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An Assessment of Validity of the Bathtub Model Hazard Rate Trends in Electronics

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ABSTRACT The bathtub model has often been cited as a hazard rate profile that predicts not only human mortality but also the hazard rate of manufactured products. This article examines the inapplicability of the bathtub model to predict the hazard rate of electronic components, products, and systems. The article reviews various literature and uses numerous experiments and field failure data to support its argument. The factors affecting the hazard rate of electronics are then discussed, common hazard rate trends for electronics are identified, and recommendations for the assessment of hazard rates are given. This article recommends that a preconceived model of hazard rate over time should not be used.

INDEX TERMS Bathtub model, electronics, hazard rate, infant mortality, useful life, wear-out.

I. INTRODUCTION AND HISTORY

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 [1].

The bathtub model was originally developed as a model of the hazard rate for human life (mortality) over time [2], [3], and it first appeared in an actuarial life-table analysis article published in the late 17th century [4], [5]. 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 [3], [6]. The third period, called the wear-out period, occurs as the population approaches old age and the rate of deaths increases [3].

Although the bathtub model was created to model human mortality and assess life insurance risks, studies [7]–[9] have noted that it no longer applies to the human population due to advances in science. Meckel [9] 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 [10].

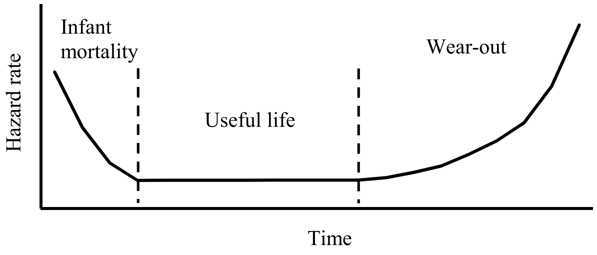

FIGURE 1. Bathtub model of hazard rate.

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 article addresses the question as to whether the bathtub model is appropriate for electronic components, products, and systems. Section II explains the bathtub model and the related terminologies. In Section III, 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 IV assesses the bathtub

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model as a whole and discusses the hazard rates of electronic products and systems. Section V presents the conclusions and recommendations.

II. THE 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, $\hat{f}$,

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

where Δn_f is the number of failures that occurred in a time interval, Δt.

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, $\hat{h}$,

$$\hat{h} = \frac{1}{n_{bp}}\frac{\Delta n_f}{\Delta t} \tag{2}$$

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.

$$h\,(t) = \frac{1}{n_s(t)}\frac{d\left[n_f\,(t)\right]}{dt} = \frac{-1}{R(t)}\frac{d\,[R\,(t)]}{dt} = \frac{f\,(t)}{R(t)} \tag{3}$$

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 [11]. 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 [12], Matlab [13], Mathcad [14], R [15], and Mathematica [16] 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 [2]. 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 [17]–[19].

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’ [17].

Many reliability prediction handbooks [20], [21] and reliability allocation methods [22] have incorrectly assumed that this region dominates the hazard rate trends of electronics; however, this assumption has also been proven to be incorrect [23]–[25].

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 [26], corrosion [26], electromigration [27], time-dependent dielectric breakdown [27], hot carrier injection [27], and negative bias temperature instability [27] and aging [17].

III. 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 [28] 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 [29] 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 [21], [30]. 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.

A. INFANT MORTALITY PERIOD

Infant mortality failures describe a decreasing hazard rate during the initial phase of a component’s or product’s life [2]. 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 [17], [31], [32] thereby reducing the occurrence of such failures. In well-designed and high-quality hardware, stresses should cause only uniform accumulation of wear-out damage [33]. 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 [34], [35].

Screening is the process of separating products with defects from those without defects. Burn-in is a screen

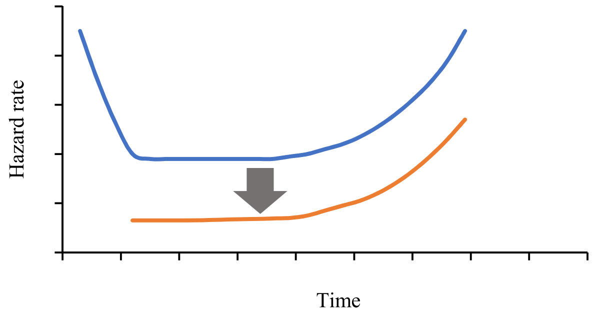

FIGURE 2. **The shape of the hazard rate curve from the effective implementation of ESS (lower curve) compared to the bathtub model (upper curve) [45].**

performed to precipitate defects by exposing the parts to accelerated stress levels [2], [36]. The goal of burn-in is to prevent failures from occurring in the field. The U.S. Food and Drug Administration (FDA) [37][1] 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 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 [38].

Any product that has undergone a successful burn-in will not have an infant mortality portion of the bathtub model [39]. The studies presented on board-mounted electronic components [40], microelectronic components [41], and integrated circuits [42] 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 [38], [43].

ESS has been so effective that most of today's products do not exhibit infant mortality trends. For example, Ryu and Chang [44] 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 [45].

Hester *et al.* [46] 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 [47], 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.

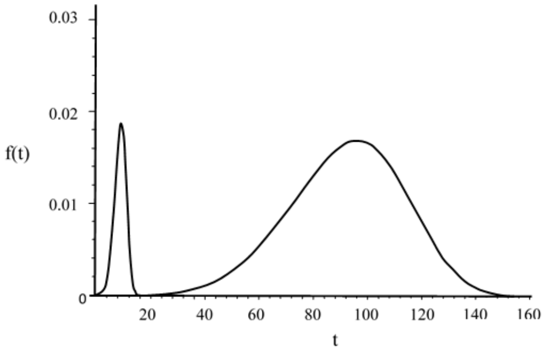

FIGURE 3. **The probability density function for a population with early failures (adapted from [5]).**

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 Fig. 3, cannot have a convex shape. English *et al.* [48] 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.

B. 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 [25] 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 [49] states that overstress failures[2] are rare and random, and if these occur frequently, it means that the device is not suitable for the application.[3]

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[1] "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."

[2] 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 [58] and thus increase the whole hazard rate distribution.

[3] "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." [49]

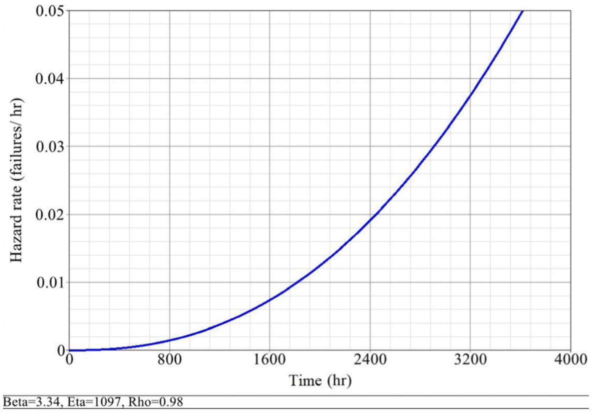

FIGURE 4. The hazard rate curve of electronic systems used in the CNC machine tool (based on data from references [51], [52]).

Yang *et al.* [50], 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 [51], Patil *et al.* [52], Keller *et al.* [53], and Dai *et al.* [54] 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 (β) 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).

The literature shows that some proponents [21], [55], [56] 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 [57], 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' [23], 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.* [58] 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.[4] Yuan *et al.* [59] 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.* [60] showed that the electronic railway signaling systems do not have a constant hazard rate. Verma *et al.* [61] 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.* [62] 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 [63] 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

$$R(t) = R_1(t) + R_2(t) - R_1(t)R_2(t) \tag{4}$$

For two components, both having a constant failure rate λ,

$$R(t) = 2R_1(t) - R_1^2(t) = 2e^{-\lambda t} - e^{-2\lambda t} \tag{5}$$

It is observed that the two exponential functions of (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.

C. 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 [17], [64]. These failure mechanisms start as soon as the product is put into operation [30] and not after a period of random failures, as implied by the bathtub model. Dasgupta *et al.* [26] 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 [30] stated,

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[4] "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." [58]

"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.* [27] 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 [65] 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 [66], 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.* [67] evaluated LED packages and found only wear-out failures for packages with various encapsulation materials. Mattila *et al.* [68], in their study on the reliability of electronic component boards, observed only wear-out failures at all testing temperatures. Mei *et al.* [69] 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.* [70] performed reliability modeling of aged SAC305 solder joints and found the hazard rate to have shape parameters greater than 2. Liu *et al.* [71] showed that the interconnects undergo wear-out when subjected to vibrations, both at fixed and random frequencies. Virkki and Tuukkanen [73] studied tantalum capacitors under various temperature ranges and observed only increasing failure rates. Hoffman *et al.* [74] showed that insulated-gate bipolar transistors (IGBTs) failed by wear-out when exposed to combined thermo-mechanical and electro-chemical stresses. White *et al.* [75] found the main failure distribution in DRAMs has an increasing hazard rate. Quintero *et al.* [76] 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 1 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 1. 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 *et al.* [77]	Tantalum electrolytic capacitors	>1.6
J. Meng *et al.* [78]	Microelectromechanical systems	1.9
Srinivas *et al.* [79]	Solder joints of package on package assemblies	>2.8
Valentin *et al.* [80]	Solder joints between package leads and printed wiring boards	4.4
Lu and Christou [81]	Transistor modules	5.6
Osterman and Pecht [82]	Printed circuit boards	>4
H. Qi *et al.* [83]	Solder joints of printed circuit board assemblies	2.6
Hwang *et al.* [84]	Capacitors	Between 2.9 and 17.4
Jozwiak [85]	Microcomputer system	4.9
Chan *et al.* [86]	White light emitting diode	>12
Munoz-Gorriz *et al.* [87]	Metal-insulator-semiconductor (MIS) capacitor	>4
Bossuyt *et al.* [88]	Stretchable electronic substrates	>2.8
Choi *et al.* [89]	IGBT power module	6.6
Liu *et al.* [90]	Ball grid array (BGA) packages	>1.9
Nogueria *et al.* [91]	Blue light emitting diode	>4.8
Putaala *et al.* [92]	Ceramic antenna assemblies	>5.5
Ferrara *et al.* [93]	Power amplifier module	>2
Le Coq *et al.* [94]	Wafer-level chip scale packages	>3.4
Schilling *et al.* [95]	Power diodes	>1.2
Rajaguru *et al.* [96]	Power electronic module	>38
Li *et al.* [97]	n-MOSFETs	10.6
Xu *et al.* [98]	Gold-plated electrical interconnects	>20

IV. DOES THE BATHTUB MODEL EXIST?

Sections III-A, III-B, and III-C 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.

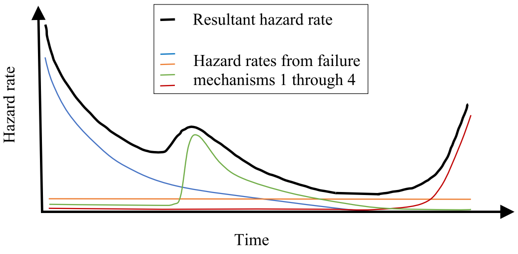

FIGURE 5. Visualization of roller-coaster curve of the hazard rate.

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 [99] stating that 96 percent of its items did not follow the bathtub curve.[5] Similarly, Moltoft [100] 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 [101] 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 [102] have raised questions on the applicability of the bathtub model for electronic components and products. A series of article s [25], [103]–[105] showed that the bathtub model was not appropriate to predict the shape of the hazard rate. Jensen and Petersen [106] 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.* [48] noted that the latent failures are non-predictable and unavoidable. Wong and Lindstorm [104] 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 Fig. 5.

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 [107]. Kapur and Pecht [2] 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 1.

V. CONCLUSION

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 article.

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 article 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.

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