CORROSION SCIENCE AND TECHNOLOGY, Vol.4, No.5(2005), pp.201~206

The Novel Concepts for Reliability Technology

† DongSu Ryu

Reliability Laboratory, CS Management Center, Samsung Electronics Co., Ltd, Suwon,
Korea Reliability Analysis Research Center, Hanyang University, Seoul, KOREA

Starting with the meaning of the word *quality*, diverse concepts connoted by the term are examined. Instead of a bathtub curve, the desirable shape of a failure rate covering the entire life of a good product, which might be called *hockey-stick* line, is introduced. From the hockey-stick line and the definition of reliability, two measurements are extracted. The terms r-reliability (failure rate) and durability (product life) are explained. The conceptual analysis of failure mechanics explains that reliability technology pertains to design area. The desirable shape of hazard rate curve of electronic items, hockey-stick line, clarifies that Mean-Time-to-failure (MTTF) as the inverse of failure rate can be regarded a nominal life. And Bx life, different from MTTF, is explained. Reliability relationships between components and set products are explained. Reshaped definitions of r-reliability and durability are recommended.

The procedure to improve reliability and the reasons for failing to identify failure mode are clarified in order to search right solutions. And generalized Life-Stress failure model is recommended for the calculation of acceleration factor.

Keywords *: quality, reliability, durability, hockey-stick line, Bx life, life-stress model*

1. Introduction

Since 1970's it has been acknowledged that there exists big crevice between reliability theory and its application to industrial fields. As we know, there have been numerous accidents suggesting the imperfection of technological theory. Thus here, novel concepts, reshaped definitions and methodologies adequate to real world are presented in order to interpret and analyze reliability problems, and to perform designing of technological complex for avoiding accidents and pursuing the exact route for safer world.

1.1 The clarification of quality and reliability concepts

1.1.1 The difference between quality and reliability

The broad concept of quality includes reliability. But the concept of quality in a narrow sense and that of reliability are totally different. To narrow down the difference between quality and reliability, let's think of quality defects and reliability defects negatively.

Quality defects, in a narrow sense, refer to deficient products or components at present. Quality defects are inspected and screened out by comparison with standard specifications that have already been confirmed at the time of the release of drawings and specifications. And reliability defects generally mean failures that might occur in the future, inside a product that has been working well so far. Therefore, reliability must be regarded as a ratio connected to units of time.

We can call this quality the *conformance-quality* at present, and reliability the *non-failure* in the future. Afterwards, conformance-quality refers to quality in a narrow sense and is abbreviated to c-quality for the differentiation from the broad concept of quality.

If a product is carefully well designed and manufactured, the accumulated failure rate of the product, $F(t)$, is proportional to the time period till acceptable life to consumers, including on and off time by them after unpacking the product as following,[1]

$$F(t)=1-R(t)=1-e^{-\lambda t}\cong\lambda t \tag{1}$$

where R is reliability function, λ is failure rate, and t is use time. In a practical sense, this proportionality is suitable below about 20 percent of cumulative failure rate.

1.2 The bathtub curve and hockey stick line

The bathtub curve depicts three regions: the decreasing rate of failure, the constant rate of failure (sometimes a slanted line) and the increasing rate of failure, as shown in Fig. 1.

† Corresponding author: dos.ryu@samsung.com

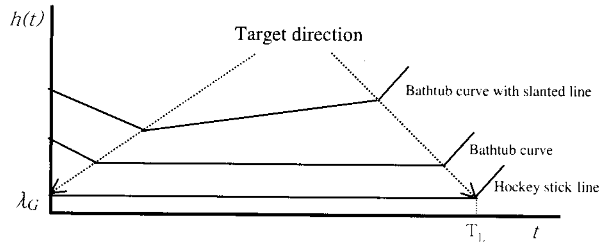

Fig. 1. The bathtub curve and hockey stick line

If the failure rate of a product goes along the bathtub curve, the product has no chance to succeed in the market due to big initial failure, high random failure rate and short product life. So we can extract targets for excellent products with respect to reliability: (1) Reduce initial failure to zero, do not just minimize. (2) Minimize random failures confirming that there exists only constant failure ¾ without any kind of wear-out failure during the working time. (3) Lengthen the product life compared with that of competitors' products delaying the occurrence of wear-out failure.

Actually, it is possible to eliminate initial failures by analyzing them through advanced NDT (non-destructive test) and DT (destructive test) technology because those are easily found in a short period. And the wear-out failures of operating time can be removed by analyzing failed sample, which can be not-laboriously collected by related test.

Eliminating the initial failure of new products means that the shape of the bathtub curve is changed, as shown at the arrow of target direction in Fig. 1, into a line, not a curve. We can call this the hockey stick line due to its rather familiar shape.

1.3 The two meanings of reliability

The two points determining hockey stick line match precisely the definition of reliability; *the ability of an item to perform a required function under stated environmental and operational conditions for a specified period of time.* According to this definition, there are two unknown variables to be measured: ability and time. *A specified period of time* refers to product life (T_L). *Ability* means the level of performance that can be calculated with failure rate and item life using the above equation (1): $1 - \lambda_G - T_L$. Thus the definition of reliability has two measurements: failure rate and life.

Although good reliability produces both a lower failure rate and longer product life, some specialists regard reliability to be only the failure rate and use *durability* as the word regarding product life. So there are two possible meanings of the terminology of reliability. Afterwards *rate-reliability* refers to reliability regarding only failure rate and is abbreviated to r-reliability for the differentiation from the concept of reliability in the definition.

The term *quality* is an ambiguous word encompassing c-quality and reliability. *Reliability* is also an ambiguous word comprising durability and r-reliability.

In addition, there is another extended concept about quality. It is *product quality*. A product without reliability failures and c-quality defects is desirable but may not be preferred over the other products in the market by customers. In order to prevail in the market, the product, if its price is similar with competitor, should be designed and manufactured with the concept of product quality, which consists of five factors;[2] performance, reliability, c-quality, customer perception, and fundamentals advantage, which can be rearranged from eight dimensions proposed by D. Garvin.[3]

1.4 The novel concepts of reliability

1.4.1 Failure mechanics

Let's consider the core concept of reliability; non-failure. Failure occurs when the materials in the components of the product are too weak to endure the applied stress, and/or when the stresses on the components are unexpectedly too great for the materials, as shown in Fig. 2.[4] Therefore reliability is best conceived of as the relationship between stresses (loads) and materials (strengths). Appropriate solutions avoiding failure mean altering the structures for the dispersion of stresses, and/or replacing the materials. Thus, the technique for reliability pertains to design area, not to manufacturing field.

1.5 The shape of hazard rate curve of electronic and mechanical items

It has been well known that the failure rate of electronic items keeps constant along with time and follows exponential distribution and that failures in mechanical items appear after a certain time and its shape of failure rate is similar to normal distribution.

But as the understanding on both microstructure and materials of electronic constituents has been deepened owing to 50 years research and failure analyses, it is recognized that the shapes of failure rate of electronic components are similar to mechanical ones because they are also considered to be another architecture. All items

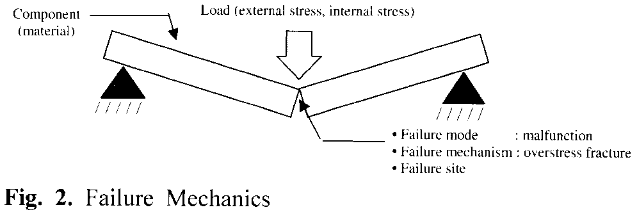

Fig. 2. Failure Mechanics

can have low failure rates until a certain period of time, which refers to their lives. It means that the failure rate of all items should be targeted to follow the hockey stick line.

1.6 Mean-time-to-failure and Bx life

The failure rate and the life of an item vary independently due to different failure mechanisms each other. And it implies that there is no convertible relationship between them. Thus the inverse of failure rate cannot be considered as the lifetime, but a kind of nominal life. Take for instances. The annual failure rate of first class television sets reaches to about two percent per year. It means that half of them are still working for fifty years, which is the inverse of failure rate. It is unbelievable.

The durability index by MTTF does not reflect our common sense about product life. For example, consumers think that the average life of television sets would be ten years. They anticipate their troubled sets within ten years to be fixed without charges. It is just mean time for consumers, but not the MTTF defined by statistician. Currently it is widely accepted that people use television sets for ten years, which implies that over eighty percents of them operate for ten years even though all of them do not work in eleventh year. Manufactures acknowledge twenty percents of failure until ten years, which we call B_{20} life reaching ten years, might affordable in the current business of electrical home appliances. Thus the durability index by Bx life is more adequate to users' feelings than that by MTTF.

And Bx life is also better index than turning point life in hockey stick line because the latter is meaningless in case that the cumulative failure rate till this point would be higher than the acceptable target.

1.7 Reliability relationships between components and set product

Customers regard the product not to be a technological complex but a convenience good performance, ease of use, no-trouble. The reliability of products should be acceptable as a whole, regardless of both the type of products and the quantity of components incorporated into products. Therefore three conclusions can be drawn about component reliability.

First, the durability of components should be longer than set product life expectancy.

Secondly, how low should be the r-reliability of components incorporated into a successful product? The failure rate of the product is the sum of the failure rates of all components and the related connections with them. The component must be reliable, so the targets of the annual failure rate of that part should be below 10-ppm/year in the television, 1-ppm/year in the motor, and 0.1-ppm/year in the plane respectively under the condition shown in Table 1, even though its life may satisfy the durability target of each product. And also presents the required target x% of component in Bx life that assumed ten years, which means the cumulative failure rate within ten years.

Thirdly, if some initial failures appear in a certain component, they are photographically transferred to the set product. The shape of failure rate of set product is also the summation of the forms of their component failure rate. Thus initial failure of all components should be eliminated and their failure rates follow the hockey-stick line, eventually.

So, manufacturer should request parts vendors to comply with the following three requirements under stated environmental and operational conditions recognized with each other. (1) There are no initial failures. (2) The failure rates of components are below the targets calculated as explained with Table 2. (3) Components lives are longer than product life.

1.8 The reshaped definition of failure rate and characteristic life

Recently, as the reliability of most items improves it is very difficult to identify failure mode. If there would

Table 1. The failure rate of product and component

Category	Television	Motor	Aircraft
Product target of annual failure rate**	1%/yr	1%/yr	1%/yr
Number of components	1,000	10,000	100,000
Required annual failure rate of component	0.001%/yr	0.0001%/yr	0.00001%/yr
Annual operation time (hour)	2,000	2,000	2,000
Required hourly failure rate of component	5×10^{-9}/hr	0.5×10^{-9}/hr	0.05×10^{-9}/hr
Required target x% in Bxlife of component*	B0.01	B0.001	B0.0001

*Assume that Bx life of each product is ten years. **Except for critical failure.

be no failure in r-reliability test the failure rate results in zero with the current definition regardless of the amount of test hours. And it is all the same with the characteristic life. In case of no failure found in durability test we cannot calculate item life with the current maximum likelihood estimation because its divisor becomes zero. That is inconsistent with our common sense. In order to differentiate results according to test hours, it is better to add one to failed number. Thus author wishes to introduce the reshaped definitions as followings:

$$\lambda \equiv (r+1)\cdot\frac{1}{n\cdot h} \quad (2)$$

$$\eta^{\beta} \equiv \frac{1}{(r+1)}\cdot n\cdot h^{\beta} \quad (3)$$

where λ is hourly failure rate, γ is failed numbers, n is test sample numbers, h is test hours, η is characteristic life by hour, and β is shape parameter of Weibull distribution. These will be the upper limit of failure rate and the lower limit of characteristic life with approximately 60% of confidence level on condition that failed numbers are below several pieces. The confidence level can be calculated with this equation, or $1/2\cdot\chi^2_{\alpha}(2r+2)=r+1$, where χ^2_{α} is 100(1-α) percentile of the chi-square distribution. In order to assess the durability mentioned earlier, characteristic life in Weibull distribution should be changed into Bx life as following;

$$T^{\beta} = \ln(1-x)^{-1}\cdot\eta^{\beta} = \left(x+\frac{x^2}{2}+\frac{x^3}{3}+\Lambda\right)\cdot\eta^{\beta}, \quad (4)$$

where T = Bx life, $x = 0.01\cdot X$.

Finally, we arrive at the following equation on Bx life on condition that $x \leq 0.2$,

$$T^{\beta} \cong x\cdot\frac{1}{r+1}\cdot n\cdot h^{\beta}. \quad (5)$$

2. Reliability improvement

2.1 No everlasting test specification on reliability

Product developers pressed to surpass competitors always adapt new components and/or innovative structures that possibly include different failure mechanisms from the ones of current product due to unfamiliar materials and stresses, which is the two key elements of reliability. So the current test specifications can never find all the failures of newly designed product. Thus there is no everlasting and deterministic test specification on reliability.

2.2 Three steps for reliability growth

The steps for reliability growth would be as follows: (1) Identify the failure modes through various time-consuming tests, sometimes including non-operating times, not by inspection. (2) Analyze failures and determine the failure mechanism, and rearrange effectively the above test methods. (3) Change structures and/or re-establish specifications according to the analysis results, and confirm the validity through the above test and eliminate the side effects of design change. All activities should be completed, now and here, before product release.

Note that failed samples should be carefully handled in order to preserve the evidence of root cause and that analysis procedure be also systematically planned based on both the knowledge of item function, structure and constituent materials, manufacturing process, and received stress history and on the opinions and tips of experienced analysts, specialists on advanced analytical instruments, and even the defensive persons who may be blamed for that failure.

2.3 The reasons for failing to identify failure in advance

As all items will fail in the end, the goal of reliability test should be positioned to indispensably find failures inside the items. Generally, there is a reason why we fail to find failures. That is not to satisfy the following two conditions simultaneously.

(1) Mathematical condition: In case of estimating failure rate, the number of test samples is insufficient to identify random failures because of tremendously low failure rate. Or in case of assessing item lifetime, the period of test time is comparatively short to make occurring long-term wear-out failures such as corrosion.

(2) Physical-chemical condition: The test conditions do not match with actual environmental and operational conditions.

First, the number of test sample would be estimated with about 60% of confidence level using equation (2), as following,

$$n \geq (r+1)\cdot\frac{1}{\lambda\cdot h} \quad (6)$$

Let's calculate the number of test sample adequate to the failure rate of television component, or 5×10^{-9}/*hour*. When you test 600,000 pieces for 1,000hours, and there would be below two failures, you might say this component have maximum value of the above rate with about

Table 2. The number of test sample for failure rate ($\times 10^3$ units)

h \ λ, r	r	0.5 FIT (0.5×10^{-9}/hr)	5 FIT (5×10^{-9}/hr)	50 FIT (50×10^{-9}/hr)	Confidence Level (%)	Multiplier required over
500	0	4,000	400	40	63	2.3
	1	8,000	800	80	59	1.9
	2	12,000	1,200	120	58	1.8
	3	16,000	1,600	160	57	1.7
1000	0	2,000	200	20	63	2.3
	1	4,000	400	40	59	1.9
	2	6,000	600	60	58	1.8
	3	8,000	800	80	57	1.7
2000	0	1,000	100	10	63	2.3
	1	2,000	200	20	59	1.9
	2	3,000	300	30	58	1.8
	3	4,000	400	40	57	1.7

60% confidence level as shown in Table 2. Even though you reduce sample numbers through accelerated test method, the task of confirming the above rate would be enormous work. Therefore you may apply load-strength interference model, which also requires lots of works, and test them not in component base but unit level.

Secondly, in order to assess life, the number of test sample would be calculated with about 60% of confidence level using equation (5) as following,

$$n \geq (r+1)\cdot\frac{1}{x}\cdot\left(\frac{T}{h}\right)^{\beta} \quad (7)$$

The shorter the test hour is compared to the target of Bx life, the more significantly the number of test sample increases, as following equation and Table 3 showing the sampling numbers for B_{10} life with about 60% of confidence level,

$$n\cdot h^{*\beta} \geq C, \quad (8)$$

where C equals $(r+1)/x$.

Table 3. The number of test sample for B_{10} life

β \ h*, r	0.5				1.0				1.5				2.0			
	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
1.5	28	57	85	113	10	20	30	40	5	11	16	22	4	7	11	14
2	40	80	120	160	10	20	30	40	5	9	14	18	3	5	8	10
3	80	160	240	320	10	20	30	40	3	6	9	12	2	3	4	5

It implies that it is inappropriate to estimate Bx life surpassing test hours. As long as life concerned, it is out of common sense to assess item life exceeding test hours. Therefore it is required to run samples at least till the durability target.

Thirdly, in order to properly establish physical-chemical test conditions, studies are needed in three areas:

(1) The product itself-that is, many different assembled components constituted of various materials and fabricated by various connection technologies (soldering, calking, etc). The materials inside the product must be analyzed in detail. (2) The environmental and operational conditions that the product or component must endure during its lifetime. This means examining the stresses produced by various environmental and operational conditions. These two studies of operating stresses and the materials inside the product, corresponding to the two possible reasons for failure can point up potential failure mechanisms. These studies respond to the inputs of IEEE STD 1413-1998.[5] (3) The appropriate test method. This involves selecting and building up the test systems with appropriate test procedures and conditions responding to the possible failure mechanisms that clarifies physical-chemical conditions.[6] General test methods can never find all the failure modes and sometimes cannot even find the dominant one. Different failure mechanisms require different test methods. Therefore, test methods should be reviewed based on the analysis of failure. Over fifty failure mechanisms have been identified so far.[7]

It is desirable to find two or more failures in test experiments, because if the identified failures could be attributed to one kind of failure mechanism consistent with the estimated as analysis results, the fact would become the proof for the adequacy of test method.

2.4 Failure models for accelerated test

The most important issue in the test method configuration is how early the potential failure mode can be found. This is the reason why we prefer accelerated test. And in order to transform accelerated test hour into real use time, it is required to obtain acceleration factor (AF). To do this, it is necessary to formulate failure model and find out related coefficients.

If there would exist Physics-of-Failure (PoF) model, which incorporates geometry and materials as well as stresses and reaction parameters, it is easy to calculate AF because coefficients are already determined. But there are not so many PoF models responding diversified failure mechanisms. Therefore we should configure Life-Stress (LS) model, which includes stresses and reaction parameters, and find out coefficients through design of experiments. As LS model, the following equation is recommendable as generalized equation because the hyperbolic function term reflecting stress can be transformed into power or exponential term.[8] Therefore, this equation can explain most of LS models about various failures such as fatigue in mechanical structure, coil degradation in motor, bond-pad corrosion in IC, etc.

$$T_f = B[\sinh(aS)]^{-1} \cdot \exp\left(\frac{E_a}{kT}\right) \tag{9}$$

where T_f is time to failure, S is stress, E_a is activation energy, k is Boltzmann constant, T is absolute temperature, B and a are coefficients. In case that there are two dominant stresses, it is good to simply attach another sine hyperbolic term to the above equation.

Now we can establish accelerated test plan, estimate r-reliability and durability, and calculate warranty cost in advance of product release.[9]

3. Conclusions

To clearly grasp the concept of quality, the double ambiguity about quality should be understood. The broad concept of quality includes reliability-that is, it encompasses both reliability and conformance quality (c-quality). C-quality, the first ambiguity, means conformance to specifications.

Meanwhile, the commonly used bathtub curve may not be the best to apply to creating a preferable product for the customer; a better curve to describe the failure rate of a successful product in the market is shaped like, and can be called, a *hockey-stick line*. From the definition of reliability and the hockey-stick line, two measurements can be extracted; product life (durability) and failure rate (rate reliability: r-reliability). Reliability consists of durability and r-reliability. R-reliability refers to reliability regarding only failure rate. This is the second ambiguity.

Reliability is conceived of as the relationship between stresses and materials. This technique pertains to design area, not to manufacturing field. The shape of failure rate of electronic items would be similar to that of mechanical ones. Therefore the shape of failure rate of all items should be targeted to follow hockey stick line. Thus some conclusions could be drawn. (1) The failure rate cannot be converted to MTTF. (2) The index of MTTF does not reflect item life adequate to customers' feelings. The Bx life is more preferable as a durability index. In order to meet our common sense, the following reshaped definition/equation are recommended on condition that the failed numbers are below several pieces and that $x \leq 0.2$;

$$\lambda = (r+1) \cdot \frac{1}{n \cdot h} \quad \text{and} \quad T^{\beta} = x \cdot \frac{1}{r+1} \cdot n \cdot h^{\beta} ,$$

where these confidence levels are around 60%.

In order to improve the reliability of a product, three steps are needed; (1) identify failure modes, (2) analyze failures, and (3) change structures and/or specifications .

As a first step, finding failure modes is requisite. To do this, two conditions should be satisfied simultaneously in test method configuration; (1) mathematical condition, which can be solved with the reshaped definition, (2) physical-chemical conditions based on the failure mechanism.

In order to reduce test time, it is necessary to configure failure model and find out its coefficients, and calculate acceleration factor (AF). The generalized Life-Stress model is recommended. And finally we can estimate r-reliability, hourly failure rate, and durability, Bx life.

References

1. D. S. Ryu, "Quality, Product Quality, and Market Share Increase," *International Journal of Reliability and Applications*, **2**(3), 163 (2001).
2. D. S. Ryu., *International Journal of Reliability and Applications*, **2**(3), 174 (2001).
3. D. A. Garvin, Competing on the Eight Dimensions of Quality, p.101-109, Harvard Business Review, Nov.-Dec. 1987.
4. J. W. Evans and J. Y. Evans, Product Integrity and Reliability in Design, p.7, Springer, 2001.
5. IEEE Reliability Society, "IEEE Standard Methodology for Reliability Prediction and Assessment for Electronic Systems and Equipment," IEEE Std. 1413, 1998, p.4.
6. J. W. Evans and J. Y. Evans, Product Integrity and Reliability in Design, p.15, Springer, 2001.
7. D. S. Ryu, Technology Innovation, Appendix 5, Seoul, Hanseung, 1999.
8. ASM International, Packaging, Electronic Materials Handbook, **1**, 888 (1989).
9. D. S. Ryu, "Quality, Product Quality, and Market Share Increase," *International Journal of Reliability and Applications*, **2**(3), 182 (2001).