the individual components coupled with circuit complexity. Once validated, the aging models will enable reliability prediction and trade-off analysis for future designs.

Keywords: High Temperature Electronics, Reliability Prediction, Physics-of-Failure

Introduction

The data collected from testing of our oscillator circuits is exhaustive [1]. From this data we are able to confidently predict how long our oscillator circuits will last under the test conditions. Recently we have taken on new projects which contain a different set of components, each with its own set of new challenges. This paper will focus on the Halliburton ROC™ permanent downhole gauge circuit (ROC) which includes larger components and somewhat higher complexity when compared with our standard oscillator circuits.

Determining reliability by testing samples requires a significant amount of time and investment. A preferred method would be to predict the effect of design trade-offs by using component-specific reliability prediction models. The focus of this paper is to predict the effective reliability of new circuits based on extrapolation of test results combined with information gleaned from FEA analysis of the components in question.

Functionality of components is not considered in this paper. The underlying assumption is that individual components have been qualified and that the circuit adequately performs the desired function at all operating temperatures. Clearly, component choice is a key element in overall

reliability, but it is beyond the scope of this paper.

In this paper we will compare the designs based on component class and size. We will discuss results of our life/cycle testing. Present shear data on components representative of all of the designs and discuss the limitations and typical failure modes of each class of components.

Circuit Comparisons

The initial requirement for the ROC circuit is for five year life at 177°C with a goal to increase that to 200°C. The circuit has several large (1712) capacitors and a large (250x350 mil) die. Multiple small die are also included. The total component count is 92, and the package size is 20% larger than the one used in the historic designs.

The ROC circuit will be compared with historic oscillator designs for which test data exists. The historic designs actually include five different models, but for the purpose of this paper they can be grouped into two classes: Discrete and ASIC (Application Specific Integrated Circuit).

The Discrete designs are built using individual transistors or small transistor arrays. These designs are of medium complexity with

approximately 75-90 components and include capacitors as large as 1210.

The ASIC designs have between 32-43 components. This component count reduction was made possible by integrating multiple functions into custom die designed specifically for our application. The largest capacitor in this design is 0805 and the design contains no discrete transistors. The ASICs have been described in prior papers [2].

Long Term Life/Cycle test results

Samples are regularly pulled from the production line and destructively tested in our Life/Cycle test [1]. Hybrid circuits are placed directly in a convection air oven at 250°C. They are removed from the oven and allowed to cool 3 times each working day to provide 15 thermal cycles per week. Additionally, parts are given a series of high-impact shocks initially, and every 330 hours thereafter until 100 shocks have been applied over 1000 hours. The shock is estimated to be about 15,000 g's with energy concentrated around 10 kHz. Units are removed from the

ovens and electrically tested every 2-6 weeks until a failure is detected. Failed units are cut open and analysed to determine the weakest link. As weak links are identified, the process is adjusted and improved. 684 hybrid circuits are represented in the data which includes tests from July 2003 through May 2011.

Figure 1 shows the **Kaplan–Meier estimator** survival curve for circuits based on our present process [3]. Markers represent actual units in test, the vertical axis being defined as the number of units that survived at least that long. The smooth lines are a best fit **Weibull distribution** of the actual points [4]. Results for Discrete and ASIC hybrids are shown separately. The ASIC hybrids show a 3-4X improvement over the discrete hybrids. This is attributable to several factors including (1) the elimination of small semiconductors requiring rigid conductive attach, (2) lower sensitivity to resistor drift (3) the elimination of larger (1012) sized capacitors and (4) a reduction in total component count. The first two factors are primary wear-out failure modes for the legacy circuits [5], while capacitor size and component count have contributed to random and infantile failures.

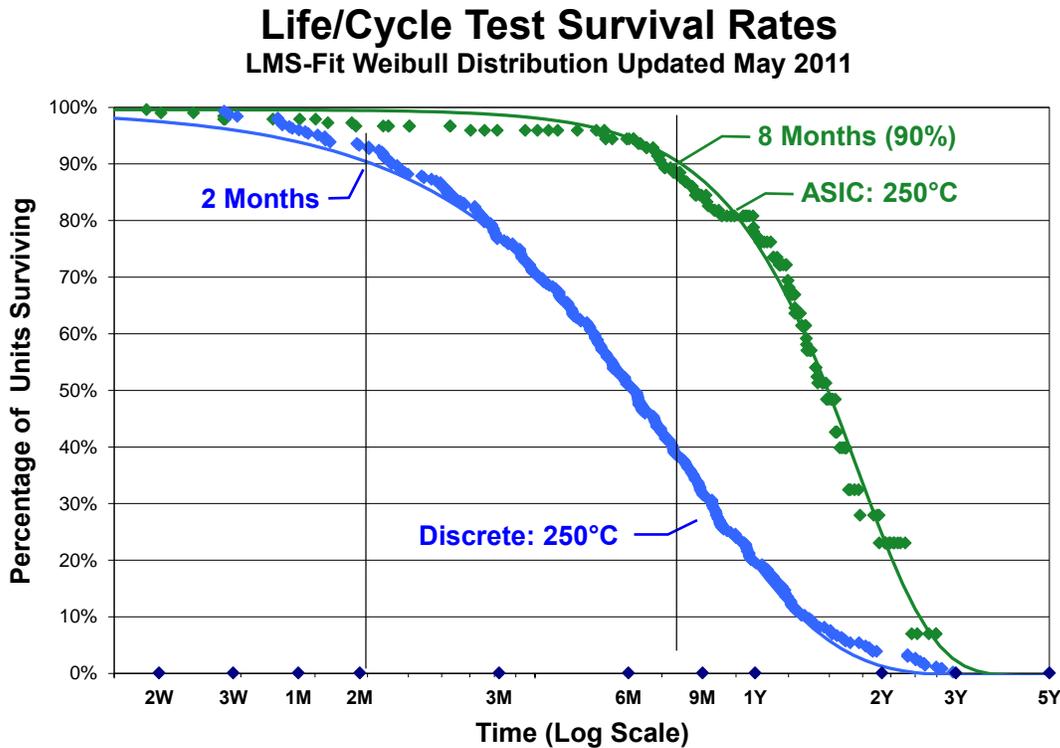


Figure 1. Survival rate based on Life/Cycle testing of discrete and ASIC Hybrid Oscillators

Life/Cycle Failure Rate July 2003 - May 2011

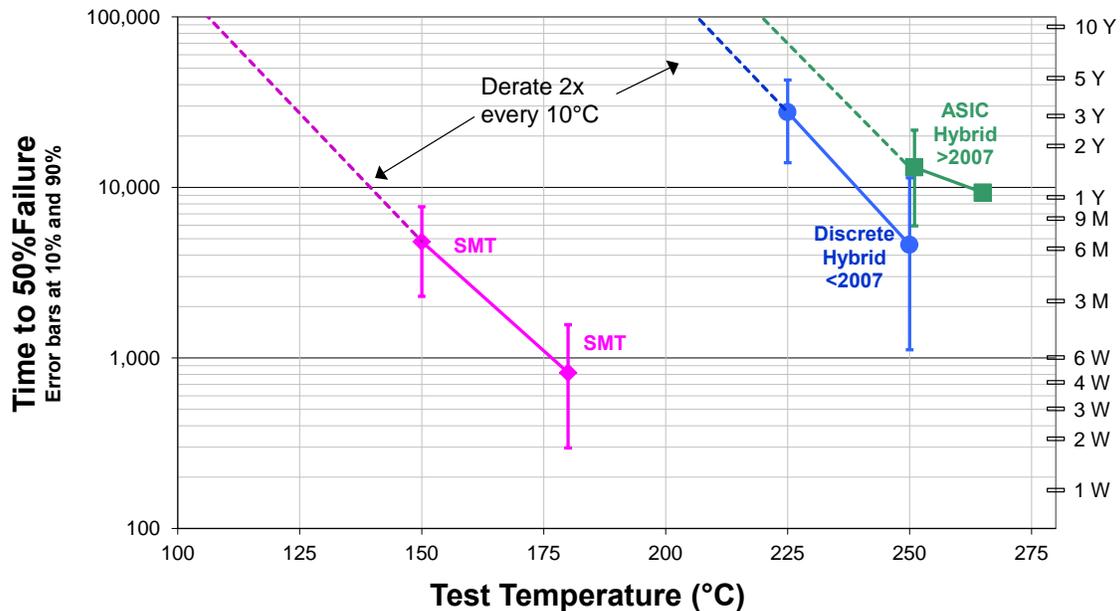


Figure 2. Life/Cycle failure rate based on tests at multiple temperatures for different circuit types. Surface mount results (SMT) are provided for reference.

In Figure 2 we have plotted the 10%, 50%, and 90% failure times from the best-fit survival curves shown in Figure 1. Also included in the chart are results from tests done at other temperatures. Initially hybrids were tested at 225°C, but in 2005 as the reliability improved, tests were moved to 250° to get results sooner. With the increased reliability of the ASIC hybrid introduced in 2007, we have again reached the point where test time is getting too long and we will be increasing the test temperature to 275° over the next year. A 265°C pilot test was started in May 2010. All fifteen units in this test are still surviving yielding the 1-year point shown.

The historic testing at lower temperatures provides an opportunity to infer a de-rating curve. A 2X/10°C estimation is reasonably supported by the data, but it should be noted that since both the process and the test are evolving over time, this de-rating is not strictly supported. In our experience it is common for early data such as the 265°C ASIC hybrid point to not line up well with the other points. The points move

as the tests progress and we expect to see these points line up better as the data matures.

Component attach methods

Small components such as resistors and discrete semiconductors have performed best in our tests with a rigid mount. We use a rigid non-conductive attachment for resistors where electrical connection is not required in the mount and rigid conductive materials for small semiconductors where backside electrical connection is required. The non-conductive attach is very robust. Failure of the conductive attach is a consistent wear-out mechanism at about 8000 hours in our Life/Cycle testing. Interestingly this wear-out mode has not been observed in field returns [6].

As the component size increases, the thermal mismatch between the component and the substrate becomes problematic. For larger components more ductile materials are required to reduce total stress, particularly in applications where the parts will be thermal cycled. Unfortunately, the ductility comes with reduced strength. For relatively thin die, the mass to area

ratio is sufficiently small that a compliant conductive attachment is adequate. But, the margin of safety decreases as the die dimension grows. For capacitors which have a much higher mass-to-area ratio, compound connection methods are necessary. Here, multiple materials are combined to give mechanical strength as well as compliance. The capacitors in this study were attached using a combination of conductive and non-conductive materials.

Aged Component Shear Test

Ten completed ROC assemblies and several Discrete and ASIC oscillator hybrids were taken for this study and divided into two groups. One group was stored at ambient temperature while the other was aged for 1000 hours at 250°C. The aged group was also subjected to 100 high impact drops and 100 thermal cycles per our standard life/cycle testing. Upon completion, all components in both sample sets were sheared using a DAGE shear tester.

After 1000 hours, when the ROC assemblies were opened cracks were observed in four of six of the substrates (Figure 3). This was not expected as the substrate attachment is robust and well qualified. Upon further investigation, a problem was found in our drop test fixture: a unit had been placed incorrectly causing the fixture to be damaged. The damaged fixture allowed the parts to rattle, greatly increasing the frequency spectrum of the shock during impact. Despite the substrate cracks, most of the components remained intact and we were able to do die shear on the remaining components. The summary data is discussed below. (Wire bond data on the damaged parts was not useful.)

Shear Test Results

The required strength of the component attach is proportional to the component's mass. A heavier component will require more force to stay attached under shock or vibration. To quantify this, we have defined a **robustness index** (RI) as the ratio of shear-strength to mass, normalized such that an RI of 1 is the limit of what is likely to fail in our drop testing.

As shown in Figure 4, the resistors with rigid non-conductive attach have more than adequate strength. The strength decreased minimally over time, but not significantly. This attachment method is not expected to be a problem.

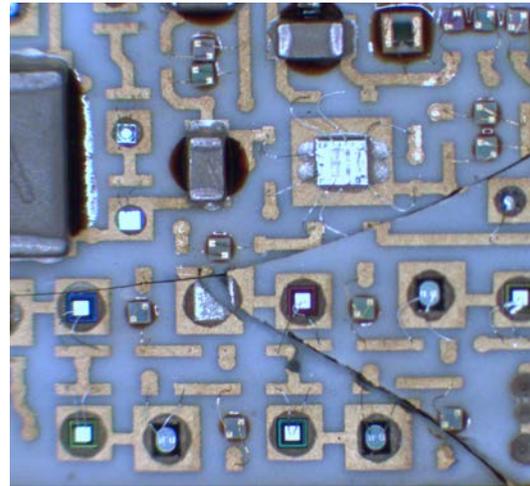


Figure 3. Cracked substrate with most components intact after drop testing

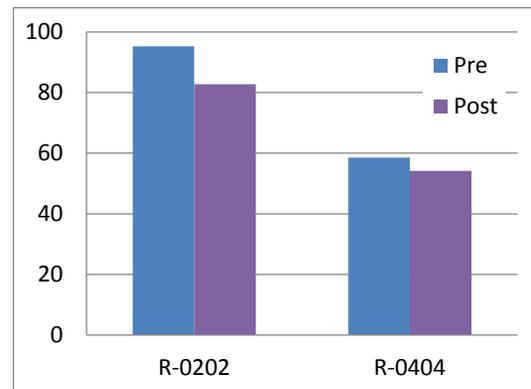


Figure 4. RI (Force/Mass) for resistors rigid non-conductive attachment

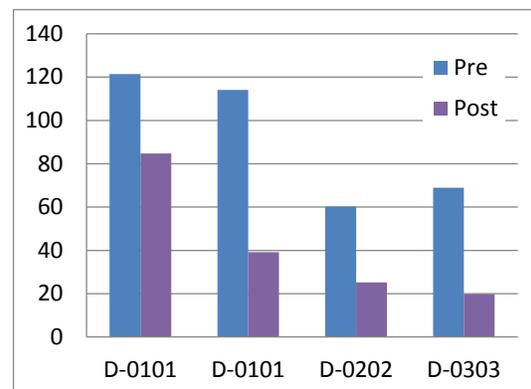


Figure 5. RI (Force/Mass) for small die with rigid conductive attachment

In Figure 5 we see that the small die with rigid conductive attach showed initial strength similar to the resistors, but the strength decreased significantly after 1000 hours of aging (72% on the D-0303 die). Assuming an exponential rate of decay in strength, the unit would be expected to fail (RI = 1) after approximately 4000 hours of testing. In our standard tests, this component typically fails between 5000 and 8000 hours which is consistent with the analysis. It is hypothesized that the reduction in strength is driven by thermally induced stress. Other factors such as metal migration may also be at play. This device is used in the discrete oscillator and the ROC circuit. It is the limiting component in the discrete oscillator.

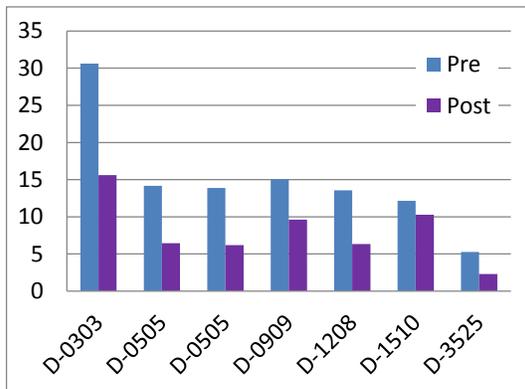


Figure 6. RI (Force/Mass) for large die compliant conductive attachment

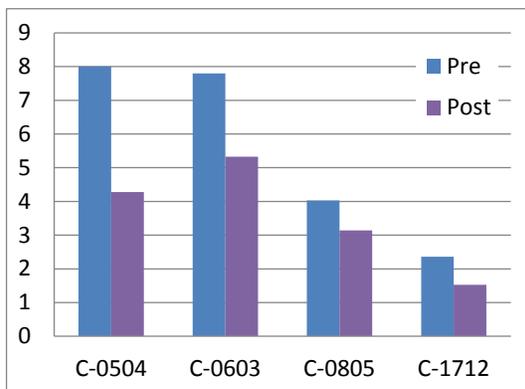


Figure 7. RI (Force/Mass) for capacitors attached using multiple materials providing strength, compliance and conductivity

The initial RI of larger die with soft or compliant conductive attach is much lower than it is for the smaller components with rigid attach (Figure 6).

The post-aging strength is also reduced, but not as dramatically as it is with the rigid material. The strength falls off significantly as the die size approaches 250 mils. With an initial RI of 2.3 and a post-aging RI of 1.5, the large D-3235 die is at the margin of acceptable strength. Assuming a continued exponential decay in strength, it is expected that this die attach will fail at approximately 2000 hours at 250°C.

Historically, capacitor attach has been the most difficult to get right. The requirement for a compliant conductive attach at the end terminations is at odds with the relatively high mass per unit area as compared to silicon die. Our solution has been to use a rigid non-conductive attachment in the area between the end terminations while a compliant conductive material is used for electrical connection. This has worked acceptably with capacitor sizes up to C-1210 (120 x 100 mils) which were used in the discrete hybrid.

The C-1217 capacitor was introduced in the ROC design. The data in Figure 7 suggests that its robustness is marginal. Projecting its RI to 1 yields an estimated time to failure of 2000 hours at 250°C. This is the same as the D-3525 discussed above. It can be concluded that this design is likely to fail for either the large capacitor attachment or the large die attachment at 200 hours, or about 1/3 of the life of the discrete hybrid and 1/12 that of the ASIC hybrid.

FEA analysis

It was hoped that FEA analysis could be used to confirm the above assumptions. Models were built to analyse the stress levels within the attachment materials due to thermal mismatch. A typical model is shown in Figure 8, and the maximum stress for each model is plotted in Figure 9. The expected high stress levels in the rigid materials were confirmed. Comparison with the shear data would suggest that 13,000 psi would be problematic for the rigid attach, and that 8,000 psi would be a reasonable upper limit for soft attach. Unfortunately, we were not able to directly correlate reduction in measured shear strengths with the models. Further work will be required to refine these models. Missing in the models were creep and fatigue analysis which will likely be necessary to create accurate or usable results.

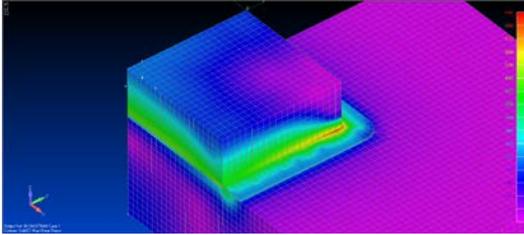


Figure 8. Stress distribution in a quarter-section-symmetric model of a Si die attached rigidly to an alumina substrate.

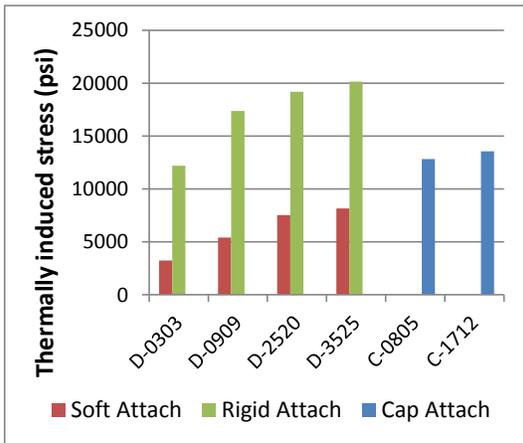


Figure 9. FEA results: Maximum thermally induced stress in various package sizes. Note that Rigid Attach is not used for D-0909 and larger die.

Testing by Customer

The ROC circuit is paired with a Quartzdyne pressure transducer and other hardware to create a complete tool. Nine of these tools were oven tested by the customer at 220°C. The units were powered and operating during the duration of the test. Survival functions were calculated and plotted for these units yielding a mean time to failure of 0.33 years at 220°C (Figure 10).

Table 1 shows an Arrhenius projection of expected lifetimes based on activation energy of 1.4eV (~2X/10°C). The 5.2 year projection for 90% survival at 177°C meets the 5 year design objective for phase 1 of the project, but phase 2 requires 5 years at 200°C.

The lifetime is significantly less than what is predicted by the packaging-only related tests described earlier in this paper (2000 hours = 0.25 years at 250°C). However, failures in the

powered tests were attributable to device functionality rather than packaging. Clearly, more work needs to be done in finding and qualifying reliable components for long-term operation at or above 200°C.

From a packaging perspective, the phase 1 goal is met, and phase 2 requirements are at the margin. By elimination of the large capacitor and die and/or improved mounting methods additional safety margin could be achieved.

From a circuit design perspective, better high temperature components must be found to meet the phase 2 goals. Future developments already in the works include a high temperature ASIC using the same technology employed in the ASIC hybrid. This will allow the elimination of the limiting components and greatly simplify the circuit. It is expected that these improvements will allow next generation tools to reach the 5-year 200°C operating goal.

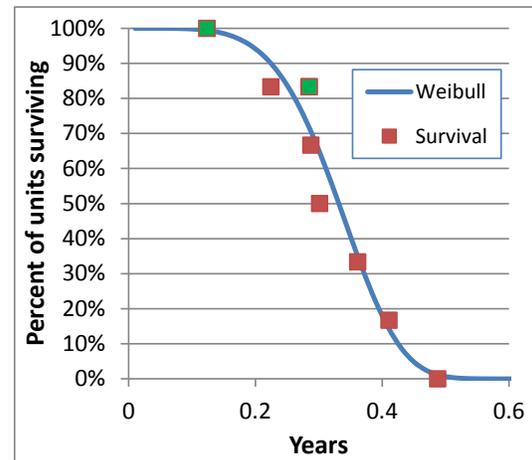


Figure 10. Survival function for complete assemblies tested by the customer powered at 220°C.

Table 1. Projected lifetime (years) of complete assembly at various temperatures based on 2X/10°C de-rating

Survival	220	200	177
90%	0.224	0.904	5.231
50%	0.332	1.336	7.728
10%	0.425	1.713	9.910

Conclusions

Shear test data at 1000 hours was used to correlate existing failure modes with longer term life test data. Using this data we are able to project that given the current component mounting technology, designs with large capacitors and die will be limited to approximately 2000 hours at 250°C. By reducing component count and size lifetimes can be extended to over 1 year at 250°C.

The robustness index defined for this project gives a clear picture of the weak links in the design and will be useful in focusing and qualifying future reliability improvement development projects. Further work to optimize FEA models to validate these conclusions is recommended.

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