Reliability Predictions – More than the Sum of the Parts

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SUMMARY AND CONCLUSIONS

Reliability predictions have been the subject of much discussion over the prior 20 years. Some articles have proclaimed them to be valueless while other articles suggest importance. Spending a great amount of time calculating numbers does not present value directly. Using the numbers as the basis for additional positive activities would seem to be one reason for predictions. Any reliability prediction should be considered as a single tool in a larger reliability improvement tool box that often feeds other more important activities. This role of predictions in a larger reliability world will be explored here. Examples of follow-on improvement activities include, lessons learned about components, identification of critical components, identification of critical design features, estimation of high-stress conditions, approaches for derating, design for reliability, design for manufacture, input to an FMEA, input to a verification test plan, and warranty and repair estimates. The prediction is not an end of the process, but rather the beginning of the larger reliability improvement and design review process. Here, the value of predictions will be tied to lessons learned and outcomes.

Predictions have fundamentally changed over the last 20 years for several reasons. As Failure-in-Time (FIT) numbers have declined in most handbooks, the MTBF prediction didn't always match subsequent field data on an absolute scale. It is possible to be a factor of three different or more. Each successive issue of Telcordia or the Mil Handbook 217 (now 217Plus), appears rather similar to the prior ones. This simplicity masks some of the evolution in numerical content and models. There is much to be learned from a short review of the prediction process itself. Failure rate estimates from tables are not trustworthy for they depend upon experience, customer applications, models and other unknown items. At some point it is time to wrap up the prediction phase and move onto improvement and feed other reliability tools. The "Lessons Learned" based upon knowledge of the design, manufacture, customer environment or are valuable. Items in lessons learned might cover a variety of situations that can enhance or detract from estimated reliability. Other lessons learned are contained in design guidelines, derating standards. All of these should be addressed early in any project, once a Bill of Materials (BOM) has been generated. Each has an impact on the prediction estimate but are not overtly included in the process.

1 INTRODUCTION

Reliability predictions represent a single number that attempts to describe a complex product through a "failure rate" estimate. This is an attempt to describe a system made up of many types of components. The newest components technology are usually not present in any handbook as it often takes two to five years of field exposure to get estimates. Mechanical components and products controlled by software are seldom described by prediction methods. Mechanical components tend to be dominated by wear through much of their life. Software controlled electronic products may have redundancy or error correction present and so impact the failure rate. Neither are easily described in predictions.

New component failure rates may be estimated from laboratory stress tests such as steady temperature, steady voltage and steady humidity. These steady conditions aren't a good representation of what the components actually see in the field. Systems in the field are dynamic and interactive. Thus laboratory data often underestimate failure rates because not all system stresses are present.

In most prediction systems, there are no entries for a variety of common situations. For example: Software induced hardware failures or even software corrected hardware failures; GaAs microwave devices, RoHS compliant solder technologies; the solder joint failure rate for a ball grid array of 1100 pins; or a 0.7 mm pitch. For other situations in which an improvement has taken place, (such as using a polymer tantalum capacitor over a regular tantalum capacitor), this improvement is not reflected in the failure rate numbers.

Initial component failure models were built up based upon observing failures as a function of gate count [1]. This may not be accurate today as package failures may now dominate gate count contributions. The Accelerated Life Test approach to estimating component failure rates is often biased toward high MTBF numbers or low failure rates [2] because of steady test conditions. Short term or infant mortality effects or even the onset of wear are usually excluded in any ALT models, even for the prediction of mechanical type components [3]. Constant failure rate is the norm for prediction models, even when it is known to be inaccurate. Recent prediction now include a variety of adjustment factors such as temperature, duty cycle, solder joint factors, electrical overstress, temperature rise, humidity and reliability growth factor [4]. One recent report suggested that a large number of field failures do not appear to be "random events" [2]. Rather the observed failure rate actually varied over time because of changing failure mechanisms. Projecting a MTBF based upon a failure rate can be highly misleading since the rate may not be constant or the underlying distribution may not be exponential. In the mid 1980s, it was observed that some Integrated Circuits did not appear to have any Infant Mortality, and the onset of wear was still far out in time [5]. This situation might be well described by a constant failure rate. With the shrinking geometry of many semiconductors, the onset of wear, such as time dependent dielectric breakdown, may have moved in dramatically [6]. This adds complications because any screening of components or systems may shorten useful life. In all cases screening should be treated as a transient event until improvement actions are complete. Stress screening of systems should be tied to elimination of failures through root cause analysis and Corrective Action for **every** failure observed in any screen [7, 8].

2 LESSONS LEARNED

One of the biggest activities associated with reliability predictions is often the lessons learned. Any prediction builds upon those from the past. Each time there is a review of components, there should also be a lessons learned review. This type of review has great value for it begins asking questions about design guidelines, derating and component selection. Lessons learned in every prediction might include looking carefully at the load and cycle life of all mechanical relays. Look at the series resistance of analog switches and how it might change over time. Ask questions about any tantalum or electrolytic capacitors. Improved versions of each do exist. Ask about the cracking failure mode of ceramic capacitors. Look at resistor arrays and the potential for overstress failure. Determine the maximum junction temperature of all integrated circuits, diodes and transistors. Make use of all history that is available concerning components and circuits. Treat this as part of a design review or FMEA. The best method is to collect the lessons from your own company product and own customer applications. Lessons from other companies or different industries usually has less value than from your own customers..

2.1. Critical Components

Most electronic reliability prediction methods start with a Bill of Materials (BOM) with full component identification and a schematic. A resistor might include a description such as 10 Kilo Ohms, 100V, 1% tolerance, Thick Film, in a SMT from supplier A. Changing this to 500 Ohms or 50V or 50PPM, or supplier B has no impact on the estimated failure rate. The situation is similar for a capacitor, inductor or for many components. Operational Amplifier failure rates are listed simply by number of transistors in most systems. No questions are asked about operating voltage (3 Volts to 50 Volts is possible), package type or size, manufacturing process (several different linear processes exist including BiFET) or most importantly, the actual circuit application. Often the information dug up while asking questions will identify critical components and circuits. Critical means important; important because of the number used, or important because of performance or may represent a large risk. Once identified as a critical component, some risk plan or mitigation may be needed to reduce the impact of potential failures. This may be closely tied to lessons learned or may be based upon estimation of sensitivity to items such as manufacturing parameters or to ESD.

2.2 Critical Design Features

Redundancy is important for reliability be it hardware and software redundancy. Each may enhance the reliability of the system. Examples include the placement of multiple grounds in a connector to reduce noise or adding parallel paths for current sharing. Sufficient design margin over operating voltage and temperature in any circuit is also a form or redundancy. This goes beyond the standard prediction and really addresses the circuit as a whole. Threshold values, timing margins and allowance for drift over temperature or age may all improve a system's function. The circuit fails to perform an expected activity within a certain time or the circuit appears noisy because of inconsistent detection of an event. About 1/3 of field failures fall into this broad category in my experience. A number of these may subsequently result in a No Fault Found as the situation can't be duplicated or disappears when the suspect circuit board is removed for trouble shooting. If not addressed during the design verification or as part of the FMEA, this can be a major source of field problems.

A last area of concern here is software dominated systems. Software can be written to improve the fault tolerance of circuits or components. Error checking and correcting codes for RAM memories are examples. Calibration of function is another way that software can compensate for hardware changes. Recalibrate on the fly when the conditions change to avoid field failures. Software itself can also be the cause of apparent field failures. Unique or untested conditions, unexpected interruptions during operation or and checking for values at the wrong time all lead to major non-functionality of the circuit. This is normally beyond the scope of a prediction. A good understanding of the circuit functions, circuit controls and circuit limits are important when estimating a failure. This is covered during an FMEA. The relationship of software and hardware should be carefully reviewed to see that what is desired for the system is actually happening.

2.3 Estimation for high stress and start-up

Stress, be it temperature, operating voltage, temperature cycles, mechanical stress, vibration or corrosion, can all lead to component failures. Many reliability prediction methods don't fully include this. They might include temperature and voltage, but not voltage margins, temperature cycling or vibration levels. What is the impact of operating a system at 3 Gs RMS versus operating at 0.5 Gs RMS? There may a difference, with both short and long term consequences. Short term effects include microphonic noise or jitter in a circuit. Long term consequences may be tied to fatigue of materials. Vibration is usually covered into a prediction only at the system level through the customer environment correction factor. The impact at the component level. What does vibration do to a capacitor? It may cause noise in the ceramic part or lead to an electrolytic capacitor failing through solder fatigue or fatigue of the leads. Vibration can also lead to temporary opens or transients in a circuit that accumulate leading to ultimate component failure. Questions start with the prediction, but answers come from test.

Start-up, transient conditions and circuit interruptions all need to be considered for systems. Voltage spikes, high surge or ripple may be present and can lead to component failure through accumulated damage. One example is fuses. Here the start-up surge may lead to a limited life unless carefully selected. Capacitors and transistors may also fail from transient voltage spikes present only during some special condition. The start up may place unusual stresses on components or circuits especially when multiple operating voltages are present. One rule of thumb, used in design, is that all components and circuits must work, failure free, after 1000 sets of start-up in the test lab. The prediction doesn't ask questions about transient conditions or circuit race conditions.

Stress screening as an input to a prediction is covered in both Telcordia and 217Plus. In the latter, an Infant Mortality Correction factor is calculated from the following equation [9].

$$\Pi_{IM} = \left(\frac{1}{1.77}\right)(t^{-0.62})\,(1\text{-}SS_{ESS}) \qquad (1)$$

At 0.1 year the nominal correction is 2.355 while at 0.5 years it is 0.868.

2.4 Approaches for Derating

Derating is a common consideration during a reliability prediction. If your company has a derating standard, include this as part of the prediction process. If no derating standard exists, look at the voltage and current stresses on all components and keep these low. In the past, I have found designs with capacitors running at 90% of maximum rated voltage with transients taking this to 110% of rating. Neither is a reliable condition. An RF transistor was found being operated at 120% or power rating instead of the recommended 80% while the junction temperature was estimated above 150ºC. Neither condition would be acceptable. Ripple and surge currents may be derated and should not be violated for many types of components. Normally, for electrolytic and tantalum capacitors, the manufacturer recommends limits. Fan-out is another area of common violation. Running at 80% or higher of the maximum fan-out at room temperature usually means degraded signals will be present at room conditions and worst at temperature. Ask about loads and fan-out during the prediction.

2.5 Design for Reliability, (DFR) and Design for Manufacturability, (DFM)

A series of good practices for reliability are called DFR. These may include mechanical keep-out zones to avoid damage to components, separation of voltage traces to avoid noise pick up and a host of other design rules. Placing all mechanical relays on a separate circuit board when high cycle life was expected may be a maintenance solution. In this way, the relays could be isolated, monitored and tested during the useful life. The down side is there could be cross talk, long traces and alignment issues with a circuit board full of relays.

Moisture sensitivity of components during storage or build should also be a consideration. Some highly sensitive components require special manufacturing handling, processing and storage conditions. Look at reflow solder profiles, maximum temperature reached or total dwell time. Some packages or semiconductors may degrade rapidly with increased soldering temperatures required to solder RoHS compliant finishes. Look also at flatness specifications of large, thin high power packages. Be sure to pay attention to maximum vertical loads (from heat sinks) as normal forces can have a strong impact upon solder joint reliability.

DFR and DFM standards can include ESD procedures and special handling requirements, or circuit board handling and protection during build and test. Test completeness could also be addressed so that circuit boards are thoroughly tested under all conditions. These conditions might include voltage at high and low margins, high and low operating temperatures, varying frequency and varying loads. Lastly, the system should loop on the test conditions and be required to pass consistently at worst conditions more than once. This test might run several times and cover all of the combinations of conditions. All of this applies to outside manufacturing subcontractors. Imagine that subcontractor on a different continent with a language barrier. How much process feedback and improvement is possible? None of this is remotely covered by any prediction method. You may wish to include a "subcontractor degradation factor" in your adjustments.

2.6 Feed the FMEA

The FMEA activity is often the best review for potential problems. A full consideration of possible component, circuit and software failure modes should occur. Consider extreme conditions and even non-conforming components or conditions in the FMEA. Be sure to look at what is not fully covered by test. Ask about manufacturing set-up or handling issues and understand how the customer uses or misuses the product. A closed-loop process for handling any serious problems is key and be sure to close out all items. Check the information contained in the FMEA failure modes against what will actually be tested in any design verification (DV). Watch for low Cpk measures.

2.7 Update the Design Verification (DV) Test Plan

This test is really part of the engineering closed-loop corrective action process. A well developed DV test plan can cover a number of system specification and circuit functions. These often include non-specification items that should be measured to assure margins, functions and process capability. Identifying signal integrity issues, susceptibility to external EMI sources, susceptibility to capacitance loads on driver circuits and problems with software bugs would be included. It is wise to identify the hottest operating components and the highest stress components, if they are not already known. An allowance for future component degradation is important for reliable operation of circuits.

2.8 Warranty and Maintenance estimates

Another reason for a reliability prediction is to estimate the need for warranty actions and planned repairs and maintenance. These estimates are usually based upon the planned use of the equipment as well as the component failure rates. Obtain good field failure cost estimates in order to look at trade-off issues. A macro that quickly calculates the cost versus reliability trade-off is a big help. Customer use estimates are often not too accurate. Customer A claims 24 hours a day of use, but in reality the equipment is actually operated 12 to 16 hours a day, five days a week and is left on the remaining time. Customer B, on the other hand, runs 3 shifts a day and actually gets 24 hours a day, seven days a week. Customer A accumulates about 4600 real operating hours a year with the rest being "on-time" while Customer B operates 8760 hours. Customer A should experience fewer failures than Customer B despite the similar descriptions of customer use.

Warranty estimates can be no better than the prediction estimate itself. Warranty numbers usually depend upon customer use time, an estimate of the failure rate and then a model. A customer use model might cover a range of customer stress or customer use hours. Light use customers (15% to 20% of population) might be operating a research system, seldom accumulating 20 hours a week. Moderate use customers (20% to 35% of population) might accumulate 3000 to 5000 hours a year. Heavy use customers (40% to 60%) might accumulate 5000 to 7000 hours a year. The worst customers (10% to 20%) might be at 7500 hours to 8760 hours a year. This model is as important as the reliability numbers. It is seldom known, unless a detailed study occurs.

Maintenance is often dependent upon customer history, use and experience. Certain component failure modes seem to lead to regular maintenance. Lubrication of a shaft or bearing, the cleaning of a filter or the end of life of a mechanical relay are typical. Warranty and maintenance can only be roughly estimated based usually upon experience and not reliability predictions.

3 PRECISION OF PREDICTION NUMBERS

Many reliability prediction methodologies over the last 30 years have focused upon getting either better component models and/or more precise FIT numbers. Decimal places in FIT numbers are not uncommon for some components. Table 1 shows the evolution of a few components in the Bellcore (now Telcordia) tables. The last column, 2007, reflects my experience and so represents an estimate of field experience in 2006.

Field data available to me totals over 100×10^9 operating hours for a variety of components. This large number may still be insufficient to make a good estimate for any component less than 1.0 FIT. Results may vary by customer environment and application. All data is ground benign. A NPO capacitor appears to have a ten times lower failure rate than either an X7R capacitor. A Y5U or a Z5U capacitor would be about a factor of 15 times higher in failure rate than the X7R. Most prediction systems list just single number for this group of ceramic capacitors, yet they would seem to have a wide range of possible FITs. A single FIT number may be a poor compromise, especially when making design trade-off decisions. Polymer tantalum capacitors appear to have about three to five times lower failure rate than the older styletantalum capacitor they might replace. No prediction system identifies these important differences yet. When sorted by application, rather than complexity, linear integrated circuits can range from 1 to 12 FITs. Traditional predictions provide one number based upon transistor count in the range of 19 FITs. Application might be a better way of looking at linear devices, rather than transistor count.

Component	1984	1992	1997	2001	2006
100 gate CMOS Digital IC	38	20	15	10	~2
90 transistor Linear IC	95	47	33	33	~9
64K CMOS SRAM	2050	69	50	34	~12
Thick Film Resistor	2	1	0.5	0.5	~0.05
X7R Cap	2	2	1	1	~0.3
Fuse	None	10	5	0.5	~5

Table 1 – Sample of FIT Data from Bellcore

How do these and other causes of uncertainty impact the prediction accuracy? Replacing a few Z5U capacitors with X7R versions may have a strong impact on the total system estimate. If the prediction system does not recognize a difference, than any design trade-off has no meaning for a proposed change. There are enough causes of uncertainty that sometimes the predictions may be far away from observed numbers. Two real examples from Teradyne are illustrative of how subtle failure causes may be.

In the first example, a circuit employs a Sample and Hold (SH) device that appeared to have many field failures, but showed few during in-house test or qualification. Upon deeper investigation, the problem may actually be attributed to the circuit design and not the component. The circuit design set a tight restriction on one device specification in order for the whole circuit to perform well. These limits were tight enough that any variability or drift could cause an apparent circuit malfunction. The SH component would be than be flagged as a "failure". Even a "good SH device" would be on the edge of failing this tight specification. This situation would be exacerbated by fluctuations in operating temperature or operating voltage. In the field, the SH component would appear to fail at a rate more than 10 times the FIT estimate in the first year. While this might seem to be low on an absolute scale, SH field failures were quickly accumulated (representing more than 5% of the components used) before the root cause was identified. Ultimately, the component problem was solved by making a circuit design change coupled with an improved test method. Why wasn't this problem picked up in Design Verification when the design team looked closely at the circuit performance? The team assumed that the "one failure" they actually saw in DV at nominal conditions was caused by "bad parts" or an escape. These would be sorted out as part of ordinary in-process test they thought. The team failed to understand that all DV failures require serious review to a root cause and that voltage margins and temperature variation should also be part of DV. The same SH failure mode was also observed during a HALT of the circuit board, but was treated as a soft failure since the problem showed up outside of the normal temperature operating range and conditions. A soft failure under those conditions didn't require full investigation or follow-up corrective action. A lesson has been learned. Today, all soft failures in HALT require full investigation and corrective action. Failures in a small sample often represent the "tip of the iceberg". Nothing new here, but the example can be a good reminder of what can go wrong.

The second example concerns an ASIC that began exhibiting field problems about 6 months after the system was released for production. Up to that point a few failures had been observed, but these represented much less than 1% of the expensive devices. When 15 field failures had accumulated, there was enough evident collected to discover there was a three part contribution to the field failures. Failure mode one was a "failure of specification"; that is, an important parameter had never become part of the test specification. It was only one of over 200 ASIC parameters tested, and more than 90% of the time, it was conforming. It wasn't caught by in-process test or in DV because the requirement wasn't in the specification. A customer who depended upon this parameter for his application discovered the problem in the field. Failure mode two represented a test condition problem. It appeared as a "correlation problem" that causes an occasional failure. Failure mode three was a device metallization problem that could be exacerbated at low voltage margin. This last mode varied significantly from lot-to-lot. Some lots had as little as 0.1% fall out, while other lots would be closer to 10% fall out in initial test. There was also a time dependent aspect to this failure mode. That is, ASICs that have passed a board level screen, may slowly degrade with time and about 12 months later might fail. Special screening was established and was thought to be more than 90% effective for mode three and perhaps 60% effective for mode two. After the screen was implemented, the observed MTBF steadily increased over the next 9 months, but the problem resurfaced over a year later. There were several lessons learned from this last example. The reliability prediction step should have begun by asking questions about important components in the circuit. Better yet, the questions could be asked with designers, manufacturing, and supplier engineers and should make a risk analysis of all the components. Components labeled a "high risk" would be targeted for special work and improvement. All of these activities help the field performance stay closer to a prediction, no matter what the source of the prediction or the method employed.

3.1 Field data

Real systems with validated failure data are usually good sources of information. The following figures show the system FIT numbers based upon field data as lumped into 3 month intervals after release to production. Figure 1 shows accumulated data for System 3. A steady decline in System FITs was observed over 300,000 plus field operating hours. This system looked like a classical bathtub curve. It took 12 months to reach the bottom of the bathtub. Figure 2 shows System 6 and a very different field performance. The initial 12 months exhibit no failures, but after that initial period, the accumulated data shows a steady linear increase for 9 months. From the twenty-first month until the thirty-third month the data remains flat. This system appears to have a residue of problems yet to be resolved. Some may be time-dependent failure modes, while others may be dependent upon customer use or new applications. Further inquiry is needed to know more about the causes of the failures.

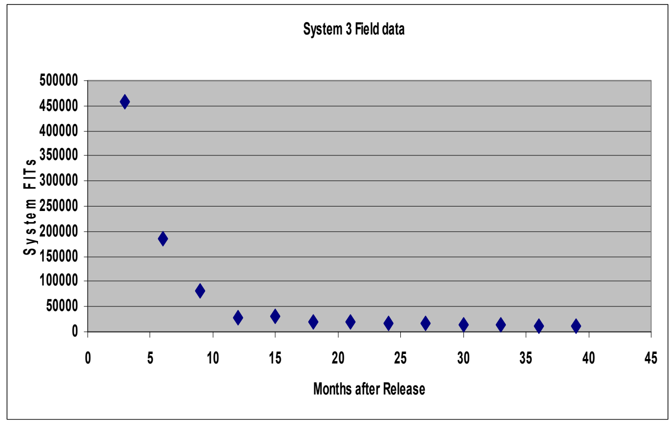

Figure 1 – FIT data accumulated for System 3

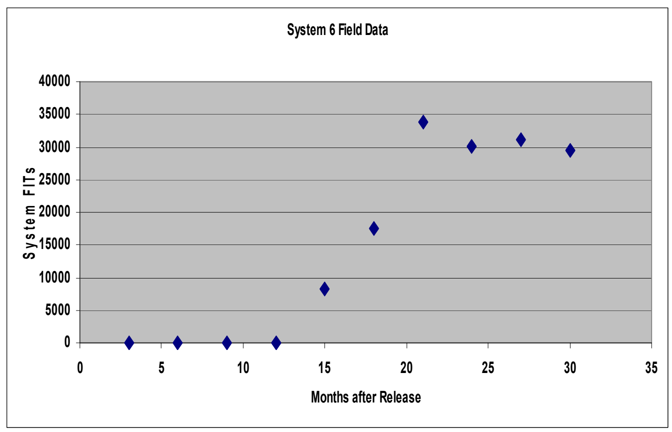

Figure 2 – Accumulated FIT Data for System 6

4 SUMMARY

The reliability prediction is a tool that can estimate a FIT number for a collection of components. Twenty years ago, a number of people suggested that predictions performed for this reason don't have a lot of value. I strongly agree. There has to be a bigger reason to continue to do predictions. This **bigger reason** is to set the stage for improvement activities in order to prevent problems. The examples noted have shown that systems are not just the sum of component failure rates. Software influences, interactions between components, external stresses and misapplications all contribute to the system failure rate. There is usually too much going on to be easily able to estimate the real performance or failure rate from book value. The goal is to identify problems early and prevent or eliminate them before going into production.

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