

## ABSTRACT

Title of Thesis: ASSESSMENT OF FIDES RELIABILITY  
PREDICTION METHODOLOGY

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The FIDES Guide is a reliability prediction handbook published by a group of European defense and aerospace manufacturers under the supervision of the French Ministry of Defense. This paper evaluates the suitability of FIDES for predicting reliability based on the model used to calculate the failure rate, and the accuracy of its reliability predictions. The evaluation makes use of IEEE Standard 1413, titled, "IEEE Standard Framework for Reliability Prediction of Hardware." The paper shows that FIDES is based on the erroneous assumption of a constant failure rate for electronics, and lacks key attributes (e.g., materials and geometry of components) required to make a prediction accurate or to be considered physics-of-failure based. FIDES predictions are not reproducible due to subjective factors, selection of which varies depending on who is making the prediction.

ASSESSMENT OF FIDES RELIABILITY PREDICTION METHODOLOGY

by

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## **Dedication**

This work is wholeheartedly dedicated to my parents and grandparents for their unwavering support, encouragement, and motivation.

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## Chapter 1. Introduction

Reliability is the probability that an item will function as expected, within design specifications, for a predetermined amount of time, and under the typical life cycle and usage conditions. Reliability predictions can help compare different products, identify opportunities to improve the design of a system, provide logistic support. Methods of predicting reliability include the use of handbooks, analysis of test data, analysis of field data, use of physics of-failure (PoF), and use of prognostics [1] [2] [3] [4].

The use of handbooks started with Radio Corporation of America's handbook [RCA TR-1100] in 1956, which was soon followed by the US department of defense's military handbook [MIL-HDBK-217] in 1961. Subsequently, various other organizations developed their approaches (progeny to MIL-HDBK-217), using the same general formulations, but with different model parameters and assumptions. These handbooks included British Telecom Materials and Components Centre's Handbook of Reliability Data [HRD5] [5], Siemens AG's failure rates of components [Siemens SN29500] [6], French National Center for Telecommunications' handbook [CNET RDF] and Bell Communications Research's handbook [Bellcore TR-TSY-000332] (now, Telcordia SR-322 [7]). Reliability prediction handbooks predict a constant failure rate ( $\lambda_p$ ) for the electronics using the following general formulation:

$$\lambda_p = f(\lambda_G, \pi_i)$$

$\lambda_G$  – constant part failure rate tabulated in the handbook

$\pi_i$  – adjustment factors for the assumed constant failure rates

## 1.1. FIDES Guide and Reliability Prediction Model

The FIDES group was formed in 2000 by Thales Avionics, Thales Underwater Systems, Thales Airborne Systems, Airbus, Nexter Electronics, Eurocopter, and MBDA Missile Systems—all European and primarily French defense and aerospace manufacturers. The objective of the group was to develop an accurate reliability prediction method for electronics that accounted for the new technologies and provided “an alternative to obsolete MIL HDBK 217 and IEC 62380 [8]. The group developed the FIDES methodology under the supervision of the French Ministry of Defense and released it as FIDES Guide 2004 Edition A in 2004. A revised version, FIDES Guide 2009, was published in 2010 [9]<sup>1</sup>. FIDES Guide is also a French standard UTE 80811 [10]. FIDES methodology is accepted as a reliability prediction method by some European defense and aerospace organizations, and it is reported to have made reliability predictions for various products such as converters in photovoltaic systems [11] [12] [13], power modules in commercial aircraft’s power electrical control units [14], shipboard circuit card assemblies [15], electronic circuit of compact fluorescent lamps [16] and mechatronic systems [17].

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<sup>1</sup> FIDES Guide is currently being adopted as an IEC standard, IEC 63142 [28]. Many commercial reliability prediction software tools (such as Reliasoft, ALD-RAM Commander, Isograph, item QT, and BQR MTBF prediction software) include FIDES methodology.

The FIDES methodology lists a process for predicting the failure rates of electrical, electronic, and electromechanical components, and claims to be designed for commercial off-the-shelf (COTS)<sup>2</sup> components [18]. FIDES methodology claims to apply to all industries where electronics are used, such as aeronautics, space, military, naval, electricity production and distribution, and home appliances [19]. This methodology, like the other handbook-based methods, assumes the failure rates of electronic systems follow a bathtub curve; that is, an initial infant mortality period is followed by a useful life period with a constant failure rate and then by a wear-out period. FIDES, like other handbooks, excludes the infant mortality and wear-out periods of this curve from its predictions, and only a constant failure rate is used as the sole metric for reliability in the form of ‘failures in time’ (FITs). FIDES Guide states that the user should ensure that the components have a sufficiently long useful life so that the components are all in their useful life period throughout their operation, without providing a methodology to make that assessment.

The reliability prediction model of FIDES is formed by three factors, namely, the physical contributing factor ( $\lambda_{\text{Physical}}$ ), the part manufacturing factor ( $\Pi_{\text{PM}}$ ), and the process factor ( $\Pi_{\text{Process}}$ ). The general model of the FIDES methodology for calculating the failure rate ( $\lambda$ ) is given by Equation 1. FIDES Guide mentions, “ $\lambda_{\text{Physical}}$  represents the physical contribution.” This factor is claimed to account for the stresses acting on the component. The FIDES Guide also claims, “ $\Pi_{\text{PM}}$  (PM for Part Manufacturing) represents the quality and technical control over manufacturing of the item” and

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<sup>2</sup> FIDES defines COTS as any item available in the domestic or foreign market, for which the customer has no control over the item definition and production process, and which can be bought from a catalogue with a supplier reference [50].

“ $\Pi_{\text{Process}}$  represents the quality and technical control over the development, manufacturing and usage process for the product containing the item” [18]. The equations for the individual factors of equation 1.1 are shown in equations 1.2, 1.3, 1.4 and 1.5. Figure 1 provides a graphical representation of the FIDES model. Table I shows the descriptions of the subfactors used in these equations.

$$\lambda = \lambda_{\text{Physical}} \times \Pi_{\text{PM}} \times \Pi_{\text{Process}} \quad 1.1$$

$$\lambda_{\text{Physical}} = \left[ \sum_i^{\text{Phases}} \left( \frac{\text{Annual\_time}_{\text{Phase}-i}}{8760} \cdot \left( \sum_j^{\text{Physical-contribution}} (\lambda_{0-j} \cdot \Pi_{\text{acceleration}-j}) \right) \cdot \left( \Pi_{\text{Placement}} \times \Pi_{\text{application}} \times \Pi_{\text{ruggedizing}} \right)^{0.511 \times \text{Ln}(C_{\text{sensitivity}})} \right) \right] \quad 1.2$$

$$\Pi_{\text{PM}}(\text{for active components}) = e^{1.39 \left( 1 - \left( \frac{(\text{QA}_{\text{manufacturer}} + \text{QA}_{\text{component}} + \text{RA}_{\text{component}}) \times \varepsilon}{36} \right) \right) - 0.69} \quad 1.3$$

$$\Pi_{\text{PM}}(\text{for passive components}) = e^{1.39 \left( 1 - \left( \frac{(\text{QA}_{\text{manufacturer}} + \text{QA}_{\text{component}}) \times \varepsilon}{24} \right) \right) - 0.69} \quad 1.4$$

$$\Pi_{\text{Process}} = e^{2.079 \left( 1 - \left( \sum_{j=1}^7 \left( \text{Contribution\_Phase}_j \times \frac{\text{Audit\_Mark}_j}{\text{Max\_audit\_mark}_j} \right) \right) \right)} \quad 1.5$$

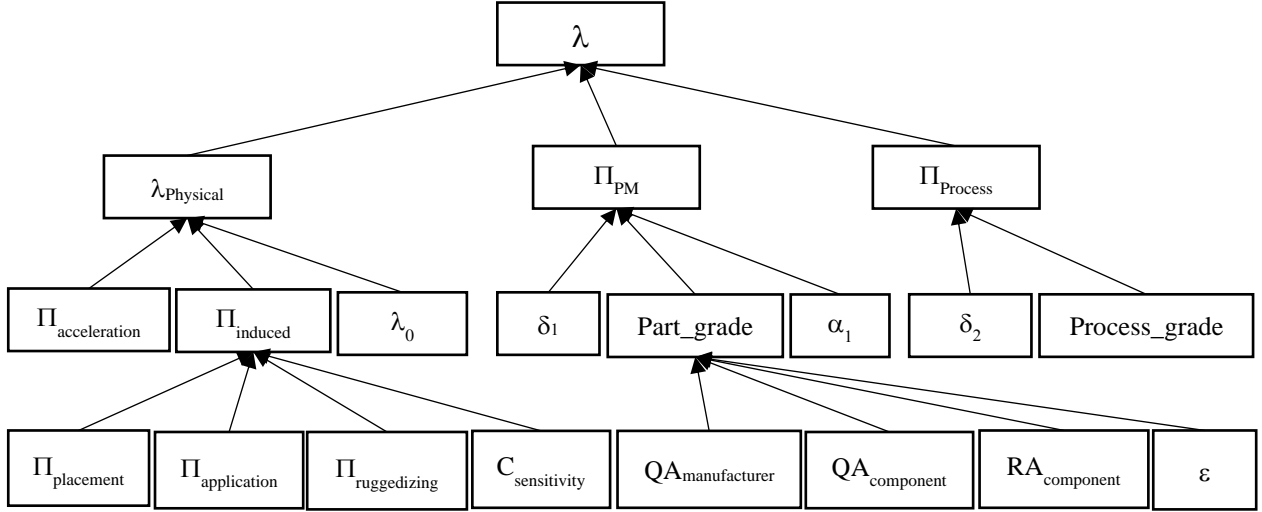


Figure 1: Factors involved in the reliability prediction model of FIDES

Table 1: Factors calculated by FIDES and their description

Factor	Description
$\lambda_0$	“ $\lambda_0$ is the basic failure rate of the item” [18]. Depending on the component family, the basic failure rate can be one value to be used for all the stresses considered, or it can vary based on the type of stress.
$\Pi_{\text{acceleration}}$	“ $\Pi_{\text{acceleration}}$ is an acceleration factor translating the sensitivity to usage conditions” [18]. The acceleration factors are calculated for all operational or non-operational phases to account for stresses such as temperature, temperature cycling, relative humidity, vibration, and chemicals on the component. These individual acceleration factors are later multiplied by their respective basic failure rates.
$\Pi_{\text{placement}}$	“ $\Pi_{\text{placement}}$ represents the influence of the item placement in the equipment or the system. In this case placement refers to the position of the item or the function in which it is integrated (particularly whether or not it is interfaced)” [18].
$\Pi_{\text{application}}$	“ $\Pi_{\text{application}}$ represents the influence of the usage environment for application of the product containing the item” [18]. It is calculated based on the possibility of exposure of the product to overstresses during usage.

Factor	Description
$\Pi_{\text{ruggedizing}}$	“ $\Pi_{\text{ruggedizing}}$ represents the influence of the policy for taking account of overstresses in the product development” [18]. It is based on the level of implementation of the recommendations (i.e., the audit questions) provided by FIDES Guide.
$C_{\text{sensitivity}}$	“ $C_{\text{sensitivity}}$ represents the coefficient of sensitivity to overstresses inherent to the item technology considered” [18]. It is provided as a fixed value for each component type.
$QA_{\text{manufacturer}}$	Takes into account the quality standards followed by the manufacturer. For each component family, FIDES Guide provides a ranking of the quality standards and assigns numerical values of $QA_{\text{manufacturer}}$ to each rank.
$QA_{\text{component}}$	“The $QA_{\text{component}}$ factor is defined for each item family. It takes account mainly of the qualification methodology without considering the severity of the tests defined in the mentioned standards” [18]. It considers the standard used for the component qualification. For each component family, FIDES Guide provides a ranking of the qualification standards and assigns numerical values of $QA_{\text{component}}$ to each rank.
$RA_{\text{component}}$	“Test severities for active components are taken into account by the $RA_{\text{component}}$ factor” [18]. This factor is not applicable for passive components.
$\varepsilon$	“The experience factor, $\varepsilon$ , must represent the component buyer's experience with his supplier. Therefore, this is a factor specific to each manufacturer” [18]. It is also selected from the tabulated values provided by FIDES Guide.
Process_grade	“Its [ $\Pi_{\text{Process}}$ ’s] purpose is to globally evaluate the maturity of the manufacturer on control over his reliability engineering process.... Process_grade is the mark reflecting this process control” [18]. It is based on the marks received during the audit (that is, Audit_mark).
Audit_mark	Total points received after the FIDES audit is performed. It is based on the weight assigned to each recommendation and the level at which the recommendation is applied
Contributing phase	The contributing phase is any phase involved in the life cycle of the product, from the formation of specifications to the operation and maintenance of the product (such as design, manufacturing of the board, integration into the assembly, and maintenance).

## 1.2. Literature Review

Literature review for this work can be classified into three categories. First category of literature includes the studies conducted on other handbooks. This includes literature assessing the fundamentals of handbooks as well as the studies comparing the prediction using other handbooks with the field data. The second category of handbooks include the literature published by the developers of FIDES Guide giving a historical perspective of the development of the FIDES methodology. The third category of literature includes the studies performed using the FIDES methodology.

While the handbooks found their way into reliability prediction practices, scientists and reliability practitioners identified the core problems with the handbook approach early on. Numerous studies have reported on the failings of the handbook methods [20] [21] [22] [23] [24]. Critiques of MIL-HDBK-217 made as early as 1993 by Cushing et al. [25] apply to all handbooks.

*“Due to Mil-Hdbk-217’s reliance upon field-failure data which are sparse until well after a new technology is mature, device failure-rate prediction methodologies heavily penalize new materials, structures, and technologies. This approach, based on fear of the unknown, rather than on science-based analysis, discourages change and cost-effective reliability enhancement. For designing and testing a new product or a product with new technologies,..., these models are both inappropriate and misleading.”*

Cushing et al. further state that the MIL-HDBK-217 did not collect and assess crucial failure details (e.g., failure site, failure mechanism, load/environment history,

materials, geometries, consequences of failure), which led to the following two consequences:

*“Mil-Hdbk-217 device failure-rate prediction methodology does not give the designer or manufacturer any insight into, or control over, the actual causes of failure since the cause-and-effect relationships impacting reliability are not captured. Yet, the failure rate obtained is often used as a reverse-engineering tool to meet reliability goals.”*

*“Mil-Hdbk-217 does not address the design & usage parameters[sic] that greatly influence reliability, which results in an inability to tailor a Mil-Hdbk-217 prediction using these key parameters.”*

Jais et al. [20] found that the handbooks have limitations associated with them. Firstly, the handbook models require historical field data and thus, the handbooks cannot keep pace with rapid advances in technology. Further, the handbooks are based on the assumption of constant failure rate which is not always true for electronics (explained in section..). Handbooks do not consider critical design parameters (such as the natural frequency of the board, location of maximum deflection on the board) while making the predictions. Also, the handbooks fail to provide insights into the causes of failure and so do not help in implementing appropriate corrective action.

In 2015, the National Research Council’s report, ‘Reliability Growth: Enhancing Defense System Reliability’ [26], made a broader statement applicable to all the handbook based methodologies by mentioning that,

*“The continued use of MIL-HDBK-217 or one of its adaptations can be destructive because it promotes poor engineering practices while also harming the growth of reliability of electronic products.”*

The report further clarified how the progeny of MIL-HDBK-217 continue to ignore the fundamental principles governing the degradation and failure of electronics by stating:

*“While each of these methodologies [progenies of MIL-HDBK-217] might have application-specific test conditions or data for newer components that were excluded from MIL-HDBK-217, they all still use the constant failure rate assumption in some capacity. Hence, each of these ‘new’ approaches continued to ignore the fundamental scientific principles that govern degradation and failure mechanics of electronic devices. These progeny, like their predecessor, failed to acknowledge that the degradation and failure of a component cannot be condensed into a single unique ‘constant failure rate’ metric.”*

These reviews reveal some fundamental problems associated with the reliability prediction handbooks. The models in the handbooks did not represent the behavior of electronics. The assumption of a constant failure (hazard) rate for electronics used by these models is faulty and misleading. The complexities of the handbook models are such that the uncertainties of the parameters of the models (such as part quality, environmental factors) cannot be assessed. Sufficient data was not there on the actual history of environmental and operating conditions to statistically develop the parameters of the model. There is no way to verify the models (and the model

parameters) independently from the available data. Finally, the failure rates of modern electronics are not only dependent on components but also factors such as interfacing, integration processes, and system maintenance, and these factors often get ignored by the handbooks.

FIDES Guide was formed to overcome the shortcomings of the previous handbooks. It claims to be different than other handbooks in its formulation. It claims that unlike previous handbooks, FIDES is not only based on curve fitting to failure data, but it also uses physics of failure.

Charpenel et al. [27] introduced the FIDES methodology before the first version of the FIDES Guide was officially released. They claim “FIDES is an alternative for the unsuitability of MIL-HSBK-217 [sic], lacks for harsh environments of UTE C 80-810 (RDF2000) and weaknesses in models and mission profile definition of PRISM methodology.” The article explains the generic FIDES model and provides information on the inputs required for using FIDES methodology. The generic FIDES model described by the article is the same as used by FIDES Guide 2009. This research assess the latest version of the handbook, FIDES Guide 2009, and the reliability prediction methodology prescribed by it.

Currently, the FIDES Guide is under revision and a PISTIS project has been conducted to collect data for this revision. Carton et al. [8] describe the PISTIS project as a study conducted for updating the FIDES models, the associated parameters and formulating new models for emerging technologies. It involves testing the components for more than two years by testing at “close to the actual extreme use conditions of

mission profiles.” This new technologies under study include Deep Sub Micron components, power microwave GaN and power transistors (MOSFET and IGBT). Bourbouse et al. [28] present updates to FIDES which will be proposed for the next revision of the FIDES guide. The updates are aimed at adapting the FIDES Guide for space applications. The authors claim that part manufacturing factors and the process factor will be updated and simplified in the next version of FIDES to adapt to the space domain.

Literature shows some studies comparing the predictions made using FIDES with that of other handbooks and field data. Marin and Pollard [15] predicted the reliability for 3 shipboard circuit card assemblies using FIDES, MIL-HDBK-217 and PRISM and compared it to the field data. The authors used the first version of FIDES, FIDES Guide 2004, for making their predictions. The results of the study showed that FIDES made mixed predictions when compared to the observed failures.

Held and Fritz [29] used FIDES Guide 2004 and RIAC 217 Plus to predict the reliability of avionics control unit and compared it with the average field failure rate. The study found that the predictions made by FIDES were optimistic when compared to field failures. However, the paper assumes a value for the process factor which is not same as the default value provided by FIDES. Thus, effectively, the authors did not follow the FIDES methodology for making their predictions.

Prodanov and Dancov [16] made reliability predictions of the electronic circuit of compact fluorescent lamp (CFL) using MIL-HDBK-217 and FIDES. The authors

found that the predictions made by both the handbooks did not match. However, they did not compare the predictions with field data.

The literature review shows that there are limited studies comparing the field failures to predictions made by FIDES. These studies compare the average hazard rate of the system to the predictions and do not provide information on the observed hazard rate trend. These studies do not assess the model used by FIDES for predicting reliability.

Some studies use FIDES as a tool for making reliability predictions without evaluating its results. Studies [11] and [12] were conducted on the reliabilities of converters in photovoltaic applications. The studies used FIDES to determine the components with highest impact on the failure rate of converter and to find the dominant stress factor. De León-Aldaco et al. [13] optimized the size of a heatsink of converter to minimize the thermal resistance and weight of the heatsink. They used FIDES to predict the reliability of the converter before and after optimization and calculated the improvement in predicted failure rate. These studies neither evaluate the FIDES methodology nor provide any comparison of the predictions with field or test data.

## Chapter 2. Bathtub Curve and Constant Failure Rate

The hazard rate of products is the conditional probability of product failure in a time interval, given that the products survived until that time interval. It is also described as the instantaneous failure rate of products. The shape of the hazard rate curve depends on when the failures occur over time. A hazard rate model in the form of a bathtub model has been used as a simplifying assumption. However, this shape (e.g., model) does not necessarily indicate any actual failures that occur in the field for any given product [30].

The bathtub model was originally developed as a model of the hazard rate for human life (mortality) over time [31] [32], and it first appeared in an actuarial life-table analysis paper published in the late 17th century [33] [34]. The model's name is derived from its shape, which is similar to a bathtub, as shown in Fig. 1. The initial period starts with high but decreasing (over time) mortality, which is representative of the high number of infant deaths (infant mortality or early failures). A period of constant mortality (called the useful life period) follows, where deaths occur from random incidents such as accidents, homicides, cancer, and food poisoning [32] [35]. The third period, called the wear-out period, occurs as the population approaches old age and the rate of deaths increases [32].

Although the bathtub model was created to model human mortality and assess life insurance risks, studies [36] [37] [38] have noted that it no longer applies to the human population due to advances in science. Meckel [38] reported that in less than 10% of the infants in underdeveloped countries, and less than 1% of infants in

developed countries die during their first year. Furthermore, each country has its own human mortality curve with different rates [39].

At the same time that human mortality scientists were starting to reject the bathtub model, reliability engineers picked up the notion and started using the bathtub model to describe manufactured goods, including electronic components and products. Educators also began using the bathtub model to explain the simple concepts and effects of a decreasing, constant, and increasing hazard rate.

Based on the review of experiments conducted at the University of Maryland and the existing literature, this paper addresses the question as to whether the bathtub model is appropriate for electronic components, products, and systems. Section 2.1 explains the bathtub model and the related terminologies. In Section 2.2, individual regions of the idealized bathtub model are assessed based on studies conducted by the researchers at the Center for Advanced Life Cycle Engineering, University of Maryland, along with the examples from literature. Section 2.3 assesses the bathtub model as a whole and discusses the hazard rates of electronic products and systems. Section 2.4 presents the conclusions and recommendations.

## **2.1. Bathtub Model and Terminology**

The reliability of an electronic product is defined as the probability that the product will function for a required period of time under the specified life-cycle conditions. For a population of products,  $n_0$ , let  $n_f(t)$  be the number that failed at time  $t$ , and  $n_s(t)$  be the number of products that are still operating satisfactorily at time  $t$ . If

we plot the percentage of failures per the total population, we obtain a histogram of the failure probability density function,  $\hat{f}$ ,

$$\hat{f} = \frac{1}{n_0} \frac{\Delta n_f}{\Delta t} \quad 2.1$$

where  $\Delta n_f$  is the number of failures that occurred in a time interval,  $\Delta t$ .

If we plot the percentage of failures per the number of products that are still operating,  $n_{bp}$ , at time  $t$ ; we obtain a histogram of the hazard rate, often called the failure rate function,  $\hat{h}$ ,

$$\hat{h} = \frac{1}{n_{bp}} \frac{\Delta n_f}{\Delta t} \quad 2.2$$

For an infinite population and in the limit as the time interval goes to 0, the hazard rate can be given as a continuous function,  $h(t)$ , noting that  $n_{bp}$  goes to  $n_s(t)$  in the limit.

$$h(t) = \frac{1}{n_s(t)} \frac{d[n_f(t)]}{dt} = \frac{-1}{R(t)} \frac{d[R(t)]}{dt} = \frac{f(t)}{R(t)} \quad 2.3$$

where  $R(t)$  is the reliability of the product at time  $t$ , expressed as the ratio of the surviving products,  $n_s(t)$ , per the original population size. Here,  $f(t)$  is the probability density function. The ratio of the number of product failures in an interval to the original population estimates the probability density function corresponding to the interval.

A mixed-Weibull distribution can be used to determine the various hazard rate distributions and determine whether a bathtub-shaped hazard rate distribution exists,

and what is the appropriate hazard rate model [40]. There are various academic and commercial tools available to perform hazard rate analysis. The equations are simple enough that general-purpose mathematical tools like Excel [41], Matlab [42], Mathcad [43], R [44], and Mathematica [45] can be used to determine the best model for the hazard rate data.

The bathtub model is often inappropriately used to represent the hazard rate curves of electronic components and products. As shown in Fig. 1, the bathtub model consists of three regions – infant mortality, useful life, and wear-out. For any given bathtub model, as in Fig. 1, the reliability decreases throughout the time period. That is, products continue to fail over time.

The first region of the bathtub model, known as the infant mortality region, burn-in region, debugging region, or the break-in region, is characterized by a decreasing hazard rate [31]. Traditionally, it is assumed to represent the failures occurring due to immature design and manufacturing processes, quality issues, substandard materials, inadequate debugging, and human errors [46] [47] [48].

The second region of the bathtub model, the useful life period, is depicted by a constant hazard rate. This region is assumed to represent failures caused due to random events such as random environmental loads, human error, abuse, and ‘acts of God’ [46].

Many reliability prediction handbooks [49] [50] and reliability allocation methods [51] have incorrectly assumed that this region dominates the hazard rate trends of electronics; however, this assumption has also been proven to be incorrect [26] [52] [53].

The third region of the bathtub model is called the wear-out period, and it is characterized by an increasing hazard rate. The bathtub model assumes that the failures due to wear-out mechanisms occur only during this region. Examples of wear-out mechanisms include fatigue [54], corrosion [54], electromigration [55], time-dependent dielectric breakdown [55], hot carrier injection [55], and negative bias temperature instability [55] and aging [46].

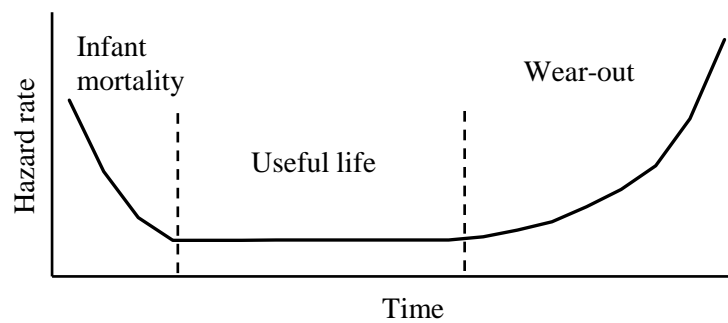


Figure 2: Bathtub model of hazard rate

## 2.2. Why the Bathtub Model Is Not an Appropriate Assumption for Electronic Components and Products

The usage of the bathtub model to characterize the hazard rate of electrical products started with the reliability practices used in the U.S. military. Smith [56] noted that the bathtub curve was formulated in the 1940s and 1950s to characterize the failure rates of electronic components such as vacuum tubes and early semiconductor technologies. Wasson [57] noted that when military systems became more complex, the reliability engineers started applying the Bathtub model to systems. However, the model was rarely used in its entirety because it was generally considered that electronics only followed the constant hazard (failure) rate during their operational life

[50] [58]. In this section, each period of the bathtub model is assessed in terms of actual hazard rate trends gathered from experimental and field data of electronic components, products, and systems.

### **2.2.1. Infant Mortality Period**

Infant mortality failures describe a decreasing hazard rate during the initial phase of a component's or product's life [31]. In electronic components and products, the competent manufacturers have worked on design deficiencies and the elimination of poorly managed manufacturing processes, lack of standardization in quality control, use of defective materials, and improper assembly, storage, and transportation [46] [59] [60] thereby reducing the occurrence of such failures. In well-designed and high-quality hardware, stresses should cause only uniform accumulation of wear-out damage [61]. In addition, any remaining causes of infant mortality failures are being eliminated by identifying the parts with potential defects and removing them from the population of products via screening and burn-in methods [62] [63].

Screening is the process of separating products with defects from those without defects. Burn-in is a screen performed to precipitate defects by exposing the parts to accelerated stress levels [31] [64]. The goal of burn-in is to prevent failures from occurring in the field. The U.S. Food and Drug Administration (FDA) [65]<sup>3</sup> states that the defective, weak, and out of specification components can be removed by means of functional testing, stress testing, and the use of burn-in. The FDA defines burn-in as

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<sup>3</sup> “for a reliable product, defective, weak or out of specification components must be weeded out. This is done by functional testing, stress testing and by burn-in.”

the process of holding an electrical device (often electrically biased and connected to a load) at elevated temperatures. The FDA further cites the MIL-STD-883, Method 1015, to mention that burn-in eliminates marginal devices that would otherwise lead to infant mortality [66].

Any product that has undergone a successful burn-in will not have an infant mortality portion of the bathtub model [67]. The studies presented on board-mounted electronic components [68], microelectronic components [69], and integrated circuits [70] have shown that these electronic components and products do not have an infant mortality period and the burn-in, and the environmental stress screening (ESS) methods are widely developed and used to eliminate weak components and products [66] [71].

ESS has been so effective that most of today's products do not exhibit infant mortality trends. For example, Ryu and Chang [72] discussed how the infant mortality failures surface by non-destructive and destructive testing for short periods and thus, can be analyzed and eliminated by a combination of ESS and design modification. The result is that the hazard rate curve shows an increasing trend and not a bathtub shape, as shown in Fig. 2 [73].

Hester *et al.* [74] assessed the value of screening components by original equipment manufacturers (OEMs) by comparing the failure data of screened and unscreened components in commercial aerospace applications. The data encompassed 181 part numbers represented by around 638,000 components. The study concluded that additional screening of high-quality components beyond that already done by the component manufacturers does not add any value. This implies that after screening

performed by component manufacturers, the component population no longer consists of defective products and thus, would not result in infant mortality. Similarly, Jordan and Pecht [75], in their study of Honeywell's ring laser gyro, observed that the unscreened commercial parts had accumulated over 200 million piece part hours without any failure and thus, did not have an infant mortality period.

Furthermore, in the presence of more than one failure mechanism, which is the case for most electronic products, the population probability density function, shown in Figure 4, cannot have a convex shape. English *et al.* [76] addressed this issue of the bathtub model and showed that the hazard rate function during the early life interval and the idealized bathtub model does not accommodate this characterization of early failures.

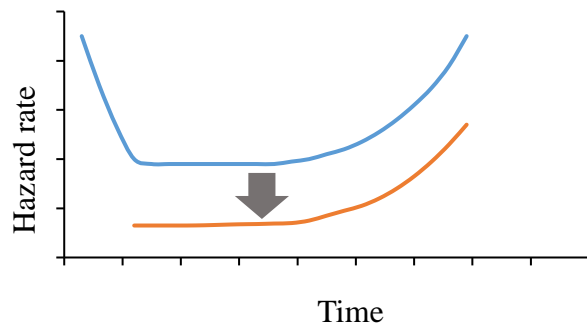


Figure 3: The shape of the hazard rate curve from the effective implementation of ESS (lower curve) compared to the bathtub model (upper curve) [73].

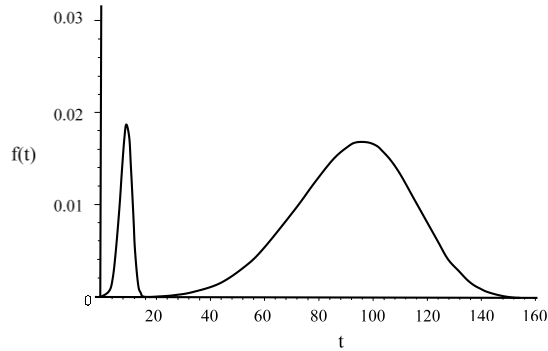


Figure 4: The probability density function for a population with early failures (adapted from [34]).

### 2.2.2. Useful Life Period

The bathtub model predicts that electronics will have a period in which the hazard rate is constant, and this will occur after an infant mortality period and before a wear-out period. This prediction of the hazard rate is based on the assumption that the only failures during this period are random and that there is no wear-out, two assumptions that are rarely true for electronics.

Wong [53] gave a historical perspective to the hazard rate for electronics, noting that “in the 1950s many people, after observing available data, which as we know now was erroneous, concluded that the failure rates of electronics are constant during the useful lifetime of the equipment. Now we know that the data was tainted by equipment accidents, repair blunders, inadequate failure reporting, reporting of mixed-age equipment, defective records of equipment operating times, mixed operational environmental conditions, complete neglect of thermal cycling data, and many additional undesirable factors.” He also stated that the influence of so many incidental factors led the data to appear random and effectively led to the erroneous observation

of a constant failure rate. Further, McLeish [77] states that overstress failures<sup>4</sup> are rare and random, and if these occur frequently, it means that the device is not suitable for the application<sup>5</sup>.

Yang *et al.* [78], using field data of machining centers, showed the shape parameter to be 1.17 for the electrical system, 1.77 for the CNC system, and 2 for the servo system (implying that their hazard rates were increasing throughout the life). The studies by Waghmode and Patil [79], Patil *et al.* [80], Keller *et al.* [81], and Dai *et al.* [82] on computerized numerical control machine tools show that the hazard rates of their electronic components are not constant. Figure 4 shows the hazard rate curve of the electronic system of a CNC machine tool. The shape parameter ( $\beta$ ) of the Weibull distribution is 3.34, with its contour limits ranging from 1.6 to 6.5, depicting an increasing hazard rate throughout its life (that is, there is no infant mortality or useful life period).

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<sup>4</sup> Overstress mechanisms in electronics are typically due to electrical overstress, electrostatic discharge, and damage due to dropping, events that can occur anytime in the life of a product [86] and thus increase the whole hazard rate distribution.

<sup>5</sup> “In items that are well designed for the loads in their application, overstress failures are rare and random. They occur only under conditions that are beyond the design intent of the device.... If overstress failures occur frequently, then the device may not be not [sic] suited for the application or the range of application stresses were underestimated.” [77]

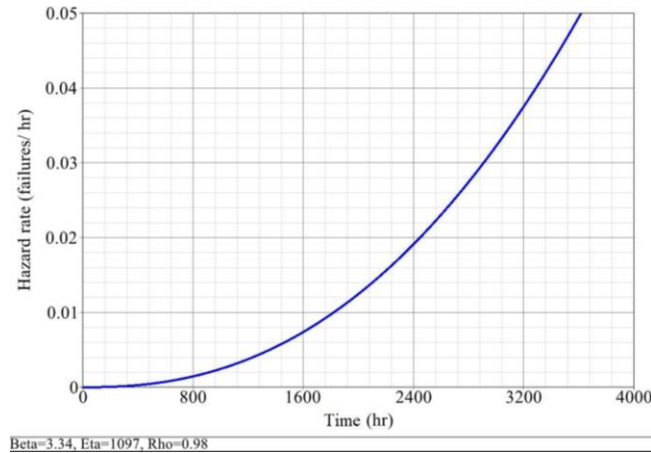


Figure 5: The hazard rate curve of electronic systems used in the CNC machine tool (based on data from references [79] [80]).

The literature shows that some proponents [50] [83] [84] of the constant hazard rate assumption believe that although most individual mechanisms may not be represented by a constant hazard rate, their superposition leads to an apparent constant hazard rate for the system. However, the resultant of the superposition of hazard rates is dependent on the distribution of dominant failure mechanisms over time. For example, Shah and Elerath [85], based on their study of disk drives, concluded that the resultant hazard rate is dependent on which failure mechanism is dominant at what time.

The distribution of failure mechanisms is dependent on the distribution of the usage and environmental stresses acting on a system. This distribution causes the hazard rate to vary over time. For example, the National Research Council's report, 'Reliability growth: Enhancing defense system reliability' [26], states that a device degrades in multiple ways, and its lifetime is thus a function of different failure mechanisms and modes. The report infers that the failure rate of a product varies throughout its life and cannot be represented by a constant failure rate model.

For a system composed of electronic components, the bathtub model is often inappropriate. Mortin *et al.* [86] modeled the hazard rate for a system having three identical electronic devices using the constant hazard rate assumption and a distribution representing the actual failure mechanism. Their study demonstrated that as the number of components increases, the difference between the instantaneous hazard rate calculated using the constant failure rate distribution and actual hazard rate distribution also increases<sup>6</sup>. Yuan *et al.* [87] observed that the fault data of an aero-engine, a complex electro-mechanical system, has a Weibull shape parameter greater than 1 (showing that the system's failure rate is increasing, not constant). Pascale *et al.* [88] showed that the electronic railway signaling systems do not have a constant hazard rate. Verma *et al.* [89] observed the failures in the electro-mechanical system of an automated hematology analyzer (used in medical laboratories) and found the system to have an increasing failure rate throughout its lifetime. Similarly, Rastayesh *et al.* [90] predicted the reliability of a power stage of wind-fuel cell hybrid energy systems assuming Weibull and exponential distributions. They found that the Weibull distribution (with increasing hazard rate) predicted the reliability more accurately.

Similarly, Chiodo and Lauria [91] stated that the hazard rate of a redundant system is a function of time and can never be constant. They proved that even for a system consisting of components with constant hazard rates, the resultant hazard rate of the system varies with time. That is, for a parallel system with two independent components, the reliability  $R(t)$  is given by

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<sup>6</sup> "Increasing the number of components further increases the difference between the lognormal and the constant failure rate distributions.... For a typical component with many competing failure mechanisms and sites, the difference between the constant failure rate and the actual instantaneous hazard rate can be even large." [86]

$$R(t) = R_1(t) + R_2(t) - R_1(t)R_2(t) \quad 2.4$$

For two components, both having a constant failure rate  $\lambda$ ,

$$R(t) = 2R_1(t) - R_1^2(t) = 2e^{-\lambda t} - e^{-2\lambda t} \quad 2.5$$

It is observed that the two exponential functions of equation 2.5 cannot be combined to express as a single exponential function. Thus, the hazard rate of the system will not be constant over time, as opposed to the useful life period of the bathtub model.

### 2.2.3. Wear-Out Period

The wear-out period describes an increasing hazard rate, which occurs after the constant failure period of the bathtub model. This period of the bathtub curve is based on the assumption that failures due to wear-out mechanisms only occur towards the end of the bathtub model, which is not true.

The mechanisms causing failures in electronics are predominantly of a wear-out nature [46] [92]. These failure mechanisms start as soon as the product is put into operation [58] and not after a period of random failures, as implied by the bathtub model. Dasgupta *et al.* [54] state that most failures in electronics are caused due to mechanical failure mechanisms like fatigue, corrosion, and fracture. As these mechanisms are primarily wear-out mechanisms, they cannot be represented by constant failure rates.

Modern electronics are observed to undergo wear-out failures earlier in life as opposed to the belief that the wear-out takes place only after the end of usage. Harms [58] stated, “the commercial industry has been driven largely by consumer electronics to produce parts that no longer compare to the parts produced prior to 1995. The parts

being used currently have a shorter service life, often in the three to five year time frame. This essentially pulls in the right hand of the bathtub curve to the point where it is now necessary to pay attention to wear-out as part of the reliability prediction process.”

One of the reasons for the early wear-out of the electronics is the reduction in the feature size of components. Customer expectations are continuously forcing electronics manufacturers to reduce the size of the components and products with enhanced processing capacity. Blome *et al.* [55] explained, “as CMOS [complementary metal-oxide semiconductor] feature size scales to smaller dimensions, voltage is expected to scale at a much slower rate, increasing on chip power densities. Areas of high power density increase local temperatures leading to “hot spots” on the die.” They further stated that as temperature and power density are the stress factors for many wear-out mechanisms in electronics such as time-dependent dielectric breakdown, hot carrier injection, electromigration, and negative bias temperature instability, the future technologies will encounter wear-out mechanisms more commonly.

The literature and the studies conducted at the University of Maryland provide numerous examples of reliability studies on electronics where the population exhibited “only” wear-out failures. In 1990, Pecht [93] showed that microelectronic packages under corrosive environments followed a Weibull distribution, with a shape factor close to 2, which corresponds to a wear-out failure mechanism. Pecht and Nash [94], in their case study conducted on light-emitting diode (LED) lasers, observed that the devices exhibited a gradually occurring wear-out failure mechanism. Similarly, Wang *et al.* [95] evaluated LED packages and found only wear-out failures for packages with

various encapsulation materials. Mattila *et al.* [96], in their study on the reliability of electronic component boards, observed only wear-out failures at all testing temperatures. Mei *et al.* [97] showed that solder joints, when exposed to self-heating, lead to wear-out failures with a shape factor above 1, indicating wear-out.

Similarly, Athamneh *et al.* [98] performed reliability modeling of aged SAC305 solder joints and found the hazard rate to have shape parameters greater than 2. Liu *et al.* [99] showed that the interconnects undergo wear-out when subjected to vibrations, both at fixed and random frequencies. Virkki and Tuukkanen [100] studied tantalum capacitors under various temperature ranges and observed only increasing failure rates. Hoffman *et al.* [101] showed that insulated-gate bipolar transistors (IGBTs) failed by wear-out when exposed to combined thermo-mechanical and electro-chemical stresses. White *et al.* [102] found the main failure distribution in DRAMs has an increasing hazard rate. Quintero *et al.* [103] conducted reliability and life studies on semiconductor die-substrate assemblies of different sizes under different temperatures. They observed that the Weibull shape parameter was always greater than 1, showing an increasing hazard rate existed rather than a constant hazard rate. Table I provides additional case studies of electronics where Weibull distribution was used to fit the data, and the observed shape parameter values were greater than 1, indicating that only wear-out was observed.

Table 2: Studies showing that the hazard rate of electronics is dominated only by wear-out mechanisms

Authors	Electronic components studied	Value of Weibull shape parameter
Romero <i>et al.</i> [104]	Tantalum electrolytic capacitors	>1.6
J. Meng <i>et al.</i> [105]	Microelectromechanical systems	1.9
Srinivas <i>et al.</i> [106]	Solder joints of package on package assemblies	>2.8
Valentin <i>et al.</i> [107]	Solder joints between package leads and printed wiring boards	4.4
Lu and Christou [108]	Transistor modules	5.6
Osterman and Pecht [109]	Printed circuit boards	>4
H. Qi <i>et al.</i> [110]	Solder joints of printed circuit board assemblies	2.6
Hwang <i>et al.</i> [111]	Capacitors	Between 2.9 and 17.4
Jozwiak [112]	Microcomputer system	4.9
Chan <i>et al.</i> [113]	White light emitting diode	>12
Munoz-Gorriz <i>et al.</i> [114]	Metal-insulator-semiconductor (MIS) capacitor	>4
Bossuyt <i>et al.</i> [115]	Stretchable electronic substrates	>2.8
Choi <i>et al.</i> [116]	IGBT power module	6.6
Liu <i>et al.</i> [117]	Ball grid array (BGA) packages	>1.9
Nogueria <i>et al.</i> [118]	Blue light emitting diode	>4.8
Putala <i>et al.</i> [119]	Ceramic antenna assemblies	>5.5
Ferrara <i>et al.</i> [120]	Power amplifier module	>2
Le Coq <i>et al.</i> [121]	Wafer-level chip scale packages	>3.4
Schilling <i>et al.</i> [122]	Power diodes	>1.2
Rajaguru <i>et al.</i> [123]	Power electronic module	>38
Li <i>et al.</i> [124]	n-MOSFETs	10.6
Xu <i>et al.</i> [125]	Gold-plated electrical interconnects	>20

### 2.3. Does the Bathtub Model Exist?

Sections 2.2.1, 2.2.2, and 2.2.3 of this article assessed the different sections of the bathtub model and examined various case studies. This section examines the bathtub model as a whole.

Reliability engineers have observed over time that the hazard rates of electronic components do not follow a bathtub model. For example, as early as 1968, United Airlines released a report [126] stating that 96 percent of its items did not follow the bathtub curve.<sup>7</sup> Similarly, Moltoft [127] noted, “There is a sound basis for rejection of the hitherto used background model for the ‘bathtub’ curve. This model based on statistical independence between early, random, and wear-out failures is seldom (if ever) seen demonstrated with results from practical experience.” Pascoe [128] also noted, “The author has not, in 40 years’ experience, seen system whole life reliability data which matches the ‘bathtub’ prediction.”

Since the early 1980s, researchers such as Wong [129] have raised questions on the applicability of the bathtub model for electronic components and products. A series of papers [53] [130] [131] [132] showed that the bathtub model was not appropriate to predict the shape of the hazard rate. Jensen and Petersen [133] analyzed the shape of the hazard rate curve for electronic devices and noted that spikes, which they called latent failures, are often observed in the hazard rate curve, and they are typically observed at an excessive rate throughout the life of a product. English *et al.* [76] noted that the latent failures are non-predictable and unavoidable. Wong and Lindstorm [131]

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<sup>7</sup> “Although it is often assumed that the bathtub curve is representative of most items, note that just 4 percent of the items fell into this pattern.”

noted that latent failures and multiple failure mechanisms in electronic components and products cause the shape of the hazard rate to resemble more of a roller-coaster shape often, as shown in Figure 6.

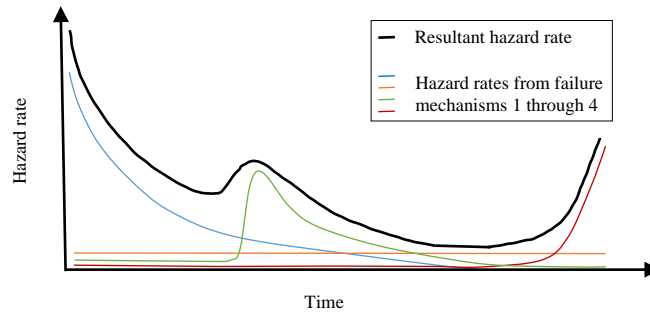


Figure 6: Visualization of roller-coaster curve of the hazard rate.

The hazard rate, being dependent on a range of variables, such as the loading conditions, dominant failure mechanisms, and parts quality, can take different shapes [134]. Kapur and Pecht [31] noted, “The failure of a population of fielded products can arise from inherent design weaknesses, manufacturing and quality control-related problems, variability due to customer usage, the maintenance policies of the customer, and improper use or abuse of the product.” The resultant hazard rate is dependent on how these factors react with each other. Due to this uncertainty, it is not possible to assign a ‘fixed shape’ to the hazard rate curve. This is also noted based on the large variability in the Weibull beta factors, as shown in Table 2.

## 2.4. Discussion

The bathtub curve was developed as a predictive hazard rate model for human mortality and later applied to numerous other things, including mechanical, civil, and electrical items. However, in actuality, the hazard data rarely follows such a bathtub

model, especially for electronic components, products, and systems, as is evident from the literature review and the over 55 case studies cited in this paper.

Assumptions of hazard rate trends for electronics, whether based on a bathtub model, or any other preconceived model, can result in inaccurate and misleading reliability predictions, poor mission and warranty planning, and inadequate maintenance scheduling. The hazard rate of electronics is dependent on the design, materials, manufacturing processes, inherent defects, and screening methods used. The actual hazard rate, and the formulation of a specific model, can only be constructed with actual data.

When electronics failure data is evaluated, it is observed that infant mortality is rarely seen for today's electronics due to improvements in the designs, manufacturing processes, quality control, screening, burn-in testing, storage, transportation, and packaging. Furthermore, as noted in the case studies, failures that occur in early life are generally not infant mortality failures but rather early wear-out failures. In addition, failure mechanisms such as time-dependent dielectric breakdown, corrosion, negative bias temperature instability, fatigue, electromigration, and hot carrier injection in modern electronics are found to be wear-out mechanisms that start the degradation process as soon as the electronics are put into operation. Finally, data from the case studies showed the Weibull shape parameters to be greater than 1, denoting wear-out failure characteristics throughout the product's life.

This paper recommends that the electronics industry stop using the bathtub model for predicting the hazard rate curve unless the data proves otherwise. The failure

data and the associated failure mechanism will determine the hazard rate distribution. As the failure of a product is dependent on multiple variables and their interactions, the hazard rate for a product should be determined using the failure data, rather than assuming a hazard rate model.

## Chapter 3. Assessment of FIDES Reliability Prediction Model

The FIDES model consists of  $\lambda_{\text{Physical}}$ ,  $\Pi_{\text{PM}}$  and  $\Pi_{\text{Process}}$  factors which are calculated as shown in equations (1.2-1.5). Sections 3.1, 3.2 and 3.3 assess if these factors are appropriate inputs for a reliability prediction model and section 3.4 assesses the claim of FIDES being based on physics of failure.

### 3.1. Physical Contributing Factor ( $\lambda_{\text{Physical}}$ )

The  $\lambda_{\text{Physical}}$  factor of FIDES is claimed to account for the stresses acting on the component using equation 1.2. FIDES provides tabulated basic failure rates ( $\lambda_0$ ) for components under various stresses (such as thermal, thermal-cycling, humidity, vibrational) which are multiplied with the corresponding acceleration factor and this product is summated for all stresses. Such a summation is correct only if all the stresses have constant failure rates (that is, follow an exponential distribution), however, numerous failure mechanisms caused by FIDES' list of stresses are wear-out mechanisms such as fatigue, electromigration, corrosion and thus, FIDES' model cannot accurately predict these failures.

Apart from the basic failure rates and acceleration factor,  $\lambda_{\text{Physical}}$  consists of factors such as  $\Pi_{\text{Placement}}$ ,  $\Pi_{\text{application}}$ ,  $\Pi_{\text{ruggedizing}}$ , and  $C_{\text{sensitivity}}$ , that are claimed to account for overstress.  $\Pi_{\text{Placement}}$  factor represents the function performed by the component in the circuit (e.g., analog, digital, power). Thus,  $\Pi_{\text{Placement}}$  attempts to account for the risk of exposure to overstress based on the function of the component.

$\Pi_{\text{application}}$  is calculated using criteria such as the user type and qualification, system mobility, electrical network stability, possibility of product manipulation, exposure to human activity, machine disturbances and external weather. Thus,  $\Pi_{\text{application}}$  attempts to represent the risk of overstress based on usage conditions.  $\Pi_{\text{ruggedizing}}$  is based on the audit results and thus, it effectively attempts to account for the risk of exposure of the components to overstress based on the policies of the manufacturer. Thus, these factors are risk assessment factors and should not be used for reliability prediction.

### **3.2. Part manufacturing factor ( $\Pi_{\text{PM}}$ )**

The part manufacturing factor ( $\Pi_{\text{PM}}$ ) of FIDES is calculated using equation 1.3 for active components and 1.4 for passives. It consists of factors such as quality assurance of the manufacturer ( $QA_{\text{manufacturer}}$ ), quality assurance of the component ( $QA_{\text{component}}$ ), reliability assurance of the component ( $RA_{\text{component}}$ ), and experience factor ( $\epsilon$ ). These factors were formed based on the policies of the companies from FIDES group.

FIDES selects  $QA_{\text{manufacturer}}$  based on the quality standards used by the component manufacturer. Quality standards include various aspects such as product traceability and product change notifications, which are inputs to determine the reliability capability of the manufacturer and effectively assess the risk in supply chain. Specific end users may prefer certain quality standards and may select the manufacturers that comply with these standards. However, these aspects do not impact the values of field reliability and thus, should not be used for predicting reliability.

FIDES selects quality assurance of the component ( $QA_{\text{component}}$ ) based on the standard used for the qualification of the components (such as AEC Q100, MIL-PRF-38535 class V), and reliability assurance of the component ( $RA_{\text{component}}$ ) based on the number of components tested using the qualification tests and the testing conditions. This information may help assess the risk of selecting the manufacturer, however, these factors lack the qualification data such as the times to failure, which can be used for predicting field reliability and hence, these factors should not be used for predicting reliability.

The experience factor ( $\varepsilon$ ) of the FIDES methodology is based on the user's past experience with the manufacturer and is meant to account for the maturity of the manufacturing process and previous disqualification or problems with feedback from the operation. This factor assesses the risk in supply chain and its criteria do not have an impact on the field reliability of a product and hence, it should not be used as a factor for predicting reliability.

### **3.3. Process factor ( $\Pi_{\text{Process}}$ )**

The process factor of the FIDES methodology is based on the audit results and is calculated using equation 1.5. FIDES divides the lifecycle of the product into seven phases and assigns a weight to them, termed as `contribution_phase`. The user of the methodology can change the distribution of weights, making it subjective. The auditor can deem questions as irrelevant and omit them, making the ratio of `audit_mark` to `max_audit_mark` subjective. The audit questions (such as Table 3) provided by FIDES assess the risk in the supply chain rather than the reliability of the component. Also,

FIDES guide notes that audit is a risk control tool [18]. As the process factor is subjective and focusses on risk assessment, it should not be included as a factor for reliability prediction.

Table 3: Examples of Audit Questions

<b>Audit Questions</b>
Is the reliability aspect dealt with in management reviews?
Has a person responsible for reliability studies been appointed?
Is training of persons working on reliability appropriate for the criticality of reliability performances expected for the product?
Are customer comments about product reliability collected during operational functioning?
Are the skills of final test operators systematically audited?
What measures have been taken so that the person concerned is qualified for the test means, measurements and relevant standards?
Is there any management of skills?
Is there a financing item for reliability studies? Have the necessary means and personnel been identified?

### **3.4. Is the FIDES model based on Physics of Failure**

Physics of failure involves identifying the potential failure modes, mechanisms and sites for a component based on its life cycle conditions and its geometry and material properties [135]. FIDES Guide [18] claims to be based on physics of failure. A reliability prediction methodology based on physics of failure needs to cover the steps shown in Figure 7

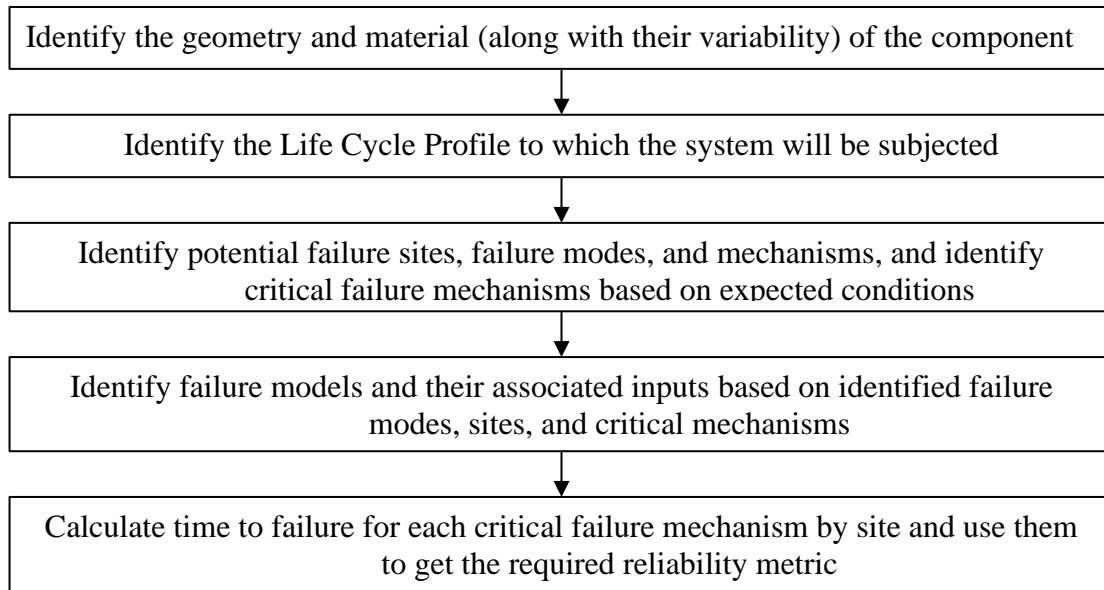


Figure 7: Steps of a physics of failure-based reliability prediction methodology

A physics of failure-based reliability prediction methodology begins by the identification of the geometry and material properties of the component's constituents, such as the die, die-attach and wire-bonds, along with their variability and the life cycle profile of the component. Next, the potential failure sites, modes and mechanisms are identified and the critical failure mechanisms for the component are identified. Critical failure mechanisms include the mechanisms which have higher probability of occurrence and that have severe impact on the reliability of the system. For the identified critical mechanisms, the suitable failure models are selected, and their inputs are decided based on the design of the component and the identified failure modes, and sites and the times to failure are calculated.

FIDES methodology considers neither the geometries and materials of constituents of the components (see section 4.3) nor the sequence of stresses in the life cycle of the component (see section 4.2). The methodology does not involve

identification of the failure modes, mechanisms and sites and uses constant values of exponents for its failure models, independent of the materials. The methodology calculates a constant failure rate for the components, while numerous failure mechanisms in electronics are wear-out mechanisms and cannot be modelled using a constant failure rate. As the FIDES methodology does not cover the steps in Figure 7 and shows a lack of understanding of failure mechanisms, it is not based on physics of failure.

## Chapter 4. Evaluation of FIDES Methodology Based On IEEE 1413

IEEE 1413 requires a reliability prediction report to include answers to thirteen questions (see Table 4). These questions encapsulate the requirements of IEEE 1413 and give the user of the prediction the information needed to assess the value of the prediction. As the methodology used for making the reliability predictions influences the predictions, this paper uses the IEEE 1413 questions to assess the FIDES reliability prediction methodology. In the subsequent sections, we discuss how FIDES addresses the topics associated with the questions.

Table 4: The thirteen questions required by IEEE 1413 to be included in a reliability prediction

Question
Does the methodology identify the sources used to develop the prediction methodology?
Are the sources used to develop the prediction methodology available in the public domain or upon request?
Does the methodology account for life cycle environmental conditions, including those encountered during 1) manufacturing, 2) product usage (including power and voltage conditions), 3) packaging, 4) handling, 5) storage, 6) transportation, and 7) maintenance conditions?
Does the methodology account for materials, geometry, and architectures of the parts and assemblies?
Does the methodology account for part quality?
Does the methodology have the flexibility to allow incorporation of new reliability data and experience?
Are assumptions used to conduct the prediction according to the methodology identified, including those used for the unknown data?
Are sources of uncertainty in the prediction results identified?
Are limitations of the prediction results identified?

<b>Question</b>
Are failure modes identified?
Are failure mechanisms identified?
Are failure causes identified?
Are statistical confidence levels and confidence intervals for the prediction results identified?

#### **4.1. Sources used for developing FIDES**

The IEEE 1413 questionnaire requires a reliability prediction report to declare if the reliability prediction methodology identifies the sources used to develop the prediction methodology and if the sources used to develop the prediction methodology are available in the public domain or upon request (see Table 4).

FIDES states that its sources of data comprise of field failure data, primarily from defense and aeronautical sector, reliability data published by part and subassembly manufacturers, and existing handbooks and standards such as MIL-HDBK-217 and IEC 62380 [18] (M. Girardeau, co-developer of FIDES, personal communication, Dec. 3, 2019). MIL-HDBK-217 and IEC 62380 are outdated and cancelled. The last version of MIL-HDBK-217 was published in 1995 and was based on data which was outdated even at that time [136]. For example, the data used by MIL-HDBK-217 for connectors was 20 years old then [137], making it more than 40 years old now.

The data used by FIDES are not available in the public domain and the developers of FIDES did not provide them upon request<sup>8</sup>. Without access to the data, there is no way to assess the distribution of data among various applications, the timeline of the data collection, the generation of devices used, the identification of failure root causes, the sufficiency of the data, and the data analysis method used to formulate the FIDES model.

## 4.2. Life-cycle environmental conditions

A life-cycle profile is a forecast of events and associated load conditions that a product experiences from manufacture to end of life. As the stresses endured during all the phases of the life cycle degrade a component to some extent, IEEE 1413 requires a prediction report to identify if the prediction methodology accounts for the life cycle profile (see Table 4)

The  $\lambda_{\text{Physical}}$  factor of FIDES is claimed to account for the environmental and usage conditions of the component. For calculating this factor, FIDES requires that the use period be divided into phases, and the calculation is an average over the phases as shown in Equation 2. The user of the FIDES methodology can only include the stresses which are listed by FIDES for the particular component family. For example, FIDES does not include relative humidity as one of the stresses for capacitors, even though literature shows that humidity impacts the reliability of capacitors [138] [104]. Also,

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<sup>8</sup> A co-developer of the FIDES methodology [28] informed the authors that the database used for forming the methodology is confidential (M. Girardeau, personal communication, Dec. 3, 2019). There are ways to provide data without disclosing the application and the concerned supply chain, however, the FIDES group did not choose to do so.

although FIDES claims to be applicable for space applications, it does not account for radiation stress.

FIDES model does not consider the sequence of stresses for predicting reliability while the reliability of a component is dependent on the life cycle sequence [139]. For example, Perkins and Sitaraman [140] noted, that thermal cycling followed by vibration load is a harsher sequence than the reverse as thermal cycling led to deformation and microstructural changes which quicken the crack initiation.

### **4.3. Materials, geometry, and architecture of parts and assemblies**

The IEEE 1413 [141] questionnaire shown in Table 4, requires the prediction report to identify if the reliability prediction methodology accounts for materials, geometry, and architectures of the parts and assemblies. For an electronic component, the architecture, materials, and geometry include factors such as the interconnect technology and materials (e.g., flip-chip or wire bond), the thickness and material of the die attach, and the types of leads. The absorption, reaction, or transfer of the stresses by the materials and their interfaces in a component have an impact on the failure sites and the stress limits at which failures occur and thus, impact the failure propensity of the components.

FIDES does not consider the materials of a component beyond the top-level packaging material. For example, for discrete components and integrated circuits, the consideration of materials is limited to packaging materials (ceramic, plastic, or glass), geometry is limited to packaging type (e.g., TO-220, PQFP, SOJ), and architecture is limited to the number of leads or pins. Critical parameters such as die dimensions, die

attach material and thickness, and wire bond lengths and materials do not impact FIDES' prediction. Thus, in our assessment, FIDES methodology does not account for materials, geometry, and architectures of the parts and assemblies.

#### **4.4. Part quality**

IEEE 1413 requires a reliability prediction report to identify if the reliability prediction methodology accounts for part quality. Defects associated with poor-quality can cause the products to fail prematurely [142] and variation in part quality impacts the times to failure distribution.

FIDES claims that the  $\Pi_{PM}$  factor accounts for part quality [18].  $\Pi_{PM}$  consists of factors such as quality assurance of the manufacturer ( $QA_{\text{manufacturer}}$ ), quality assurance of the component ( $QA_{\text{component}}$ ), reliability assurance of the component ( $RA_{\text{component}}$ ), and experience factor ( $\epsilon$ ).

Quality assurance of the manufacturer ( $QA_{\text{manufacturer}}$ ) factor of FIDES is based on the quality certifications of the manufacturer. Conforming to a quality standard does not provide information on the values of the process control parameters, and effectively, qualifying to a standard does not provide information about the variability in the process. Thus, this factor does not account for part quality.

Quality assurance of the component ( $QA_{\text{component}}$ ) is based on the standard used for the qualification of the components (such as AEC Q100, MIL-PRF-38535 class V) and reliability assurance of the component ( $RA_{\text{component}}$ ) is based on the qualification test conditions and the number of components tested. This data from the qualification tests does not account for the variations in the products typically caused due to raw

materials and manufacturing processes or defects in products. Thus, the factors  $QA_{\text{component}}$  and  $RA_{\text{component}}$  are not representative of the part's quality.

The experience factor ( $\epsilon$ ) of the FIDES methodology is based on the user's past experience with the manufacturer. This factor is meant to account for the maturity of the manufacturing process and previous disqualification or problems with feedback from the operation [18]. The past record of the manufacturer cannot be quantified as an impact on the reliability of the components in field and thus, it should not be used for predicting reliability.

#### **4.5. Incorporation of new reliability data and experience**

IEEE 1413 requires previous reliability and test data and experience including sample size to be used for making reliability predictions. The standard requires the prediction report to identify if the prediction methodology has the flexibility to allow incorporation of new reliability data and experience (see Table 4).

FIDES contains a static list of basic failure rates of components to be used while making reliability predictions. It does not provide any method of updating those failure rates using the user's reliability data or experience. As shown in Section III-A, FIDES neither provides the data used to calculate the basic failure rates nor informs the user of the method used for translating failure data to the tabulated basic failure rates. Thus, FIDES does not have the flexibility to allow incorporation of new reliability data and experience.

## 4.6. Assumptions

IEEE 1413 [141] requires the listing of assumptions made for a reliability prediction. The assumptions built into FIDES will carry over to the predictions made. As shown in Table 4, IEEE 1413 requires the prediction report to identify if the assumptions used to conduct the prediction according to the methodology identified, including those used for the unknown data.

Applicability of the bathtub curve for all electronics and a constant failure rate over the useful life period are the primary assumptions in FIDES. The FIDES methodology also assumes that the component for which the failure rate is being predicted is within its useful life period.

FIDES does not state the implied assumptions in its basic failure rates, such as, the difference in the coefficients of thermal expansion between the printed circuit board and the component, the materials of pins, the curvature of pins, the substrate materials of ceramic ball grid array, flex ball grid array and plastic ball grid array [18]. IEEE 1413.1 [143] requires a prediction report to document “assumptions used for unknown input data.” However, the FIDES Guide does not list the assumptions made while using the default values for factors such as  $\Pi_{PM}$ ,  $\Pi_{Ruggedizing}$ , and  $\Pi_{Process}$ .

## 4.7. Sources of uncertainty in predictions

IEEE 1413 requires a prediction report to declare if the sources of uncertainty in the prediction results have been identified (as shown in Table 4). IEEE 1413 [141] mentions that the uncertainty may be due to key unknowns, sources of error, incomplete

knowledge, model parameter uncertainty, and design immaturity. In this section, we show how FIDES does not account for model parameter uncertainty.

Model parameter uncertainty includes the uncertainty in the values of coefficients and exponents of failure models used by FIDES. The evaluation of acceleration factors (for thermal stress, stress due to temperature cycling, and stress due to humidity) by FIDES uses activation energy as a model parameter. Activation energies vary with the failure mechanisms [144], with temperatures, production lots [144] [145], and different versions of products [144] [145], all of which get ignored by the FIDES methodology as it provides a single value of activation energy to be used for environmental stress for a given component family. Like the activation energy, the other exponents of the failure models (such as Peck's model) depend on the components' materials and geometries. FIDES does not consider this and uses constant values of exponents for a component family. Also, FIDES does not consider the model parameter uncertainty due to variations in materials and geometries of parts.

#### **4.8. Limitation of the prediction results**

IEEE 1413 [141] requires a prediction report to state if the limitations of the prediction results have been identified (see Table 4). The limitation of prediction results corresponds to cases when the prediction results do not hold valid

FIDES Guide mentions that it is limited to predicting reliabilities within the ambient temperature range of  $-55\text{ }^{\circ}\text{C}$  to  $125\text{ }^{\circ}\text{C}$ . The FIDES methodology clarifies that it does not cover software failures, unconfirmed failures, failures due to lack of preventative maintenance, or failures known to have been caused by overstress [18].

Although the FIDES Guide provides a disclaimer about some of its limitations, its listing of the limitations is incomplete. For example, although it is known that the combination of stresses [146] [147] as well as the sequence of stresses has an impact on the reliability of the component [140], FIDES does not consider these factors. Another limitation of the FIDES methodology is its inability to account for the degradation of components due to exposure to radiation [28] [148], while claiming to be applicable for space applications [18] [19].

#### **4.9. Failure modes, mechanisms, and causes**

IEEE 1413 [141] requires a prediction report to declare if the failure modes, mechanisms and causes have been identified in the prediction. Identification of the failure cause, such as design weaknesses, manufacturing processes, or usage conditions, can be used as feedback for the design, which helps in improving the reliability of the part. The effect by which the occurrence of a failure is observed is a failure mode [149]. The process by which the specific combinations of physical, chemical, and mechanical stresses induce failure is termed the failure mechanism [142].

Although FIDES lists a set of stresses such as thermal, thermo-electrical, chemical, vibrational, stress due to humidity, and stress caused by temperature cycling, it does not identify them as causes of failure. The reliability prediction from FIDES does not include the modes, mechanisms, or causes of the failures limiting itself to a constant failure rate metric.

#### **4.10. Confidence level and confidence interval**

IEEE 1413 [141] requires that all reliability prediction reports shall include a statistical confidence statement, or, if such calculations are not possible to make, the report shall include a statement to that effect. A confidence level is the probability of the true value of the reliability metric lying within the accompanying confidence interval. For example, if the failure rate was stated as having a 95% confidence interval of 45 FITs (failures-in-time) to 60 FITs, the user of the prediction can infer that there is a 95% probability that the true mean of the failure rate of the population is contained within the stated confidence interval.

The FIDES Guide does not provide the confidence level or interval for its predictions. It states that “In the case of FIDES, while it might be possible to calculate a confidence interval on some basic failure rates, it is practically impossible to estimate confidence in all correcting parameters, even in the case of known and widely used physical acceleration laws” [50].

## Chapter 5. Comparison of FIDES Prediction and Failure Data

This section uses some examples to show the limitations of FIDES methodology and compares its prediction with failure data. Surface mount tantalum electrolytic capacitor (330 $\mu$ F, 6.3V) with polyethylene dioxythiophene (PEDOT) solid electrolyte is selected for this comparison. The failure data was obtained at 7.9V, 85°C and 85% RH. The test data analysis found 2 parameter Weibull distribution was the best fit for the data with shape parameter around 1.6 and the characteristic life of 760 hours [104].

For FIDES prediction, the basic failure rate for surface mount tantalum capacitor with solid electrolyte under thermal stress was selected and the acceleration factor for thermal stress was calculated using the ratio of applied voltage to rated voltage and the environmental temperature. The capacitor was considered to have an analog non-interface function in the circuit, making  $\Pi_{\text{placement}}$  as 1.3. Based on usage conditions,  $\Pi_{\text{application}}$  was calculated to be 1.27 and the default value of 1.7 was used for  $\Pi_{\text{ruggedizing}}$ . Default values for  $\Pi_{\text{PM}}$  as 1.6 and  $\Pi_{\text{Process}}$  as 4 were used due to lack of information on the supply chain.

FIDES predicted a failure rate of 731 FIT, and a mean time to failure (MTTF) of  $1.3 \times 10^6$  h. The MTTF from FIDES and the characteristic life from data analysis, both of which are times to 63.2% failures, differed by 3 orders of magnitude (see Table 5). The possible range of values for  $\Pi_{\text{PM}}$  is 0.5 to 2 and  $\Pi_{\text{Process}}$  is 1 to 8, that gives a MTTF range of  $5 \times 10^5$  h to  $2 \times 10^7$  h, which is orders of magnitude different than test

data. The FIDES model did not consider the stress due to humidity, although literature [104] shows that humidity impacts the reliability of tantalum capacitors. The model did not consider the materials of the constituents such as the electrolyte. Similar comparison of FIDES prediction to test data were made for light emitting diodes which showed 3 orders of degree difference (see Table 5). These examples show that FIDES, like other handbooks, provides inaccurate and misleading results.

Table 5: Comparison of times to 63.2% failures predicted using FIDES and test data

Electronic	Life cycle conditions	FIDES prediction	Test data analysis
Tantalum capacitor	85°C, 85% RH, 7.9V	$1.3 \times 10^6$ h ( $\approx$ 148 years)	760 h ( $\approx$ 32 days) [104].
White light emitting diodes (LED)	110°C, 85% RH, unbiased	$10^6$ h ( $\approx$ 114 years)	721 h ( $\approx$ 30 days) [113]
Blue light emitting diodes (LED)	120°C, 70% RH, 20 mA	$1.6 \times 10^7$ h ( $\approx$ 1826 years)	719 h ( $\approx$ 30 days) [118]

## Chapter 6. Conclusions

This paper assessed the suitability of FIDES for predicting reliability based on the model used to calculate the failure rate and the accuracy of its reliability predictions. The IEEE Std 1413 questionnaire for identification of risks associated with a reliability prediction is used in this assessment.

It was shown that the FIDES model assumes a constant failure rate, although the literature shows that many electronics undergo only wear-out failures and some electronics only exhibit a decreasing failure rate. As a result, a general model that uses constant failure rate for reliability prediction of electronics is not correct. This assessment reinforces the conclusions of the National Academies' report [26], "Reliability Growth: Enhancing Defense System Reliability," which states that "all methodologies based on the assumption of a constant failure rate are fundamentally flawed and cannot be used to predict reliability in the field."

It was shown that the FIDES model is based on subjective factors that adjust its constant failure rate metric. The use of subjective factors makes the value of the prediction dependent on who is making the prediction, makes the results non-reproducible and provides an opportunity to adjust the prediction results to match contractual needs. Even in an ideal situation, these subjective factors represent the uncertainty associated with risks in the supply chain and uncertainty cannot be represented by the single value FIDES prediction. Uncertainty should be accounted for by using methods such as Monte Carlo to get an interval prediction, however, FIDES does not follow this approach.

It was shown that FIDES prediction can be a hindrance to product development and support as it lacks consideration of the architecture of the product, and coverage of failure modes, mechanisms, and sites. The National Academies' report [26] also notes that "Without knowledge or understanding of the site, root cause, or mechanism of failures, the load and environment history, the materials, and the geometries, the calculated failure rate is meaningless in the context of reliability prediction...not only does this undermine reliability assessment in general, it also obstructs product design and process improvement." Lack of consideration of these attributes also invalidates the claim of FIDES being physics of failure based.

The IEEE 1413 evaluation also led to the following results. As the sources used for developing FIDES are not accessible, there is no way to assess the approach used to formulate the FIDES methodology including the timeline of the data collection, the generation of electronics from which the data came, the completeness of information on the lifecycle conditions and the data analysis method used. The assumptions for calculating the basic failure rates and the default values of factors such as  $\Pi_{PM}$  and  $\Pi_{Process}$  are not provided by FIDES, making it impossible for the user to judge the applicability of the assumptions for his application. Also, FIDES does not properly account for part quality and does not provide any means to incorporate new reliability data into the prediction. The prediction results of FIDES does not include any confidence interval or level and the user does not know the uncertainty associated with the reliability prediction.

Comparison of FIDES predictions to test data made in this work show that the predictions are inaccurate and inconsistent. It was noted that FIDES did not use the key

attributes about the electronics such as the material properties and geometries and their life cycles that is needed while making an accurate prediction. For example, it did not consider humidity stress during the operating state of the electronics. Also, the FIDES predictions could be varied over a wide range due to the inclusion of subjective factors.

In summary, the FIDES methodology is fundamentally flawed, lacks the key attributes for an accurate prediction (e.g., materials and geometries of component constituents) and makes subjective predictions. Thus, FIDES prediction should not be used as input for product reliability improvement, designing of reliability tests, or making decisions on support and sustainment of electronic products.

## Chapter 7. Contributions

This study assessed if the FIDES methodology is appropriate for predicting the reliability of electronics. The contributions from the study are as follows:

1. It was proven that the fundamental assumption of the FIDES methodology of the existence of the constant failure rate for electronics is flawed.

The hazard rate of electronics is dependent on the design, materials, manufacturing processes, inherent defects, and screening methods used and cannot be represented by a preconceived model. The actual hazard rate, and the formulation of a specific model, can only be constructed with actual data.

2. It was proven that the FIDES model is not an appropriate model to predict reliability. FIDES uses inappropriate reliability prediction metric and combines reliability prediction with supply chain risk assessment
3. It is Proven that FIDES is a progeny of MIL-HDBK-217 as it is based on the same fundamental assumptions and uses the same general formulation for predicting reliability.

It is shown that FIDES does not consider the materials and geometries of the component's constituents and does not identify the failure modes, mechanisms and causes and thus, the claim of FIDES is being based on physics of failure is refuted.

## Appendix

### Frequently Asked Questions

1. Has there been any interest in using FIDES predictions?

Yes, based on our conversations with multiple companies, the result of our informal survey, and the review of various conferences, we notice that there is a global interest in using FIDES predictions, especially for the military and aerospace sector.

2. Regardless of the failure distribution of individual components, if you combine several components and form a system, would the top-level be exponentially distributed (MTBF)?

No, the resultant hazard rate of several components is dependent on the individual hazard rates of the components and their superposition. The exponential distribution (constant failure rate) is a specialized case of the resultant and should not be used to develop a generalized prediction. Refer Section 2.2.2 for more information.

Also, FIDES makes its predictions assuming that the components themselves have constant failure rates, which is inaccurate.

3. Understanding that the predicted failure rate is incorrect, do the individual factors such as  $\Pi_{\text{process}}$  and  $\Pi_{\text{PM}}$  of FIDES provide any useful information?

No. The individual factors do not provide any useful information for reliability prediction. Refer Chapter 3 for the assessment of individual factors.

4. Are life cycle conditions accounted for in FIDES predictions?

FIDES requires the lifecycle to be divided into phases and for each phase, calculations are made using certain stresses acting on the component. For a given component, FIDES Guide provides a list of stresses to be included in the calculation of the failure rate and any stress beyond this list stays unaccounted. For example, polymeric tantalum capacitors are known to be sensitive to humidity, however, humidity stress is unaccounted in the FIDES model for tantalum capacitors. Also, the stresses that are listed by FIDES do not get considered for all the life cycle phases. For example, humidity stress is not considered for the operating phases and thermal stress is not considered for the non-operational phases. Refer Section 4.2 for more information.

5. It is shown that FIDES does not account for materials and geometry of components. Which methodology allows accounting for this level of detail?

There are alternative ways of predicting reliability that account for the materials and geometry of components such as use of physics of failure models or testing based on physics of failure. Although these methods are capable of making accurate predictions, the proponents of handbooks often critique these methods for the cost and time required to follow them. Yes, there is some investment necessary to gather and validate the information required for these models or simulations, however, for military, aerospace, medical and other applications where mission success is critical, reliability and safety should be the primary concern over cost and time. For example, in the aerospace industry, there is significant efforts to understand wing

reliability which includes performing finite element analysis, and testing of prototypes. Thus, it is surprising why people want to look in a handbook to assess the reliability of electronics that control the operation of the plane.

6. FIDES Guide claims the inclusion of a factor to account for part quality, then why does the IEEE Std 1413 based evaluation answer "no" for the quality being taken into account?

The evaluation based on IEEE Std 1413 was made by referring to the requirements listed by the standard and the similar evaluations made by IEEE 1413.1 for the other reliability prediction methodologies.

Although FIDES Guide claims to account for part quality using the  $\Pi_{PM}$  factor, assessment of the factor shows that it does not account for part quality. For example, the quality system used by a company does not give a quantitative impact on reliability of its components. Refer Section 4.4 for details.

7. Why are only the weaknesses and shortcomings of FIDES being presented and not what is interesting in FIDES methodology?

The weaknesses in FIDES outnumber the interesting points (if any) of the methodology. Thus, the inclusion of any interesting points in FIDES becomes redundant as they get masked by the weaknesses and result in an inaccurate and misleading prediction. Many organizations are considering the adoption of FIDES for reliability prediction and it is the aim of this work to make these organizations aware of the risks in adopting FIDES methodology.

8. While it does not accurately predict, Does FIDES correctly rank the lifetime of components?

FIDES uses various subjective factors to calculate the failure rate of components and thus, the ranking of the lifetimes (calculated from the predicted failure rates) of components is also subjective to who is making the prediction.

9. Did you compare actual results with calculated values with FIDES?

Yes, some comparison of actual results to FIDES predictions is shown in Chapter 5.

10. What method of predicting reliability is suggested for the industry?

IEEE Std 1413.1 [3] lists several methods of predicting reliability and includes a comparison of these methods based on the IEEE Std 1413 [141] questionnaire. Some of these methods include the use of test data, field data and the physics of failure models.

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