New Reliability Prediction Methodology Incorporates Field and Test Experience

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A reliability prediction methodology is now available that addresses shortcomings in earlier models and provides for the incorporation of field and test data through Bayesian analysis techniques.

Keywords
Reliability prediction, failure rate model, MIL-HDBK-217, 217Plus

Funded by the Department of Defense (DoD) and sponsored by the Defense Technical Information Center (DTIC), the Reliability Information Analysis Center (RIAC) released 217Plus™ in July 2006 as the DoD-designated replacement for the earlier Reliability Analysis Center (RAC) PRISM®* methodology. In conjunction with this release, the new component and system failure rate models were published for the first time in the RIAC *Handbook of 217Plus Reliability Prediction Models*, providing the detail missing from the RAC predecessor to support users in understanding the validity of the methodology in comparison to outdated, pessimistic reliability prediction methods such as MIL-HDBK-217, *Reliability Prediction of Electronic Equipment.*[1] This article highlights features of the new methodology that correct several recognized deficiencies of MIL-HDBK-217. A simple example illustrates how the improved prediction results compare to more traditional reliability prediction approaches, and discussion is provided that shows favorable correlation between the new methodology and actual field experience.

Deficiencies in traditional reliability prediction approaches

Traditional methods of reliability prediction model development have typically yielded component failure rate model forms that are multiplicative in nature; that is, the predicted failure rate is the product of a base failure rate and several adjustment factors that account for the stresses and component variables that influence reliability. A generic example of a failure rate model that takes this form is:

$$\lambda_p = \lambda_b \pi_e \pi_q \pi_s \tag{1}$$

[*] PRISM® is a registered trademark of Alion Science and Technology

where:

λ_p = predicted failure rate
λ_b = base failure rate
π_e = environmental factor
π_q = quality factor
π_s = stress factor

The primary disadvantage of the multiplicative model form is that the predicted failure rate becomes unrealistic when all factors are at their highest or lowest values. Also, the use of a single base failure rate, λ_b, is an inherent limitation of the model form, as individual failure mechanisms (or classes of failure mechanisms) are not explicitly accounted for. For MIL-HDBK-217, this means that operating, non-operating, and cycling failure rates are all lumped into a single base failure rate that is defined in units of failures/10^6 operating hours.

A second major deficiency of the multiplicative model form is related to the part quality factor multiplier. Traditionally used as primary variables affecting predicted component failure rates, part quality factors were usually defined by an appropriate military specification. Developers of MIL-HDBK-217 component models continually grappled with the inability to isolate the effects of quality and environment. Multiple linear regression analysis of field failure rate data to quantify the quality and environment factors assumed that these factors were statistically independent. In reality, the historical use of "higher" quality parts in more severe environments and "lower" quality parts (read "commercial") in more benign environments violated this assumption, making it difficult to discern their individual effects. Additionally, several process attributes were pooled into the quality factor, including part qualification, process certification, screening, and quality systems.

A third deficiency of the multiplicative approach is the static nature of the models and of the data the models rely on. The last update to MIL-HDBK-217 was Version F, Notice 2, February 1995. There are no official plans for future revisions. As time passes, the MIL-HDBK-217F, Notice 2 component models become increasingly obsolete, as the models are not designed to reflect improvements or advancements in component technology.

Finally, traditional empirically based reliability prediction approaches do not readily accommodate test and field experience data that could be used to refine an initial reliability prediction to more accurately reflect the experience associated with the reliability of a component, assembly, equipment/product, or system.

Historical context

Figure 1 provides an overview of the evolution of the reliability prediction methodology that began in 1996 as recognition of the noted deficiencies in the MIL-HDBK-217 approach.[2]

In 1996, the RAC's William Denson published a model for plastic encapsulated microcircuits (PEMs) that overcame a major deficiency of MIL-HDBK-217 in dealing with failure rate predictions for commercial components.[3] The PEM model introduced a new component failure rate prediction form that acknowledged advances in integrated circuit plastic packaging related to reliability in severe environments. The PEM model served as the basis for the development of all subsequent 217Plus models.

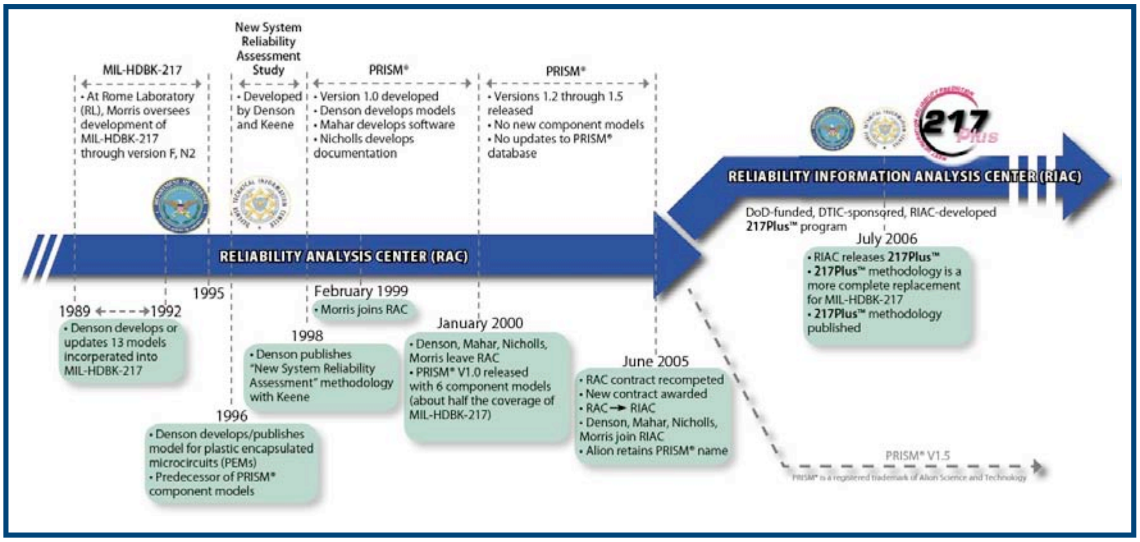

Figure 1—The Evolution of the 217Plus Methodology.[2]

Concurrently, the US Air Force Rome Laboratory was pursuing improvements in the MIL-HDBK-217 prediction approach. The US Air Force Rome Laboratory funded a study to have the RAC develop a new methodology for assessing system reliability under a separate, competitively awarded R&D contract. The "New System Reliability Assessment Methodology," completed in 1998, provided the basis for adopting a system-level assessment approach for estimating reliability[4,5] by introducing system-level Process Grading Factors (PGFs) that would become an integral part of 217Plus. Initially, Denson developed PEM-like models for capacitors, diodes, integrated circuits, resistors, thyristors, and transistors that were the basis of the RAC methodology. With the transition of the RAC contract and key personnel to RIAC in June 2005, Denson developed six additional models covering connectors, inductors, optoelectronic devices, relays, switches, and transformers. The addition of these component models made the RIAC methodology a viable replacement for the outdated MIL-HDBK-217 approach.

Correcting traditional reliability prediction model deficiencies

Correcting multiplicative model deficiencies

The RIAC approach to the component models combines additive and multiplicative model forms that predict a separate failure rate for each class of failure mechanism (operating, non-operating, cycling, etc.). Each of these failure rate terms is then accelerated by an appropriate stress or component characteristic. A general model form of this type is:

$$\lambda_p = \lambda_o \pi_o + \lambda_e \pi_e + \lambda_c \pi_c + \lambda_i + \lambda_{sj} \pi_{sj} \qquad (2)$$

where:

λ_p = predicted failure rate
λ_o = failure rate from operational stresses
π_o = product of failure rate multipliers for operational stresses
λ_e = failure rate from environmental stresses
π_e = product of failure rate multipliers for environmental stresses
λ_c = failure rate from power or temperature cycling stresses
π_c = product of failure rate multipliers for cycling stresses

λ_i = failure rate from induced stresses, including electrical overstress and electrostatic discharge (ESD)
λ_{sj} = failure rate from solder joints
π_{sj} = product of failure rate multipliers for solder joint stresses

By modeling failure rates in this manner, factors that account for application- and component-specific variables that affect reliability (pi-factors) can be applied to the appropriate additive failure rate term. A primary advantage of the RIAC modeling approach, therefore, is that it independently addresses the operating, non-operating, and cycling-related failure rates that are appropriately weighted in accordance with the operational profile of the system (operating/non-operating duty cycle and power cycling rate). Pi-factors modify only the relevant failure rate terms, thereby eliminating the extreme value problems associated with multiplicative models.

Correcting part quality factor deficiencies

The new methodology treats the quantification of part quality as one of the failure causes for which a PGF is determined. With this approach, issues related to part qualification, process certification, part screening, and quality systems are independently addressed.

Correcting static model deficiencies

A good component failure rate model reflects state-of-the-art technology. However, empirical models are typically developed from the analysis of field data, which takes time to collect and represents a static snapshot in time. Reliability of some part types, such as integrated circuits, has improved considerably over the past 20 years. The steeper the growth rate, the more difficult it is to derive an accurate model. Therefore, the component models in 217Plus include a factor that accounts for these technology improvements based on the reliability growth characteristics of data collected from the past.

The methodology also includes a factor for assessing the reliability growth characteristics of a system, based on the premise that the processes that contribute to system reliability growth in the field may or may not exist. The extent to which reliability growth exists is estimated by a PGF that assesses the processes that contribute to system reliability improvements over time.

Correcting the inability to consider experience data

The user is encouraged to collect as much test and field experience data as possible and incorporate the data into the reliability assessment. This is accomplished by mathematically combining the best "pre-build" failure rate estimate for the system (i.e., the initial reliability assessment) with relevant field and test failure rate experience data. Bayesian techniques based on the exponential distribution are used for this purpose. The technique accounts for the quantity of data collected by weighting large amounts of data more heavily than small amounts. The resulting failure rate estimate forms the "prior" distribution.

Elements of the new methodology

The two primary elements of the new methodology are component-level reliability prediction and system-level reliability prediction. The component models are used first to estimate the failure rate of each component. Individual component failure rates are then summed to estimate assembly, and ultimately system, failure rates. The methodology has the ability to modify the estimated system reliability with various system-level factors that account for non-component effects (PGFs).

The 12 component models covered by 217Plus Version 2.0 include capacitors, connectors, diodes, inductors, integrated circuits, optoelectronic devices, relays, resistors, switches, thyristors, transistors, and transformers. The methodology also includes a basic software reliability prediction model.

The categories of PGFs defined within the methodology to account for system-level effects are Design, Manufacturing, Parts Quality, Systems Management, Can Not Duplicate (CND), Induced, and Wearout. In addition, the system model includes system-level effects that account for (1) environmental effects at the non-component level, (2) infant mortality impacts (quantified through reliability screening programs), and (3) reliability growth (from a process perspective).

Extensive detail and development rationale regarding the component and system models can be found in Denison.[6]

Example comparison of reliability prediction approaches

Consider the Bill of Materials (BOM) for a digital multiplexer circuit card manufactured in 2007, as depicted in Table 1.

Table 1. BOM for a Digital Multiplexer Circuit Card

Component Description	No. of Parts
Capacitor, Aluminum, Electrolytic	4
Capacitor, Ceramic	32
Capacitor, Tantalum	3
Connector, D-Miniature	5
Connector, Signal	7
Crystal	1
Diode, General Purpose	11
Diode, Zener	1
Fuse	1
IC, Digital	15
IC, Linear	6
IC, Microprocessor/Memory	3
LED	6
Resistor, Carbon Film	3
Resistor, Metal Film	115
Resistor, Thin Film	6
Socket, PGA	1
Inductive Coil, Fixed	1
Potentiometer, Type RJR	1
Potentiometer, Type RV	3
Printed Wiring Board	1
Relay, Armature	1
Resistor, Wirewound	6
Switch, 6PDT	1
Thermistor	1
Transformer, Audio	3
Transformer, Power	2

A parts count reliability prediction was performed using a variety of reliability prediction methods for Ground Benign and Ground Fixed environments (as defined by MIL-HDBK-217). The ambient temperature in both cases was 70 °C (158 °F), and operational stress ratios were defaulted to 50%. Required information unique to performing a 217Plus prediction included a non-operating temperature of 23 °C (73 °F), relative humidity of 40%, 0.0 G_{RMS} vibration, an 80% operating/non-operating duty cycle, and 184 power on/off cycles per year. The methodology provides defaults for these parameters as a function of the selected environment and application (e.g., Industrial), but the parameters can be individually tailored to suit the environmental and operational profiles of any specific application. All information required to exercise the component models is provided either as a default value (a constant or a table look-up value), or is readily available from a part manufacturer (basic parametric ratings), the circuit designer (operational stress conditions and year of part manufacture), and the anticipated environmental conditions (which can be specified, calculated, or measured). The effort to obtain the data required to perform a 217Plus prediction is typically less labor intensive than that required to obtain the data necessary to support a MIL-HDBK-217 part stress prediction.

The PGFs applied to the 217Plus prediction in this example were left at their default values, representing typical commercial practices, meaning that the sum of the seven PGFs defined earlier in this article is equal to 1.0 within the system-level model. Prediction results using "Best Commercial Practice" and "Worst Commercial Practice" PGF multipliers were also calculated.

It should be noted that the methodology predicts all failure rates in units of failures per million *calendar* hours. This is necessary because the methodology accounts for all contributing failure rate terms, i.e., operating, non-operating, cycling, induced, etc. Therefore, the only common time basis that can be used to describe the resulting failure rates is calendar hours. For comparison purposes in this example, the prediction results were converted to failures per million *operating* hours by dividing the calculated circuit card failure rate by the operational duty cycle of 80% (a stated condition of this example).

The results of these reliability predictions are provided in Table 2.

Table 2. Comparison of Reliability Predictions for Digital Multiplexer Circuit Card Example (Failures per Million Operating Hours) ***(Adapted from Denison[5])***

Generic Application Environment	Ground Benign	Ground Fixed
Ambient Operating Temperature	**70 °C**	**70 °C**
Operational Stress	**50%**	**50%**
ALCATEL	19.89	47.27
Bellcore Issue 4	35.43	53.14
Bellcore Issue 5	137.85	275.70
British Telecom HDR4	6.72	9.84
British Telecom HDR5	2.59	2.59
MIL-HDBK-217 E Notice 1	111.36	165.91
MIL-HDBK-217 F Notice 1	35.40	79.46
MIL-HDBK-217 F Notice 2	26.76	119.21
217Plus V2.0 ("Typical" Commercial PGFs)	4.89	6.04
217Plus V2.0 ("Best" Commercial Practice PGFs)	0.30	0.37
217Plus V2.0 ("Worst" Commercial Practice PGFs)	19.65	24.27

The "typical" commercial practice 217Plus prediction provides lower predicted failure rates than all other methods except for the British Telecom HDR5 method. The "worst" commercial practice prediction provides more optimistic results than all other methods, except for the two British Telecom handbooks. While these results are encouraging, given the prevailing attitude that MIL-HDBK-217 based reliability predictions tend to be pessimistic, a comparison between 217Plus reliability prediction results and actual field experience is more meaningful.

Comparisons with experienced field reliability

Three notable references published in the literature between 2002 and 2004 have independently compared reliability prediction results using 217Plus with results obtained from the field based on direct experience. Since the RIAC methodology evolved from, and is the DoD-designated replacement for, the old RAC PRISM program, the assessments of PRISM that follow are applicable, by extension, to the RIAC methodology.

In 2002, TRW Automotive published the results of a 10-month in-house effort "in response to prohibitive limitations in traditional methodologies, including MIL-HDBK-217" to identify improved methodologies for assessing reliability and estimating warranty costs.[7] The study chose the RIAC methodology for comparison because of its departures from traditional reliability prediction methodologies. A comparison between the predicted value and the first six months of manufacturer warranty data indicated a very strong correlation between the predicted and field failure rate values when the warranty data was factored into the prediction using the Bayesian analysis capabilities of the RIAC methodology. Also, the Pareto output results from the tool confirmed many of the high failure rate items identified from the warranty data.

Northrop Grumman Electronic Systems presented a paper at the 2003 Annual Reliability and Maintainability Symposium (RAMS) that compared reliability predictions for three digital circuit card assemblies (CCAs) to field data for plastic parts used in a military airborne environment.[8] Initial findings indicated that the RIAC tool yielded higher mean time to failure (MTTF) values than were demonstrated by the field data. Further evaluation of the models, however, indicated that improvements in the results could be obtained by replacing model default values with operational and environmental stresses that were more representative of actual field conditions. One recommendation from this study was that the component "models embedded in the (RIAC) tool should be used to the maximum extent possible," as these models resulted in predictions that tracked the field results much better than using alternate data sources. Additionally, it was noted that specific knowledge of the design, manufacturing, quality, and management processes of an organization is necessary to obtain an accurate assessment when using the PGFs associated with the RIAC tool.

Finally, Raytheon presented a paper at the 2004 RAMS that assessed the capabilities of the RIAC methodology as a field failure prediction tool[9] by comparing its predicted failure rates to observed field failure rates for three of their military electronics units used in an Air Force fighter aircraft, a Navy helicopter, and a Navy surveillance aircraft. For two of the electronics units, the inherent reliability predictions using the RIAC tool exhibited no more than 3% deviation from the observed failure rates. While the third unit exhibited a deviation of 18% between the predicted and observed failure rate values, the probable cause was attributed to the relatively large percentage of user-defined failure rates in the third unit rather than the modeled and database-supported failure rates. A similar result was achieved when the logistics failure rate models of the prediction tool were used. The paper concluded that the RIAC tool's inherent and logistics failure rate predictions both agreed well with observed field failure rates when the default PGFs were used, and there was less than 0.6% discrepancy for all three units when the Bayesian analysis capabilities of the tool were factored into the prediction. When program-specific PGFs were used instead of the defaults, the discrepancy between the predicted and observed failure rates did not exceed 1.8% for any unit.

Summary

The RIAC 217Plus system reliability prediction methodology overcomes the major deficiencies of approaches such as MIL-HDBK-217 by (1) eliminating the extreme results inherent in multiplicative failure rate model formats, (2) eliminating built-in model biases against using commercial parts, (3) introducing component- and system-level reliability growth factors to sustain model relevancy, and (4) providing for the incorporation of field and test data through Bayesian analysis techniques that consider the influence of actual experience data on the overall reliability prediction.

Future updates to the methodology will include the addition of new component models; the refinement of existing models; significant expansion of the integrated RIAC failure rate database; appropriate refinement of system PGFs; and feature enhancements that will allow the software to (1) capture, track, and perform life modeling on field and test data, (2) combine predicted reliability data with actual experience data based on Weibull, exponential, and lognormal distributions, and (3) provide outputs with statistical confidence limits around relevant distribution parameters.

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"Reliability Toolkit: Commercial Practices Edition" and "Reliability Blueprint" series. Nicholls was a primary contributor to the development of the RAC PRISM® software tool and its replacement, 217Plus™. He holds a BS in physics from the Rochester Institute of Technology, and an MBA and MS in Manufacturing Systems Engineering from Rensselaer Polytechnic Institute.