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The objective of this effort is to demonstrate that transmission gears of rotary wing aircraft, which are scrapped due to minor foreign object damage (FOD) and grey staining, can be repaired and re-used with significant cost avoidance. The Isotropic Superfinishing (ISF) process is used to repair the gear by removing surface damage. It has been demonstrated in this project that this surface damage can be removed while maintaining original equipment manufacturer (OEM) specifications on gear size, geometry and metallurgy. Further, scrap CH-46 Mix Box Spur Pinions, repaired by the ISF process, were subjected to gear tooth strength and durability testing and their performance compared to new Spur Pinions procured from the approved Navy vendor. The performance of the repaired Spur Pinions met or exceeded the performance of the new Spur Pinions, clearly demonstrating that repair and re-use of precision transmission gears is highly feasible.

Background

The CH-46 Sea Knight aircraft is a medium lift helicopter used by the US Marine Corps, which serves as the “workhorse” of the Corps for troop deployment. From a maintenance perspective, the Naval Air Depot at Cherry Point (NADEP CP), the Marine Corp’s only aircraft depot, scraps many H-46 transmission gears. Prominent among them is the “Mix” gear box Collector gear, P/N A02D2066 and its mate the Spur Pinion gears, P/N A02D2065, shown in Figure 1. Also frequently scrapped have been the Sun gears, P/N 107D2256-7 in the main transmission and Input Pinion gears, P/N A02D2059-3 in the “Mix” gear box. Primary reasons for scrapping these gears is minor FOD or contact fatigue damage usually termed as gray staining (also sometimes referred to as micro-pitting). The criterion for scrapping the gear is surface damage that snags a sharp scriber when it is traversed over the damage. Annual procurement costs on these four part numbers alone is in the range of several million dollars at NADEP CP. Analysis of the scrap gears indicated a potential greater than 50% of repair and re-use of these gears with significant cost avoidance.

The primary focus of this effort was to demonstrate the safe reuse of scrap gears that are currently discarded and would have significant reduction on sustainment costs. From an operational perspective several additional issues are also of relevance. They are the operational lives of gears, vibration levels in the gear mesh pair and the heat losses in gear meshes in a transmission of a helicopter, all of which could be impacted by the improved surface finish generated by the superfinishing process. Increase in operational lives and reduction in vibration levels, which would attenuate the occurrence of clutch raceway failure, would directly impact CH-46 sustainment costs. Further, heat losses in gear meshes in a transmission have to be absorbed by additional lubrication oil and on-board lubricant cooling systems. The additional lubricant, and the cooling systems required for this purpose, add weight to the aircraft and subtract from the payload. Reduction in heat loss in gear meshes would favorably impact aircraft payload.

Technical Approach

The primary causes of a gear being considered scrap is FOD, as shown in Figure 2 (circled in red), and gray staining as shown in Figure 3. The effort to demonstrate the feasibility of gear repair was conducted in two major phases. In the first phase scrap, gears from the NADEP CP were analyzed for damage, superfinished by the ISF process and then inspect-
ed for dimension, geometry and metallurgy. In the second phase test hardware for traditional gear tooth strength and durability testing were designed and fabricated for the Spur Pinion (P/N A02D2065). This included a Single Tooth Fatigue fixture, as shown in Figure 4.

For dynamic tests the Spur Pinion and Collector gear pair was considered and a Power re-Circulating test rig was designed and fabricated. This is shown in Figure 5. New Spur Pinions were procured from the approved Navy vendor and sufficient quantities of the scrap Spur Pinions were repaired by the ISF process. A detailed Test Plan was defined and presented to the Navy. After test hardware was available, new and repaired pinions were evaluated for Single Tooth bending fatigue (STF), contact fatigue (CF) and Scoring Resistance (SR), as per the approved Test Plan.  

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The repaired gears (scrap gears that had been superfinished to remove surface damage) were inspected for dimension, geometry and metallurgical integrity. The tooth thickness was smaller than before by the amount of material removed, but still well within the OEM tolerance. The lead, profile and index error were relatively unchanged after superfinishing and found to be within OEM specifications. Some of the gears were sectioned, mounted and examined for hardness, hardness profile, retained austenite and residual stress. The repaired gears met all OEM specifications on these parameters. The microstructure of the repaired gears was also examined and no deleterious impact on the microstructure due to the ISF process was observed. The surface roughness of the repaired gears was generally in the 4-6 microinches $R_m$ while the ground gears generally had a surface roughness in excess of 16 microinches $R_m$.

The repaired gears and new gears were then subjected to bending fatigue, contact fatigue and scoring resistance tests, as per the approved test plan. Standard statistical analysis was also conducted on the collected data to establish the results on a firm basis. In all these three tests, the repaired gears met or exceeded the performance of new gears. Further, the repaired gears, due to their superior surface finish, operated at about 20-30 degrees F cooler than the new gears, as measured by the out-of-mesh oil temperature in the Power re-Circulating test rig.

### Conclusion

This project has clearly established that a significant subset of gears that are considered scrap, because of surface damage such as FOD or gray staining, can be repaired and re-used with significant savings in cost. The lead times for the fabrication of new replacement aircraft gears has, in many instances, extended into the 12-18 month time frame. Consequently, utilizing scrap gears has the potential of minimizing aircraft downtime and increasing aircraft availability.

While this specific effort was focused on CH-46 gears, the repair and reuse is applicable to transmission gears of all fixed-wing and rotary-wing aircraft. The implementation of this process will, however, require the approval and acceptance of the aircraft manufacturer. This acceptance and approval is being pursued.

### Acknowledgement

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**THE JOURNAL OF THE RELIABILITY INFORMATION ANALYSIS CENTER // FIRST QUARTER - 2007**

The Journal of the Reliability Information Analysis Center is published quarterly by the Reliability Information Analysis Center (RIAC). The RIAC is a DoD Information Analysis Center (IAC) sponsored by the Defense Technical Information Center (DTIC) and operated by a team led by Wyle Laboratories, and including Quanterion Solutions, the Center for Risk and Reliability at the University of Maryland, the Penn State University Applied Research Lab (ARL) and the State University of New York Institute of Technology (SUNYIT).

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Wyle Laboratories, Inc. has provided trusted agent test and evaluation services for more than 57 years. Throughout that period, Wyle has provided quality data that has been key to reducing program risk, resulting in increased system effectiveness for the warfighter. From component testing in the early development phases to independent test engineering services supporting the operational test phase, through ongoing life cycle evaluation and support, Wyle’s exceptional services have been unparalleled across the test continuum.

Through its dedication to provide high level engineering expertise at all stages of the testing process, Wyle today significantly improves the operational performance, effectiveness, and suitability of sea, air, land and space systems and platforms. With capability, capacity and commitment, Wyle reduces program risk, getting the very best systems fielded for the warfighter.
As the transition to Pb-free progresses from consumer and computer electronics to applications with longer life requirements and more extreme use environments, there is a rising concern regarding the long-term reliability of Pb-free interconnections. In response, several publications have recently presented Pb-free solder joint reliability models. All of these models, while useful, have severe limitations. Strain rate equations and damage models allow for the use of finite element modeling (FEM) to predict solder joint reliability, but this is a specialized tool that requires the use of scarce resources. A modified Norris-Landzberg equation provides a correlation between test results and field performance, but there is a strong impetus to ensure robustness during the design stage, rather than identify potential issues after thousands of hours of testing. Extending work done by Engelmaier [Ref. 3] and available experimental results from literature, DfR proposes a Pb-free first-order solder joint reliability model based upon cyclic strain energy density. The maximum strain range of the solder joint is determined using formulas developed by Engelmaier. The stresses on the solder joint are determined by using a simplified structural model that accounts for the various stiffnesses of the structure. These strain and stress results are then used to determine the strain energy dissipated by the solder joint. The strain energy was then used to make life predictions using equations developed by Syed [Ref. 6] and Dasgupta [Ref. 7]. These time-to-failure predictions are then compared to existing accelerated test data, which allowed for the calibration of model constants.

Model Development

Solder Shear Stress Computations
The structure of the component attached to the printed wiring board is represented by a combination of axial and shear springs, consisting of:

- Component axial stiffness
- Solder shear stiffness
- Bond-pad shear stiffness
- Printed wiring board bond pad interface stiffness (foundation stiffness)
- Printed wiring board axial stiffness

A schematic representation of the structure is shown in Figure 1. To this structure, the global deformation due to the CTE mismatch is applied and the stress in the solder joint is determined using compatibility of displacements. Bending of the substrate and component are ignored since the members are very short (aspect ratios less than 10), and will have axial and shear deformations dominating.

The component displacement due to a temperature rise is shown in Equation 1:

\[ U_i = \alpha_i \cdot \Delta T \cdot L_o + \frac{FL_o}{E_i A_i} \]

Where \( U_i \) is the displacement, \( \alpha_i \) is the coefficient of thermal expansion (CTE), \( \Delta T \) is the temperature change, \( L_o \) is one-half the component length, \( F \) is the force, \( E_i \) is the elastic modulus of the component and \( A_i \) is the cross-sectional area of the solder.

The model is broken down into four portions, a solder shear stress equation, a solder strain range computation, a strain energy computation and a solder fatigue equation. The solder shear stress equation is used to determine the amount of shear stress available to drive the deformation of the solder joint during temperature cycling. The solder strain range computation is then used to convert that stress, along with the thermal cycling details (temperature, dwell times) to determine the strain energy per thermal cycle. This strain energy is used in a solder fatigue equation to determine the number of cycles to failure.

Introduction

One of the original assumptions of simple distance to neutral point solder reliability models is that of complete stress relaxation, i.e., the differential expansion between the part and the printed wiring board is directly related to the shear strain in the solder joint. After many years of experience with SnPb solders it has been proven to provide fairly good thermal cycling fatigue predictions. However, due to the increased stiffness of SnAgCu solder this is unlikely to provide adequate (and may yield overly conservative life predictions). The primary goal of this study is to generate a simplified Distance to Neutral Point (DNP) model that accounts for the increased stiffness of the Pb-free solder.
The cross-sectional area of the component is its thickness, \( h_c \), multiplied by its width.

The board displacement due to a temperature rise is shown in Equation 2:

\[
U_1 = \alpha_t \cdot \Delta T \cdot L_0 + \frac{FL}{E_s A_s}
\]

Where \( U_1 \) is the displacement, \( \alpha_t \) is the CTE, \( \Delta T \) is the temperature change, \( F \) is the force, \( E_s \) is the elastic modulus of the printed wiring board, and \( A_s \) is the cross-sectional area of the printed wiring board. The area of the board is calculated by multiplying the thickness, \( h_p \), by two times the bond pad width.

Deformation of the interconnect for a given shear force - \( F \), the interconnect includes the effect of the solder, copper and board interface stiffness and is computed using Equation 3:

\[
U_i = \frac{Fh_s}{\Delta e G_s} + \frac{Fh_b}{\Delta b G_b} + F \left( \frac{2 - \nu}{9 \cdot \nu_G} \right)
\]

Where \( U_i \) is the displacement, \( h_s \) is the solder joint thickness (assumed to be 4 mils), \( A_s \) is the effective solder joint area, \( G_s \) is the solder shear modulus, \( A_b \) is the copper bond pad area, \( h_b \) is the copper thickness (0.035 mm), and \( G_b \) is the copper shear modulus. The additional equation represents the effective foundation stiffness of the bond-pad to PWB interface and is the shear stiffness of a rigid square on a half space [Ref. 1, 2], where “\( \nu \)” is the Poisson’s ratio, \( G_b \) is the shear modulus of the printed wiring board and “\( a \)” is one half the side length of the bond pad.

The force “\( F \)” can then be solved for using the following compatibility equation shown in Equation 4:

\[
(\alpha_s - \alpha_t) \cdot \Delta T \cdot L_0 = F \left( \frac{L_s}{E_s A_s} + \frac{L_s}{E_s A_s} + h_p + h_s \cdot \frac{2 - \nu}{9 \cdot \nu_G} \right)
\]

The shear stress on the solder is then calculated by dividing the force by the effective area of the solder joint. The effective solder joint area, \( A_s \) is assumed to be 75% of the pad area.

Solder Strain Calculations

The shear strain in the solder is computed using equations developed by Werner Engelmaier for leadless components. This is then multiplied by the previously calculated shear stress to determine the cyclic strain energy. The basic calculation for strain range is shown in Equation 5:

\[
\Delta \gamma = C \frac{L_0}{h_s} \Delta \alpha \Delta T
\]

Where C is 0.5, an empirical correction factor, \( L_0 \) is \( \frac{1}{2} \) the length of the component, \( h_s \) is the solder joint height (assumed to be 0.1016 mm or 4 mils), and \( \Delta \alpha \Delta T \) is the differential thermal expansion between the component and substrate. This strain is assumed to be the maximum strain that can be developed in the solder joint.

Solder Strain Energy Calculations

The strain energy density dissipated during the thermal cycle is assumed to be approximately equal to the formula shown in Equation 6:

\[
\Delta W \approx \Delta \gamma \cdot \tau
\]

Where \( \Delta W \) is the change in strain energy density, \( \Delta \gamma \) is the strain range, and \( \tau \) is the shear stress.

Life Predictions

The energy dissipated per thermal cycle is used to make fatigue life predictions using damage laws developed by Syed [Ref. 6]. Syed developed two damage equations for strain energy density based upon two different creep strain rate equations. The one used in this study is based upon the double power law creep model shown in Equation 7:

\[
N_f = (0.0015 \omega_m)^{-1}
\]

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Additional calculations using an energy damage law developed by Zhang and Dasgupta [Ref. 7] were also done as a comparison. The damage law they proposed is shown in Equation 8:

\[
N_f = \left( \frac{\omega_{acc}}{5920} \right)^{17}
\]

In Equations 7 and 8, \(N_f\) represents the average number of cycles to failure and \(\omega_{acc}\) is the accumulated strain energy per cycle.

**Validation**

Validation of the model was performed by comparing predictions to experimental findings from available publications.

**Failure Data**

Data on the thermal cycling behavior of leadless chip resistors attached with SnAgCu is outlined in Table 1. This data was plotted and is displayed as a function of component size and temperature cycle in Figure 2 through Figure 4. All datasets cited in Table 1, except for Franhofer, used a SnAgCu alloy with an elevated silver content (3.9 or 3.8). Based on recent data published by IPC, providing that the SnAgCu composition is between Sn3.9Ag0.7Cu and Sn3.0Ag0.5Cu, the time to failure behavior during temperature cycling seems to be relatively insensitive to the exact alloy content.

Comparing the information retrieved from the various papers can be difficult as a number of experimental designs were set up to assess the influence of parameters separate from the component, interconnect or environment. For example, the dataset from Woodrow [Ref. 9] included varying the Pb-free solderability plating between immersion silver (ImAg), organic solderability preservative (OSP), and electroless nickel/immersion gold (ENIG). A similar effort was made by Schubert [Ref. 17]. Other non-environmental drivers investigated included cooling rates [Ref. 13] and the number of reflows [Ref. 16].

Several preliminary findings were derived from an initial review of the validation data. Ramp rates were found to have

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* Estimated. Eta not provided in original paper.
a relatively negligible impact on time-to-failure when compared across several datasets. In addition, thermal cycles with a maximum temperature above 125°C did not consistently result in a shorter lifetime. This may suggest that the current standard of maintaining temperatures below 125°C during accelerated testing of SnPb solder interconnections may also be valid for SnAgCu solder interconnections. In the same regard, thermal cycles with minimum temperatures below -40°C did also not seem to reduce the time to failure significantly. Other drivers, such as solderability plating and cooling rates, were also found to have a negligible or secondary effect when compared to environmental and component parameters.

These findings should only be considered preliminary as there are two major limitations to the datasets that were identified. The first limitation was that none of the publications provided all test parameters necessary to assess the relevancy of the time to failure information. Data that was found to be absent included board thickness, board coefficient of thermal expansion (CTE), procedure for monitoring failure, number of samples tested, number of samples failed, and validation that failures were not at other locations (such as vias). Also, almost all the publications failed to provide details on the solder volume, such as board bond pad dimensions, stencil thickness, or solder joint height. This absence of data can be critical, as all predictive models for long-term reliability of SnAgCu solder depend on test results to validate their output. Lack of reliable data can result in a lack of reliable end-of-life models and should drive professional organizations, such as SMTA, IEEE, IPC, and IMAPS, to consider a global specification on required data formats when reporting the results of reliability testing.

The second limitation was the lack of repeatability. Repeatability and reproducibility (R&R) have become a standard practice in manufacturing to ensure a sufficient level of quality control. While the cost and time associated with temperature cycling to failure can definitively hinder the implementation of R&R, it should be strongly considered as a review of the literature seems to identify several examples of test data that do not correlate with test results from other publications and may not be repeatable.

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Two components were studied to compare the model predictions to the failure data, a 2512 and a 1206 ceramic resistor. The material properties for various parts of the assembly were assumed to be the values shown in Table 2, which are typical of values found in literature. The geometric variables (component dimensions) used in the model are shown in Table 3. Some typical results for the solder shear stress, inelastic strain energy and life predictions are shown in Table 4 for a -55 to 125°C thermal cycle.

As shown in the table, the maximum stress developed in the solder joint only decreases slightly as the component size shrinks. A comparison of predictions from the DfR reliability model and experimental data from Table 1 is displayed in Figure 5. The data shows a very strong fit to the predictive results, especially considering that no iterative fitting to the data was performed before this comparison was performed. Three data points lie outside the 2X banding, two of which correspond to thermal cycling that was conducted up to 150°C, which may be close to or beyond the glass transition temperature of the circuit board; the one data point that falls well away from the 2X band is from Reference 1. Comparing the results from this reference to other results from other organizations, as shown in Figure 2, seems to suggest that some unknown aspect of the test setup or conditions resulted in unexpectedly much longer times to failure. Both the energy models gave adequate life predictions.

**Validation Example**

Two components were studied to compare the model predictions to the failure data, a 2512 and a 1206 ceramic resistor. The material properties for various parts of the assembly were assumed to be the values shown in Table 2, which are typical of values found in literature. The geometric variables (component dimensions) used in the model are shown in Table 3. Some typical results for the solder shear stress, inelastic strain energy and life predictions are shown in Table 4 for a -55 to 125°C thermal cycle.

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<th>Shear Modulus (MPa)</th>
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<td>Width</td>
<td>3.05 mm</td>
<td>1.52 mm</td>
</tr>
<tr>
<td>Printed Wiring Board</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>1.6 mm</td>
<td>1.6 mm</td>
</tr>
<tr>
<td>Solder Joint</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>1.5 mm</td>
<td>1.125 mm</td>
</tr>
<tr>
<td>Width</td>
<td>3.05 mm</td>
<td>1.52 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.1016 mm</td>
<td>0.1016 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>2512</th>
<th>1206</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔT</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Δγ</td>
<td>0.0225</td>
<td>0.0108</td>
</tr>
<tr>
<td>τ</td>
<td>203 MPa</td>
<td>199 MPa</td>
</tr>
<tr>
<td>ΔW</td>
<td>0.572</td>
<td>0.269</td>
</tr>
<tr>
<td>N [Ref. 6]</td>
<td>1315 cycles</td>
<td>2792 cycles</td>
</tr>
<tr>
<td>N [Ref. 7]</td>
<td>1382 cycles</td>
<td>2468 cycles</td>
</tr>
</tbody>
</table>

**Figure 5**: Validation of DfR end-of-life model for thermally cycled leadless chip components (red lines indicate 2X bands)
Discussion

As shown by the results, the model provides a relatively good estimate of the fatigue behavior of the leadless chip resistors as a function component size and thermal cycle for SnAgCu using calculations that can be easily implemented into a spreadsheet or simple calculator. This model adds in the effect of the printed wiring board to solder bond pad by using a foundation shear stiffness equation. An example of the life predictions for a 2512 resistor at various temperature deltas is shown in Figure 6.

The model is currently undergoing minor modifications to account for dwell times. Additional work is being done to check the sensitivity of the model to various geometric parameters and some modification to the strain range calculation may be implemented. Additional work in using the stress calculation for doing 2nd order predictions is also planned so that stress strain hysteresis loops can be generated for improved strain energy calculations.

References

11. Unknown, RoHS Readiness, June 2004, update, Web-based  

Figure 6: Life predictions for 2512 resistor as a function of $\Delta T$
Item ToolKit
- Reliability Prediction
  - Mil-HDBK-217
  - Bellcore/Telcordia
  - NSWC
  - RDF (IEC 62380)
  - China 299B
- Fault Tree Analysis
- Event Tree Analysis
- Markov Analysis
- Reliability Block Diagram
- Failure Mode Effect Analysis (FMEA – ISO 9000)
- Failure Mode Effect & Criticality Analysis (FMECA – Mil-STD-1629)
- Failure Mode Effect & Diagnostics Analysis (FMEDA – IEC 61508)
- Maintainability Analysis
- SpareCost Analysis

Item QRAS
- Quantitative Risk Assessment
- Risk scenario modeling
- Event Sequence Diagram
- Fault Tree Analysis
- System level risk aggregation
- Quantified Risk Levels
- “What if” sensitivity analysis
- Binary Decision Diagram

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In the Fourth Quarter 2006 edition of the RIAC Journal [Ref. 1], I provided an overview of the 217Plus™ system reliability assessment methodology. In that article, I introduced the generic elements of the methodology that contribute to the assessment of system reliability:

- Use of component failure rate models and data
- Application of system process grading factors
- Combination of failure rate data using Bayesian analysis

Figure 1 from that article, reprised below, provides a review of the 217Plus™ approach to failure rate estimation.

The 217Plus™ System Reliability Model

The basic 217Plus™ failure rate model for a system [Ref. 2] is:

\[ \lambda_p = \lambda_{IA} \left( \Pi_F + \Pi_D + \Pi_M + \Pi_S + \Pi_I + \Pi_N + \Pi_W \right) + \lambda_{SW} \]

where the sum of the Pi-factors in the parentheses represents the cumulative multiplier that accounts for the processes used in system development and sustainment. The sum of these values is normalized to unity for processes that are considered to be the mean of industry practices.

Figure 1: The 217Plus™ Approach to Failure Rate Estimation
\begin{align*}
\lambda_p &= \text{Predicted failure rate of the system} \\
\lambda_{IA} &= \text{Initial assessment of the failure rate. This failure rate is based on the new component failure rate models developed by the RIAC.} \\
\Pi_p &= \text{Parts process multiplier} \\
\Pi_d &= \text{Design process multiplier} \\
\Pi_m &= \text{Manufacturing process multiplier} \\
\Pi_s &= \text{System Management process multiplier} \\
\Pi_i &= \text{Induced process multiplier} \\
\Pi_n &= \text{No-defect process multiplier} \\
\Pi_w &= \text{Wearout process multiplier} \\
\lambda_{SW} &= \text{Software failure rate prediction}
\end{align*}

The initial assessment of the failure rate, \( \lambda_{IA} \), is the seed failure rate value for the system model, and is obtained by using the 217Plus™ component reliability prediction models developed by the RIAC, along with other available data. In this article, we begin to take a closer look at the 217Plus™ component models that contribute to \( \lambda_{IA} \).

The 217Plus™ Component Reliability Models

Traditional methods of reliability prediction model development, such as those for MIL-HDBK-217, have relied on the statistical analysis of empirical failure rate data. The statistical methods typically result in a model form that is multiplicative (i.e., the predicted failure rate is the product of a base failure rate and several factors that account for the stresses and component variables that influence reliability). An example of a multiplicative model is:

\[ \lambda_p = \lambda_b \pi_e \pi_q \pi_s \]

where,

- \( \lambda_p \) = Predicted failure rate
- \( \lambda_b \) = Base failure rate
- \( \pi_e \) = Environmental factor
- \( \pi_q \) = Quality factor
- \( \pi_s \) = Stress factor

A primary disadvantage of the multiplicative model is that the predicted failure rate can become unrealistically large or small under extreme value conditions (i.e., when all factors are at their lowest or highest values). This is an inherent limitation, primarily due to the fact that individual failure mechanisms, or classes of failure mechanisms, are not explicitly accounted for.

With the 217Plus™ methodology, the RIAC believes that a better approach is a combination of additive and multiplicative models that predict a separate failure rate for each generic class of failure mechanisms. Each of these failure rate terms is then accelerated by the appropriate stress or component characteristic. The general model form is:

\[ \lambda_p = \lambda \pi_o + \lambda \pi_e + \lambda \pi_i + \lambda \pi_{sj} \]

where,

- \( \lambda \) = Predicted failure rate
- \( \lambda_o \) = Failure rate from operational stresses
- \( \pi_o \) = Product of failure rate multipliers for operational stresses
- \( \lambda_e \) = Failure rate from environmental stresses
- \( \pi_e \) = Product of failure rate multipliers for environmental stresses
- \( \lambda_i \) = Failure rate from power or temperature cycling stresses
- \( \pi_i \) = Product of failure rate multipliers for cycling stresses
- \( \lambda_{sj} \) = Failure rate from induced stresses, including electrical overstress and ESD
- \( \pi_{sj} \) = Product of failure rate multipliers for solder joint stresses

By modeling the failure rate in this manner, factors that account for the application and component-specific variables that affect reliability (Pi-factors) can be applied to the appropriate additive failure rate term. continued on next page
There are currently twelve component models defined within Version 2.0 of the 217Plus™ methodology. They are:

› Capacitors
› Connectors
› Diodes
› Inductors
› Integrated Circuits
› Optoelectronic Devices
› Relays
› Resistors
› Switches
› Thyristors
› Transformers
› Transistors

Treatment of Environmental Stresses

MIL-HDBK-217 has traditionally used environmental factors which were qualitatively defined. The manner in which the models were developed was to collect field failure rate data and perform regression analysis on the data to quantify model variables. The environment was treated as a single variable, with single multipliers for each generic environment. Additionally, operating profile variables were also inherently included in the factor. As such, the effects of all environmental and operating stresses were pooled into a single variable. It is highly desirable for a reliability model to provide the capability of performing analysis as a function of specific stresses, and to analyze the tradeoffs among those stresses. Therefore, the model must be separately sensitive to the specific environmental and operational stresses. Since reliability engineers are often required to perform such sensitivity and tradeoff studies, the goal of the 217Plus™ methodology is to provide the ability to perform analysis as a function of specific environmental and operational stresses.

Acceleration Factors

Acceleration factors (or Pi-factors) are used in the 217Plus™ component models to estimate the effect of various stress and component variables on failure rate. In cases where the factor could be quantified from the available data, it was. In some cases they were not, and the Pi-factors were derived by utilizing either industry accepted values, values determined separately from data available to the RIAC, or values from previous modeling efforts. For example, the models typically include both an operating and nonoperating temperature factor based on the Arrhenius relationship, which requires an activation energy for both operating and nonoperating conditions. To estimate these values for the model, previous modeling studies (along with existing prediction methodologies) were used. Similarly, some factors were based on test data. For example, the exponent used in the \( \Delta T \) Pi-factor for the 217Plus™ integrated circuit component model is based on fallout-rate data from temperature cycling tests that were performed over various ranges of \( \Delta T \).

Reliability Growth of Components

Another issue that faces reliability model developers is the manner in which reliability growth is accounted for. A good model reflects state-of-the-art technology. However, empirical models are usually developed from the analysis of field data, which takes time to collect. Some part types, such as integrated circuits, have exhibited a large degree of reliability improvement over the last twenty years. The faster the growth, the more difficult it is to derive an accurate model. Therefore, the component models in 217Plus™ include a factor that accounts for this reliability improvement over time. The growth rate model used for this purpose (for each component) takes the form:

\[
\lambda \propto e^{\beta(t_1 - t_2)}
\]

where,

\( \lambda \) = Estimated failure rate as a function of year of manufacture

\( \beta \) = Growth rate

\( t_1 \) = Year of manufacture for which a failure rate is estimated

\( t_2 \) = Year of manufacture of parts on which the data was collected

Table 1 contains, for each currently defined 217Plus™ component type, the achieved growth rate.

Failure Mode to Failure Cause Mapping

There are two primary types of data upon which the 217Plus™ component models are based, i.e., failure rate and failure mode. The model development process required that the failure rate data be apportioned into the five defined failure cause categories from the generic model (operational, environmental, power/temperature cycling, induced, and solder). Since the available failure mode data contained in the RIAC databases is typically not classified according to these categories, it was necessary to transform the failure mode distribution data into the failure cause distribution. This data was collected by the RIAC and is based primarily on failure analysis results of parts that have failed in the field.
The primary stresses that potentially accelerate operational failure modes are operating temperature, vibration, current and voltage. The stresses that accelerate environmental failure causes are nonoperating ambient temperature, corrosive stresses (contaminants/heat/humidity), aging stresses (time) and humidity. As an example, Table 2 summarizes this process for a generic resistor. Each of the six identified failure modes is listed across the top of the table (i.e., EOS, contamination, etc.) and each of the accelerating stresses/causes is listed down the left side. Each combination is identified with either a blank, a “P” (primary) or an “S” (secondary). The associated relative percentage of failures attributable to the accelerating stress/cause is listed down the right columns.

### Derivation of Base Failure Rates

Once the Pi-factors were defined for each component type that was modeled, and once the failure rate was apportioned among the failure causes, the base failure rate could be determined. This was accomplished by (1) gathering all of the failure rate data within the RIAC database, (2) estimating the model input variables (temperatures, stresses, etc.) for each source of data, (3) calculating the associated Pi-factor for...
each failure rate, and (4) deriving a base failure rate for each of the failure cause categories. For example, the failure rate associated with operational stresses equated to the product of the base failure rate and the operational Pi-factors:

\[ P_{FC} \cdot \lambda_{obs} = \lambda_{b} \pi_{o} \]

where,

- \( P_{FC} \) = Percentage of failure rate attributable to operational failure causes
- \( \lambda_{obs} \) = Observed failure rate
- \( \lambda_{b} \) = Base failure rate to be derived
- \( \pi_{o} \) = Product of model Pi-factors

Solving for \( \lambda_{b} \) and adding a factor to account for data points which have had no observed failures yields:

\[ \lambda_{b} = \frac{P_{FC} \cdot \lambda_{obs} \cdot P_{f}}{P_{f}} \]

where \( P_{f} \) is a factor that scales the failure rate to account for data records for which there were no failures (i.e., survivals and suspensions). Once this value of \( \lambda_{b} \) was calculated for each data record, the geometric mean was used as the best estimate of the base failure rate.

### Global Constants

Several variables are common to all of the 217Plus™ component models. These are known as global parameters. These global parameters are defined as:

- \( Y \) = Year of manufacture
- \( DC \) = Duty cycle (the percent of calendar time that the system in which the component is operating is in an operational state)
- \( TAO \) = Ambient temperature, operating (in degrees C)
- \( TAE \) = Ambient temperature, nonoperating (in degrees C)
- \( CR \) = Cycling rate (the number of power cycles per year to which the system is exposed). In this case, it is assumed that the system transitions from a nonoperating environment to an operating environment at the same time that the power is applied.
- \( RH \) = Relative humidity

The constants defined within 217Plus™ for these parameters are provided in Tables 3 and 4.

### Table 3: 217Plus™ Default Operating Profile Values

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Operating Profile</th>
<th>DC</th>
<th>CR (cycles/year)</th>
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<tr>
<td>Automotive</td>
<td></td>
<td>5</td>
<td>1000</td>
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<td>Commercial Aircraft</td>
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<td>25</td>
<td>2982</td>
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<tr>
<td>Computer</td>
<td></td>
<td>80</td>
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<tr>
<td>Consumer</td>
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<td>30</td>
<td>368</td>
</tr>
<tr>
<td>Emergency Power</td>
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<td>50</td>
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<td>Industrial</td>
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<tr>
<td>Military Aircraft</td>
<td></td>
<td>25</td>
<td>1001</td>
</tr>
<tr>
<td>Military Ground</td>
<td></td>
<td>45</td>
<td>263</td>
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<tr>
<td>Naval</td>
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<td>80</td>
<td>50</td>
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<tr>
<td>Telecommunications</td>
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<td>80</td>
<td>368</td>
</tr>
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</table>

### Table 4: 217Plus™ Default Environmental Stress Values

<table>
<thead>
<tr>
<th>Environment</th>
<th>TAO (deg C)</th>
<th>TAE (deg C)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
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<td>55</td>
<td>14</td>
<td>40</td>
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<tr>
<td>Airborne, Fixed Wing</td>
<td>55</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>Airborne, Fixed Wing, Inhabited</td>
<td>55</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>Airborne, Fixed Wing, Uninhabited</td>
<td>71</td>
<td>14</td>
<td>50</td>
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<tr>
<td>Airborne, Missile</td>
<td>55</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>Airborne, Missile, Flight</td>
<td>55</td>
<td>14</td>
<td>40</td>
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<tr>
<td>Airborne, Missile, Launch</td>
<td>55</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>Airborne, Rotary Wing</td>
<td>55</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>Airborne, Rotary Wing, Inhabited</td>
<td>55</td>
<td>14</td>
<td>40</td>
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<tr>
<td>Airborne, Rotary Wing, Uninhabited</td>
<td>71</td>
<td>14</td>
<td>50</td>
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<tr>
<td>Airborne, Space</td>
<td>55</td>
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<tr>
<td>Ground</td>
<td>35</td>
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<td>Ground, Man Pack</td>
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<td>14</td>
<td>40</td>
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<tr>
<td>Ground, Mobile, Heavy Wheeled, Engine Compartment</td>
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<td>40</td>
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<td>Ground, Mobile, Heavy Wheeled, Engine Mounted</td>
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<td>14</td>
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<tr>
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<tr>
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<td>40</td>
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<td>40</td>
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<td>Ground, Mobile, Tracked</td>
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<td>40</td>
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<tr>
<td>Ground, Stationary</td>
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<td>Ground, Stationary, Indoors</td>
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<td>23</td>
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<td>Ground, Stationary, Outdoors</td>
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<td>50</td>
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<td>Naval</td>
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<td>Naval, Shipboard</td>
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<td>Naval, Shipboard, Unsheltered</td>
<td>60</td>
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<td>90</td>
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<tr>
<td>Naval, Submarine</td>
<td>55</td>
<td>23</td>
<td>50</td>
</tr>
</tbody>
</table>
Comments on Part Quality Levels

Part quality level has traditionally been used as one of the primary variables affecting the predicted failure rate of a component. The quality level categories were usually the quality levels defined by the applicable military specification.

One of the problems that model developers had when developing MIL-HDBK-217 models was de-convolving the effects of quality and environment. For example, multiple linear regression analysis of field failure rate data was usually used to quantify model variables as a function of independent variables such as quality and environment. A basic assumption of such techniques is that the variables are statistically independent of each other. However, in reality, they are not since the “higher” quality components are generally used in severe environments and the commercial quality components are used in more benign environments. This correlation makes it difficult to discern the effects of each of the variables individually. Additionally, there are several attributes pooled into the quality factor, including qualification, process certification, screening, and quality systems.

The approach used in the 217Plus™ methodology to quantify the effects of part quality is to treat it as one of the failure causes for which a process grade is determined. In this manner, issues related to qualification, process certification, screening and quality systems are individually addressed.

A significant issue is the application of commercial components in harsh environments. Specifically, the temperature rating of a part is a primary consideration. For a commercial part, the temperature range over which the manufacturer will guarantee performance is typically limited to 0 to 70 degrees C. Military and aerospace applications often require guaranteed performance over wider temperature ranges (i.e., -55 to 125 degrees C). While use of a commercial part in these environments is not a reliability issue, per se, it does confound the definition of failure criteria. For example, although a part may not perform beyond its rated temperature, it usually does not catastrophically fail and, therefore, is not considered a reliability failure. However, many practitioners do consider this a reliability issue and, as such, turn to reliability models for the quantification of the part’s reliability in the specific extended range application. There are no reliability models currently available that can quantify the reliability of parts when used beyond their ratings. All existing models make the implicit assumption that parts are used within their ratings. A separate, but critical, requirement for the reliable application of components is the qualification of parts and manufacturers to ensure that specific parts will function reliably in their intended application.

Explanation of Failure Rate Units

The 217Plus™ methodology (component models and the empirical data contained in the RIAC databases used in the 217Plus™ tool) predicts the failure rate in units of failures per million calendar hours. This is necessary because the 217Plus™ methodology accounts for all failure rate contribution terms (i.e., operating, nonoperating, cycling, and induced), and the only manner in which they can be combined is to use a common time basis for the failure rate, which is calendar hours.

If an equivalent operating failure rate is desired in units of failures per million operating hours, the 217Plus™ reliability prediction should be performed with the actual duty cycle to which the unit will be subjected, and the resulting failure rate (in $f/10^{6}$ calendar hours) should be divided by the duty cycle to yield a failure rate in terms of $f/10^{6}$ operating hours. In this case, the resulting “operating” failure rate will be artificially increased to account for the nonoperating and cycling failures that would not otherwise be accounted for.

The incorrect way to predict a product or system failure rate in units of failures per million operating hours is to set the duty cycle equal to one. The resulting failure rate in this case would be valid only if the actual duty cycle is 100%. But if it is not 100%, then the failures during nonoperating periods are not accounted for.

Next Issue

The next issue of the RIAC Journal (2nd Quarter 2007) will begin to present the individual 217Plus™ component failure rate models in more detail.

References


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The purpose of this article is to provide designers and manufacturers with a method to increase their products’ reliability, compress their design cycle and improve their quality while keeping their cost under control. There are three separate parts of the article. The first part will deal with Design Development Issues. The second part provides recommendations for Manufacturing Line Development, and the final part will suggest a Production Line Maintenance Method. Each part is necessary in order for the product’s lifetime success.

Part 1 – Design Development Issues

A large part of a product’s success depends on being able to launch the design from concept to final validation within a reasonable time. Another success key is the design’s quality and reliability. The product’s reliability is set by the product specification and/or regulation to which it is designed. The specifications and regulations are hereby going to be referred as the “requirements”. The requirements are the best guess as to what the product’s operational environment and stresses will be. The environmental validation requirements are typically derived from the Arrhenius Model [Ref. 1]. The Arrhenius Model is the basis for old familiar standards such as MIL-HDBK-217 and MIL-STD-781 and/or their international counterparts.

The Arrhenius Model places an extraordinary emphasis on temperature as the leading element for product failures (see Figure 1). Newer technologies and materials are generating non-traditional failure modes. For example, electronic products may experience lock up conditions due to power dips, sags and transients during operation. These failure modes are often undetected (No Trouble Found – NTF’s) when the suspect products are returned for analysis. The product’s operational environment is completely different from the laboratory environmental/test conditions when the product was tested and validated [Ref. 2]. For example, electromagnetic compatibility (EMC) validation is normally performed at laboratory ambient temperatures. Plus, the dips, surges, transients, etc., during validation are applied one discreet interference signal at a time. The product’s “field” environment is a composite of electromagnetic interference, as well as varying environmental conditions. The electromagnetic/environmental variance may make all the difference between marginal designs versus robust designs.

Many times the requirements themselves are treated as cookie cutter elements which the Project Team checks off on the way to Start of Production (SOP). This rationale may lead Project Teams to completely disregard the importance of the requirements. How many of you have overheard a Project Engineer state, “Of course, it failed the durability test. The durability test is too severe. It can’t survive.” Clearly the Project Engineer does not understand the purpose of Durability/Reliability testing. Durability/Reliability tests are designed to take the product to near its maximum operational threshold. Marginal designs and latent defects will not survive the extreme environmental conditions. Latent defects will develop into patent failures. These failures will reveal weaknesses in the product. If the results are analyzed properly, then the product design will be modified (hardened) in order to survive the Durability/Reliability requirements. This individual Product Engineer’s behavior may explain why quality goal part per million (PPM) levels and warranty levels are not within acceptable tolerances. It also demonstrates the other side of the coin within the Design Development Issue arena; knowing your design margins...
do not meet requirements, justifying the non-compliance and ignoring the consequences.

Another issue that decreases chances for product success is schedule versus resources. Typically, the Project Design Core and Extended Support Teams are responsible for a product’s functional operation, requirement compliance and product maturation. In addition, they are responsible for prototype builds and deliveries to the customer. As the due dates loom closer and closer you know who and/or what is going to be given the highest priority. The customer’s ship dates will almost always override every other consideration (product maturation, functionality and compliance). It is expected. Customer satisfaction is one of the primary goals. Keeping them happy secures your future, so the prototypes will be shipped even if they do not completely comply with the functional requirement because prototypes, by definition, are not expected to meet all of their requirements. They are expected to demonstrate “proof of concept”. As long as they meet minimal requirements they are shipped out. The issue occurs when product maturation is sacrificed and forgotten due to the short term goals. If you fail to correctly prioritize long-term customer satisfaction against the short term, your customer will discover the issues for you. The past short term (prototype delivery) satisfaction will be completely forgotten when/if issues arise.

**Design Development Recommendations**

Let’s turn back and reflect on the specifications and regulations (requirements). By definition, the requirements are equal to the product’s final platform (system) environment. This is not always the case. At times, the requirements may not accurately reflect the final product environment and issues develop. However, that discussion is best left for another time. Generally, if you meet the customer’s durability/reliability requirements [Ref. 3] you can be reasonably sure that the majority of your products will be issue free. Typically, test sample quantities are not sufficient to generate a high degree of confidence. You won’t know the products’ life distribution. You can either increase the sample size so it accurately reflects the entire population and statistical analysis can be performed, or you increase the testing duration beyond the “required” test length until you are able to develop mean time between failures. No matter what method you choose, you should know where your design margins are and whether or not there could be issues in the field. You also need to understand where you can improve your product maturation/design functionality.

Another product maturation method is the use of Highly Accelerated Life Tests (HALT) to compress the time required to mature the product and ensure acceptable design margins. It takes a large engineering paradigm shift to understand HALT [Ref. 4]. The goal of HALT is not how much the product/design can experience and survive. The HALT concept is based on Miner’s Criterion [Ref. 1] (Figure 2).

The goal is to precipitate failure modes, detect those failure modes using real time acquisition, then analyze the failures (determining whether or not the failure is an acceptable failure mode). For example, if a printed circuit board (PCB) was tested, the PCB solder would soften and melt as the material was stressed well above, or at, its rated temperature. It would be an acceptable failure mode. However, if the PCB vias crack prior to reaching the upper or lower destruct limits, continued on next page

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**Figure 2: Basic Highly Accelerated Life Test Concept [Ref. 1]**

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then it may be advisable to review the PCB design to determine why the fractures are occurring. If it makes economic sense to modify the PCB stress points and strengthen them, then you make the corrective action. Verify that the action has the desired impact and incorporate it into the design. The importance of verifying the corrective action is VITAL. If you do not verify the corrective action, issues may find their way back into production, or new issues may develop because the verification portion of the methodology was not completed.

The Design Failure Mode and Effects Analysis (FMEA) is an excellent tool to use in order to design specific HALT methods to precipitate and detect potential product failure modes. In addition, taking advantage of present technology such as using abnormal (minimum-maximum) load conditions and simulating system voltage operating conditions and temperature extremes/transition with six-axis vibration, may develop these failure modes quicker and feed the results back into the FMEA database and mathematical models. It is not just a matter of gathering the data, but using the data to improve your process and design.

Achieving HALT’s goal will ensure there are sufficient design margins between field conditions and product characteristics. The greater the difference there is between the field (platform) condition and product minimum/maximum operating characteristics, the lower the risk you have for customer issues. There is a fine line when using HALT methodology between adding value to the design and overdesign (“no value added” cost). The individual tasked with performing the HALT must understand the difference.

One example of a successful HALT campaign was an automotive sensor, manufactured in Auburn, IN. The air-air thermal shock customer specification was approximately 63 days. However, the customer requested that the total test length be doubled so that the total test duration equaled 126 days. A HALT test using thermal chamber (hot) and dunking the product into liquid nitrogen (cold) was devised. This HOT Dunk developed the same failure modes revealed within the air-air thermal shock testing within 1 to 2 days initially. The air-air failure modes took approximately 50 days to develop. The product’s design was revised and verified using the HOT Dunk test, then validated using the air-air thermal shock test. Product test samples lasting approximately 300 cycles in the HOT Dunk test went well beyond the 126 days in the air-air thermal shock test. The air-air thermal shock test was discontinued when the duration reached twice the customer requirement without failures.

Manufacturing Line Development Issues

Traditionally, prototypes are built and/or assembled within the design laboratory. A highly skilled technician painstakingly, and almost lovingly, brings to life the concept he/she was given. Prototypes are tweaked and diagnosed, and malfunctions corrected. When everything is as good as the technician can make it, the samples are either shipped to the customer or evaluations using functional/environmental characteristics tests are performed. Years ago this led to great difficulties, as designers hurled the product over the wall into the manufacturing arena.

All too often you will discover that a product built within the laboratory using traditional methods does not transfer well to the manufacturing process. There are hidden lessons learned that are not passed onto the Manufacturing Designers. The skill sets are not the same from the traditional prototype build method versus the general hourly manufacturing associate. This creates a higher risk for unforeseen issues.

Manufacturing Line Development Recommendations

A paradigm shift has been occurring within manufacturing line development. Many successful production lines will create a Prototype Production Line after the product’s proof of concept phase is complete. All future prototypes are built on a Prototype Production Line. The Prototype Production Line Team is staffed with hourly and salaried personnel. The team works in cooperation. Design and Manufacturing Engineers observe and participate with the operators as they assemble and build prototypes.

In order to implement a Prototype Production Line, you may have to beg, borrow or steal production floor space from an already crowded manufacturing floor. You also need to add personnel resources and reassign resources every time a build is scheduled or rescheduled. You may have to deal with the possible personality conflicts as designer and assembler discourse could go from cooperative to argumentative. It provides large administrative nightmares.

The reality is far different. You will witness designers communicating with the assemblers. Assemblers will show the designers what was giving them grief, with the designers attempting the task, comprehending the issue and walking away to come back one or two days later with a solution. It will change the manufacturing line’s design numerous times
Production Line Issues

One constant in life is change. Whether we acknowledge it or not, people change, equipment changes and even processes will change over time. Failing to acknowledge and control this fact will lead to disappointment and issues. A Six Sigma Process develops methods to measure and control the processes, as well as the changes that occur.

Even if you were to follow the recommendations discussed in the sections above, it will not guarantee flawless production. High production volumes tend to impact other activities designed to ensure flawless behavior during production. For example, preventive/calibration maintenance is a much lower priority than production throughput. Equipment will operate and function normally for quite a period without maintenance, however it will develop problems. An excellent maintenance example is your vehicle. Failing to change/replace the motor’s oil will eventually cause the engine to seize, generating a significant cash demand on your resources and, normally, at the most inopportune time.

Another example of this is an automotive sensor developed and manufactured in Auburn, IN. This sensor is used in the Developmental and Manufacturing Line Maturation Process. Yet it still experienced issues during its third production year. These issues generated great concern and worry until the problems were corrected. Many of the issues were generated by life’s constant - change. Processes changed as equipment aged, line personnel transferred and priorities changed.

One of the product’s latent issues developed due to one of the environmental (conditioning) thermal chamber’s heat links opening. The conditioning chamber had two heater elements and, subsequently, two independent heat links. When one link opened the other continued the chamber’s operation. However, one side of the chamber was much hotter than the other side. This resulted in the product on that side being subjected to temperatures well above the desired level. The chamber’s thermal sensor did not reveal the problem. It was located in the air flow and measured the chamber’s temperature at that one set spot. The chamber’s temperature was not uniform. Solder reflowed on some of the products, scrap counted/cost rose and some products developed latent defects. The latent defects entered the field and, over a short period, went patent. Discovering the root cause to the issue was quite involved. The chamber was on a six-month preventive/calibration maintenance schedule. Looking at the historical chamber log did not provide data to determine what went wrong. It was only discovered by bit-mapping the chamber’s thermal characteristics and by the vigilance of the team assembled to solve the issue. The preventive/calibration maintenance process alone is not sufficient to contain equipment issues. The main failing is that preventive/calibration maintenance is not predictive. However, the data gathered during the preventive/calibration maintenance process may be used to develop a predictive maintenance system.

Production Line Recommendations

Many of these production issues may have been avoided if a Six Sigma Process Control program and a competent calibration/preventive/predictive maintenance process was implemented.

If the chamber in the example mentioned above was on a calibration/preventive/predictive maintenance schedule, the chamber’s voltage and current would have been measured, and the data logged and plotted. Its demise could have been predicted and action taken prior to its destruction. Critical processes would have been identified, measured and controlled by the Six Sigma approach. Trends would have been observed, and corrective action taken, before issues developed.

Conclusions

One of the most difficult tasks is mass production. The world conspires against you as you try to acquire components, assemble them, then pack and deliver the products to your customers. Nothing is ever easy and anything that can go wrong will go wrong [Ref. 5]. Everyone should have a deep respect for individuals within the manufacturing field. Building any product is difficult. Building the perfect part, defect free and reliable, is a mountainous task. We need to use every tool that will benefit us and, where needed, create and/or revise our tools as our needs change. There are four tools you should continue to develop:

› Product Maturation
› Manufacturing Line Maturation paralleling the product’s development
› Using a Six Sigma Approach during production to measure and control our Processes
› An effective calibration/preventive/predictive maintenance program

continued on next page
Should you effectively accomplish these tasks, you will increase the product’s capability above its field environment, understand its production processes and control the variables which could adversely impact your quality.

Product maturation will ensure adequate margins exist between the product’s capability and the field environment. Manufacturing Line Maturation will develop the production line in tandem with product development and permit flawless launches. Six Sigma and effective calibration/preventive/predictive maintenance processes are measured and controlled, and ensure that the product we designed and built at our initial production is of the same quality as the final product years and years down the line.

We have shown many of the components necessary to launch a successful Zero-Tolerance to Defects and improved Reliability process. Here is where you can and should make the difference. We strongly recommend revising your development processes and procedures to include Product and Prototype Manufacturing Maturation after feasibility prototypes are completed, conducting an awareness campaign and measuring the results, if Six Sigma has already been adopted into your corporate structure. It leaves changing your maintenance from calibration/preventive to calibration/preventive/predictive. Voltage and current are excellent measures that can be made and recorded, with trends analyzed. Acceptable tolerances can be derived from Original Equipment Manufacturer’s (OEM’s) equipment manuals, or defaults that are set to less than or equal to 20% of nominal operation should be acceptable (general rule).

**Bibliography**

5. Murphy’s Law, unknown

![Figure 3: Basic Highly Accelerated Life Test Concept [Ref. 1] with Six Sigma Control](image-url)
RIAC Versatile Reliability Centered Maintenance Course Restructured

The Reliability Information Analysis Center (RIAC) recently restructured its “Versatile Reliability Centered Maintenance” on-site training course into two separate courses. As with all Reliability Information Analysis Center on-site courses, the following courses can be tailored to meet the specific needs of your organization.

Basic Reliability-Centered Maintenance (RCM) Analyst

This 3-day course covers the origins of RCM, from the efforts of Stanley Nowlan and Howard Heap to develop a basis for maintenance based on a better understanding of the relationship between scheduled maintenance and reliability culminating in the airline industry’s Maintenance Steering Group (MSG), through adaptation of the MSG approach to the DoD environment, to recent developments in both commercial and military environments. It provides an overview of the RCM process and details the seven steps of RCM analysis defined by SAE Standard JA1011. Emphasis is placed on the FMEA, the failure consequence evaluation, and the range of function preservation strategies. The final day of the course includes a series of small-group exercises designed around common technologies common in industry, and a computer-based workshop that provides students with an opportunity to apply their newly learned theory to actual analysis problems utilizing RCM software.

Instructors for the course are Mr. Roger Collard, CMRP, Mr. David Nelson, CMRP and Mr. William Walter, CMRP.

To view more details about this course, please go to: http://theriac.org/Training/Presentations/RCMAnalyst.asp

Naval Air Systems Command (NAVAIR) Fundamentals of RCM

This course is a 3-day offering of the Naval aviation approach to RCM. The course gives an initial view of such topics as the RCM philosophy, history, and goals. It introduces students to the basic analysis concepts and terminology that are unique to RCM. The course includes a series of lectures, small-group exercises, and a workshop that provide students with an opportunity to apply their newly learned theory to actual analysis problems. Participants are encouraged to share their knowledge of RCM and relate prior experiences with fellow students. The Integrated Reliability-Centered Maintenance System (IRCMS) software, which most NAVAIR RCM programs will use to document their RCM analyses, is also taught during this course. The course provides an excellent foundation upon which analysts can continue to build their expertise through on-the-job RCM training and experience. It also fulfills a basic requirement for NAVAIR personnel and contractors to become NAVAIR Level I certified in RCM.

Instructors for the course are Mr. David Nelson, CMRP and Mr. William Walter, CMRP.

To view more details about this course, please go to: http://theriac.org/Training/Presentations/NAVAIRFundamentalsOfRCM.asp

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Reliability and Quality in Microelectronic Manufacturing

by Aris Christou and Willie M. Webb

The manufacture of microcircuits begins with the silicon or gallium arsenide wafer and, after several processing operations, results in a fully packaged electronic component. For semiconductor manufacturing, the processing operations allow the industry to design-in reliability through the proper selection of materials, processing parameters, and technologies. The student of manufacturing must therefore be taught the critical relationships between manufacturing, reliability, and quality. These relationships are even more critical in fabrication steps which involve elevated temperatures, e.g., thin film deposition, oxidation and diffusion/implantation. The rapid progress achieved in microelectronics is the result of a planar technology using resists and lithography, which has made it possible to process thousands of transistors in a single circuit.

Technology challenges in microelectronics include:

- High lithography resolution with no resist defects
- Achievement of scaled tolerances
- Improved etching processes with no radiation damage
- Reliable thin gates
- Shallow implants with no enhanced diffusion
- Low temperature processes
- Reliable interconnect technology
- Removal of process-induced radiation damage
- Enhanced package reliability

The intent of this book is to explain and examine the principles, processes, and materials of reliable microelectronic manufacturing. It is aimed at students and technologists who will be applying reliability principles to manufacturing, as well as researchers who must select materials and processes in order to achieve maximum yield at the lowest manufacturing cost in order to achieve the quality necessitated by the competitive market.