SOME WAYS TO IMPROVE PRODUCTS RELIABILITY

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1. INTRODUCTION

Modern engineering products, from individual components to large systems[1], must be designed and manufactured to be reliable in use. If the market for the product is competitive, improved quality and reliability can generate very strong competitive advantages. W. E. Deming[2] (1900-1993) taught the fundamental connections between quality, productivity, and competitiveness, but unfortunately, the development of quality and reliability engineering has been afflicted with more nonsense than any other branch of engineering. This has been the result of the development of methods and systems for analysis and control that contravene the deductive logic that quality and reliability are achieved by knowledge, attention to detail, and continuous improvement on the part of the people involved. Therefore it can be difficult for students, teachers, engineers, and managers to discriminate effectively, and many have been led down wrong paths.

Paradoxically, failure[3] at the detailed, individual level is absolutely necessary for the health and vitally of the system as a whole. We need change and evolution to make progress. But evolution implies extinction, the discarding of ways of working that have outlived their usefulness.

Product failure is deceptively difficult to understand. It depends not just on how customers use a product but on the intrinsic properties of each part - what it's made of and how those materials respond to wildly varying conditions. Estimating a product's lifespan is an art that even the most sophisticated manufacturers still struggle with. And it's getting harder. In our Moore's law-driven age, we expect devices to continuously be getting smaller, lighter, more powerful, and more efficient. This thinking has seeped into our expectations about lots of product categories: Cars must get better gas mileage. Bicycles must get lighter. Washing machines need to get clothes cleaner with less water. Almost every industry is expected to make major advances every year. To do this they are constantly reaching for new materials and design techniques. All this is great for innovation, but it's terrible for reliability.

Change is difficult, change is disturbing, and change brings uncertainty. Change creates failures, but it also creates success [1]. Understanding when and why things fail is critical to our economic and societal well-being.

Often when materials fail unexpectedly it is not because the external circumstances were particularly severe, but because the materials microstructure is sub-optimal, there are defects present or develop in service, or because there are stresses locked into the material that we didn't know about.

Materials are stored to failure. One of the biggest challenges in predicting when a product will fail, is understanding the material it's made from. Every material, from metals to composites to ceramics, will have microscopic variations from unit to unit that affect a product's lifespan. The company Vextec hopes to solve this problem, by creating statistically accurate computer 3D-models, down to the grains, voids, and crystals that make up a material's microstructure (Figure 1).

What causes these failures? They can be due to inadequate design, improper use, poor manufacturing, improper storage, inadequate protection during shipping, insufficient test coverage and poor maintenance, to name just a few. A product can be designed to fail, although unintentionally. To achieve product reliability, we

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[1] "A system is a network of interdependent components that work together to try to accomplish the aim of the system. A system must have an aim. Without an aim, there is no system. The aim of the system must be clear to everyone in the system. The aim must include plans for the future. The aim is a value judgment. (We are of course talking here about a man-made system.)" [Deming].

[2] In the 1970s, Deming's philosophy was summarized by some of his Japanese proponents with the following '*a*'-versus-'*b*' comparison:
(a) When people and organizations focus primarily on quality, defined by the following ratio:

$$\text{Quality} = \frac{\text{Results of work efforts}}{\text{Total costs}}$$

Quality tends to increase and costs fall over time.
(b) However, when people and organizations focus primarily on *costs*, costs tend to rise and quality declines over time.

[3] A failure is anytime the product does not function to specification when the product or service is needed. The degree of failure can be varied, but the negative effect on your business is the same. A dissatisfied consumer results in the loss of repeat business.

a *b.* *c,*

Figure 1. Failure under the microscope. ***a***) Photo of a metal’s microstructure. ***b***) Vextec’s simulation – complete with voids, grains, and impurities. ***c***) The 3D version will show how and when cracks form [2].

must ask the question ‘‘what will wearout before the end of the customer expected product life and why?’’ By identifying the things that will fail in the field, design changes can be made to improve product performance or a maintenance program can be established. Through design changes, the poorly chosen fastener that slowly leads to an eventual failure can be removed from the possibility of causing a failure.

2. DEFECT, ERROR, FAULT

The following three terms are crucial and related to system failure and thus need to be clearly defined, which are named *defect*, *error*, and *fault*.

A defect in an electronic system is the unintended difference between the implemented hardware and its intended design. Some typical defects of VLSI chips include:

- Process defects, taking the form of missing contact windows, parasitic transistors, oxide breakdown, etc.;
- Material defects, due to bulk defects (cracks, crystal imperfections), surface impurities, etc.; and
- Age defects, taking the form of dielectric breakdown, electromigration, etc.

Defects can be also classified by the statistical effect they produce:

- Systematic, defects that have the same impact across large dimensions, such as die or wafer, and that can be modelled in a systematic way. These defects are usually the result of process–design interaction.
- Random (stochastic), all types of defects that cannot be controlled or modelled in a predictable and systematic way. They include random particles in the resist or in the materials, inserted or removed, or defects in the crystal structure itself that alter the intended behaviour of the material and results in excessive leakage or in a shift in the device threshold (V_{th}), eventually causing the failure of the device.

The failure modes resulting from these defects are: *(i)* Opens; *(ii)* Shorts; *(iii)* Leakage; *(iv)* V_{th} shift; *(v)* Variability in mobility (μ)

Random defects do not necessarily result in a complete failure of the device, but in a significant deterioration of its performance.

A wrong output signal produced by a defective system is called an *error*. An error is an effect whose cause is some defect.

A *fault* is a representation of a defect at the abstracted functional level. A fault is present in the system when physical difference is observed between the “good” or “correct” system and the actual system.

If error detection and recovery do not take place in a timely manner, a *failure* can occur that is manifested by the inability of the system to provide a specified service. *Fault tolerance* is the capability of a system to recover from a fault or error without exhibiting failure. A fault in a system does not necessarily result in an error; a fault may be latent in that it exists but does not result in an error; the fault must be sensitized by a particular system state and input conditions to produce an error. Error sources can be classified according to the phenomenon causing the error. Such origins are for instance related to the manufacturing process, physical changes during operation, internal noise caused by other parts of the circuit, and external noise originating from the chip environment. [3].

3. RELATIONSHIP BETWEEN FAULTS, ERRORS AND FAILURES

The creation and manifestation mechanisms of faults, errors, and failures are illustrated by Figure 3, and summarized as follows:

$$\text{fault} \xrightarrow{\textit{activation}} \text{error} \xrightarrow{\textit{propagation}} \text{failure} \xrightarrow{\textit{causation}} \text{fault}$$

Figure 2. The fundamental chain of dependability threats (after [4]).

The arrows in Figure 2 express a causality relationship between faults, errors and failures. They should be interpreted generically: by propagation, several errors can be generated before a failure occurs. Faults can be categorized according to their activation reproducibility: faults whose activation is reproducible are called *hard*, faults, whereas faults whose activation is not systematically reproducible are *soft* faults. The similarity of the manifestation of elusive design faults and of transient physical faults leads to both classes being grouped together as *intermittent faults*. Errors produced by intermittent faults are usually termed *soft errors* [5].

4. FIRST IN, FIRST OUT (FIFO); LAMBDA; FAILURE IN TIME (FIT)

The grocery store places their products on shelves. When a new shipment arrives, the old product is rotated to the front of the shelf and the new product is placed at the rear. This is commonly known as rotating or facing the shelves. This ensures that some items do not rest on the shelf too long to spoil. This is done on dairy products everyday. The term used in industry is *FIFO, First In First Out*.

Many electronics components actually start to wear out right after they are produced. How soon after they arrive at the manufacturing location they are installed in the product and shipped to the customer can be important. These parts also have to be used on a FIFO basis to ensure that the decaying process does not accumulate to lower the part's life expectancy. For example, adhesives have short shelf lives. If not used for several months, many adhesives are susceptible to early failure. Sticky-backed labels are often purchased in large quantities to get good pricing. Often these labels are in storage for several years before the last ones are applied to the product. In the field, these old labels will usually fall off in a few months and as such their value is lost.

When a product has failed, the failure mechanism must be learned to determine the root cause of the failure. The design of the product or the process must be updated to remove the failure possibility from happening.

Since 1980s, the reliability of electronic components (in general) has improved two to four orders of magnitude. Parts were often specified in failures per million hours of operation [the term used is λ (lambda)]. Today, parts are specified in failures per billion hours of operation, which are referred to as *FITs* (Failures in Time). If parts were the main contributor to failures, then, with the vastly improved complexity of new devices, they would be failing constantly. We can all attest that they are not. Televisions, radios, and automobiles all have more parts and last longer. This is due to the inherent design and the manufacturing processes, not the parts count. What is needed to improve the reliability of a manufactured assembly is to improve the design and the manufacturing process. Much work has been done over the past few decades to improve the quality and reliability of components. This effort has, for the most part, been very successful. In fact, the measurement used to describe the quality of components has been changed three orders of magnitude as well (from λ to FIT).

5. RELIABILITY

The world is changing. Companies have to change to stay in business. Today's managers have to adapt their companies to these new paradigms[4]. Change the rule and you change the outcome. What we see in the marketplace is that the same old rules don't work any more. The paradigm has changed. Rules change on a continuous basis. Today, they change even faster.

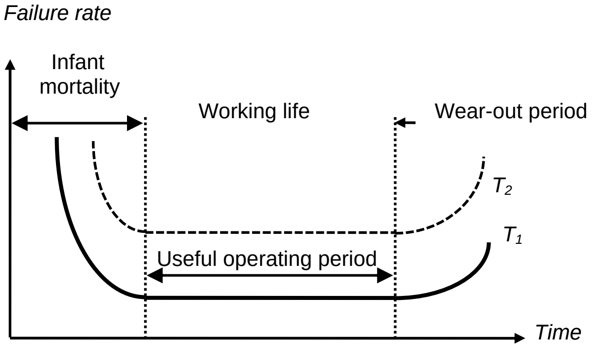

Figure 3. The "bathtub" failure curve of a large population of statistically identical items (electronic components), for two ambient temperatures $T_2 > T_1$ (After [6]). The time axis is not to scale.

Another new paradigm is reliability. When your designs are mature and your processes are in control, the reliability of your product will be high. The return is in dollars/euros not lost to warranty claims and upset customers. You, as a manager, have to make the changes that ensure quality and reliability. Otherwise the market will look to those who have learned these new rules earlier.

The process yield of a manufacturing process is defined as the fraction, or percentage, of acceptable parts among all parts that are fabricated. A system failure occurs or is present when the *service*

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[4] Paradigms don't change rapidly. Rules do; one at a time. Paradigms are what we believe to be true, not necessarily what really is true. Paradigms are made up of an assortment of rules. With more rules, the paradigm is more entrenched. With more established rules, our belief in the paradigm is stronger. When many rules support the old paradigm, more obstacles have to be overcome to move into the new paradigm [3].

provided by the system differs from the specified service or the service that should have been offered. In other words, the system *fails* to perform what it is expected to. The so-called bathtub curve which is shown in Figure 3 is widely accepted to represent a realistic model of the failure rate of electronic equipment and systems over time. The bathtub curve consists of three characteristic zones. Failure rates follow a decreasing pattern during the early times of operation, where infant mortality deteriorates the system, typically due to oxide defects, particulate masking defects, or contamination-related defects. Failure rate remains constant over the major part of the system operation life. Failures are random, mostly manifesting themselves as soft errors. Wearout occurs in the final stage of the system lifetime, where failure rate increases, typically due to electromigration-related defects, oxide wearout, or hot carrier injection.

There are many possible classifications of the failures that could appear in the functioning of technical systems (including electronic systems and electronic components).

From the reliability viewpoint, the most known classification depends on the moment when the failure appears, and is synthesized in Table 1. Other types of classifications are mentioned in Table 2. One must be note that an investigator of product reliability must go beyond these classifications of failures and find out the failure mechanism in each case. This is the only way to facilitate both the selection of best components and their correct use, helping to the reliability growth, in general.

At the beginning, reliability engineering efforts were carried out as a part of semiconductor device development so that maximum inherent reliability can be designed into the device. These efforts encompass physics of failure, failure analysis, reliability testing, and reliability sciences.

6. CAN THE BATCH RELIABILITY BE INCREASED?

The reliability of a batch of components can be increased in three different ways, which may be used separately or combined.

Firstly, it is the so-called *pre-aging,* which can be applied to all components before the input control. The pre-aging eliminates a part of the early failures and awards to the surviving components a stable behaviour during the operation time. This type of pre-aging has nothing to do with the pre-aging performed – for example – by the manufacturer of the components, as part of the fabrication process, for stabilizing the normal operating properties. To increase the reliability by pre-aging it is necessary to know the conditions of the input control in order to design the stress conditions during pre-aging. In general, the pre-aging is realized by an inferior component loading (in comparison with the ulterior operating conditions). If a rapid pre-aging is

Table 1. Classifications of Failures Depending on the Moment of Appearance (after [7])

Types of failures	***Comments***
Early (infant mortality) failures that appear during the early period of product life.	Can be explained by a faulty manufacture and an insufficient quality control. Could be eliminated by a systematic screening test.
Accidental failures that appear during the useful life of the product.	Cannot be eliminated neither by a screening test, nor by an optimal use politics (maintenance). Could be provoked by sudden voltage increases that can strongly influence the component quality and reliability. These failures appear erratically, accidentally, and unforeseeably.
Wear out failures that appear in the final period of product life.	Are indicators of the product aging.

Table 2. Various Classifications of the Failures (after [7])

Classification parameter	***Types of failures***
Failure cause	Failure due to an incorrect assembling Failure due to an inherent weakness
Speed of the phenomenon	Sudden failure Progressive failure
Technical complexity	Total failure Partial failure Intermittent failure
Emergence manner	Catastrophic failure Degradation failure

needed, a load greater than the nominal operational load value could be selected. However, the loading must not be too high, because otherwise the component can reach the failure limit, will be damaged and will not have at the input control the desired behaviour.

The second way is the operational derating or the devaluation that contributes to a substantial increase of reliability.

The third method is linked to the tolerance limits, which can also influence the system reliability. By using this method, one may pay attention to the outrunning, since an optimal efficiency can be obtained only as parts are inside the established limits. Exceeding these limits can operate inversely, reducing the reliability. With the aim to not allow to these variations to perturb the system function, the circuit designer must establish tolerance limits that are harmonized with the parameter variations. To define these tolerance limits, the density function and the long-term behaviour of the given parameters must be known. By modifying the distribution function for the lifetime, those parameters that exceed the prescribed limits can be identified. The knowledge of this behaviour of the parameters allows either to select the parameters that are inside the prescribed limits, or to establish the limits that must not to be exceeded during the operation.

7. DERATING TECHNIQUES

One of the most used methods to improve the reliability of the equipped printed circuits boards (PCBs) is the *derating technique:* the mounted component is functioning at values of voltages, currents, tests and/or temperatures that are well below the manufacturer's rating for the part (nominal operating values). In this way an increase of the lifetime duration for the respective component is obtained. We encourage users to implement derating as appropriate for their application in all instances. The under loading values can be found by the manufacturer or in failure rates handbooks such as GPRD-97, RDF 2000 [8-10], PRISM [11], FIDES [12]. This data – in which the values corresponding to the prescriptions are taken as parameter – can provide specific failure rates for each one of the operating conditions. You must begin with the study of the operating conditions of the system, by evaluating–in percentage of the nominal values–the voltage, the load and the temperature, for each component. With the aid of the given tables the value for the specific operating conditions can be determined and the sum of the failure rates with a tolerance of approximately 10% can be found, allowing to take into account the solder joints, the connections, and so forth.

On demand, special selection tests (thermal cycles, high temperatures, thermal shocks, vibrations) could be designed. By using a minimum number of components operating well below the nominal values, the circuit designer himself may settle the circuit reliability.

If the reliability problem is correctly treated, any apparatus, device or equipment can be decomposed in modules, subsystems, units, ensuring for each element the best reliability level, so that the desired reliability of the ensemble can be obtained.

8. METHODS FOR INCREASING THE RELIABILITY OF ELECTRONICS

The technical direction of CALCE EPRC has concentrated on evaluating widely accepted reliability methods, including allocation, parts selection, reliability prediction, derating, environmental control, screening, and qualification. It became apparent that many manufacturers of electronic hardware had come to rely on the security of government-approved reliability documents such as *MIL-STD-785* (*Reliability Program for Systems and Equipment*) and *MIL-HDBK-217* (*Reliability Prediction of Electronic Equipment*), even though following them often led to poor part selection, improper derating, high-cost cooling solutions, and long development times. Using these documents, any solution to a reliability question was deceptively simple: select specific devices, derate them, run them cool, and introduce redundancies. Auditing quality was accomplished similarly, with government mandated tests such as *MIL-STD-883* (*Test Methods and Procedures for Microelectronics*), perpetuating the myth that reliability and quality could be tested into a product. The costs for following the mandated guidelines were passed on to the customer, resulting in more expensive products without a commensurate increase in performance or reliability.

The CALCE EPRC is now implementing a fundamentally new approach to addressing reliability. Based on research into the mechanics of failure processes, knowledge of how failures occur is being gathered in order to gain control over failure mechanisms and manufacturing flaws. Coupling this data with novel simulation techniques, the CALCE EPRC is enabling design for reliability, reliability assessment, and virtual qualification (or qualification by design) of new electronic products [13].

9. ACCELERATED AGING METHODS FOR EQUIPPED BOARDS

Another recommended method for increasing the reliability of the system, which is complementary to the screening performed at component level, is the accelerated aging of printed circuits boards (PCBs).

An example of such proceedings is given below:

- Visual control; rough electrical testing;
- 10 temperature cycling (-40°C / +70°C), with a speed of 4°C/minute and a break of maximum 10 minutes. During cooling, the bias will be disconnected;
- 24 hours burn-in at ambient temperature or, even better, at +40°C ("debugging"), with periodic "on" and "off";
- Final electrical testing.

This method is complementary with the screening performed at component level.

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