START
Selected Topics in Assurance Related Technologies

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Reliability Prediction

Summary

The total assessment of reliability requires the quantitative estimate of three distinct and separate classes of failure; that is, early life, event-related and wearout. The early life, also known as infant mortality, is a result of relatively severe defects introduced during any level of manufacture or assembly, and typically results in decreasing failure rates as defects fail and are replaced. Event-related failure mechanisms occur randomly and are a result of undetected defects that fail as a result of external and internal stresses. Wearout failure mechanisms occur as a result of prolonged exposure to environmental and operating stresses and will occur in the entire population of items if they are in service long enough. These classes of failure and time periods are shown in Figure 1.

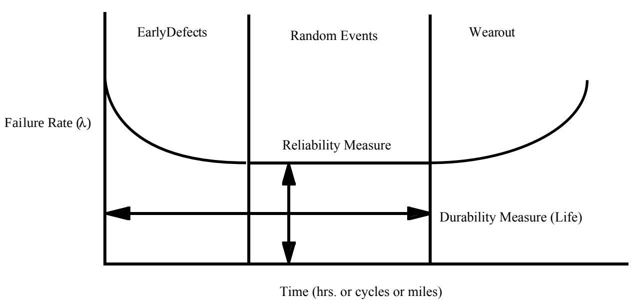

Figure 1: Failure Class vs Time

The estimation of product reliability requires knowledge about the components, the design, the manufacturing processes and the operating conditions expected. Empirical prediction techniques based on modeling past experience and data present good estimates of reliability for similar or modified products but often do not predict well for new products or conditions. The use of deterministic physics-of-failure techniques may predict wearout or end of life reliability with accuracy, but are often difficult to use and do not predict failures in the other domains. Field operational data on the same or similar products is the best estimate of a product's reliability, but is difficult and expensive to collect. A new system reliability assessment method developed by the Reliability Analysis Center (RAC) and Performance Technology, Inc. combines empirical techniques with process and operating conditions and allows the prediction to be combined with test data.

The choices of methodology to be used to predict reliability are summarized in Table 1. The period of time that each method is effective is indicated by the use of check marks. The order of effectiveness by relative rank is determined by experience data and the number of periods the methodology is appropriate.

Predictions From Test or Field Data Analysis

Reliability predictions for modified or off-the-shelf products often make use of existing equipment (or assembly) designs or designs adapted to a particular application. If this situation exists, Table 2 summaries the data needed for reliability analyses.

The specific prediction for the product is simply a matter of determining operating hours and types of failures expected. The failure rate of the product can be determined from the following equation:

$$\text{Failure Rate} = \frac{\text{Number of Failures}}{\text{Operating Time}}$$

The advantage of predicting from field and test data is that the reliability results can be accurately determined including the associated uncertainty of the estimate. The disadvantage is the difficulty of obtaining accurate field and test data.

Prediction Using the New System Reliability Assessment Method

The predictive modeling of the RAC and Performance Technology, Inc., approach takes place in two successive stages, as shown in Figure 2. First, the system pre-build model is developed using the consolidated reliability assessment method (CRAM) model. This model combines process grading factors with the operating profile, software assessment and the initial reliability prediction. This forms the best estimate of product reliability. The second step consolidates the best estimate with test and process data using Bayesian techniques.

Table 1: Reliability Prediction Methodologies

Rank	Methodology	Early Defects	Random Events	Wearout	Description
1	Test or Field Data	✔	✔	✔	In-house test or operational data is used to estimate reliability of the product based on failures and operating times.
2	System Reliability Assessment	✔	✔	✔	Consolidated assessment technique that combines predictions, process grading, operational profiles, software and test data using Bayesian techniques.
3	Similar Item Data	✔	✔		Based on empirical reliability field failure rate data on similar products operating in similar environments. Uses generic data from other organizations.
4	Translation	✔	✔		Translates a reliability prediction based on an empirical model to an estimated field reliability value. Implicitly accounts for some factors affecting field reliability that is not explicitly accounted for in the empirical model.
5	Empirical	✔	✔		Typically relies on observed failure data to quantify part-level empirical model variables. Premise is that valid failure rate data is available.
6	Physics-of-Failure			✔	Models each failure mechanism for each component individually. Component reliability is determined by combining the probability density functions associated with each failure mechanism.
7	Software Estimate	✔			Most prediction methods rely on estimating the number of initial defects (program errors) and the rate of removal.

Table 2: Use of Existing Reliability Data

Information Required	Product Field Data	Product Test Data	Piece Part Data
Data collection time period	X	X	X
Number of operating hours per product	X	X	
Total number of part hours			X
Total number of observed maintenance actions	X		
Number of "no defect found" maintenance actions	X		
Number of induced maintenance actions	X		
Number of "hard failure" maintenance actions	X		
Number of observed failures		X	X
Number of relevant failures		X	X
Number of nonrelevant failures		X	X

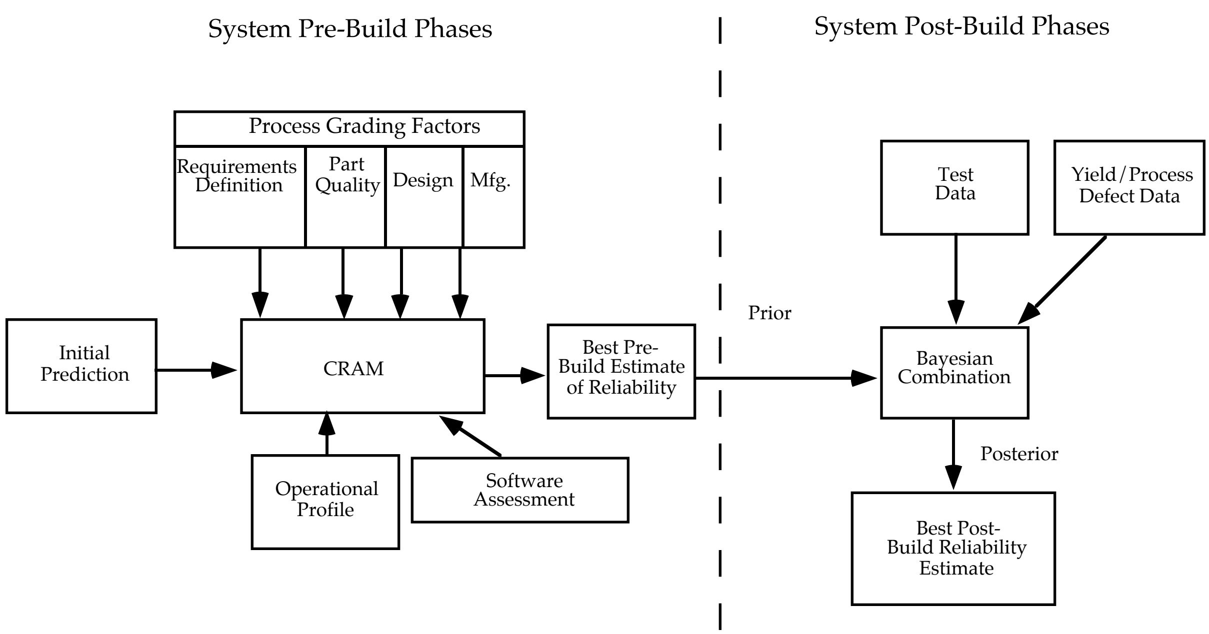

Figure 2: New System Reliability Assessment Modeling Approach

The intent of this model is not to provide a methodology that needs to be strictly adhered to, as standards have traditionally been applied, but rather to form the basis of a methodology that can be tailored to specific situations by its user. This tailoring is accomplished in several ways:

- Application of the process grading factors accounts for the specific processes used in system development and manufacture.
- The user of the model is encouraged to collect and utilize empirical data to the maximum extent possible.
- The user is encouraged to tailor the assessment by utilizing experience from similar system development efforts. This tailoring is implemented if the user has more accurate data than indicated by the default conditions on which the model is based. The areas for this type of tailoring are the percentage and variance of system failures attributable to the specific failure causes, and the weight given to specific process grading factors.

The mathematical form for this inherent failure rate model is:

$$\lambda_P = \lambda_{IA}(\Pi_P + \Pi_D + \Pi_M + \Pi_S) + \lambda_{SW} + \lambda_{WO}$$

where:

λ_P	=	Predicted system failure rate
λ_{IA}	=	Initial assessment failure rate (based on empirical data or similar item information)
Π_P	=	Part multiplier, function of parts process grade
Π_D	=	Design multiplier, function of design process grade
Π_M	=	Manufacturing multiplier, function of manufacturing process grade
Π_S	=	System management multiplier, function of requirements and quality grade
λ_{SW}	=	Software failure rate
λ_{WO}	=	Wearout failure rate from physics of failure evaluation

Advantages of this method are that all phases of predictions can be included, confidence bounds on the results can be determined and software considerations can be incorporated. The disadvantage is that the effort requires a lot of knowledge and information on manufacturing processes. Detailed examples of this technique are included in Reference 2.

Similar Item Prediction

This method starts with the collection of past experience data on similar products. The data is evaluated for form, fit and function compatibility with the new product. If the new product is an item that is undergoing a minor enhancement, the collected data will provide a good basis for comparison to the new product. Small differences in operating environment or conditions can be accounted for by using translation methods based on previous experiences. If the product does not have a direct similar item, then lower level similar circuits can be compared. In this case, data for components or circuits is collected and a product reliability value is calculated. The general expression for product reliability calculated from its constituent components using the similar item method is:

$$R_p = R_1 \bullet R_2 \ldots . R_n$$

where:

R_p	=	Product reliability
$R_1, R_2 \ldots R_n$	=	Component reliability

The advantage to using the similar item prediction method is that it is the quickest way to estimate a new product's reliability, and is applicable when there is limited design information. The disadvantage is the possibility that the new product will actually be substantially different from the similar item, resulting in incorrect or inaccurate predictions.

Predicted to Operational Translation

It has long been known that failure rate prediction models derived from empirical data will yield estimates that deviate from the actual observed failure rates. Field (operational) reliability differs from the inherent reliability because empirical models only assess inherent component reliability, and the reliability of systems in field operation includes all failure causes, including induced failures and problems resulting from inadequate design, system integration problems, manufacturing defects, etc. Since the intent is to assess total system reliability including all factors that can affect system reliability, a translation is necessary to convert the empirical predicted failure rate to an expected field failure rate. Specific techniques and models for determining the translation factors are included in Reference 9.

The advantages of this technique are the ease of use and application of environmental factors for harsh conditions. The disadvantage is the lack of up-to-date empirical data.

Empirical Model Prediction Techniques

Empirical models are those that have been developed from historical reliability data. This data can be either from fielded applications or from laboratory tests. As a result of the manner in which these models are developed, their relevance is a function of the data used to derive them.

Therefore, reliability predictions will vary as a function of the specific empirical prediction methodology used, because the empirical data on which they are based was collected from different sources. The methodology and some of the sources of the models are shown in Table 3.

Table 3: Methodologies and Model/Data Source

Methodology	Source of Model
Part Count Method	MIL-HDBK-217 British Telecom French CNET* Siemens
Part Stress Analysis	MIL-HDBK-217 British Telecom Bellcore RPP** French CNET

*CNET - National Center for Telecommunication Studies
**RPP - Reliability Prediction Procedure

The parts count method is generally used to analyze electronic circuits in the early design phase, when the number and type of parts in each class (such as capacitor, resistor, transistor, microcircuit, etc.) are known and overall design complexity is likely to change during later phases of design/development. The method starts with the listing of the part types and their expected quantities. Reliability data is then taken from source books such as MIL-HDBK-217 "Reliability Prediction of Electronic Equipment." Failure rates, quantities of parts and adjustment factors are multiplied and the results for each part type are summed to determine the product reliability. This method assumes that the times-to-failure of the parts are exponentially distributed. The general expression for a product failure rate using this method is:

$$\lambda_{product} = \sum_{i=1}^{n} N_i \left(\lambda_G \pi_A\right)_i$$

where:

$\lambda_{product}$ = Total failure rate (failures per unit time)

λ_{Gi} = Generic failure rate for the i^{th} generic part

π_{Ai} = Adjustment factor for the i^{th} generic part (quality factor, temperature factor, environmental factor)

N_i = Quantity of i^{th} generic part

n = Number of different generic part categories

The part stress analysis method is used in the detailed design phase when individual part level information and design stress data are available. The method requires the use of defined models that include electrical and mechanical stress factors, environmental factors, duty cycles, etc. Each of these factors should be known, or be capable of being determined, so that the effects of those stresses on the parts' failure rates can be evaluated. Table 4 shows several major factors which influence device reliability.

As an example, a stress-temperature failure rate plot is shown in Figure 3. As can be seen from the plot, the failure rate increases as the temperature goes up, or as the applied stress (voltage) increases.

The advantage of the empirical prediction is the ease of use as the various models for components already exist in the literature. The disadvantage is the data base may be outdated resulting in pessimistic estimates for new technology components.

Physics-of-Failure Prediction

The objective of any physics-of-failure analysis is to determine or predict when a specific end-of-life failure mechanism will occur for an individual component in a specific application. A physics-of-failure prediction looks at each individual failure mechanism such as electromigration, solder joint cracking, die bond adhesion, etc., to estimate the probability of component wearout within the useful life of the product. This analysis requires detailed knowledge of all material characteristics, geometries, and environmental conditions. Specific models for each failure mechanism are available from a variety of reference books as noted in Reference 5.

The advantage of the physics-of-failure approach is that accurate predictions using known failure mechanisms can be performed to determine the wearout function. The disadvantage is that this method requires access to component manufacturers' material and process data. In addition, the actual calculations and analysis are complicated activities requiring knowledge of materials, processes and failure mechanisms.

Software Reliability Prediction

Predicting software reliability is difficult because software failures arise from software faults resulting, in turn, from defective coding. The time to failure often depends on the execution speed of the computer and size of the program. A software growth model mathematically summarizes a set of assumptions about the phenomenon of software failure. Models that could be considered are described in Reference 12 and include:

- Musa Model
- Putnam Time Axis Model
- Exponential Model

The advantage of software reliability prediction is the ability to estimate the number of problems or faults that exist in the early stages of development. The disadvantage is only early life defects can be estimated.

There is also a capability maturity model developed by the Software Engineering Institute that measures the capability of an organization to produce reliable software. Its output is a rating of one (worst) to five (best).

Overview

The figures of merit for each reliability prediction method are shown in Table 5 to summarize the areas where each method is effective.

References

1. Bowles J.B., "A Survey of Reliability Prediction Procedures for Microelectronic Devices," IEEE Transactions on Reliability, March 1992.

2. Denson W., Keene, S., "New System Reliability Assessment Methods," Reliability Analysis Center, Interim Report for Project #A06839, March 97.

3. Morris, S., Reilly J., "MIL-HDBK-217 - A Favorite Target, " Proceedings of the Annual Reliability and Maintainability Symposium, 1993.

4. Pecht M., Ramappan, "Are Components Still the Major Problem," IEEE Transactions on Components, Hybrids and Manufacturing Technology, Vol. 15, 1992.

Table 4: Major Influence Factors on Device Reliability

Device Type	Influence Factors	Device Type	Influence Factors
Integrated Circuits	• Temperature • Package Type • Supply Voltage	Capacitors	• Temperature • Voltage • Type
Semiconductors	• Temperature • Power Dissipation • Breakdown Voltage • Material	Inductive Devices	• Temperature • Current • Voltage • Insulation
Resistors	• Temperature • Power Dissipation • Type	Switches and Relays	• Current • Contact Power • Type

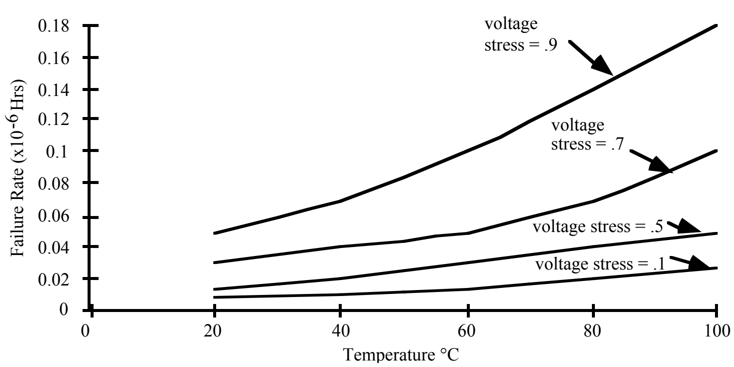

Figure 3: Trimmer Ceramic Capacitor Failure Rates/Stress Plot from MIL-HDBK-217

Table 5: Figures of Merit per Prediction Method

Methodology	Mean-Time-Between-Failure	Mean-Time-To-Failure	Mean Time Between Maintenance Action	Operational Reliability	Total Defects	Confidence Level
Test or Field	X	X	X	X	X	X
System Reliability Assessment	X	X	X	X		X
Similar Data	X		X	X		
Translation	X			X		
Empirical	X					
Physics-of-Failure		X				X
Software Estimates	X				X	

5. Pecht M., "The Reliability Physics Approach to Failure Prediction Modeling," Quality and Reliability Engineering International, Vol. 6, 1990.

6. Spencer J.L., "The Highs and Lows of Reliability Predictions," Proceedings of the Annual Reliability and Maintainability Symposium, 1986.

7. Talmor M., Arueto S., "Reliability Prediction: The Turn-Over Point," Proceedings of the Annual Reliability and Maintainability Symposium, 1997.

8. Wong K.L., "A New Framework for Part Failure-Rate Prediction Models," IEEE Transactions on Reliability, March 1995.

9. RADC-TR-89-299, "Reliability and Maintainability Operational Parameter Translation," 1989.

10. MIL-HDBK-217F, Notice #2 "Military Handbook, Reliability Prediction of Electronic Equipment," 1995.

11. TR-332 "Reliability Prediction Procedure for Electronic Equipment," Bell Communications Research, 1995.

12. Reliability Analysis Center Report SWREL, "Introduction to Software Reliability: A State of the Art Review," 1996.

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