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Reliability Guidelines on Failure Rates for Space Electrical, Electromechanical, and Electronic (EEE) Parts

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Abstract

Mission Success Improvement Workshops (MSIWs) are collaborative industry and government efforts to address industry-wide space systems mission assurance challenges. Their charter is to develop recommendations and actionable best practice documentation to improve program execution efficiency and, ultimately, on-orbit mission success. This Aerospace technical report (ATR) is the result of an MSIW that addressed the need for improved reliability modeling methods and guidance required to support the transition from single (or few) satellite procurements to satellite constellation architectures. It builds on work documented in *Functional Availability (FA) Analysis* (ATR-2019-01877) [1]. A "sister" ATR, *Functional Availability and Constellation Reliability Guidelines for Acquisition and Development of Space Systems* (ATR-2024-02064) [2], was also produced to address the need for improved reliability modeling methods and guidance required to support the transition from single (or few) satellite procurements to satellite constellation architectures.

Contents

Figures

Tables

1. Introduction

1.1 Purpose

Requests for proposals and contracts often present reliability requirements in terms of a single probability of success (P_s) number at design life for an individual satellite (or sometimes separately for the satellite bus and the payload). A common approach to addressing compliance with such requirements involves the application of MIL-HDBK-217F Notice 2 (MIL-HDBK-217FN2) [3], which was last updated in February of 1995, to calculate the appropriate electrical, electromechanical, and electronic (EEE) part failure rates used in the modeling to determine P_s. It is well-known throughout the industry that MIL-HDBK-217FN2 produces incorrect failure rates, especially regarding EEE parts. These issues present persistent challenges in reliability prediction, especially when bidding optimized system solutions that use commercial off-the-shelf (COTS) parts.

It is well-known that all prediction models have inherent limitations. The primary limitation in conventional methodologies is that they do not have the provisions to assess the reliability of electronic systems as a function of all factors that can affect reliability [4]. More specifically, when a handbook is published, the models are based on data available at the time the handbook was published. Furthermore, those calculated failure rates attempt to represent all possible events; however, assumptions are always created to show that they do not account for every possible event. Many projects have been taken on to update and account for all predominant failure causes of electronic systems and require a significant effort to thoroughly assess the processes used in the design and development of a system. While this can be a time-consuming process, handbook data and calculations will never accurately predict true reliability. The calculations that are provided should not be considered absolute predictions of performance. They should be performed to develop a figure of merit to compare options that revolve around design decisions and part selection [5].

This document provides an overview of alternate handbooks and approaches to tailoring or replacing MIL-HDBK-217FN2 and puts forward a recommended decision tree–based approach that can be used to consistently obtain or calculate EEE part failure rates. A "sister" document, *Functional Availability and Constellation Reliability Guidelines for Acquisition and Development of Space Systems* [2], describes an approach that may be used in contracts to specify reliability requirements at the constellation, rather than individual satellite, level and provides modeling methodology guidance.

The purpose of both documents, used together, is to improve the value of reliability metrics to enable optimized (cost, schedule, and performance) solutions for future space mission requirements. While this document covers failure rate predictions for EEE part types, improvements for calculating COTS failure rates is especially needed. It is important to consider the use of COTS for schedule, cost, availability, and performance advantages when supported by program risk profiles, such as for short contract award-to-launch constellation architecture procurements. This MSIW effort supports the need to counter recent advances in adversary threats to U.S. space capabilities, which threaten our nation's long-standing status as the preeminent space power.

1.2 Scope

Section 2, Failure Rate Sources, describes relevant ways to obtain failure rate data (i.e., vendor High Temperature Operational Life [HTOL] and Early Life Failure Rate [ELFR] data) through website URLs or requests, on-orbit performance assessments, or expert elicitation. It also describes the strengths and weaknesses of the most frequently used handbook-based failure rate calculation tools:

- MIL-HDBK-217FN2, with some discussion about supplemental tools:
  - Reliability Analysis Center (RAC) factors from Rome Laboratory Supplement (A06830) [4]
  - International standard ANSI/VITA 51.1 [6]
  - Aerospace Enterprise, Partnerships, Innovation, Culture (EPIC) Speed Electronics document (TOR-2020-01447) [7]
- 217Plus™ [8]
- Telcordia SR-332 [9]
- FIDES Guide [10]

Section 3, Industry Recommendations, contains recommendations and provides failure rate calculation examples.

Section 3.1, Decision Tree, provides a recommend hierarchy in flowchart form, for failure rate source use. On-orbit performance data is deemed the most relevant source of data. Ground-based life test data, whether performed by vendor or independent test facilities, is considered the second-best source. The third-tier recommended failure rate data source is from one of the failure rate calculation tools listed in Section 2. The main point is that a modernized prediction approach seeks to use the most directly applicable data available for components, subsystems, or systems, not just from one source such as MIL-HDBK-217FN2, in support of higher-level systems analysis. It should consider all data sources and prediction techniques.

Section 3.2, Example BOM and Calculations of EEE Components, provides a thorough example of implementing this modernized prediction philosophy by exercising the various paths of the flow diagrams illustrated in Section 3.2. The bill of materials (BOM) provided is hypothetical in that it is not for an actual circuit function. It contains, however, actual part entries strategically selected to cover most part types (i.e., capacitors, resistors, diodes, etc.) and a mix of component quality types (i.e., commercial, military, space, etc.). Failure rate calculations are shown for each of the BOM entries using the above-listed failure rate calculation tools.

The ultimate goal of this improved prediction approach is to consider an array of failure data sources to most accurately reflect the expected risk for the part types being used, while preserving the ability to perform trades assessing the relative risk of design or component alternatives.

The following subjects were beyond or outside of the scope of this effort:

- Part Testing: No testing of parts was conducted to prove or disprove any of the prediction models.

- Radiation: Historically, radiation concerns have not been included in failure rate calculations. Part-level testing, circuit design (e.g., reset circuits), satellite design (e.g., shielding), etc. have been considered independently of the failure rate calculations. Testing is recommended for devices with known radiation degradation concerns and, if parts do not meet needed requirements, radiation testing results can be used to increase the failure rate for those parts or otherwise inform quantification of such concerns to be integrated into the system reliability prediction. However, discussion of the methodology for this quantification is beyond the scope of this effort.

- Non-EEE Part-Based Reliability Prediction: While some physics-of-failure methods are discussed in the context of standard EEE parts (e.g., capacitors, resistors) or handbooks (e.g., FIDES), detailed examination of techniques such as stress-strength interference, finite-element, or multiphysics analysis applied to non-EEE or strictly mechanical components are outside the scope of this effort.

- Constellation Modeling: As mentioned above, reliability modeling methods required to support the transition from single (or few) satellite procurements to satellite constellation architectures are addressed in ATR-2024-02064, *Functional Availability and Constellation Reliability Guidelines for Acquisition and Development of Space Systems* [2].

- Wearout: To fully consider the reliability of a space system, one must consider the expected longevity of life-limiting systems, also known as wearout modeling. However, such modeling is beyond the scope of this effort. For further discussion see Section 0, "Commentary on the Bathtub Curve," and TOR-2021-00259, *Estimating Satellite Reliability Beyond Design Life* [11].

- Part Selection Guidance: For guidance on part selection, the reader is referred to contract documents, their own company guidance, and ATR-2023-01935, *Expanding Space Design Options Using COTS* [12].

- Contract Documentation Wording: For some suggestions of failure rate requirement wording, the reader is referred to ATR-2023-01981, *Acquisition Considerations to Expand Space Design Options Using Commercial Off-the-Shelf (COTS) Electrical, Electronic, and Electromechanical (EEE) Parts and Units* [13].

- Physics-Based Simulations: This ATR does not cover the physics of failure or physics-based simulations to understand a component's failure modes beyond what has already been captured in the various handbooks.

- Next Higher Assembly: This document focuses on the assessment of piece parts and not a circuit card, unit, assembly, subsystem, etc. There are recognized methods to assess reliability at the various levels above the component level.

- Expert Elicitation: For the purposes of this guide, expert elicitation can be thought of as aggregation of failure rate, probability, or reliability estimates from relevant subject matter experts for the components or systems being analyzed. It may be applied when there is a lack of relevant or trusted data from other sources (i.e., on-orbit data, test data, handbooks, etc.) or when there are constraints with attaining such relevant or trusted information when needed to perform analysis. Expert elicitation has been successfully used by government agencies such as NASA and the Nuclear Regulatory Commission (NRC). More information regarding the application of expert elicitation can be found in Chapter 2 of the NRC's publication *White Paper: Practical Insights and Lessons Learned on Implementing Expert Elicitation* [14].

1.3 Commentary on the Bathtub Curve

The bathtub model was originally developed as a model of the hazard rate for human life (mortality) over time and first appeared in an actuarial life-table analysis article published in the late 17th century [15]. The model's name is derived from its shape, which is similar to a bathtub, as shown in Figure 1.

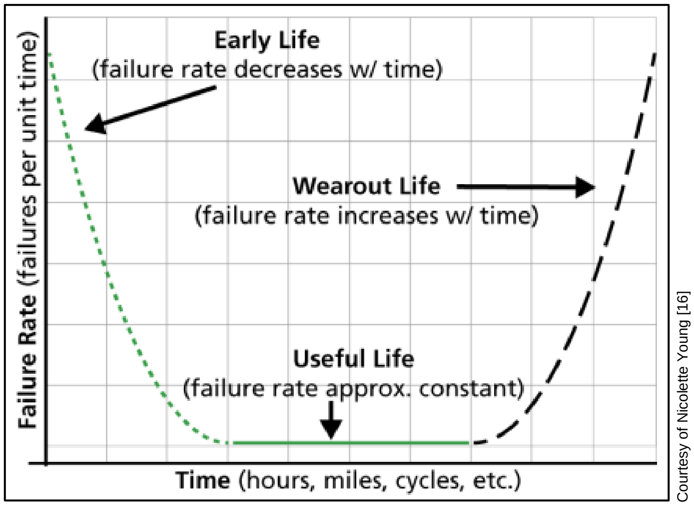

Figure 1. Traditional bathtub curve.

The bathtub curve was adopted in the 1940s and 1950s to characterize the failure rates of electronic components such as vacuum tubes and early semiconductor technologies. It has widely been referenced ever since.

Utilizing the Weibull distribution, the shape parameter β is the failure rate behavior parameter as well. When β<1, the failure rate decreases with t (green dots). When β>1, then the failure rate increases with t (black dashes). When β=1, the failure rate is constant with t (green line).

References cited within this ATR germane to failure rate prediction assume:

- Parts have been adequately tested such that any "infant mortality issues" due to workmanship, design, and application have been designed out.
- The failure rates predicted apply to the "useful life" portion of the curve, which will be random in nature over the duration of the useful life and follow constant failure rate models [15][17].
- The design life of the system that the parts will be qualified for use in is less than the time where "wearout" failures become a concern.
- That all piece parts in use are selected to operate within environmental, application, and lifetime requirements.

Some comments regarding these three phases of the bathtub curve as it pertains to current, state-of-the-art, EEE parts and the failure rate prediction tools discussed within this ATR are below:

- Infant Mortality: EEE part infant mortality is less of a concern today for trusted/approved manufacturers due to improved manufacturing (including automation), improved materials, statistical process controls, and testing methods. Therefore, failure rate models do not need to include infant mortality considerations if reputable manufacturers (e.g., known pedigrees) are used and it is verified that they have testing, monitoring, and corrective action systems in place. However, infant mortality remains a concern for space systems, especially in a resource-constrained environment where mission assurance activities are usually limited. Care should be taken to consider the impact of infant mortality in system-level reliability predictions and a check of assumptions should be done to ensure that infant mortality is not a concern.

- Useful Life: It is beyond the scope of this MSIW to study whether today's modern electronics fail according to constant failure rate models. Therefore, this ATR shows the relative pros and cons of the prediction tools on the market, all of which assert this constant failure rate assumption. There are academic groups that actively study and research microelectronics and electronic components. The Center for Advanced Life Cycle Engineering is such an institution.

- Wearout: Wearout (e.g. electromigration, time-dependent dielectric breakdown, hot carrier injection, negative bias temperature instability, positive bias temperature instability, and stress migration) have historically not been an issue for EEE parts, even for 15-year geosynchronous Earth orbit missions. For new technology parts, however, care should be taken to understand if wearout might be a concern since some part types might not be designed for extended missions and the prediction tools discussed herein do not model wearout failure modes.

2. Failure Rate Sources

Our objective in this report is to provide guidance on how to develop realistic failure rates.

This section provides guidance on how to develop more realistic failure rate estimates given challenges faced by the space industry when limited or no on-orbit data, vendor test data, or applicable handbook data is available.

Since some parts available today are not adequately addressed within the handbooks discussed in this report and, given that many programs are using alternate-grade parts (e.g., parts meeting Automotive Electronics Council [AEC] standards), this document will provide an extensive reliability prediction example to illustrate various modernizing reliability prediction approaches. Many part suppliers have online databases that present failure rates associated with their parts based on accelerated life testing. Typically, the results are for wafers and do not include packaging, which should be included in some manner if not available from the part supplier. In this case, it is necessary to ensure that the packaging is accounted for by further testing or generating a failure rate from a handbook.

2.1 Matrix of Handbooks and Failure Rate Sources

Source	Use/Purpose/Summary	Recommend Use	Pros (Advantages)	Cons (Disadvantages)
MIL-HDBK-217FN2 [3]	Provides a common basis for reliability predictions during acquisition programs for military electronic systems and equipment	Useful for assessing the relative reliability of alternate architectures being considered during early design phase	Good for capacitors and resistors that are built to military specification (MIL-SPEC) parameters	Does not account for the leaps in technology, improvements in manufacturing, and various integrated circuits (ICs)
New System Reliability Assessment (A06830) [4]	Developed by Rome Laboratory to account for reliability growth in EEE components. A06830, *New System Reliability Assessment Report*, was published to document the approach. After using MIL-HDBK-217FN2 to calculate a failure rate, a growth factor is then applied.	Since MIL-HDBK-217FN2 has not been updated since 1995, contractors are using part reliability growth factors included in A06830 to apply a correction factor to MIL-HDBK-217FN2 components' basal failure rates. It is recommended for use only for MIL-SPEC components.	A06830 presents reliability growth factors based on surveyed failure data from suppliers of electronic equipment. The growth factors are applied to MIL-HDBK-217FN2 calculations to modernize the results.	Part reliability growth pattern does not extend beyond 2010.
ANSI/VITA 51.1 [6]	ANSI/VITA 51.1 provides some updates to MIL-HDBK-217FN2, like the use of COTS components, growth of memory devices, and other updates.	Recommended for COTS components and features or technology that is not accounted for in MIL-HDBK-217FN2	Adjusts MIL-HDBK-217FN2 quality factors (p_Q) for COTS components of known or enhanced pedigrees	Does not account for advanced integrated circuits (memories, systems-on-chips [SoCs], etc.)
Telcordia SR-332 (Issue 4, 2016) [9]	Telcordia SR-332 adapts the equations in MIL-HDBK-217FN2 to represent the conditions that telecommunications equipment experience in the field.	Recommended use for COTS components as the handbook is consistently kept up to date	The Telcordia standard is the second most popular handbook and is frequently updated; it addresses COTS components and discusses approaches for failure rate data for the component level, unit level, field data, and test data.	Mentions commercial space; however, does not address MIL-SPEC components. The typical environmental factor (p_E) is not applied to an individual component but at the next highest level (e.g., circuit card), which makes using Telcordia for a few components mixed with other methods that assign the p_E factor at the component-level challenging.

Source	Use/Purpose/Summary	Recommend Use	Pros (Advantages)	Cons (Disadvantages)
217Plus™ (2015) [13]	Funded by the DOD and created by the RAC and Reliability Information Analysis Center, the handbook is based on a process that includes component effects similar to MIL-HDBK-217FN2, with additional system-level factors that try to account for noncomponent effects.	This handbook is an alternative to MIL-HDBK-217FN2 and is recommended for use when conducting initial reliability assessments.	Unique methodology for assessing piece part failure rates	Like other handbooks, it is difficult to collect good quality field data. Difficult to distinguish correlated variables (i.e., quality and environment). Does not address specific failure mechanisms.
EPRD-2024 [18]	*Electronics Part Reliability Data* (EPRD) is a collection of EEE component reliability failure rate data that is maintained by Quanterion.	EPRD-2024 is recommended for use when surrogate analysis is applicable.	Contains more than 1.2 million field failure rate data records. Data can be modified to fit mission profile and environment.	Data can be quite historic and does not represent current technology. Data is known to contain outliers, so special care should be taken when using an aggregation representing the mean.
FIDES Guide [10]	Europe's replacement to MIL-HDBK-217FN2 and was updated in 2022. The FIDES Guide aims to enable a realistic assessment of the reliability of electronic equipment, including systems operating in severe environments.	The FIDES Guide is a global methodology for reliability engineering in electronics. However, it is not yet widely accepted in the U.S. space industry.	The FIDES Guide presents a process for predicting electrical, electronic, and electromechanical failure rates and claims to be designed for COTS components.	Requires extensive knowledge of many factors covering a component's technology, manufacturing processes, and usage, so use early in the design process is challenging.
Siemens SN 29500 [19]/ IEC 61709 [20]	This handbook, also known as IEC 61709, is spread across twelve individual documents. It is a simple standard with limited component type coverage.	There is insufficient experience within the space industry to determine its recommended use.	Documentation suggests that the SN 29500 environment type is probably an average industrial environment and comparable with a ground-mobile and ground benign mix of MIL-HDBK-217FN2, or GL of Telcordia SR-332. Sophisticated models for electromechanical components (relays, switches, etc.).	Simple standard with limited component type coverage

Source	Use/Purpose/Summary	Recommend Use	Pros (Advantages)	Cons (Disadvantages)
China GJB/Z 299C [21]	299C is a Chinese standard with very low recognition in the Western World. Upon review, it is very similar to MIL-HDBK-217FN2.	The use of 299C is not recommended.	There is insufficient experience to make any conclusions	There is insufficient experience to make any conclusions
British Telecom Handbook HRD5 [22]	The British *Handbook of Reliability Data for Electronic Components Used in Telecommunication Systems (HRD5)*. This handbook has component field performance data, collected by British Telecom, French Telecom, and laboratory-derived data.	There is insufficient experience to determine its recommended use.	There is insufficient experience to make any conclusions.	There is insufficient experience to make any conclusions.
On-orbit Flight Data	On-orbit data is a desirable source since it represents real-world hardware that has been designed, developed, tested, and flown.	The use of on-orbit data is strongly encouraged as it represents demonstrated reliability.	Considered to be the most applicable and accurate method of determining failure rates when utilizing the correct methods (Bayesian, etc.)	Data sets may contain zero failures and can skew failure rates due to right-censored data. Failure data of boxes or modules may not distinguish reliability issues at the circuit card or component levels.
Original Equipment Manufacturer (OEM) Reliability Data	Manufacturers and vendors often collect, summarize, and publish reliability data on their components that can be acquired when performing a reliability estimate of a system.	This is the preferred method to acquiring reliability data.	No testing or additional data is needed. The data characterizes and represents the reliability of the EEE device under the specified conditions.	This data is often collected in ground environments and consideration of other environments (e.g., space) requires adjustments. There may be issues and errors in the data provided. It is strongly encouraged to vet the data before incorporating into analyses. Some vendors provide a rolling date range of life data (e.g., last five years), so early failures are obscured.

2.2 Focus Discussion of Sources

The following sections go into more detail with focus on the sources that the industry has experience with.

2.2.1 MIL-HDBK-217 Rev F, Notice 2

The purpose of this handbook is to establish and maintain consistent and uniform methods for estimating the inherent reliability (i.e., the reliability of a mature design) of military electronic equipment and systems. It provides a common basis for reliability predictions during acquisition programs for military electronic systems and equipment. It also establishes a common basis for comparing and evaluating reliability predictions of related or competitive designs. The handbook is intended to be used as a tool to increase the reliability of the equipment being designed. Along with expert comments, the handbook's Section 3.3 lists several limitations; the reader is encouraged to review those limitations.

Pros

- It provides an easy-to-use methodology and little additional data is needed.
- Component predictions are based on empirical models that attempt to quantify the risk of a component failing based on various use, technology, and environmental factors.
- The handbook contains both the part stress analysis method (Sections 5 through 23) and a simpler parts count method (Appendix A) that can be used in early design and acquisition stages.
- The methodology covers most common electronic components.
- An effective stress method is available for use as a relative metric to compare various design options that would impact thermal and electrical stresses.
- This method has widespread use and understanding within the reliability community.
- Several modernization and tailoring approaches have been developed in industry, centered around the framework put forward in MIL-HDBK-217FN2.

Cons

- The source data for the components in many handbooks, MIL-HDBK-217FN2 included, are out of date, decades in some cases, as the basal failure rates (lb) and the quality factors (pQ) of many of the components have not been updated since the last notice was issued in February 1995.
- The methodology assumes a constant failure rate of parts that do not fully consider actual failure modes and mechanisms.
- Many causes of failures are not covered.
- The components in the handbooks are often not identical to those being studied or were not used in identical ways or under identical environments.

- The C1 factor for integrated circuits, the die complexity factor, is antiquated and the use of this component model does not represent the latest technology; every effort to utilize operational or life data (often accelerated) for integrated circuits should be strongly considered and encouraged.

- The handbook explicitly states that none of the models predict nuclear survivability or the effects of ionizing radiation from either recoverable or destructive events.

- The prediction model for quartz crystals, transformers, coils, and fuses is antiquated and provides incorrect results. Common modernizing techniques of RAC factors and ANSI/VITA 51.1 are mute on this component type; other prediction methods (e.g., FIDES), operational data, or life test data should be strongly considered.

- Since the handbook has not been updated since the mid-1990s, it can no longer represent newer component design and technology (e.g., GaN integrated circuits, photonics, SoC devices).

MIL-HDBK-217FN2 methodology can be a viable prediction approach for many component types when augmented with modernizing techniques including, but not limited to, those listed below:

- RAC factors from Rome Laboratory Supplement (A06830) [4]
- International standard ANSI/VITA 51.1 [6]
- Aerospace EPIC Speed Electronics document (TOR-2020-01447), Section 3.3.3.4 [7]

2.2.2 RAC Factors

Rome Laboratory (RL) initiated a project to develop a new reliability assessment technique to supplement MIL-HDBK-217FN2 and to overcome some of its perceived problems. RL awarded a contract to the RAC, which formed a team composed of personnel from the Illinois Institute of Technology Research Institute and Performance Technology. They developed a model that used collected data to estimate a reliability growth factor for each part type in MIL-HDBK-217FN2. The results were used to lower MIL-HDBK-217FN2 predictions to account for part reliability growth patterns. It should be noted that the part reliability growth pattern does not extend beyond 2010 for the MIL-HDBK-217FN2 values. The approach and model were documented in RAC report A06830, *New System Reliability Assessment Method*, June 1998.

Pros

- Developed models flexible enough to suit the needs of system reliability analysts regardless of their preferred (or required) initial prediction methods

- Modifies a base reliability estimate with process grading factors for the parts, design, manufacturing, system management, induced, and no defect found failure causes

- Base reliability estimates further modified by empirical data taken throughout system development and testing using Bayesian techniques by applying weights for the different data elements

- Models consider separately the following five contributions to total component constant failure rate: (1) operating conditions, (2) nonoperating conditions, (3) temperature cycling, (4) solder joint reliability, and (5) electrical overstress

- Methodology uses all available information to form the best estimate of field reliability, is tailorable, has quantifiable confidence bounds, and has sensitivity to the predominant system reliability drivers

Cons

- Part reliability growth pattern does not extend beyond 2010 for the MIL-HDBK-217FN2 values
- Model requires significant effort to assess processes used in the design and development of a system
- Unclear if models can account for the dependencies between the various components and their operations under different environmental conditions at the system level
- Condensing results from Bayesian analysis to give a point estimate of either the lifetimes or failure rates suffers from the same shortcomings that the constant failure rate estimates (of MIL-HDBK-217FN2 and the like) have, in that it would not be able to account for variations in field conditions.
- Modeling approach's process grading factors are covariant with a mathematical limitation where the model has too many components and insufficient quantitative data to reduce the multicollinearity of the factor.
- Methodology takes on limitations listed in MIL-HDBK-217FN2, Section 3.3

2.2.3 ANSI/VITA 51.1

ANSI/VITA 51.1-2013 (R2018), *Reliability Prediction MIL-HDBK-217 Subsidiary Specification* [6], provides some updates to MIL-HDBK-217FN2 and has been used by some spacecraft and launch vehicle prime contractors. The document consists primarily of several observations and recommendations. Known pedigree is interpreted as the buyer having insight into the manufacturer's process with a well-known OEM. It advises to exercise caution regarding the qualify factor if procuring from other than an OEM or one of their authorized distributors. The quality factor can vary from one commercial supplier to another for the same family of parts. The default values assume that one knows little about the supplier, but action is taken to ensure the parts are appropriate for the application. The quality factor can be lowered (i.e., enhanced pedigree) from the default value provided there is evidence to justify the change, such as knowing more about the supplier's quality program and the levels of controls that are implemented. [7]

The use of this specification is recommended as it provides updates to adjust the models in MIL-HDBK-217FN2 when utilizing COTS components in electronic units. The standard also provides recommendations on certain components that are not covered in MIL-HDBK-217FN2, and provides rationale for each adjustment or factor that is provided.

Pros

- Addresses COTS components and provides guidelines for known and enhanced pedigrees
- Some component types and features not covered in MIL-HDBK-217FN2 addressed in the standard
- Attempts to provide more consistent failure rate calculations

Cons

- Does not completely cover today's technology and advanced integrated circuits and memories
- Provides updated inputs regarding only COTS components and is silent on MIL-SPEC components
- General guidance to use a common quality factor for parts of "known pedigree" and an assessment should be made to account for the variance of the "known pedigree" from one supplier to another per TOR-2020-01447.
- If an item of interest not covered in the standard, then, default is to use MIL-HDBK-217FN2.

2.2.4 217Plus™

Another resource is the 217Plus™ *Handbook of Reliability Prediction Models*. The handbook's development was funded by the Department of Defense (DOD) and sponsored by the Defense Technical Information Center. The Reliability Information Analysis Center (RIAC) released 217Plus in July 2006 (latest version is 2015 Notice 1) as the DOD-designated replacement for the earlier RAC PRISM software. The tool is based on a process that includes component effects similar to MIL-HDBK-217FN2 plus additional system-level factors that try to account for noncomponent effects (e.g., operational profiles, manufacturing processes, assembly processes, and reliability growth, which are difficult to determine). [7]

217Plus is recommended for use when looking to use other handbooks to acquire failure rates. The calculated failure rates are less conservative than MIL-HDBK-217FN2 and cover more part types. The models also account for environmental factors and other profiles so adequate trade studies can be conducted.

Pros

- Doubles the number of part-type failure rate models from PRISM and contains six new constant failure rate models not available in PRISM
- Contains reliability prediction models for both the component and system levels
  - The component models are determined first to estimate the failure rate of each component and then summed to estimate the system failure rate. This estimate of system reliability is further modified by the application of "system-level" factors (called process grade factors) that account for noncomponent impacts of overall system reliability. "The goal of a model is to estimate the 'rate of occurrence of failure' and accelerants of a component's primary failure mechanisms within an acceptable degree of accuracy." (Reliability Information Analysis Center, 2006, p. 2)
- Models account for environmental factors and operational profile factors so that various tradeoff analyses can be performed
- 217Plus prediction can be performed using both a predecessor system and a new system. A predecessor is a product with similar technology and design and manufacturing processes. If the item under analysis is an evolution of a predecessor item, then the field experience of the

predecessor item can be leveraged and modified to account for the differences between the new item and the predecessor item.

- 217Plus methodology also accommodates the incorporation of test/field reliability experience into the analytical prediction of new systems

Cons

- Not capable of addressing system-level reliability or physics-of-failure issues adequately
- Process grades (stand in for part grades) not handled at the piece part level but rather at the system level
- Methodology assumes a constant failure rate of parts that do not fully consider actual failure modes and mechanisms
- Has not been widely utilized in space industry acquisitions

2.2.5 Telcordia SR-332 Issue 4

The purpose of this reliability prediction procedure is to document recommended methods for predicting device and unit hardware reliability. This procedure also documents a recommended method for predicting serial system hardware reliability. This document contains instructions for suppliers to follow when providing predictions of their device, unit, or serial system reliability. It also can be used directly by telecommunications service providers for system reliability and evaluation.

The initial issues of SR-332 were developed from MIL-HDBK-217FN2 with customizations included to better harmonize with communications applications and equipment. These subsequent issues of SR-332 were revised to incorporate (1) field return data for failed equipment, (2) life-testing data from participants (users and manufacturers) for components and assemblies, (3) new requirement components and design combinations of devices, and (4) feedback from reliability calculations and use of the software tool for network equipment reviews. The overall goal of SR-332 has remained to provide a consistent means to quantitatively compare the intrinsic reliability of different assemblies and combinations of communications components and units.

Device and unit failure rate predictions generated using this procedure are applicable for commercial electronic products whose physical design, manufacture, installation, and reliability assurance practices meet the appropriate Telcordia (or equivalent) generic and product-specific requirements. In general, Telcordia SR-332 adapts the equations in MIL-HDBK-217FN2 to represent the conditions that telecommunications equipment experience in the field. Results are provided as a constant failure rate, and the handbook provides the upper 90 percent confidence-level point estimate for the constant failure rate. Telcordia SR-332 also has the ability to incorporate burn-in, field, and laboratory test data for a Bayesian analytical approach that incorporates both prior information and observed data to generate an updated posterior distribution.

Pros

- Handbook supports commercial components applicable to the environmental factors and limitations listed in the handbook
- Handbook last updated in 2016 (compared to 217, which was last updated in 1995)

- Defines quality levels to categorize pedigrees of components
- Less conservative (implying more accurate) than MIL-HDBK-217FN2

Cons

- Does not address MIL-SPEC components
- Methodology assumes a constant failure rate of parts that do not fully consider actual failure modes and mechanisms
- Does not incorporate the environmental factor at the component level, so makes it difficult to integrate this methodology with others for a collection of components (e.g., circuit card)
- Has not been widely adopted in space industry acquisitions

2.2.6 FIDES Guide 2022 Edition A (July 2023) [10]

In 1999, several major French companies joined their efforts to define the specifications for a new reliability prediction methodology for electronic parts, called FIDES. The output of a study conducted between 2001 and 2004 resulted in the FIDES methodology, which was first issued in 2004 and standardized as a French standard as UTE C80-811, *FIDES Guide 2004 Issue A – Reliability Methodology for Electronic Systems* [23]. The methodology was updated in 2010, along with an updated FIDES application guide. The latest edition was released in 2022. Although not yet widely accepted in the U.S. space industry, it is gaining wider acceptance in Europe as a replacement to MIL-HDBK-217FN2. The tool is available from the FIDES website (https://www.fides-reliability.org). [7]

The FIDES Guide is a global methodology for reliability engineering in electronics. It contains two parts:

- A reliability prediction guide
- A reliability process control and audit guide

The FIDES Guide aims to enable a realistic assessment of the reliability of electronic equipment, including systems operating in severe environments (aeronautics, defense systems, industrial electronics, transport, etc.). The FIDES Guide also aims to provide a concrete tool to develop and control reliability. Its key features are:

- Providing models for electrical, electronic, and electromechanical components, and for the printed wiring assemblies or some subassemblies.
- Revealing and taking into consideration all technological and physical factors that play an identified role in a product's reliability.
- Taking into consideration the mission profile.
- Taking into consideration the electrical, mechanical, and thermal overstresses.
- Taking into consideration the failures linked to the development, production, field operation, and maintenance processes.

- The possibility of distinguishing several suppliers of the same component.
- By identifying the factors contributing to reliability—whether technological, physical, or process based—the FIDES Guide makes it possible to revise product definition and intervene throughout the product lifecycle, to improve and control reliability.

Pros

- FIDES presents a process for predicting electrical, electronic, and electromechanical failure rates and claims to be designed for COTS components. The FIDES methodology is supposed to apply to all industries where electronics are used, such as aeronautics, space, military, naval, electricity production and distribution, and home appliances.
- The reliability prediction model of the FIDES methodology includes three factors: a physical contributing factor (λPhysical), a part manufacturing factor (PPM), and a process factor (PProcess).
- An updated version was released in 2022.

Cons

- The FIDES methodology requires extensive knowledge of so many factors covering a component's technology, manufacturing processes, and usage that its use early in the design process is challenging.

2.2.7 Electronics Parts Reliability Data (EPRD-2024)

This document contains reliability data on both commercial and military electronic components for use in reliability analyses. It contains failure rate data on integrated circuits, discrete semiconductors (e.g., diodes, transistors, optoelectronic devices), resistors, capacitors, and inductors/transformers, all of which were obtained from the field usage of electronic components. At 2,716 pages, the format of this document is the same as RIAC's popular *Nonelectronic Parts Reliability Data (NPRD)* document that contains reliability data on nonelectronic component and electronic assembly types.

The data includes part descriptions; quality levels; application environments; point estimates of failure rates; data sources; numbers of failures; total operating hours, miles, or cycles; and detailed part characteristics.

This document represents a major update to the previous Electronic Part Reliability Data (EPRD-97) databook. Its purpose is to provide empirical field failure rate data on electronic components. EPRD-97 data was limited to capacitors, diodes, integrated circuits, optoelectronic devices, resistors, thyristors, transformers, and transistors. EPRD-2024 adds millions of hours of operating time and hundreds of failures to these component types, as well as adding (and updating) field failure rate data on electronic connectors, relays, switches,and inductors/coils, previously contained only in the RIAC NPRD-2011 release. Reliability data is required to perform reliability assessments of systems. The part types for which data is contained in this document are those contained in existing reliability prediction methodologies, such as MIL-HDBK-217FN2, and whereas MIL-HDBK-217FN2 and 217Plus contain mathematical models that have been derived from empirical field failure rate data, the data contained in EPRD-2024 represents historically observed field failure rates. This data can be used as an alternative to existing prediction methodologies. Commercial quality components continue to be widely used in many applications, including military systems, and much of the data contained in this document relates to commercial quality components. It can, therefore, be used to predict reliability for both commercial and military s-ystems containing commercial-quality components.

Pros

- EPRD-2024 represents historically observed field failure rates and can be used as an alternative to existing prediction methodologies.

Cons

- The number of vendors across component types that are providing reliability (failure rate) data may not be statistically significant enough to be a true representation of expected reliability (failure rate) for most component types.

- Supporting data provided to describe and qualify the component types may not be sufficient to identify whether it represents the operational reliability in the system being analyzed.

- Some failure rates are based on zero observed failures and, in those cases, the failure rate is calculated assuming more than one failure occurring over the operating time for the data collected and summarized for the component type.

- It does not provide a methodology to adjust failure rates for different applications (e.g., environments, temperatures, or other stress levels).

- Data is known to contain outliers, so special care should be taken when using an aggregation representing the mean.

2.2.8 On-Orbit and Flight Data

On-orbit data, or any flight data (e.g., deep space, interplanetary, other worldly) is the most desirable source since it represents real-world hardware that has been designed, developed, tested, and flown using standard design philosophies, testing, qualification, burn-in, and other institutional-type processes. This is very important as there is an exponential growth of proliferated assets and this is expected to bring about a paradigm shift in the way satellite reliability and constellation predictions are performed. It does not rely on methods that are decompositions of a larger problem, which is clear when examining the historical perspective of various handbooks that attempt to simulate the real world. Although there is always subjectivity involved in determining applicability from one usage to another, or how to relate data from one source or environment to another, it is still the preferred method to determine failure rates even though different analysts may treat the data differently.

While there are many proprietary and restricted on-orbit satellite performance/anomaly tracking activities, Seradata is by far the most popular commercially available tracking database. Key advantages of making on-orbit satellite data analysis a part of reliability analysis include but are not limited to:

- Generating and refining failure rate data leading to more accurate projections.

- Deriving high fidelity part/component failure rate data on known assets with sufficiently large population.

- Analyzing mean life estimates of existing assets.

- Identifying common /dominant failure modes observed on orbit.

Challenges in satellite reliability tracking:

- Unreported events due to lack of detail and/or commercial/military secrecy
- Inability to determine root cause due to insufficient telemetry information
- Incomplete/insufficient design, configuration, and hardware quality level data of tracked assets
- Prelaunch predictions that fail to account for design defects and/or creative on-orbit workarounds

On-orbit statistical data analysis methods:

- Nonparametric statistics (e.g., kernel density estimate, Kaplan-Meier estimator)
- Descriptive/inferential statistics
- Bayesian method
- Time series analysis (e.g., moving average method)
- Machine learning methods (e.g., classification/clustering)

On-orbit failure rate analysis steps:

1. Determine the following:
    a. Hardware/component of interest
    b. Satellite size and class category
    c. Orbit information
    d. Operational period
2. Extract data from available on-orbit database by means of queries.
3. Explore data (using sorts/filters and/or scripts).
4. Clean up and simplify data.
5. Analyze data.
6. Iterate periodically.

Pros

- Considered to be the most applicable and accurate method of determining failure rates or probabilities

- Represents real-world experience

- Despite the numerical predictions that may be determined from various handbook values, starting with real-world data reduces both the error and uncertainty compared to generic handbook

Cons

- Lack of failures will result in large uncertainties, some larger than others depending on the methodology used to reduce the data.

- Physics-of-failure and other mechanisms not addressed in statistical methods may be the failure mode.

- Analysis requires some subjectivity when relating past data to future applications, as not all missions are identical and not all are in the same environment (e.g., aviation to space).

- Analysis needs the incorporation of consistent approaches to create failure models based on (likely weak) evidence.

- Using public (open-sourced) data may not provide the complete technical history of the complied data. It is possible that the results will lack context and will be applied incorrectly.

2.2.9 Original Equipment Manufacturer (OEM) Data

Manufacturers and vendors sometimes determine failure rates by testing or by collecting field failure data and publishing reliability data on their components that can be acquired when performing a reliability estimate of a system.

Pros

- No testing or additional data is needed. The supplier data and estimates can be used.

Cons

- Suppliers may have biased the data, intentionally or unintentionally, by censoring data, collecting only some data, or using poor data collection methods.

- Some vendors provide a rolling date range of life data (e.g., last five years, where there is no change in process beyond five years), so early failures are obscured.

- Suppliers may not explain how estimates were made using the data.

- Supplier may have used MIL-HDBK-217FN2 or MIL-HDBK-472 [24] to make reliability and maintainability calculations, adding additional risk and uncertainty.

- The item may have been used in an environment or in ways (e.g., duty cycle) not representative of that for the new system.

- The data is often collected in ground environments and consideration of other environments (e.g., space) requires adjustments.

- It can be difficult to accelerate failure modes, especially for newer complex technologies.

2.2.9.1 High-temperature Operating Life (HTOL)

Most integrated circuits and semiconductor devices have lifetimes that extend over many years at normal use. However, part suppliers cannot economically test for years to determine device failure rates. Suppliers then increase the applied stress during testing to shorten the time needed. Applied stresses enhance or accelerate potential failure mechanisms, help identify the root cause, and help to take actions to prevent the failure mode. Temperature is often the acceleration factor and is calculated using the Arrhenius relationship.

High-temperature operating life (HTOL) is a reliability test applied to integrated circuits (ICs) to determine their intrinsic reliability. This test stresses the IC at an elevated temperature, high voltage, and dynamic operation for a predefined period of time. The IC is usually monitored under stress and tested at intermediate intervals. This reliability stress test is sometimes referred to as a *lifetime test*, *device life test*, or *extended burn-in test* and is used to trigger potential failure modes and assess IC lifetime.

HTOL is used to determine the reliability of a device at high temperature while under operating conditions. The test is usually run over an extended period of time according to the JESD22-A108 standard [30].

It is not uncommon for these accelerated life tests to witness no failures and thus an activation energy for the component is assumed (e.g., 0.70 eV) and a 60th percentile of the χ^2 distribution is utilized and translated to a typical use temperature of 55°C to make an estimate of the component's FITs (i.e., failure rates). A typical test places hundreds of like components under a temperature accelerant of 125°C for 1,000 hours.

Pros

- Failure rates determined from testing are generally thought to be better than failure rates predicted by purely analytical calculations.

Cons

- All potential failure modes cannot be accelerated by increasing operating temperature. Thinner gate oxide layers on modern devices, for example, are more prone to time-dependent dielectric breakdown and hot carrier injection failure modes that make HTOL less predictive without careful stress control during testing.

- Such accelerated test data is useful as part of a holistic assessment of reliability, but it cannot viably be used to predict the lifetime of a sufficiently derated part.

- As semiconductor devices are scaled down to nanometer sizes (e.g., 7 nm, 5 nm, and below), transistors become more sensitive to heat, voltage stress, and other reliability factors. HTOL testing at high temperatures can exacerbate these issues, leading to premature failures that may not be representative of actual use cases.

- HTOL testing is not applicable to modern system-on-chip (SoC) devices. The SoCs have regions with different power densities, creating uneven heating during HTOL testing. This can lead to temperature gradients across the chip, making it difficult to correlate HTOL results with actual operating conditions, where heat dissipation might be more uniform.

2.2.9.2 Reliability Life Test

This method consists of performing a life test and analyzing the observed times to failure. The latter are the data that is statistically analyzed, typically using Weibull analysis, to determine the underlying distribution of time to failure and the parameters of that distribution. Based on the parameters, the reliability can be estimated (in terms of mean time between failures, a percent of failures at time *t*, the reliability after *x* hours, etc.).

Pros

- Failure rates determined from testing are generally better than failure rates predicted by purely analytical calculations.

- It is a statistically valid method for determining reliability characteristics and trends from field or test failure data.

- It is flexible and versatile and can model different types of failure modes, such as wearout, infant mortality, random, or mixed.

- It is accurate and robust, as it can handle censored data, incomplete data, or small sample sizes.

- It is useful for reliability prediction, design optimization, maintenance planning, and warranty analysis.

Cons

- It requires testing actual parts to failure to establish the Weibull parameters.

- Testing may not be possible early in a program because parts, or at least enough parts, will not be available for testing.

- Predictions outside the scope of the test observations are not possible.

- It describes the statistical behavior of the failure data, but the test may not account for all the mechanisms or environmental applications (e.g., packaging, vibration, thermal) that influence failure mechanisms.

- A component must be qualified to specifications and component failure mechanisms need to be analyzed.

- The amount of testing possible is limited by program budget and schedule.

3. Industry Recommendations

The following sections provide recommendations on the sourcing of failure rates. A decision tree (Section 3.1) and a set of examples (Section 3.2) highlight the many possibilities of obtaining failure rates. The section assumes that the reader has intermediate knowledge of various reliability and statistical methods and has applied those methods in the past. The decision tree is set up in a way to provide guidance in how to obtain failure rates for components. The decision tree assumes that the reader applies engineering judgement to use what is best based on what is currently available.

3.1 Decision Tree

A modernized prediction approach seeks to use the best data available for each component, not just from one source such as MIL-HDBK-217FN2. This section provides a recommend hierarchy, in flowchart form as shown in Figure 2, for selecting the source to obtain or calculate failure rates.

On-orbit performance data is deemed the best source if there are enough on-orbit hours available and operational performance can be validated to make relevant failure rate calculations.

Ground-based life test data, whether performed by a vendor or by an independent test facility, is considered the second-best source. Due diligence must be performed to determine if the ground-based data is statistically relevant, especially if failure mode acceleration factors are used. The pedigree of the part tested must also be representative of the one being used.

The third-tier recommended failure rate data source is to use one of the failure rate calculation tools described in Section 2. The three that are most commonly used are shown in the flow chart as examples, but others can be used with adequate justification. Examples of several different methods are provided in Section 3.2.

There are times that surrogate data or engineering judgment (e.g., expert elicitation described in the introduction) can be used. This method would be used for:

- Pre–contract award.
- Early program modeling.
- When failure rate data is not available.
- When the handbook method does not adequately address the part/part technology being analyzed.

Prediction models should be updated as better data becomes available, as indicated in the decision tree text boxes at the bottom of Figure 2.

A description of the methodologies used at different points of the product lifecycle should be included in the reliability program plan, design review, or product reliability analysis.

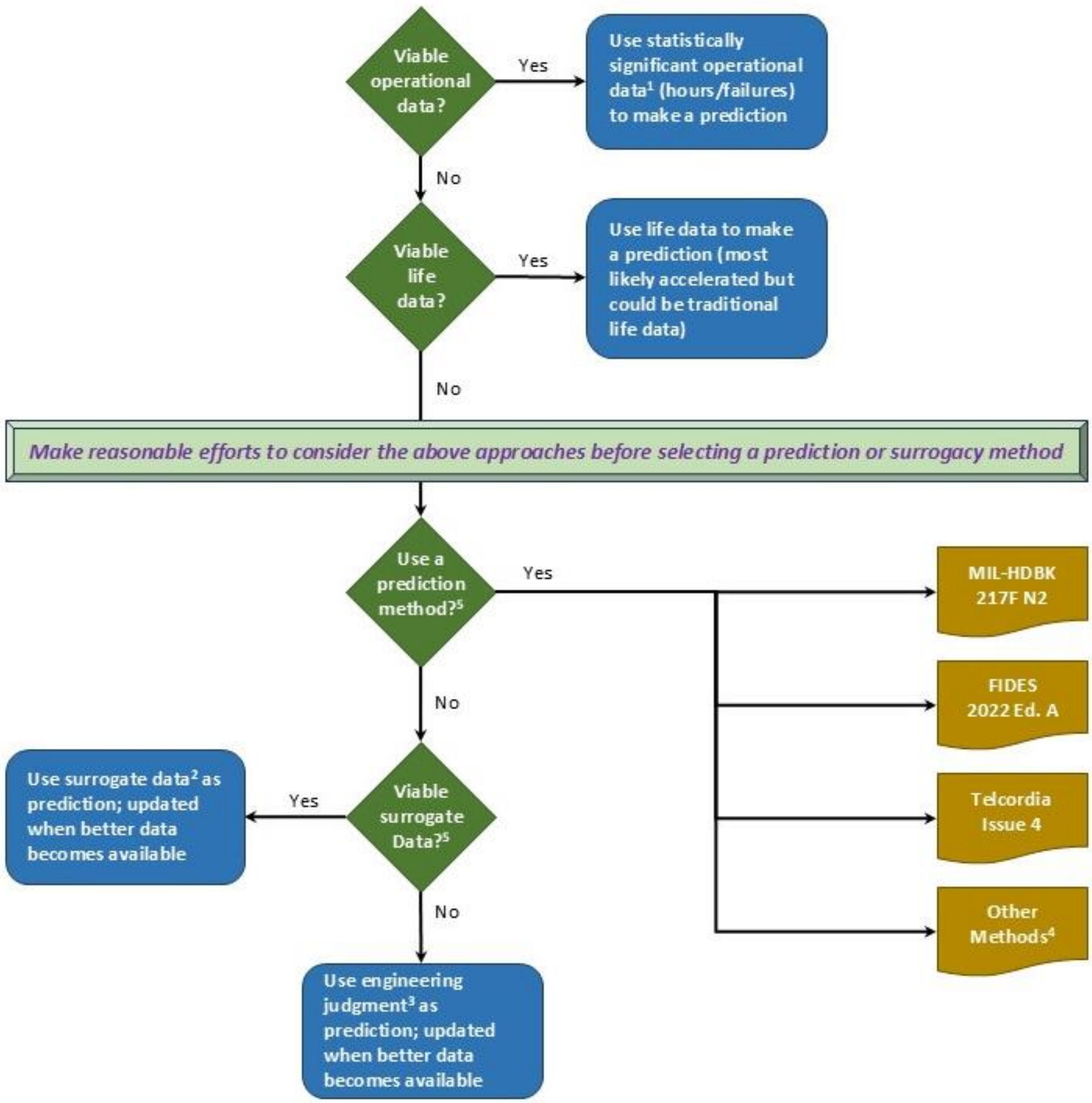

Figure 2. Top-level flowchart.

Flowchart notes:

1. Operational data includes on-orbit, at-sea, or in-air actual hours and pertinent failures.
2. For example, use EPRD or in-house heritage databases.
3. Engineering judgment should use data anchors; consider expert elicitation methodology.
4. For example, use the Reliability Data Handbook (IEC TR 62380) [25].
5. The decision points can be interchanged based on what is best and if there is sufficient data.

3.2 Example BOM and Calculations of EEE Components

The execution of a modernized prediction approach seeks to use the best data available for each component. A modernized prediction is not necessarily restricted to one methodology (e.g., MIL-HDBK-217, FIDES, Telcordia) but instead is a methodology that seeks to produce the best results while considering all prediction techniques. This section provides a thorough example of implementing this modernized prediction philosophy by exercising the various paths of the flow diagram illustrated in Figure 2. The ultimate goal of this improved prediction approach is to utilize an array of failure data sources to more accurately develop predictions that reflect the expected risk of a prediction analysis (which implies the attempt to reduce the historical conservatism of prior prediction efforts, using fewer resources).

3.2.1 Notional Bill of Materials (BOM)

A hypothetical BOM containing 100 components representing a single circuit card is delineated within Appendix A and this BOM will be used to develop a modernized prediction. The prediction analysis that follows is meant to be an academic exercise that explores the various modernizing techniques. The BOM does not represent a true circuit card design and is specifically contrived for this pedagogical endeavor. The BOM purposely contains a mix of component quality types (e.g., commercial, military, space) to illustrate the various modernizing techniques and may not truly reflect how circuit cards are designed for particular environments (e.g., all commercial grade, all space grade parts).

3.2.2 Predictions by Component Type

The following sections will explore various failure data sources and prediction techniques by classical electronic component types (e.g., capacitors, resistors, inductors, diodes, ICs). The prediction will assume a circuit card baseplate temperature of 30°C and will further assume the intended use of this design is for the spaceflight environment in low Earth orbit (LEO). The following prediction does not tackle the difficult task of assessing impacts to reliability predictions based on destructive and intermittent radiation effects, especially within LEO, as this type of analysis is beyond the scope of this effort. Additionally, the BOM does not include all component types (e.g., thyristors, hybrids, filters, solder, plated through holes) that one might encounter in the interest of providing a succinct analysis example.

3.2.2.1 Capacitors

The BOM contains three different capacitor types: a commercial capacitor with ***enhanced pedigree*** (GRT31CR61H106ME01L), a commercial capacitor with ***known pedigree*** (C0603V332KCRAC7867), and a military-grade capacitor (M3253505E2Z105KZTB). Using the flow diagram of Section 3.1, it was determined for all these capacitors that there was insufficient operational data for the circuit card design under consideration. Additionally, it was determined that no viable life testing data was available. Hence, a prediction method was considered and for these capacitors, the MIL-HDBK-217N2 approach was initially utilized because it is believed that the methodology, albeit with dated basal failure rates, still utilizes a good physics-of-failure model for these capacitors.

The phrases "known pedigree" and "enhanced pedigree" are subjective assessments as to the quality of a part. ANSI/VITA 51.1 suggests that various capacitor styles (i.e., CDR, PS, CWR, CKR, CSR, and CLR) are considered to be enhanced pedigrees while some organizations assert that any capacitor that adheres to AEC-Q200 [26] (an automotive standard) achieves the status of enhanced pedigree. Regardless of the characterization for a known or enhanced-pedigree part, each organization should develop and articulate its own definitions based on their heritage and experiences.

The MIL-HDBK-217 model for capacitors is shown as Eq. (1). The expression is comprised of basal failure rate (λ_b) and various adjustment factors associated with how the component is utilized within the design (π_T, π_C, π_V, π_{SR}), the quality of the part (π_Q), and the expected use environment (π_E).

$$\lambda_p = \lambda_b \pi_T \pi_C \pi_V \pi_{SR} \pi_Q \pi_E \times 1\text{E-}06\ Failures\ per\ hour \tag{1}$$

This document is not meant to be a tutorial on the MIL-HDBK-217 methodology or any other prediction approach, so the details of how many of these factors are determined are left to others. For the prediction modernization approach, the focus will be on λ_b and various part π_Q parameters.

For all of the following prediction models, the λ_b is 0.002000 (chip style ceramic capacitor), the π_T factor is 2.655 (i.e., a capacitor with an expected activation energy of 0.35, a baseplate temperature of 30°C, and an assumed 17°C temperature rise to the component), the π_V factor is 1.072 (i.e., a 25 percent voltage stress), the π_{SR} factor is 1.000 (by definition) and the π_E factor is 0.500 (i.e., assuming a spaceflight environment). The π_C and π_Q factors vary for each model based on the part's capacitance (in microfarads) and the part's quality, respectively.

Capacitor Model for Commercial Quality of Enhanced Pedigree (GRT31CR61H106ME01L)

This capacitor has 10 μF of capacitance, so its π_C factor is 1.230 and given that it is AEC-Q200 qualified, the pedigree is asserted to be enhanced, which, per ANSI/VITA 51.1, suggests a π_Q of 0.100. The modernized MIL-HDBK-217 prediction model for this single capacitor is shown as Eq. (2) and the resultant value as Eq. (3).

$$\lambda_p = (0.002000)(2.655)(1.230)(1.072)(1.000)(0.100)(0.500) \times 1\text{E-}06 \tag{2}$$

$$\lambda_p = 3.5032\text{E-}10\ (or\ 0.350\ FITs) \tag{3}$$

Capacitor Model for Commercial Quality of Known Pedigree (C0603V332KCRAC7867)

This capacitor has 3300 pF of capacitance, so its π_C factor is 0.598 and, given that it is asserted to be of known pedigree, ANSI/VITA 51.1 suggests a π_Q of 1.000. The modernized MIL-HDBK-217 prediction model for this single capacitor is shown as Eq. (4) and the resultant value as Eq. (5).

$$\lambda_p = (0.002000)(2.655)(0.598)(1.072)(1.000)(1.000)(0.500) \times 1\text{E-}06 \tag{4}$$

$$\lambda_p = 1.7027\text{E-}09\ (or\ 1.703\ FITs) \tag{5}$$

Capacitor Model for Military Quality (M3253505E2Z105KZTB)

This capacitor has 1 μF of capacitance, so its π_C factor is 1.000 and, given that it is of military quality, the MIL-HDBK-217 asserts a π_Q of 0.030. The initial MIL-HDBK-217 prediction model for this single capacitor is shown as Eq. (6) and the resultant value as Eq. (7).

$$\lambda_p = (0.002000)(2.655)(1.000)(1.072)(1.000)(0.030)(0.500) \times 1\text{E-}06 \tag{6}$$

$$\lambda_p = 8.5425\text{E-}11\ (or\ 0.085\ FITs) \tag{7}$$

This prediction has yet to be modernized and can be adjusted via RAC factors. Assuming a ΔT of 15 years, a RAC factor of 0.884 for this type of capacitor is used to augment the basal failure rate. The modernized MIL-HDBK-217 prediction model for this single capacitor is shown as Eq. (8) and the resultant value as Eq. (9).

$$\lambda_p = (0.002000 \times 0.884)(2.676)(1.000)(1.072)(1.000)(0.300)(0.500) \times 1\text{E-}06 \tag{8}$$

$$\lambda_p = 7.5516\text{E-}11\ (or\ 0.076\ FITs) \tag{9}$$

It is interesting to note that the traditional MIL-HDBK-217 approach would likely use a π_Q factor of 10 for commercial-grade capacitors and thus would predict an order of magnitude worse reliability for these types of capacitors. Many within the reliability community do not support this outdated π_Q factor for commercial-grade capacitors based upon operational experience and vendor life data. Thus, it is imperative that modernizing techniques (e.g., ANSI/VITA, RAC factors) be considered for capacitor predictions.

3.2.2.2 Resistors

The BOM contains five different resistor types: a commercial resistor with enhanced pedigree (ERJ-2RKF1004X), a commercial resistor with known pedigree (PHP00603E20R0BST1), a military-grade resistor (M55342E06B1B00R), a space-grade resistor (RNC90Z62K000AM) and a commercial resistor that has vendor failure rate data available (CRCW0603562RFKEC). Reviewing the flow diagrams of Section 3.2, it was determined for all these resistors that there was insufficient operational data for the circuit card design under consideration. For the first four resistor types, it was determined that no viable life testing data was available. Hence, a prediction method was considered and, for these resistors, the MIL-HDBK-217 approach was initially utilized because it is believed that the methodology, while suggesting dated basal failure rates, still proposes a good physics of failure model for these resistors.

The ANSI/VITA 51.1 perspective suggests that various resistor styles (i.e., RM and RZ) are considered to be enhanced pedigrees while some organizations assert that any resistor that adheres to the AEC-Q200 (an automotive standard) achieves the status of enhanced pedigree. Again, regardless of the characterization for a known or enhanced pedigree part, each organization is strongly encouraged to develop and articulate its own definitions based on their heritage and experiences.

The MIL-HDBK-217 model for resistors is shown as Eq. (10). The expression is comprised of basal failure rate (λ_b) and various adjustment factors associated with how the component is utilized within the design (π_T, π_P, π_S), the quality of the part (π_Q), and the expected use environment (π_E).

$$\lambda_p = \lambda_b \pi_T \pi_P \pi_S \pi_Q \pi_E \times 1\text{E-}06\ Failures\ per\ hour \tag{10}$$

For all of the following prediction models, the λ_b factor is 0.003700 (chip style fixed film resistor), the π_T factor is 1.239 (i.e., a resistor with an expected activation energy of 0.08, a baseplate temperature of 30°C, and an assumed 17°C temperature rise to the component), the π_S factor is 0.935 (i.e., a 25 percent derating of the power stress) and the π_E factor is 0.500. The π_P and π_Q factors vary for each model based on the part's rated power capabilities (in watts) and the part's quality, respectively.

Resistor Model for Commercial Quality of Enhanced Pedigree (ERJ-2RKF1004X)

This resistor is rated for 0.10 W power, so its π_P factor is 0.237 (i.e., assuming a 25 percent derating of the power dissipation) and, given that this resistor is AEC-Q200 qualified, the pedigree is asserted to be enhanced, which, per ANSI/VITA 51.1, suggests a π_Q of 0.100. The modernized MIL-HDBK-217 prediction model for this single resistor is shown as Eq. (11) and the resultant value as Eq. (12).

$$\lambda_p = (0.003700)(1.239)(0.237)(0.935)(0.100)(0.500) \times 1\text{E-}06 \tag{11}$$

$$\lambda_p = 5.0825\text{E-}11\ (or\ 0.051\ FITs) \tag{12}$$

Resistor Model for Commercial Quality of Known Pedigree (PHP00603E20R0BST1)

This resistor is rated for 0.375 W power, so its π_P factor is 0.397 (i.e., assuming a 25 percent derating of the power dissipation) and, given that this resistor has a known pedigree, ANSI/VITA 51.1 suggests a π_Q of 1.000. The modernized MIL-HDBK-217 prediction model for this single resistor is shown as Eq. (13) and the resultant value as Eq. (14).

$$\lambda_p = (0.003700)(1.239)(0.397)(0.935)(1.000)(0.500) \times 1\text{E-}06 \tag{13}$$

$$\lambda_p = 8.5104\text{E-}10\ (or\ 0.851\ FITs) \tag{14}$$

Resistor Model for Military Quality (M55342E06B1B00R)

This resistor is rated for 0.15 W power, so its π_P factor is 0.278 (i.e., assuming a 25 percent derating of the power dissipation) and, given that it is of military quality (type R), the MIL-HDBK-217 asserts a π_Q of 0.100. The initial MIL-HDBK-217 prediction model for this single resistor is shown as Eq. (15) and the resultant value as Eq. (16).

$$\lambda_p = (0.003700)(1.239)(0.278)(0.935)(0.100)(0.500) \times 1\text{E-}06 \tag{15}$$

$$\lambda_p = 5.9532\text{E-}11\ (or\ 0.060\ FITs) \tag{16}$$

This prediction has yet to be modernized and can be adjusted via RAC factors. Again, assuming a ΔT of 15 years, a RAC factor of 0.987 for this type of resistor is used to augment the basal failure rate. The modernized MIL-HDBK-217 prediction model for this single resistor is shown as Eq. (17) and the resultant value as Eq. (18).

$$\lambda_p = (0.003700 \times 0.987)(1.239)(0.278)(0.935)(0.100)(0.500) \times 1\text{E-}06 \tag{17}$$

$$\lambda_p = 5.8758\text{E-}11\ (or\ 0.059\ FITs) \tag{18}$$

Resistor Model for Space Quality (RNC90Z62K000AM)

This resistor is rated for 0.60 W power so its π_P factor is 0.477 (i.e., assuming a 25 percent derating of the power dissipation) and, given that it is of space quality (type S), the MIL-HDBK-217 asserts a π_Q of 0.030. The initial MIL-HDBK-217 prediction model for this single resistor is shown as Eq. (19) and the resultant value as Eq. (20).

$$\lambda_p = (0.003700)(1.239)(0.477)(0.935)(0.030)(0.500) \times 1\text{E-}06 \tag{19}$$

$$\lambda_p = 3.0667\text{E-}11\ (or\ 0.031\ FITs) \tag{20}$$

This prediction has yet to be modernized and can be adjusted via RAC factors. Again, assuming a ΔT of 15 years, a RAC factor of 0.987 for this type of resistor is used to augment the basal failure rate. The modernized MIL-HDBK-217 prediction model for this single resistor is shown as Eq. (21) and the resultant value as Eq. (22).

$$\lambda_p = (0.003700 \times 0.987)(1.239)(0.477)(0.935)(0.030)(0.500) \times 1\text{E-}06 \tag{21}$$

$$\lambda_p = 3.0269\text{E-}11\ (or\ 0.030\ FITs) \tag{22}$$

Resistor Model for Commercial Quality Using Vendor Data (CRCW0603562RFKEC)

This particular resistor happens to have viable data from the vendor (Vishay Dale) and its datasheet states a failure rate of ≤0.1E-09 or 0.1 FITs. The vendor indicated that this data was based on the number of automotive resistors of this type operationally deployed and the number of resistor defects documented and communicated back to the vendor. The vendor-based prediction model for this single resistor is shown as Eq. (23).

$$\lambda = 1.0000\text{E-}10 \tag{23}$$

Using vendor data comes with many challenges. While the π_Q value can be inferred since it is a commercial-grade resistor, the vendor did not specify how a typical resistor is utilized, so no knowledge is provided about the application π-factors (i.e., π_T, π_P, π_S). Assuming similar temperature environment, power stress derating, and commercial quality, there still remains how to adjudicate the π_E factor for a specific environment. Assuming the vendor data is based upon the ground-mobile environment (i.e., automotive), a conversion to the spaceflight environment is feasible. The Rome Laboratory Reliability Engineer's Toolkit [27] indicates that the failure rate conversion factor from a ground-mobile to a spaceflight environment is 0.185 (i.e., 1/5.4; see Table A11-2), which becomes the effective environmental factor for this notional prediction effort. The prediction model for this single resistor is shown as Eq. (24) and the resultant value as Eq. (25).

$$\lambda = (0.000100)(1)(1)(1)(1)(0.185) \times 1\text{E-}06 \tag{24}$$

$$\lambda = 1.8519\text{E-}11\ (or\ 0.019\ FITs) \tag{25}$$

An additional warning about using vendor component reliability data is that it should not be modernized with say ANSI/VITA or RAC factor techniques because the basal data already contains the effects of modernization (i.e., the data is contemporary). To further modernize this vendor provided value would effectively be double counting the effect of modernization.

It is interesting to note that the traditional MIL-HDBK-217 approach would likely again use a π_Q factor of 10[1] for commercial-grade resistors and thus would predict an order of magnitude worse reliability for these types of resistors. Many within the reliability community do not support this outdated π_Q factor for commercial-grade resistors based upon operational experience and vendor life data. Thus, it is imperative that modernizing techniques (e.g., ANSI/VITA, RAC factors) be considered for resistor predictions.

[1]Refer to Aerospace report number TOR-2020-01447, Table 3.3-2, for a further discussion of modifying π_Q for commercial components. [7]

3.2.2.3 Diodes

The BOM contains four different diode types: a commercial diode with known pedigree (SK310A-LTP), a commercial diode with vendor life data (NSVR0170P2T5G), a military-grade diode (JANTX1N4620UR-1) and a space-grade diode (JANS1N941B-1). Reviewing the flow diagrams of Section 3.2, it was determined for all these diodes that there was insufficient operational data for the circuit card design under consideration. Only one of the four diodes has viable life testing data (i.e., NSVR0170P2T5G from ON Semiconductor Corporation or onsemi). For the other diodes, a MIL-HDBK-217 approach was initially utilized because it is believed that the methodology, while suggesting dated basal failure rates, still proposes a good physics-of-failure model for these diodes.

The MIL-HDBK-217 model for these types of diodes (i.e., low frequency) is shown as Eq. (26). The expression is comprised of basal failure rate (λ_b) and various adjustment factors associated with how the component is utilized within the design (π_T, π_S, π_C), the quality of the part (π_Q) and the expected use environment (π_E).

$$\lambda_p = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E \times 1\text{E-}06 \; Failures\ per\ hour \tag{26}$$

For all the following prediction models, the λ_b is 0.003000 or 0.002000 for the Schottky- or Zener-type diodes, respectively, and likewise the π_T factor is 2.232 or 1.649 (i.e., a baseplate temperature of 30°C and an assumed 20°C temperature rise to the component). The π_S factor is 0.186 (assuming a voltage stress of 50 percent) or 1.000 for the Schottky- or Zener-type diodes, respectively, and all diode types have a π_C factor of 1.000 (i.e., metallurgically bonded). The π_E factor is again 0.500 since this is a spaceflight environment prediction effort. The π_Q factor will vary for each model based on the part's quality.

Diode Model for Commercial Quality of Known Pedigree (SK310A-LTP)

Given that this Schottky diode is assumed to be of known pedigree for this prediction endeavor, ANSI/VITA 51.1 suggests a π_Q of 1.000. The modernized MIL-HDBK-217 prediction model for this single diode is shown as Eq. (27) and the resultant value as Eq. (28).

$$\lambda_p = (0.003000)(2.232)(0.186)(1.000)(1.000)(0.500) \times 1\text{E-}06 \tag{27}$$

$$\lambda_p = 6.2123\text{E-}10 \; (or\ 0.621\ FITs) \tag{28}$$

Diode Model for Commercial Quality Using Vendor Accelerated Life Data (NSVR0170P2T5G)

This particular Schottky diode happens to have viable accelerated life data from the vendor (onsemi). Appendix B provides a list of a subset of component vendors that offer accelerated life data (mostly for semiconductors and integrated circuits). The vendor's website indicates that this part underwent 6,889,897,810 equivalent device hours (e.g., 500,000 units tested for approximately 13,780 hours) based upon the Arrhenius model with an assumed activation energy (E_a) of 0.70 eV. This life test did not witness any failures so the 60th percentile χ^2 estimate for mean life was 7,519,341,270 hours or a failure rate of 0.133 FITs. The vendor-based prediction model for this single diode is shown as Eq. (29).

$$\lambda = 1.3299\text{E-}10 \tag{29}$$

This vendor data is based upon a diode junction temperature of 55°C, but for this prediction effort, the junction temperature would be 50°C (i.e., a 30°C baseplate temperature plus a 20°C rise), so an adjustment needs to be considered for the equivalent device hours and thus the λ value. Using the Arrhenius model, the 0.133 FITs at 55°C equates to 0.091 FITs at 50°C, all considered at the 60th percentile of the χ^2 distribution. Assuming the vendor accelerated life testing was executed within a ground-benign environment (typical Earth-based laboratories), a conversion to the spaceflight environment is feasible. The Rome Laboratory Reliability Engineer's Toolkit indicates that the failure rate conversion factor from a ground-benign to a spaceflight environment is 0.833 (i.e., 1/1.2; see Table A11-2), which becomes the effective environmental factor for this notional prediction effort. Assuming the other application π-factors (i.e., π_S, π_C) utilized during the accelerated life test are typical, the prediction model for this single diode is shown as Eq. (30) and the resultant value as Eq. (31).

$$\lambda = (0.000091)(1.000)(1.000)(1.000)(1.000)(0.833) \times 1\text{E-}06 \tag{30}$$

$$\lambda = 7.5561\text{E-}11\ (or\ 0.076\ FITs) \tag{31}$$

Again, when using contemporary vendor component reliability data, it should not be modernized with, for example, ANSI/VITA or RAC factor techniques because the basal accelerated life data already contains the effects of modernization.

Diode Model for Military Quality (JANTX1N4620UR-1)

Given that this Zener diode is a military quality of JANTX (Joint Army Navy, manufactured and tested to MIL-S-19500 [28]), the MIL-HDBK-217 asserts a π_Q of 1.000. The initial MIL-HDBK-217 prediction model for this single diode is shown as Eq. (32) and the resultant value as Eq. (33).

$$\lambda_p = (0.002000)(1.649)(1.000)(1.000)(1.000)(0.500) \times 1\text{E-}06 \tag{32}$$

$$\lambda_p = 1.6487\text{E-}09\ (or\ 1.649\ FITs) \tag{33}$$

This prediction has yet to be modernized and can be adjusted via RAC factors. Again, assuming a ΔT of 15 years, a RAC factor of 0.105 for this type of diode is used to augment the basal failure rate. The modernized MIL-HDBK-217 prediction model for this single diode is shown as Eq. (34) and the resultant value as Eq. (35).

$$\lambda_p = (0.002000 \times 0.105)(1.649)(1.000)(1.000)(0.100)(0.500) \times 1\text{E-}06 \tag{34}$$

$$\lambda_p = 1.7311\text{E-}10\ (or\ 0.173\ FITs) \tag{35}$$

Diode Model for Space Quality (JANS1N941B-1)

This Zener diode is a top-quality part with a JANS (Joint Army Navy, manufactured to MIL-S-19500, space qualified) designation. Unfortunately, the MIL-HDBK-217 is mute on this level of quality and fails to suggest a π_Q factor. This technology was likely too new when the latest edition of the handbook was published in December 1991. The RAC factors and ANSI/VITA approaches are also silent as to how to handle the π_Q factor for a JANS-quality semiconductor.

A major industry integrator contractor uses a π_Q of 0.330 based upon their heritage and experience with using JANS-style diodes. MIL-HDBK-388 Volume II , *Electronic Reliability Design Handbook* [29], implies a π_Q of 0.350 based upon a relative failure adjustment for a JANTXV (Joint Army Navy, manufactured and tested to MIL-S-19500, underwent verification during testing before packaging) diode (i.e., a JANTXV has a π_Q of 0.700 from MIL-HDBK-217, and Table 7.1.2.2-1 of MIL-HDBK-388 suggests half the failure rate when comparing JANTXV to JANS, so a π_Q = 0.700/2 = 0.350). Hence, the initial MIL-HDBK-217 prediction model for this single diode is shown as Eq. (36) and the resultant value as Eq. (37).

$$\lambda_p = (0.002000)(1.649)(1.000)(1.000)(0.350)(0.500) \times 1\text{E-}06 \tag{36}$$

$$\lambda_p = 5.7704\text{E-}10\ (or\ 0.577\ FITs) \tag{37}$$

This prediction has yet to be modernized and can be adjusted via RAC factors. A RAC factor of 0.105 (assuming a ΔT of 15 years) for this type of diode is used to augment the basal failure rate. The modernized MIL-HDBK-217 prediction model for this single diode is shown as Eq. (38) and the resultant value as Eq. (39).

$$\lambda_p = (0.002000 \times 0.105)(1.649)(1.000)(1.000)(0.350)(0.500) \times 1\text{E-}06 \tag{38}$$

$$\lambda_p = 6.0589\text{E-}11\ (or\ 0.061\ FITs) \tag{39}$$

While the above MIL-HDBK-217 method works well enough for developing modernized predictions for JANS diodes, the convoluted approach may suggest that another methodology (e.g., FIDES, Telcordia) might be more simplistic.

It is interesting to note that the traditional MIL-HDBK-217 approach would likely use a π_Q factor of between 5.5 and 8.0 for commercial-grade diodes and thus would predict a half to almost full order of magnitude worse reliability for these types of diodes. Again, many within the reliability community do not support this outdated π_Q factor for commercial-grade diodes based upon operational experience and vendor life data.

3.2.2.4 Transistors

The BOM contains three different transistor types: a commercial transistor with enhanced pedigree (BSS138WH6327XTSA1), a commercial transistor with vendor life data (MMBT5962), and a space-grade transistor (JANS2N2222A). Reviewing the flow diagrams of Section 3.2, it was determined for all these transistors that there was insufficient operational data for the circuit card design under consideration. First, for one transistor, a comparison of the MIL-HDBK-217 approach (augmented via ANSI/VITA) with the Telcordia approach is explored. Next, one of the three transistors has viable life testing data. Finally, a space-grade transistor augmented with RAC factors is considered.

Transistor Model for Commercial Quality of Enhanced Pedigree (BSS138WH6327XTSA1)

The MIL-HDBK-217 model for an N-channel transistor is shown as Eq. (40). The expression is comprised of basal failure rate (λ_b) and various adjustment factors associated with how the component is utilized within the design (π_T, π_A), the quality of the part (π_Q), and the expected use environment (π_E).

$$\lambda_p = \lambda_b \pi_T \pi_A \pi_Q \pi_E \times 1\text{E-}06\ Failures\ per\ hour \tag{40}$$

For a metal-oxide semiconductor field-effect transistor (MOSFET) N-channel transistor, the λ_b factor is initially 0.012000, the π_T factor is 1.904 (i.e., a baseplate temperature of 30°C and an assumed 28°C temperature rise to the component) and the π_A factor is 0.700 (assuming a small signal switching device). The π_E factor is again 0.500 and the π_Q factor will vary for each model based on the part's quality. Given that this transistor is assumed to be of enhanced pedigree for this prediction endeavor, ANSI/VITA 51.1 suggests a π_Q of 1.000 (like for a known pedigree), but also that the basal failure rate should be improved by an order of magnitude, or a λ_b of 0.001200. The modernized MIL-HDBK-217 prediction model for this single transistor is shown as Eq. (41) and the resultant value as Eq. (42).

$$\lambda_p = (0.001200)(1.904)(0.700)(1.000)(0.500) \times 1\text{E-}06 \tag{41}$$

$$\lambda_p = 7.9973\text{E-}10\ (or\ 0.800\ FITs) \tag{42}$$

The Telcordia methodology was also considered for this transistor to provide a direct comparison of two modernizing approaches. The Telcordia model for this type of transistor is shown as Eq. (43). Notice that the Telcordia method uses FITs (or 1E-09 failures per hour) as its baseline prediction units compared to the MIL-HDBK-217 model, which uses failures per million hours (or 1E-06 failures per hour).[2]

$$\lambda = \lambda_G \pi_Q \pi_S \pi_T \times 1\text{E-}09\ Failures\ per\ hour \tag{43}$$

The expression is comprised of basal failure rate (λ_G) and various adjustment factors associated with how the component is utilized within the design (π_S, π_T) and the quality of the part (π_Q). When developing Telcordia predictions for components, the environmental factor (π_E) is not included within the steady-state lambda expression (i.e., Eq. [43]) but is integrated within unit-level assessments. For this prediction effort, a derating of 25 percent and a junction temperature of 58°C (similar to the previous transistor predictions) will be assumed. The basal failure rate (λ_G) is 3.44 FITs (from Telcordia SR-332 [9], Table 8-25), π_S is 0.549 (Telcordia SR-332, Table 9-2, stress curves 4 and E) and π_T is 1.000 (Telcordia SR-332, Table 9-1). Since the component is qualified to an automotive grade standard, a π_Q of 1.000 is assigned. The modernized Telcordia prediction model for this single transistor is shown as Eq. (44) and the resultant value as Eq. (45).

$$\lambda = (3.44)(1.000)(0.549)(1.000) \times 1\text{E-}09 \tag{44}$$

$$\lambda = 1.8879\text{E-}09\ (or\ 1.888\ FITs) \tag{45}$$

It is interesting to note that the MIL-HDBK-217 approach augmented with ANSI/VITA yielded a similar FIT prediction (0.800 versus 1.888) as the Telcordia approach and both are significantly different than a traditional MIL-HDBK-217 approach, which would yield approximately 64 FITs (34 to 80 times worse) for this transistor. For this notional prediction effort, it was decided to utilize the modernized MIL-HDBK-217 prediction of 0.800 FITs for this transistor as the best estimate of this component's risk.

Transistor Model for Commercial Quality Using Vendor Accelerated Life Data (MMBT5962)

This particular transistor happens to have viable accelerated life data from the vendor (onsemi, see Appendix B for more vendor references). The vendor's website indicates that this part underwent 4,654,891,639 equivalent device hours based upon the Arrhenius model with an assumed E_a of 0.70 eV.

[2]MIL-HDBK-217 uses the term "base failure rate" (λ_b) and Telcordia uses the term "generic failure rate" (λ_G) to describe the same idea. We use the term "basal failure rate" (λ_G) to make it clear that the idea is the same despite the differences between these two documents.

This life test did not witness any failures so the 60th percentile χ^2 estimate for mean life was 5,080,150,646 hours or a failure rate of 0.197 FITs. The vendor-based prediction model for this single transistor is shown as Eq. (46).

$$\lambda = 1.9684\text{E-}10 \tag{46}$$

This vendor data is based upon a transistor junction temperature of 55°C, but for this prediction effort, the junction temperature would be 58°C (i.e., a 30°C baseplate temperature plus a 28°C rise), so an adjustment needs to be considered for the equivalent device hours and thus the λ_p value. Using the Arrhenius model the 0.197 FITs at 55°C equates to 0.246 FITs at 58°C, all considered at the 60th percentile of the χ^2 distribution. Again, assuming the vendor accelerated life testing was executed within a ground-benign environment, a conversion to the spaceflight environment is feasible. The conversion factor from a ground-benign to a spaceflight environment is 0.833, which becomes the effective environmental factor for this notional example prediction effort.

The MIL-HDBK-217 model for a low-frequency bipolar negative-positive-negative (NPN) transistor is shown as Eq. (47). The expression is comprised of basal failure rate (λ_b) and various adjustment factors associated with how the component is utilized within the design (π_T, π_A, π_R, π_S), the quality of the part (π_Q), and the expected use environment (π_E).

$$\lambda_p = \lambda_b \pi_T \pi_A \pi_R \pi_S \pi_Q \pi_E \times 1\text{E-}06\ Failures\ per\ hour \tag{47}$$

Assuming the other application π-factors (i.e., π_T, π_A, π_R, π_S) utilized during the accelerated life test are typical, the prediction model for this single transistor is shown as Eq. (48) and the resultant value as Eq. (49).

$$\lambda_p = (0.000246)(1.000)(1.000)(1.000)(0.833) \times 1\text{E-}06 \tag{48}$$

$$\lambda_p = 2.0528\text{E-}10\ (or\ 0.205\ FITs) \tag{49}$$

Again, when using contemporary vendor component reliability data, it should not be modernized because the basal accelerated life data already contains the effects of modernization.

Transistor Model for Space Quality (JANS2N2222A)

The MIL-HDBK-217 model for a bipolar NPN FET transistor is shown as Eq. (50). The expression is comprised of basal failure rate (λ_b) and various adjustment factors associated with how the component is utilized within the design (π_T, π_A, π_R, π_S), the quality of the part (π_Q), and the expected use environment (π_E).

$$\lambda_p = \lambda_b \pi_T \pi_A \pi_R \pi_S \pi_Q \pi_E \times 1\text{E-}06\ Failures\ per\ hour \tag{50}$$

For this transistor, the λ_b factor is 0.000740, the π_T factor is 2.028 (i.e., a baseplate temperature of 30°C and an assumed 28°C temperature rise to the component), and the π_A factor is 0.700 (assuming a switching device). The π_R factor is 0.774 (since the power rating is 500 mW), and the π_S factor is 0.212 (assume a voltage stress factor of 50 percent). The π_E factor is again 0.500 and the π_Q factor for a JANS semiconductor is 0.350, as previously discussed using MIL-HDBK-388. The modernized MIL-HDBK-217 prediction model for this single transistor is shown as Eq. (51) and the resultant value as Eq. (52).

$$\lambda_p = (0.000740)(2.028)(0.700)(0.774)(0.212)(0.350)(0.500) \times 1\text{E-}06 \quad (51)$$

$$\lambda_p = 3.0166\text{E-}11\ (or\ 0.030\ FITs) \quad (52)$$

This prediction has yet to be modernized and can be adjusted via RAC factors. A RAC factor of 0.015 (assuming a ΔT of 15 years) for this type of transistor is used to augment the basal failure rate. The modernized MIL-HDBK-217 prediction model for this single transistor is shown as Eq. (53) and the resultant value as Eq. (54).

$$\lambda_p = (0.000740 \times 0.015)(2.028)(0.700)(0.774)(0.212)(0.350)(0.500) \times 1\text{E-}06 \quad (53)$$

$$\lambda_p = 4.5248\text{E-}13\ (or < 0.001\ FITs) \quad (54)$$

3.2.2.5 Inductors

The BOM contains three different types of commercial inductors and three distinctive modernized prediction approaches will be illustrated. For the shielded drum core power inductor (744771112), a Telcordia approach was deemed the best prediction tool since the MIL-HDBK-217 method for these types of coils yields questionable results and the ANSI/VITA and RAC factor augmentations are mute for this type of component. For a generic toroidal transformer, the approach of using surrogate data from the EPRD will be explored. Finally, for the radio frequency (RF) balanced-to-unbalanced (BALUN) transformer (TCM1-83X+), a FIDES approach was deemed to be the best prediction method.

Inductor Model for Commercial Quality Using Telcordia (744771112)

The Telcordia methodology was considered for this general-purpose power inductor with a ferrite core and the Telcordia model for this type of inductor is shown as Eq. (55). The expression is comprised of basal failure rate (λ_G) and various adjustment factors associated with how the component is utilized within the design (π_S, π_T), and the quality of the part (π_Q). Again, the environmental factor (π_E) is not included within the steady-state lambda expression (i.e., Eq. [55]) but is integrated within unit-level assessments.

$$\lambda = \lambda_G \pi_Q \pi_S \pi_T \times 1\text{E-}09\ Failures\ per\ hour \quad (55)$$

For this prediction effort, a junction temperature of 48°C (i.e., a baseplate temperature of 30°C and an assumed 18°C temperature rise to the component) will be assumed. The basal failure rate (λ_G) is 0.240 FITs (from Telcordia SR-332, Table 8-4), π_S is 1.000 (Telcordia SR-332, Table 9-2, stress curves 3) and π_T is 1.000 (Telcordia SR-332, Table 9-1). Since the component is qualified to an automotive grade standard (i.e., AEC-Q200, Grade 1 qualified), a π_Q of 1.000 is assigned. The modernized Telcordia prediction model for this single inductor is shown as Eq. (56) and the resultant value as Eq. (57).

$$\lambda = (0.240)(1.000)(1.000)(1.000) \times 1\text{E-}09 \quad (56)$$

$$\lambda = 2.4000\text{E-}10\ (or\ 0.240\ FITs) \quad (57)$$

Inductor (Transformer) Model for Commercial Quality Using EPRD Surrogacy

At this point in the design, all that is known about this particular part is that a commercial-grade toroidal transformer will be utilized but an actual component (with a specific part number) has not yet been selected by the circuit designers. It was determined with the lack of specificity for this component, a surrogacy approach was deemed the best prediction method until more part details are obtained as the design matures. The EPRD source document is meant to provide historical reliability data on a wide variety of components to aid in the estimation of component reliability. Data for the following seven transformers utilized within a ground-benign environment was obtained and illustrated as Table 1.

Table 1. EPRD Toroidal Transformer Ground-Benign Surrogacy Data

Part Number	Category	Subcategory	Quality	Failure Rate (FPMH)
(Merged FR)	Transformer	Toroidal	Commercial	0.012396
EPRD-31441	Transformer	Toroidal	Commercial	0.022918
EPRD-31442	Transformer	Toroidal	Commercial	0.023616
EPRD-31443	Transformer	Toroidal	Commercial	0.810570
EPRD-31444	Transformer	Toroidal	Commercial	17.482517
EPRD-31449	Transformer	Toroidal	Commercial	0.027001
EPRD-31450	Transformer	Toroidal	Commercial	0.029495
EPRD-31451	Transformer	Toroidal	Commercial	0.319315

The EPRD document develops a merged failure rate by deriving the geometric mean of all the failure rates associated with records of interest having failures and multiplying the derived failure rates by the proportion of observed hours with failures to total observed hours. This central tendency aggregate approach is deemed appealing by the EPRD authors since the geometric mean will inherently apply less weight to failure rates that are significantly greater than the others for the same part type. The merged failure rate should be representative of the population of parts since it takes into consideration all observed operating hours, regardless of whether there were observed failures. Notice within this toroidal transformer example, one of the surrogate values (EPRD-31444) is clearly an outlier compared to the other data sources and the geometric mean approach helps to mitigate its impacts to the merged result. Some prefer to use the median of the surrogacy values (i.e., EPRD-31450) to mitigate the effects of potential outliers. For this prediction effort, the data needs to be converted to the space environment using the previously discussed 0.833 factor. The updated data is shown as Table 2.

Table 2. EPRD Toroidal Transformer Space Surrogacy Data

Part Number	Conversion Factor to Space Failure Rate (FPMH)	Failure Rate (FITs)
(Merged FR)	0.010330	10.330
EPRD-31441	0.019098	19.098
EPRD-31442	0.019680	19.680
EPRD-31443	0.675475	675.475
EPRD-31444	14.568764	14,568.764
EPRD-31449	0.022501	22.501
EPRD-31450	0.024579	24.579
EPRD-31451	0.266096	266.096

Unfortunately, the surrogate data makes no mention of the junction temperature or any other factors associated with the use of a component within a design. Thus, the use of the surrogacy data is more analogous to a lower-fidelity parts-count prediction method (except for the environmental factor) than a part-stress prediction method (implemented for most of the parts of the notional BOM). The surrogacy prediction model for this single transformer is shown as Eq. (58) and the resultant value as Eq. (59).

$$\lambda = (0.012396 \times 0.833) \times 1\text{E-}06 \tag{58}$$

$$\lambda = 1.0330\text{E-}08\ (or\ 10.330\ FITs) \tag{59}$$

Inductor (Transformer) Model for Commercial Quality Using FIDES (TCM1-83X+)

The FIDES methodology is based on the physics-of-failure approach of developing a prediction model with an emphasis on developing prediction factors for the technology of the part, how the part is utilized, and how the part is processed (or manufactured). The FIDES general reliability model is shown as Eq. (60) with $\lambda_{Physical}$ representing the physical factors of the prediction model, Π_{PM} is an expression of a part's manufacturing, and $\Pi_{Process}$ is an expression of a part's manufacturing processing controls.

$$\lambda = \lambda_{Physical}\Pi_{PM}\Pi_{Process} \tag{60}$$

For this transformer type, the $\lambda_{Physical}$ and Π_{PM} expressions are shown as Eq. (61) and Eq. (62), respectively.

$$\lambda_{Physical} = \lambda_{0\_Magnetic} \times \sum_i^{Phases} \left(\frac{t_{annual}}{8766}\right)_i \times \left(\Pi_{TE} + \Pi_{TCy} + \Pi_{Mech}\right)_i \times (\Pi_I)_i \tag{61}$$

$$\Pi_{PM} = e^{1.39\times(1-Part\_Grade)-0.69} \tag{62}$$

This document is not meant to be a tutorial for the FIDES methodology or any other prediction approach so the details of how many of these factors are determined are left to others. For this transformer prediction effort, the various prediction factors are denoted within Eq. (63) through Eq. (65).

$$\lambda_{Physical} = 0.250 \times 1 \times (0.306 + 0.052 + 0.160) \times (1.000) = 0.130\ FITs \tag{63}$$

$$\Pi_{PM} = e^{1.39\times(1-0.083)-0.69} = 1.793 \tag{64}$$

$$\Pi_{Process} = 4\ (i.e., FIDES\ default\ for\ this\ part\ type) \tag{65}$$

The modernized FIDES prediction model for this single transformer (inductor) is shown as Eq. (66) and the resultant value as Eq. (67).

$$\lambda = (0.130)(1.793)(4.000) \tag{66}$$

$$\lambda = 9.3236\text{E-}10\ (or\ 0.932\ FITs) \tag{67}$$

It is interesting to note that the traditional MIL-HDBK-217 approach would likely use a π_Q factor between 5.0 and 30.0 for commercial-grade inductors and thus would predict a half to more than a full order of magnitude worse reliability for these types of inductors.

3.2.2.6 Connectors

The BOM contains two different types of a commercial connectors. For the Micro-D connector (MMDS-009-N00-VV), operational data from the Global Positioning System (GPS) constellation will be utilized. The RF connector (853050232) was assumed to be of known pedigree, so a modernized MIL-HDBK-217 methodology will be implemented.

Connector Model for Commercial Quality Using Operational Data (MMDS-009-N00-VV)

Reviewing the flow diagrams of Section 3.2, it was determined for the Micro-D connector that statistically sufficient operational data existed for this part type. A major industry integrator contractor has accumulated more than two billion on-orbit operating hours without failure from the GPS constellation. Often connector predictions are based upon one-half of a mating pair, but this operational data was collected not on a connector half but on the full connecting pair. Utilizing the 60th percentile of the χ^2 approach for components without failures, the prediction model for this single connector pair is shown as Eq. (68).

$$\lambda = 4.1408\text{E-}10\ (or\ 0.414\ FITs) \tag{68}$$

It is interesting to note that this operational data was based upon a wide range of operating temperatures, so no π_T adjustment is applied.

Connector Model for Commercial Quality of Known Pedigree (853050232)

The MIL-HDBK-217 model for connectors is shown as Eq. (69). The expression is comprised of basal failure rate (λ_b) and various adjustment factors associated with how the component is utilized within the design (π_T, π_K), the quality of the part (π_Q), and the expected use environment (π_E).

$$\lambda_p = \lambda_b \pi_T \pi_K \pi_Q \pi_E \times (1/2\ \ mating\ pair) \times 1\text{E-}06\ Failures\ per\ hour \tag{69}$$

This particular connector is a male RF connector plug, so the λ_b factor is 0.000410, the π_T factor is 1.455 (i.e., a baseplate temperature of 30°C and an assumed 17°C temperature rise to the component), the π_K factor is 1.000 (i.e., less than 0.05 mate-demate cycles per 1,000 hours), and the π_E factor is 0.500. This connector has a known pedigree and ANSI/VITA 51.1 suggests a π_Q of 1.000. The modernized MIL-HDBK-217 prediction model for this single connector is shown as Eq. (70) and the resultant value as Eq. (71).

$$\lambda_p = (0.000410)(1.455)(1.000)(1.000)(0.500) \times (1/2) \times 1\text{E-}06 \tag{70}$$

$$\lambda_p = 1.4911\text{E-}10\ (or\ 0.149\ FITs) \tag{71}$$

The traditional MIL-HDBK-217 approach would likely use a π_Q factor of two for general commercial-grade connectors and thus would predict twice as worse reliability for these types of connectors.

3.2.2.7 Crystals

The BOM contains a single commercial crystal (NX3225SA-24.000M-STD-CRS-2) of known pedigree operating at 24 MHz. A first approach of using the MIL-HDBK-217 methodology for quartz crystals will be implemented for reference but ultimately rejected for a more modernizing prediction using FIDES.

The MIL-HDBK-217 model for crystals is shown as Eq. (72). The expression is simply comprised of the basal failure rate (λ_b), the quality of the part (π_Q), and the expected use environment (π_E).

$$\lambda_p = \lambda_b \pi_Q \pi_E \times 1\text{E-}06\ Failures\ per\ hour \tag{72}$$

The basal failure rate is dependent on the operating frequency and, for 24 MHz, the λ_b is 0.027002, the π_Q factor is 2.100, and the π_E factor is 0.500 for a spaceflight environment. It is interesting to note that this is one of few components whose MIL-HDBK-217 model does not contain a π_T factor since the component's physics-of-failures model was deemed to be negligibly affected by temperature.

Given that this crystal is of known pedigree for this prediction endeavor, ANSI/VITA 51.1 suggests a π_Q of 1.000. The modernized MIL-HDBK-217 prediction model for this single crystal is shown as Eq. (73) and the resultant value as Eq. (74).

$$\lambda_p = (0.027002)(1.000)(0.500) \times 1\text{E-}06 \tag{73}$$

$$\lambda_p = 1.3501\text{E-}08\ (or\ 13.501\ FITs) \tag{74}$$

MIL-HDK-217 does a poor job at modernizing the prediction for quartz crystals (i.e., oscillators and resonators), so another approach using FIDES was considered and implemented. Recall that the FIDES general reliability model was previously shown as Eq. (60). For this crystal type, the $\lambda_{Physical}$ and Π_{PM} expressions are shown as Eq. (75) and Eq. (76), respectively.

$$\lambda_{Physical} = \lambda_{0\_Piezoelectic} \times \sum_i^{Phases} \left(\frac{t_{annual}}{8766}\right)_i \times \left(\Pi_{TE} + \Pi_{TCy} + \Pi_{Mech} + \Pi_{RH}\right)_i \times (\Pi_I)_i \tag{75}$$

$$\Pi_{PM} = e^{1.39 \times (1 - Part\_Grade) - 0.69} \tag{76}$$

For this crystal prediction effort (a surface-mounted resonator), the various prediction factors are denoted within Eq. (77) through Eq. (79).

$$\lambda_{Physical} = 0.790 \times 1 \times (0.800 + 0.042 + 0.150 + 0) \times (1.000) = 0.784\, FITs \tag{77}$$

$$\Pi_{PM} = e^{1.39\times(1-0.500)-0.69} = 1.005 \tag{78}$$

$$\Pi_{Process} = 4\ (i.e., FIDES\ default\ for\ this\ part\ type) \tag{79}$$

The modernized FIDES prediction model for this single crystal is shown as Eq. (80) and the resultant value as Eq. (81).

$$\lambda = (0.784)(1.005)(4.000) \tag{80}$$

$$\lambda = 3.1517\text{E-}09\ (or\ 3.152\ FITs) \tag{81}$$

The traditional MIL-HDBK-217 approach would likely use a π_Q factor of about two for commercial-grade connectors and thus would predict about twice as worse reliability for these types of crystals.

3.2.2.8 Fuses

The BOM contains a single commercial surface-mounted fuse (MFU0603FF05000P500) and a first approach of using the MIL-HDBK-217 methodology for fuses will be implemented for reference but ultimately rejected for a more modernizing prediction using FIDES. The MIL-HDBK-217 model for fuses is shown as Eq. (82). The expression is simply comprised of basal failure rate (λ_b) and the expected use environment (π_E), and contains no input to reflect a part's quality (π_Q). Additionally, the ANSI/VITA 51.1 document is mute about fuses and their likely commercial π_Q values.

$$\lambda_p = \lambda_b \pi_E \times 1\text{E-}06\ Failures\ per\ hour \tag{82}$$

The basal failure rate (λ_b) is 0.010000 and the π_E factor is 0.900 (not the typical 0.500 value) for a spaceflight environment. Again, it is interesting to note that this is one of few components whose MIL-HDBK-217 model does not contain a π_T factor since the component's physics-of-failure model was deemed to be negligibly affected by temperature. The traditional MIL-HDBK-217 prediction model for this single fuse is shown as Eq. (83) and the resultant value as Eq. (84).

$$\lambda_p = (0.010000)(0.900) \times 1\text{E-}06 \tag{83}$$

$$\lambda_p = 9.0000\text{E-}09\ (or\ 9.000\ FITs) \tag{84}$$

MIL-HDK-217 does a poor job at modernizing the prediction of fuses, so another approach using FIDES was considered and implemented. Recall that the FIDES general reliability model was previously shown as Eq. (60). For this fuse type, the $\lambda_{Physical}$ and Π_{PM} expressions are shown as Eq. (85) and Eq. (86), respectively.

$$\lambda_{Physical} = \lambda_{0\_Fuse} \times \sum_i^{Phases} \left(\frac{t_{annual}}{8766}\right)_i \times \left(\Pi_{TE} + \Pi_{TCy} + \Pi_{Mech} + \Pi_{RH} + \Pi_{Chem}\right)_i \times (\Pi_I)_i \tag{85}$$

$$\Pi_{PM} = e^{1.39\times(1-Part\_Grade)-0.69} \tag{86}$$

For this fuse prediction effort, the various prediction factors are denoted within Eq. (87) through Eq. (89).

$$\lambda_{Physical} = 0.500 \times 1 \times (0.026 + 0.036 + 0.060 + 0 + 0) \times (1.000) = 0.061\ FITs \tag{87}$$

$$\Pi_{PM} = e^{1.39\times(1-0.500)-0.69} = 1.005 \tag{88}$$

$$\Pi_{Process} = 4\ (i.e., FIDES\ default\ for\ this\ part\ type) \tag{89}$$

The modernized FIDES prediction model for this single fuse is shown as Eq. (90) and the resultant value as Eq. (91).

$$\lambda = (0.061)(1.005)(4.000) \tag{90}$$

$$\lambda = 2.4631\text{E-}10\ (or\ 0.246\ FITs) \tag{91}$$

It is interesting to note that the FIDES modernized approach to predicting fuse reliability is more than 36 times better (more reliable) than the traditional MIL-HDBK-217 methodology.

3.2.2.9 Integrated Circuits

The BOM contains 10 different commercial IC types to allow for the full exploration of the various modernizing prediction methods of these often-high-risk components. Reviewing the flow diagrams of Section 3.2, it was determined for all these ICs that there was insufficient operational data for the circuit card design under consideration. For the most part, vender accelerated life data will be utilized whenever possible since the various IC prediction models are often outdated or it is difficult to obtain all the pertinent data for the numerous factors. To simplify this analysis, it will be assumed that all the ICs experience a 16°C temperature rise from the baseplate temperature of 30°C (i.e., 46°C junction temperature).

IC Model for Commercial Quality Using Vendor Accelerated Life Data (LTC6993-1)

This IC has viable accelerated life data from the vendor (Analog Devices, see Appendix B for more vendor references). The vendor's website indicates that this part underwent 6,321,676,310 equivalent device hours based upon the Arrhenius model with an assumed E_a of 0.70 eV. This life test did not witness any failures, so the 60th percentile χ^2 estimate for mean life was 6,899,209,104 hours or a failure rate of 0.145 FITs. This vendor data is based upon a junction temperature of 55°C, but the website allows for assessments at different temperatures. For a junction temperature of 46°C, the failure rate is 0.072 FITs. Assuming the vendor accelerated life testing was executed within a ground-benign environment, a conversion factor to the spaceflight environment of 0.833 was utilized and the vendor-based prediction model for this single IC is shown as Eq. (92).

$$\lambda = (7.2116\text{E-}11 \times 0.833) = 6.0097\text{E-}11\ (or\ 0.060\ FITs) \tag{92}$$

IC Model for Commercial Quality Using Traditional MIL-HDBK-217 (XR21B1424IV64-F)

Unfortunately, this IC does not have viable accelerated life data from the vendor, so the MIL-HDBK-217 model for this type of IC is shown as Eq. (93). The expression is comprised of various adjustment factors associated with how the component is utilized within the design (π_T, π_L), the quality of the part (π_Q), and the expected use environment (π_E). The IC model also contains a die complexity factor (C_1) and a packaging factor (C_2) correlated to the number of functional pins (or leads).

$$\lambda_p = (C_1\pi_T + C_2\pi_E)\pi_Q\pi_L \times 1\text{E-}06\ Failures\ per\ hour \tag{93}$$

This IC is a universal serial bus–to–universal asynchronous receiver-transmitter bridge with 64 functional pins. It can be difficult to obtain all the information needed to execute a prediction from a component datasheet, but for this exercise, it will be assumed that the IC is a digital silicon metal-oxide semiconductor (MOS) device with 200,000 gates, flatpack packaging, and has been in production for more than 2 years.

For this device, the π_T factor is 0.245 (i.e., a baseplate temperature of 30°C and an assumed 16°C temperature rise to the component), the C_2 factor is 0.058, the π_E factor is again 0.500, the π_Q factor is 10.000 for commercial quality, and the π_L factor is 1.000. Determining the C_1 factor is often the most difficult aspect of utilizing the MIL-HDBK-217 methodology for IC parts because MIL-HDBK-217 does not have contemporary tables for the numbers of transistors, gates, and bits. Using the existing C_1 table values for digital MOS gates to fit a linear expression and then extrapolating to 200,000 gates yields a C_1 factor of 1.837. The prediction model for this single IC is shown as Eq. (94) and the resultant value as Eq. (95).

$$\lambda_p = [(1.837)(0.245) + (0.058)(0.500)](10.000)(1.000) \times 1\text{E-}06\ Failures\ per\ hour \tag{94}$$

$$\lambda_p = 4.7965\text{E-}06\ (or > 4{,}796\ FITs) \tag{95}$$

This result is so ridiculous that it clearly demonstrates the futility of using the MIL-HDBK-217 methodology for IC components. The part cannot utilize RAC factors as it is a commercial-grade part, and ANSI/VITA offers some help by suggesting the π_Q factor of 1.000, but that would still yield a prediction of more than 479 FITs for this component and many within the reliability community would say this prediction is still implausible. The preeminent approach for ICs is to visit the vendor's website for a component's accelerated life data, but the vendor did not provide such details for this part. This part prediction, if left as is, would dominate the card prediction by so much that the remainder of the prediction effort for the other components would be moot. The FIDES method was considered for this part, but again, obtaining all the factors to construct a viable prediction model can be challenging. Instead, a call was placed to the vendor seeking more insight into the design and possible existing vendor life data. The vendor indicated that the part has undergone extensive accelerated life data testing and at 46°C, and this part has a prediction of 31.2 FITs. The vendor confirmed that the accelerated life testing was executed within a ground-benign environment, so the conversion factor to the spaceflight environment of 0.833 was utilized and the vendor-based prediction model for this single IC is shown as Eq. (96).

$$\lambda = (3.1200\text{E-}08 \times 0.833) = 2.6000\text{E-}08\ (or\ 26.000\ FITs) \tag{96}$$

IC Model for Commercial Quality Using Vendor Accelerated Life Data (MIC2041-1YMM)

This IC has viable accelerated life data from the vendor (Microchip Technology) and the vendor's website indicates that this part underwent 6,835,792 equivalent device hours based upon the Arrhenius model with an assumed E_a of 0.70 eV. This life test did not witness any failures, so the 60th percentile χ^2 estimate for mean life was 581,364,998 hours or a failure rate of 1.720 FITs. This vendor data is based upon a junction temperature of 55°C and the website does not allow for additional assessments at different temperatures. Given that the test was executed at 125°C, an Arrhenius acceleration factor (A_F) of 156.1 was determined for a use temperature of 46°C. Thus, the equivalent device hours become 1,066,766,444 (i.e., 156.1 × 6,835,792 hours) and the failure rate becomes 0.859 FITs. Assuming the vendor accelerated life testing was executed within a ground-benign environment, a conversion factor to the spaceflight environment of 0.833 was utilized and the vendor-based prediction model for this single IC is shown as Eq. (97).

$$\lambda = (8.5893\text{E-}10 \times 0.833) = 7.1578\text{E-}10\ (or\ 0.716\ FITs) \tag{97}$$

IC Model for Commercial Quality Using Vendor Accelerated Life Data (USB5744-I/2G)

This IC has viable accelerated life data from the vendor (Microchip Technology) and the vendor's website indicates that this part underwent 12,803,571 equivalent device hours based upon the Arrhenius model with an assumed E_a of 0.70 eV. This life test witnessed one failure, so the 60th percentile χ^2 estimate for mean life was 493,373,741 hours or a failure rate of 2.027 FITs. This vendor data is based upon a junction temperature of 55°C and the website does not allow for additional assessments at different temperatures. Given that the test was executed at 125°C, an Arrhenius A_F of 156.1 was determined for a use temperature of 46°C. Thus, the equivalent device hours become 1,998,092,970 and the failure rate becomes 1.012 FITs (assuming the 60th percentile χ^2 estimator with one failure). Assuming the vendor accelerated life testing was executed within a ground-benign environment, a conversion factor to the spaceflight environment of 0.833 was utilized and the vendor-based prediction model for this single IC is shown as Eq. (98).

$$\lambda = (1.0121\text{E-}09 \times 0.833) = 8.4343\text{E-}10\ (or\ 0.843\ FITs) \tag{98}$$

IC Model for Commercial Quality Using Vendor Accelerated Life Data (M74VHC1G125DFT2G)

This IC has viable accelerated life data from the vendor (onsemi) and the vendor's website indicates that this part underwent 6,465,777,234 equivalent device hours based upon the Arrhenius model with an assumed E_a of 0.70 eV. This life test witnessed 2 failures, so the 60th percentile χ^2 estimate for mean life was 2,082,122,187 hours or a failure rate of 0.480 FITs. This vendor data is based upon a junction temperature of 55°C, but the website allows for additional assessments at different temperatures. For a junction temperature of 46°C, the failure rate is 0.239 FITs. Assuming the vendor accelerated life testing was executed within a ground-benign environment, a conversion factor to the spaceflight environment of 0.833 was utilized and the vendor-based prediction model for this single IC is shown as Eq. (99).

$$\lambda = (2.3896\text{E-}10 \times 0.833) = 1.9913\text{E-}10\ (or\ 0.199\ FITs) \tag{99}$$

IC Model for Commercial Quality Using Vendor Accelerated Life Data (TPS26600RHFT)

This IC has viable accelerated life data from the vendor (Texas Instruments) and the vendor's website indicates that this part underwent 87,285,000 equivalent device hours (i.e., 1,000 units tested for 87,285 hours) based upon the Arrhenius model with an assumed E_a of 0.70 eV. This life test did not witness any failures, so the 60th percentile χ^2 estimate for mean life was 7,470,000,000 hours or a failure rate of 0.134 FITs. This vendor data is based upon a junction temperature of 55°C and the website does not readily allow for additional assessments at different temperatures. Given that the test was executed at 125°C, an Arrhenius A_F of 156.1 was determined for a use temperature of 46°C. Thus, the equivalent device hours become 13,621,476,763 and the failure rate becomes 0.067 FITs. Assuming the vendor accelerated life testing was executed within a ground-benign environment, a conversion factor to the spaceflight environment of 0.833 was utilized and the vendor-based prediction model for this single IC is shown as Eq. (100).

$$\lambda = (6.7268\text{E-}11 \times 0.833) = 5.6057\text{E-}11\ (or\ 0.056\ FITs) \tag{100}$$

IC Model for Commercial Quality Using Vendor Accelerated Life Data (TLV1704AMPWTPSEP)

This IC has viable accelerated life data from the vendor (Texas Instruments) and the vendor's website indicates that this part underwent 40,590,000 equivalent device hours (i.e., 1,000 units tested for 40,590 hours) based upon the Arrhenius model with an assumed E_a of 0.70 eV. This life test witnessed one failure so the 60th percentile χ^2 estimate for mean life was 1,580,000,000 hours or a failure rate of 0.633 FITs. This vendor data is based upon a junction temperature of 55°C and the website does not readily allow for additional assessments at different temperatures. Given that the test was executed at 125°C, an Arrhenius A_F of 156.1 was determined for a use temperature of 46°C. Thus, the equivalent device hours become 6,334,372,937 and the failure rate becomes 0.319 FITs (assuming the 60th percentile χ^2 estimator with one failure). Assuming the vendor accelerated life testing was executed within a ground-benign environment, a conversion factor to the spaceflight environment of 0.833 was utilized and the vendor-based prediction model for this single IC is shown as Eq. (101).

$$\lambda = (3.1926\text{E-}10 \times 0.833) = 2.6605\text{E-}10\ (or\ 0.266\ FITs) \tag{101}$$

IC Model for Commercial Quality Using Vendor Accelerated Life Data (XQZU9EG)

This IC has viable accelerated life data from the vendor (Advanced Micro Devices) that is periodically published in a reliability report. Utilizing the vendor's May 2023 report, the accelerated life test data for this 16 nm Xilinx field-programmable gate array (FPGA) UltraScale+ device is delineated within Table 36 of that reliability report. For this part, the vendor report indicates a reliability of about 11 FITs based upon approximately 83 million equivalent device hours at 55°C with no failures witnessed. Again, this accelerated life data utilizes the Arrhenius model with an assumed E_a of 0.70 eV and the 60th percentile χ^2 estimate for mean life was 91,159,804 hours or a failure rate of 10.970 FITs. This vendor data is based upon a junction temperature of 55°C and the report does not readily allow for additional assessments at different temperatures. Given that the test was executed at 125°C, an Arrhenius A_F of 156.1 was determined for a use temperature of 46°C. Thus, the equivalent device hours become 167,882,575 and the failure rate becomes 5.458 FITs (assuming the 60th percentile χ^2 estimator with no failures). Assuming the vendor accelerated life testing was executed within a ground-benign environment, a conversion factor to the spaceflight environment of 0.833 was utilized and the vendor-based prediction model for this single IC is shown as Eq. (102).

$$\lambda = (5.4579\text{E-}09 \times 0.833) = 4.5483\text{E-}09\ (or\ 4.548\ FITs) \tag{102}$$

IC Model for Commercial Quality Using Vendor Accelerated Life Data (93LC56BT-I/OT)

This IC has viable accelerated life data from the vendor (Microchip Technology) and the vendor's website indicates that this part underwent 29,655,960 equivalent device hours based upon the Arrhenius model with an assumed E_a of 0.70 eV. This life test witnessed 6 failures so the 60th percentile χ^2 estimate for mean life was 1,051,540,155 hours or a failure rate of 0.951 FITs. This vendor data is based upon a junction temperature of 55°C and the website does not allow for additional assessments at different temperatures. Given that the test was executed at 150°C, an Arrhenius A_F of 520.9 was determined for a use temperature of 46°C. Thus, the equivalent device hours become 15,448,509,488 and the failure rate becomes 0.475 FITs (assuming the 60th percentile χ^2 estimator with 6 failures). Assuming the vendor accelerated life testing was executed within a ground-benign environment, a conversion factor to the spaceflight environment of 0.833 is utilized and this vendor-based prediction model for this single IC is shown as Eq. (103).

$$\lambda = (4.7530\text{E-}10 \times 0.833) = 3.9608\text{E-}10\ (or\ 0.396\ FITs) \tag{103}$$

This particular IC is an electrically erasable programmable read-only memory (EEPROM) memory device and, historically, the MIL-HDBK-217 approach has significant difficulties providing a viable prediction, mainly due to archaic die complexity (C_1) and life programming cycles (λ_{cyc}) factors within the prediction model. This example used vendor accelerated life data to overcome those limitations, but the next example of an IC memory component will illustrate the quandary of using MIL-HDBK-217 for memory devices.

IC Model for Commercial Quality Using Vendor Accelerated Life Data (MT41K256M16TW)

This IC is a synchronous dynamic random-access memory (SDRAM) memory device with 32 MB of memory and 96 ball connections (i.e., functional pins). As illustrated previously, the MIL-HDBK-217 methodology for IC components yields questionable results. The MIL-HDBK-217 approach does not have contemporary factors for modern gigabyte-sized memory devices and thus alternative approaches to developing a viable prediction should be considered. First, the vendor was contacted, and they indicated that device underwent extensive accelerated life testing yielding 27 FITs at 46°C. The vendor confirmed that the accelerated life testing was executed within a ground-benign environment, so the conversion factor to the spaceflight environment of 0.833 was utilized and the vendor-based prediction model for this single IC is shown as Eq. (104).

$$\lambda = (2.7000\text{E-}08 \times 0.833) = 2.2500\text{E-}08\ (or\ 22.500\ FITs) \tag{104}$$

There was some concern that the accelerated life data may have been too optimistic, based on limited operation data, so it was decided to construct a dedicated accelerated life test for this part to vet the vendor's analysis. An Arrhenius accelerated life test of 150 units was conducted for a month (720 hours) with 50 units each undergoing a thermal accelerant of 125°C, 135°C, or 150°C. Unfortunately, this test was not long enough to witness any failures at any of the three thermal stress levels, so the activation energy could not be determined by the test data. Assuming an E_a of 0.70 eV (as also assumed by the vendor's analysis) and a use temperature of 46°C, this part underwent 33,632,786 equivalent device hours and the 60th percentile χ^2 estimate for mean life was 36,705,365 hours or a failure rate of 27.244 FITs. This result was so nearly the vendor's own life test results that the vendor's analysis was vetted and deemed appropriate for this prediction exercise.

Again, it should be emphasized that when using contemporary vendor component reliability data, it should not be modernized (i.e., using RAC factors, ANSI/VITA, etc.) because the basal accelerated life data already contains the effects of modernization.

3.3 Summary

This modernized prediction effort of a notional circuit card illustrated use of the best data available for each component. The goal of this prediction effort was meant to thoroughly explore the various paths of the flow diagram delineated within Section 3. This prediction example was intended to be an academic exercise and not meant to bias the reader toward one prediction method over another, but to examine several prediction tools readily available. Assuming the 100 components of the notional BOM are all needed for the viable operations of the circuit card (i.e., no internal redundancy or telemetry aspects embedded on the card), the aggregate card prediction is shown as Eq. (105) (See Appendix A for part type and quantity).

$$\lambda_{card} = \sum \lambda_{components} = 1.8953\text{E-}07\ (or\ {\sim}190\ FITs) \tag{105}$$

A risk breakdown of the components is illustrated as Figure 3. The top risk driver is based upon the aggregate risk of the 31 IC components. The vast majority of this risk is from the four USB bridge parts that collectively represent approximately 55 percent of the card risk, and the single SDRAM memory device, which is approximately 12 percent of the card risk. Another approximately 11percent of the card risk comes from the toroidal transformer that is using the surrogacy approach from establishing its failure rate. These proportionally-higher-risk driver components could warrant a deeper review of their prediction methods and failure rate data sources. Obtaining higher fidelity predictions via operational data or life test should be contemplated for these particular components of the circuit card.

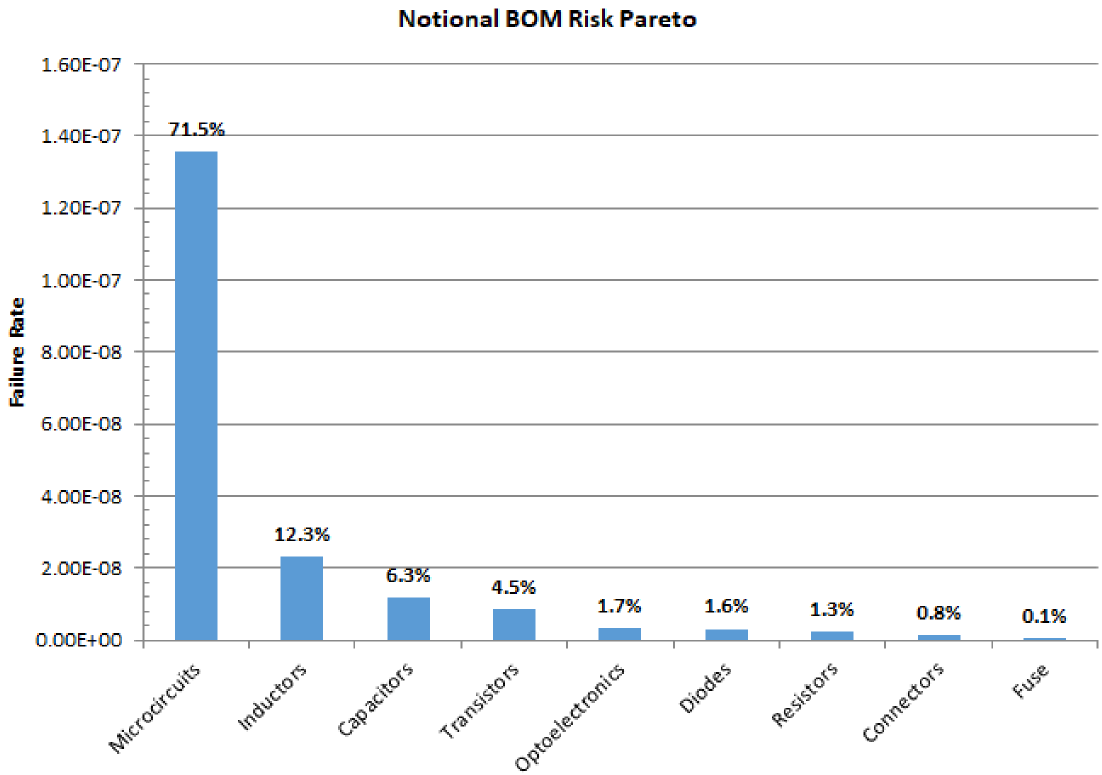

Figure 3. Notional circuit card risk Pareto graph.

It is interesting to note that solely using MIL-HDBK-217 results in a card-level failure rate prediction of approximately 20,800 FITs, while the alternate or modernized methods demonstrated in this ATR results in a prediction of 189.5 FITS. The traditional MIL-HDBK-217 approach, yielding results that are two orders of magnitude worse, strongly supports the necessity to utilize modernizing prediction techniques or, better yet, viable operational data or life data when it is available.

Figure 4 summarizes the results from the modernized approaches shown in Section 3.2 and compares them to the traditional MIL-HDBK-217 approach. The table also identifies the method utilized and the failure rate improvement (%) when using the recommendations from Section 3.2.

Ref Des	Name	Part No	$\Sigma\lambda_P$ (217)	$\Sigma\lambda_P$ (New)	Method	%
C1-C8	Cap Ceramic 10uF 50V X5R 20% Pad SMD 1206 85C Automotive T/R	GRT31CR61H106ME01L	2.803E-07	2.803E-09	ANSI/VITA	99%
C9-C13	3300pF ±10% 500V Ceramic Capacitor X7R 0603	C0603V332KCRAC7867	2.554E-08	8.513E-09	ANSI/VITA	67%
C14-C20	Capacitor, Ceramic, 1uF, 10%, 25V	M3253505E2Z105KZTB	5.286E-10	5.980E-10	RAC Factor	13%
R1-R10	RES SMD 1M OHM 1% 1/10W 0402	ERJ-2RKF1004X	5.082E-08	5.082E-10	ANSI/VITA	99%
R11, R12	RES SMD 20 OHM 0.1% 3/8W 0603	PHP00603E20R0BST1	1.702E-08	1.702E-09	ANSI/VITA	90%
R13, R14	Resistor, 1K ohm, 0.1%, 0.15W	M55342E06B1B00R	1.175E-10	1.191E-10	RAC Factor	1%
R15, R16	62 kOhms ±0.05% 0.6W Resistor Radial Non-Inductive Metal Foil	RNC90Z62K000AM	6.054E-11	6.133E-11	RAC Factor	1%
R17	562 Ohms ±1% 0.1W, 1/10W Chip Resistor 0603	CRCW0603562RFKEC	8.288E-11	1.852E-11	Datasheet	78%
D1	DIODE SCHOTTKY 100V 3A DO214AC	SK310A-LTP	4.970E-09	6.212E-10	ANSI/VITA	88%
D2, D3	DIODE SCHOTTKY 70V 100MA SOD923	NSVR0170P2T5G	1.209E-09	1.511E-10	RAC Factor	88%
D4	DIODE ZENER 3.3V 500MW DO213AA	JANTX1N4620UR-1	1.154E-09	1.649E-09	RAC Factor	43%
D5	Zener Diode 11.7 V 500 mW ±5%	JANS1N941B-1	1.154E-09	5.770E-10	RAC Factor	50%
Q1-Q10	MOSFET N-CH 60V 280MA SOT-323, 500mW	BSS138WH6327XTSA1	6.398E-07	7.997E-09	ANSI/VITA	99%
Q11, Q12	TRANS NPN 45V 0.1A SOT-23, 350mW	MMBT5962	3.156E-10	4.106E-10	Vendor Data	30%
Q13-Q15	Bipolar (BJT) Transistor NPN 50 V 800 mA 500 mW	JANS2N2222A	1.810E-10	9.050E-11	RAC Factor	50%
L1	12 µH Shielded Drum Core, Wirewound Inductor 3.91 A 27mOhm	744771112	1.980E-07	7.200E-10	Telcordia	100%
L2	Transformer, toroidal, Ground Benign	Surrogate Data	6.198E-08	2.066E-08	EPRD	67%
L3	RF Balun 10MHz ~ 8GHz 50 / 50Ohm 6-SMD Module	TCM1-83X+	1.800E-08	1.865E-09	FIDES	90%
J1, J2, J3	9 Pin, Micro-D, Surface Mount Vertical, Sockets	MMDS-009-N00-VV	2.484E-09	1.242E-09	Op Data	50%
J4	SMP Connector Plug, Male Pin 50 Ohms Surface Mount Solder	8.5305E+08	5.964E-10	2.982E-10	ANSI/VITA	50%
Y1	4 MHz ±15ppm Crystal 8pF 50 Ohms 4-SMD	NX3225SA-24.000M-STD-CRS-2	2.835E-08	3.152E-09	FIDES	89%
F1	5 A AC 32 VDC Fuse Board Mount	MFU0603FF05000P500	9.000E-09	2.463E-10	FIDES	97%
U1-U16	IC MONOSTABLE MULTIVIBRATOR 6DFN	LTC6993-1	9.615E-09	9.615E-10	Vendor Data	90%
U17-U20	IC UART BRIDGE TO USB 4CH 64LQFP	XR21B1424IV64-F	1.919E-05	1.040E-07	Vendor Data	99%
U21, U22	IC DISTRIBUTION SW SGL 10-MSOP	MIC2041-1YMM	1.432E-08	1.432E-09	Vendor Data	90%
U23	USB Hub Controller, USB 2.0, 3.0, 3 V, 3.6 V, SQFN, 56 Pins	USB5744-I/2G	8.434E-09	8.434E-10	Vendor Data	90%
U24	Buffer, Non-Inverting 1 Element 1 Bit per Element 3-State Output	M74VHC1G125DFT2G	1.991E-09	1.991E-10	Vendor Data	90%
U25, U26	IC PWR MGMT EFUSE 60V 24VQFN	TPS26600RHFT	1.121E-09	1.121E-10	Vendor Data	90%
U27, U28	Analog Comparators 2.2-V to 36-V, space enhanced plastic	TLV1704AMPWTPSEP	5.321E-09	5.321E-10	Vendor Data	90%
U29	XQ Zynq UltraScale+ MPSoC	XQZU9EG	4.548E-08	4.548E-09	Vendor Data	90%
U30	EEPROM Memory IC 2Kbit Microwire 2 MHz SOT-23-6	93LC56BT-I/OT	3.961E-09	3.961E-10	Vendor Data	90%
U31	SDRAM - DDR3L Memory IC 4Gbit Parallel 933 MHz 20 ns 96-FBGA	MT41K256M16TW	2.250E-07	2.250E-08	ALT	90%
		Total	**2.084E-05**	**1.895E-07**		**99%**

Figure 4. Comparison of traditional MIL-HDBK-217 and modernized predictions from Section 3.2.

4. Future Work

This ATR presents an overview of alternative handbooks and approaches to tailoring or replacing MIL-HDBK-217, and puts forward a recommended approach along with a set of examples. The ATR defines the scope of what is being addressed and a short list of what is defined to be “out of scope.” The following is a list of topics that can be covered in future updates of this ATR or in a new ATR:

- Part Testing: Define general test methods and approaches to demonstrate component failure modes and part lifetime.
- Exploring other Handbooks: Conduct a deep dive on other handbooks such as FIDES.
- Radiation: Develop methods to employ radiation testing results and incorporate destructive single event effect rates in the failure rate analysis of a component.
- Non-EEE Part-Based Reliability Prediction: Analyze methods to address electromechanical and nonelectromechanical assemblies.
- Wearout: Address component reliability beyond required design life. For further discussion, see Section 0, “Commentary on the Bathtub Curve,” and TOR-2021-00259, *Estimating Satellite Reliability Beyond Design Life* [11].
- Physics-Based Simulations: Compare and contrast recommended methods to define physics-of-failure or physics-based simulations to understand a component’s failure modes.
- Expert Elicitation: Describe methods and examples to demonstrate when expert elicitation is useful and necessary.
- Unit and System Reliability: Recommend best approaches on conducting reliability assessments at unit, subsystem, and system levels utilizing various techniques, such as highly accelerated life test (HALT), highly accelerated stress test (HAST), etc.
- Study Case: Recommend a known program that has been on orbit for some time and compare the old versus new method versus on-orbit data.

5. Summary and Conclusions

This ATR discussed the various approaches to obtain failure rate data, via handbooks, that address the deficiencies of MIL-HDBK-217. The document discussed the pros and cons of the various published handbooks along with the recommended uses. Throughout the document, examples are shown, along with various recommendations from a team of representatives across the space systems industry. These recommendations are in place to provide consistency throughout the industry when conducting failure rate analysis of EEE parts, circuit card assemblies, and units. This document enables all reliability engineers to utilize various sources and encourages alternative ways to the legacy practice of using MIL-HDBK-217. Contract language should reference this ATR and use it as a basis to drive consistency among all subcontractors. Finally, the space industry should align these recommendations through the means of presentations and education so that desired use of these recommendations will be achieved.

6. Acronyms and Abbreviations

ANSI	American National Standards Institute
BALUN	balanced-to-unbalanced
BOM	bill of materials
E_a	activation energy
EEE	electrical, electromechanical, and electronic
ELFR	Early Life Failure Rate
EPRD	Electronic Parts Reliability Data
eV	electron volt
FET	field-effect transistor
FIT	failure in time (one billion hours)
FPMH	failures per million hours
GPS	Global Positioning System
HALT	highly accelerated life test
HAST	highly accelerated stress test
HDBK	handbook
HTOL	High Temperature Operational Life
JANS	Joint Army Navy Space
JANTX	Joint Army Navy Testing Extra
MHz	megahertz
MIL	military
MOSFET	metal-oxide semiconductor field-effect transistor
NPN	negative-positive-negative
OEM	original equipment manufacturer
RAC	Reliability Analysis Center
RF	radio frequency
RIAC	Reliability Information Analysis Center
URL	uniform resource locator
VITA	VMEbus International Trade Association

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Appendix A. A Notional Bill of Materials

The BOM excerpt in Figure 5 does not represent a true circuit card design and is specifically contrived for the pedagogical endeavor to develop a modernized prediction by exploring the various failure sources and prediction techniques. The BOM excerpt is provided to facilitate readers in attempting to mimic the analyses of Section 3.3 or develop their own modernizing prediction approaches.

Ref Des	Name	Part No	Qty
C1-C8	Cap Ceramic 10uF 50V X5R 20% Pad SMD 1206 85C Automotive T/R	GRT31CR61H106ME01L	8
C9-C13	3300pF ±10% 500V Ceramic Capacitor X7R 0603	C0603V332KCRAC7867	5
C14-C20	Capacitor, Ceramic, 1uF, 10%, 25V	M3253505E2Z105KZTB	7
R1-R10	RES SMD 1M OHM 1% 1/10W 0402	ERJ-2RKF1004X	10
R11, R12	RES SMD 20 OHM 0.1% 3/8W 0603	PHP00603E20R0BST1	2
R13, R14	Resistor, 1K ohm, 0.1%, 0.15W	M55342E06B1B00R	2
R15, R16	62 kOhms ±0.05% 0.6W Resistor Radial Non-Inductive Metal Foil	RNC90Z62K000AM	2
R17	562 Ohms ±1% 0.1W, 1/10W Chip Resistor 0603	CRCW0603562RFKEC	1
D1	DIODE SCHOTTKY 100V 3A DO214AC	SK310A-LTP	1
D2, D3	DIODE SCHOTTKY 70V 100MA SOD923	NSVR0170P2T5G	2
D4	DIODE ZENER 3.3V 500MW DO213AA	JANTX1N4620UR-1	1
D5	Zener Diode 11.7 V 500 mW ±5%	JANS1N941B-1	1
Q1-Q10	MOSFET N-CH 60V 280MA SOT-323, 500mW	BSS138WH6327XTSA1	10
Q11, Q12	TRANS NPN 45V 0.1A SOT-23, 350mW	MMBT5962	2
Q13-Q15	Bipolar (BJT) Transistor NPN 50 V 800 mA 500 mW	JANS2N2222A	3
L1	12 µH Shielded Drum Core, Wirewound Inductor 3.91 A 27mOhm	744771112	2
L2	Transformer, Power, Ground Benign	Surrogate Data	1
L3	RF Balun 10MHz ~ 8GHz 50 / 50Ohm 6-SMD Module	TCM1-83X+	2
J1, J2, J3	9 Pin, Micro-D, Surface Mount Vertical, Sockets	MMDS-009-N00-VV	3
J4	SMP Connector Plug, Male Pin 50 Ohms Surface Mount Solder	853050232	2
Y1	4 MHz ±15ppm Crystal 8pF 50 Ohms 4-SMD	NX3225SA-24.000M-STD-CRS-2	1
F1	5 A AC 32 V DC Fuse Board Mount	MFU0603FF05000P500	1
U1-U16	IC MONOSTABLE MULTIVIBRATOR 6DFN	LTC6993-1	16
U17-U20	IC UART BRIDGE TO USB 4CH 64LQFP	XR21B1424IV64-F	4
U21, U22	IC DISTRIBUTION SW SGL 10-MSOP	MIC2041-1YMM	2
U23	USB Hub Controller, USB 2.0, 3.0, 3 V, 3.6 V, SQFN, 56 Pins	USB5744-I/2G	1
U24	Buffer, Non-Inverting 1 Element 1 Bit per Element 3-State Output	M74VHC1G125DFT2G	1
U25, U26	IC PWR MGMT EFUSE 60V 24VQFN	TPS26600RHFT	2
U27, U28	Analog Comparators 2.2-V to 36-V, space enhanced plastic	TLV1704AMPWTPSEP	2
U29	XQ Zynq UltraScale+ MPSoC	XQZU9EG	1
U30	EEPROM Memory IC 2Kbit Microwire 2 MHz SOT-23-6	93LC56BT-I/OT	1
U31	SDRAM - DDR3L Memory IC 4Gbit Parallel 933 MHz 20 ns 96-FBGA	MT41K256M16TW	1

Figure 5. Example bill of materials.

Appendix B. Vendor Data Source Rolodex

A list of common component vendors' life testing websites are provided as Table 3. While this list is extensive, it is not exhaustive and future work would seek to expand this list.

Table 3. Table of Vendor Data Sources

Company	Reliability Website
Texas Instruments (TI)	https://www.ti.com/quality/docs/estimator.tsp?partType=tiPartNumber&partNumber
National Semiconductor	Acquired by TI September 2011; life data included in Texas Instruments' website
Analog Devices	https://www.analog.com/en/about-adi/quality-reliability/reliability-data/wafer-fabrication-data.html
Linear Technology	Acquired by Analog Devices March 2017; life data included in Analog Devices' website
Maxim Integrated	Acquired by Analog Devices August 2021; life data not yet included in Analog Devices' website
ON Semiconductor	https://www.onsemi.com/PowerSolutions/reliability.do?device
Microchip Technology	
Microsemi	Acquired by Microchip May 2018; FPGA RT0001 v17 reliability report
	https://www.microchip.com/reliabilityreport/#/
Advanced Micro Devices (AMD)	
Xilinx	Acquired by AMD February 2022; FPGA 2nd half 2021 UG116 v19.16 device reliability report
	https://www.xilinx.com/support/quality.html#documentation
Renesas	https://www.renesas.com/us/en/support/quality-reliability/reliability-report-search
Intersil	Acquired by Renesas February 2017; life data included in Renesas' website
SEMTECH	https://www.semtech.com/quality/reliability
Murata Manufacturing	
Peregrine Semiconductor (pSemi)	Quarterly reliability report available; acquired by Murata Manufacturing in September 2014
	https://www.psemi.com/company/quality
Cobham	Request data via supplier
Data Device Corp (DDC)	Request data via supplier
GlobalFoundries	Vendor maintains quarterly reliability and quality report that is available upon request
Efficient Power Conversion	https://epc-co.com/epc/design-support/gan-fet-reliability
Infineon Technologies	https://www.infineon.com/cms/en/product

Appendix C. List of Published Handbook Sources [20]

Data Source	Data Source
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Export Control Office Approval Granted Electronically by:

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