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Calculating Failure Rates of Series/Parallel Networks

By: Vito Faraci, BAE Systems

Introduction

Recently, the author attempted to calculate the failure rate (FR) of a series/parallel (active redundant, without repair) reliability network using the Reliability Toolkit: Commercial Practices Edition published by the System Reliability Center as a guide. The Toolkit's approach for FR calculation for a single branch seemed to be very thorough. So the FR for each individual branch was calculated. Since several branches were in series, the FRs the branches were then added together. Closer examination revealed that this approach was an oversimplification and failed to account for all possible combinations (ways) that individual components could fail. A closer review of the Reliability Toolkit revealed it treats FR calculations of single branches with n components in parallel very thoroughly but lacks detail in describing a method for handling multiple branches in series

A quick review of the software QuART Pro Version 2.0 Release 1 Build 70 was performed. It also seemed to deal with single branches very thoroughly but not multiple branches in series.

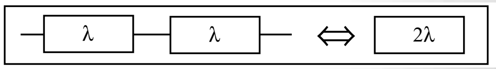
Objectives

The objectives of this article are to:

- Describe two erroneous approaches commonly performed when calculating FR of Serial/Parallel reliability networks.
- Provide an example of a correct approach.
- Approximate the percent errors one can expect when FR is calculated erroneously.

Nature of the Problem

System reliability is calculated as a combination of series and parallel paths and can be expressed as a failure rate. Calculating the FR of a series network as shown in Figure 1 is a simple act of just adding all of the FRs in the series string together, and should need no further explanation.



⇔ indicates equivalency

Figure 1. Series Network

However, calculating the reliability and/or FR of parallel networks requires a little more work. The Toolkit contains excellent information for doing this. See Reliability Toolkit Table 6.2-2 for calculating reliability, and Table 6.2-3 for calculating FR for parallel networks.

For example, consider the network in Figure 2.

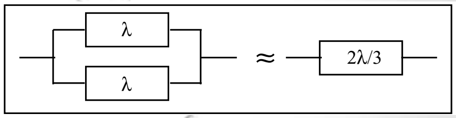


Figure 2. Parallel Network

From Table 6.2-2 we get $R(t) = 2e^{-\lambda t} - e^{-2\lambda t}$ and from Table 6.2-3 (equation 4) we get

$$FR = \frac{\lambda}{\frac{1}{1}+\frac{1}{2}} = \frac{2\lambda}{3}$$

For the network in Figure 3, first collect (add) all lambdas in series as shown, and then from the Reliability Toolkit tables get:

$$R(t) = 2e^{-2\lambda t} - e^{-4\lambda t} \text{ and } FR = \frac{2\lambda}{\frac{1}{1}+\frac{1}{2}} = \frac{4\lambda}{3}$$

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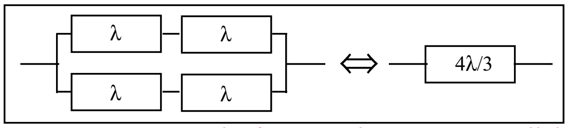

Figure 3. Network of Series Elements in Parallel

The tables provide correct solutions for the networks in Figures 1, 2, and 3. However, a potential problem occurs when calculating the FR of a series/parallel network as shown in Figure 4. Analysts commit a very common error by intuitively calculating the FR of each parallel branch first, then add each branch FR together, since the branches are in series, and erroneously calculate FR = 4λ/3 as in this example. This FR calculation actually correlates to that for the network in Figure 3. It is very important to understand that the network in Figure 3 and the network in Figure 4 are **not** equivalent.

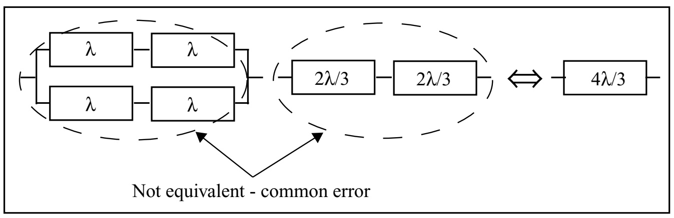

Figure 4. Series-Parallel Network

Root Cause of Problem

The correct approach to calculate the FR of the network in Figure 4 (or any other network for that matter) is to *calculate the reliability of each branch first, then multiply together the reliability of each branch*. Assume the reliability of Branch 1 is $R_1(t)$, the reliability of Branch 2 is $R_2(t)$, etc. Then network reliability = $R(t) = R_1(t) \cdot R_2(t) \cdots R_n(t)$. It is important to note that *the reliability of each branch $R_i(t)$ must be kept in terms of the failure rates of the components within the branch, and **not** in terms of the failure rate of the branch itself*. Therein lies the root cause of the problem. The network FR can then be computed using the following definition.

$$FR = \frac{1}{MTTF} = \frac{1}{\int_0^\infty R(t)\,dt}$$

Correct Approach (Network in Figure 4)

From the Reliability Toolkit Table 6.2-2, the reliability of each branch is:

$$2e^{-\lambda t} - e^{-2\lambda t} \Rightarrow$$

$$R(t) = (2e^{-\lambda t} - e^{-2\lambda t})(2e^{-\lambda t} - e^{-2\lambda t}) = 4e^{-2\lambda t} - 4e^{-3\lambda t} + e^{-4\lambda t} \Rightarrow$$

$$MTTF = \int_0^\infty R(t)dt = \int_0^\infty (4e^{-2\lambda t} - 4e^{-3\lambda t} + e^{-4\lambda t})\,dt \Rightarrow$$

$$MTTF = \frac{4}{2\lambda} - \frac{4}{3\lambda} + \frac{1}{4\lambda} = \frac{11}{12\lambda} \Rightarrow \text{True FR} = \frac{12}{11}\lambda$$

Incorrect Approach A (Network in Figure 4)

From the Reliability Toolkit Table 6.2-3, the FR of the each branch is 2λ/3. It is intuitive to add these failures rates since the two branches are in series. This erroneous approach yields 2λ/3 + 2λ/3 = 4λ/3 which is obviously not equal to 12λ/11. This approach will yield an approximate 22% error.

Incorrect Approach B (Network in Figure 4)

Another erroneous approach is to try to calculate FR as a function of time. For example, given that t = 10 hours, and λ = 250 fpmh (failures per million hours), one may be tempted to calculate network FR as follows:

$$R(10) = 4e^{-2\lambda t} - 4e^{-3\lambda t} + e^{-4\lambda t} = 4e^{-2*250*10/10^6}$$

$$- 4e^{-3*250*10/10^6} + e^{-4*250*10/10^6} = 0.99998753$$

Then using FR = -ln(R(t))/t:

$$FR = -\ln(0.99998753)/10 = 1.246 \times 10^{-6} = 1.246 \text{ fpmh}$$

This does **not** equal 12λ/11 = 12*250/11 = 273 fpmh.

Note that 1.246 fpmh is only an "apparent" FR measured during a period 10 hours, not to be confused with the FR as formally defined previously.

Given t = 100 hours, then:

$$R(100) = 4e^{-2*250*100/10^6} - 4e^{-3*250*100/10^6} + e^{-4*250*100/10^6}$$

$$= 0.99878117 \Rightarrow$$

$$FR = -\ln(0.99878117)/100 = 12.196 \times 10^{-6} = 12.196 \text{ fpmh.}$$

Note that 12.196 fpmh is another "apparent" FR measured at 100 hours. Notice also that the value of the "apparent" FR will vary with t.

Networks with *all* components having the same lambda are not very common. An example of the correct approach on a more practical (common) network is shown next.

A Correct Approach for Calculating Network Failure Rate

Consider the network shown in Figure 5 with failure rates a, b, and c. The definition of success for the network, is defined as at least 1 of 2 components of the left branch, and at least 2 of 3 components of the middle branch must be functional. From the Reliability Toolkit Table 6.2-2, the reliability of the left branch is $2e^{-at} - e^{-2at}$, and the middle branch is $3e^{-2bt} - 2e^{-3bt}$. By definition, the reliability of the right branch is e^{-ct}. Network reliability R(t) is calculated by multiplying the three branch reliabilities together.

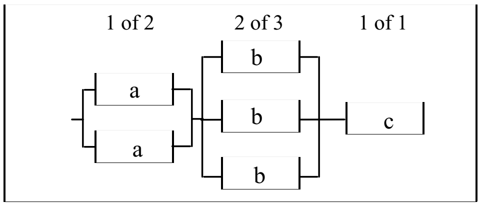

Figure 5. Example with Multiple Paths

Therefore:

$$R(t) = (2e^{-at} - e^{-2at})(3e^{-2bt} - 2e^{-3bt}) \bullet e^{-ct}$$

$$= 6e^{-(a+2b+c)t} - 4e^{-(a+3b+c)t} - 3e^{-(2a+2b+c)t} + 2e^{-(2a+3b+c)t}$$

$$\text{and MTTF} = \int_0^{\infty} R(t)dt =$$

$$\int_0^{\infty} (6e^{-(a+2b+c)t} - 4e^{-(a+3b+c)t} - 3e^{-(2a+2b+c)t} + 2e^{-(2a+3b+c)t})dt$$

The rest is algebra. Calculate MTTF using known values of a, b, and c, then take the reciprocal since FR = 1/MTTF.

$$\text{MTTF} = \frac{6}{a+2b+c} - \frac{4}{a+3b+c} - \frac{3}{2a+2b+c} + \frac{2}{2a+3b+c}$$

Erroneous Method A

A common error is performed when the analyst calculates the FR of each individual branch first, then adds all calculated branch FRs together. Note in the previous example, the FR of the left branch is 2a/3, FR of the middle branch is 6b/5, and the FR of the right branch is c.

Therefore, FR (erroneous) = 2a/3 + 6b/5 + c

= (10a + 18b + 15c)/15

Now simple algebra will show that (10a + 18b + 15c)/15 is not equal to:

$$\frac{1}{\frac{6}{a+2b+c} - \frac{4}{a+3b+c} - \frac{3}{2a+2b+c} + \frac{2}{2a+3b+c}}$$

Error Magnitude Estimation for Erroneous Approach A

Five sample networks were chosen starting with a 2 row by 2 column network as shown in Table 1. For the sake of simplicity, all network components were assigned the same lambda. In each case, the true FR was compared with the FR calculated erroneously by simply adding FRs of each branch. The % error was then measured. From the table, it can be easily seen, that the larger the network, the larger the error.

Error Magnitude Estimation for Erroneous Approach B

The error magnitude for this approach will depend on the chosen value of t, and would be very difficult to express as an equation. Suffice to say that the FR calculated by this approach may not come close, or even resemble the correct result.

Conclusions

Calculating the failure rate (FR) of a series/parallel (active redundant, without repair) reliability network is not as simple as one might believe, an incorrect approach can lead to subtle but substantial errors. Closer examination reveals that one must carefully account for all possible paths of success for multiple networks having branches in series.

In general, the larger the network, the larger the potential error when oversimplified approaches are used in calculating the reliability of these complex networks. The percent error, although not proven here, is a function of network size, network configuration, values of lambdas, and in some cases, a function of time.

Reference

Reliability Engineering, ARINC Research Company, Michael Pecht, Editor, Prentice-Hall Inc, pages 202 to 226.

About the Author

Vito Faraci is a mathematician by education and electrical engineer by trade. He has worked as a Reliability and Maintainability Engineer for an aerospace company for 18 years. Mr. Faraci's aerospace work experience is concentrated on System Failure Analyses and Built-In-Test design.

Mr. Faraci has given seminars to the Federal Aviation Administration on probability, reliability, Fault Tree Analysis (FTA), FMEA, and Markov Analysis. He has given seminars at

Table 1. Error Magnitude Estimation Table for Erroneous Approach A

Network Configuration (Rows x Columns)	True FR	Erroneous FR (adding FRs of each Branch)	% Error
2x2	12/11 λ	2/3 λ + 2/3 λ = 4/3 λ	22
2x3	10/7 λ	2/3 λ + 2/3 λ +2/3 λ = 6/3 λ	40
2x4	280/163 λ	2/3 λ + 2/3 λ +2/3 λ +2/3 λ = 8/3 λ	55
3x2	60/73 λ	6/11 λ + 6/11 λ = 12/11 λ	32
3x3	2520/2467 λ	6/11 λ + 6/11 λ + 6/11 λ + 6/11 λ = 18/11 λ	60

various engineering symposiums on FTA vs. Markov Analysis (combinatorial vs. non-combinatorial type problems) and written several articles on FTA vs. Markov Analysis.

As a consultant, Mr. Faraci designed various pieces of test equipment for the Long Island Railroad. As a consultant, he wrote software for a medical electronics firm.

RMSQ Headlines

Putting It All Together, UPTIME, NetExpressUSA, Inc., January 2006, page 4. This article discusses how Condition-Based Maintenance (CBM) is more than simply conducting condition monitoring activities and becoming proficient in the use of CBM tools and technology. It provides some guidelines for creating a CBM culture in production plants and other large facilities.

Recovering from Disaster, UPTIME, NetExpressUSA, Inc., January 2006, page 28. Hurricanes Katrina, Rita, and Wilma left many plants along the Gulf Coast shut down and badly damaged electric motors and generators. In this article, the author describes the creative solutions maintenance professionals used to remove moisture from thousands of motors and restore them to operation.

Warming Up for Takeoff, Aerospace Engineering, SAE, Jan/Feb 2006, page 17. The article describes how Chromalox and NASA worked to make the shuttle safer following the loss of Columbia in January of 2003. The target of the effort was the design, qualification, and installation of heaters to replace foam previously used to prevent the formation of ice.

FAA Actions Far from Inert on Fuel Tank Vapors, Aerospace Engineering, SAE, Jan/Feb 2006, page 20. For more than seven years, the FAA and private industry have been conducting research into technologies for making fuel tanks inert, preventing flammable vapor fires. The article describes some of the results of that research and how this safety improvement has been determined to be economically as well as technically feasible.

Maintaining Reliability, Aerospace Engineering, SAE, Jan/Feb 2006, page 22. Regional airlines and operators of business jets consistently list engine reliability as their top priority. To do this, they take very specific maintenance actions intended to ensure that their passengers can depend on safe flights with no engine anomalies.

After Six Sigma, What Next?, Quality Progress, ASQ, January 2006, page 30. Six Sigma has evolved from Total Quality Management and is widely used in a broad range of industry. Some critics, however, contend that Six Sigma is merely "old wine in new bottles." This article discusses the next step in the continuing evolution of Six Sigma in the never-ending quest to improve an organization's competitive position, satisfy customers, and reduce costs.

The House that Fraud Built, Quality Progress, ASQ, January 2006, page 52. Quality Function Deployment (QFD) has long been used to analyze customer needs and develop product requirements. This article describes a rather unconventional use of QFD. Specifically, QFD was used to identify and prioritize warning signs that an organization may be guilty of financial statement fraud.

An Index to Measure and Monitor a System of Systems' Performance Risk, Defense Acquisition Review, Defense Acquisition University, December 2005-March 2006, page 405. This article presents a method for combining individual system Technical Performance Measures (TPMs) into an overall measure, and extends the approach to a system of systems.

Using Design of Experiments as a Process Road Map, Quality Digest, QCI International, February 2006, page 29. In this article, the author explains that factorial designs and/or orthogonal arrays may not be the most effective way to apply Design of Experiments.

The V-22 Program, Defense AT&L, Defense Acquisition University, March-April 2006, page 18. The author discusses how the V-22 Obsolescence Team proactively manages and mitigates obsolescence problems in the V-22 weapon systems.

Project Management and the Law of Unintended Consequences, Defense AT&L, Defense Acquisition University, March-April 2006, page 29. The article discusses how a strong risk management program can deal with the Law of Unintended Consequences. Although not named, the law was described by Adam Smith in 1776 in *The Wealth of Nations*. Smith wrote that an individual was "led by an invisible hand to promote and end which was no part of his intentions." Program managers today constantly face the possibility of unintended, and often undesirable, consequences. Risk management provides the means for dealing with these consequences.

Link Satisfaction to Market Share and Profitability, Quality Progress, ASQ, February 2006, page 50. Increased market share and profitability are two objectives common to every company no matter the product or service. Capturing and keeping customers requires a focused, continuing effort to provide good products at a fair price, while still ensuring a reasonable profit. This article discusses how customer satisfaction can lead to profitability and increased market share. The article discusses several methods of linking satisfaction data to financial performance data. Choosing the "best" method depends on the amount and type of data available.

A Brief Tutorial on Impact, Spalling, Wear, Brinelling, Thermal Shock, and Radiation Damage

Editor's Note: This is the second of a two-part article on failure modes and mechanisms in materials. It is based on a three part series of articles by Benjamin D. Craig that appeared in issues of the AMPTIAC Quarterly.

Introduction

The purpose of this article is to briefly introduce several material failure modes. A better understanding of these failure mechanisms will enable more appropriate decisions when selecting materials for a particular application. Even a basic knowledge and awareness can help design engineers to be better equipped in delaying or preventing the failure of a material or component. Failure can occur in systems with moving or non-moving parts. In systems with moving parts, friction often leads to material degradation such as wear, and collisions between two components can result in surface or more extensive material damage. Systems with non-moving parts are also prone to material failure, especially when certain types of materials are subjected to extreme temperature changes or to high energy radiation environments. Material failure often manifests itself in the form of cracking but can also appear as material disintegration, mechanical property degradation, or even physical deformation. For instance, impact failure can occur by fracture, deformation, or material disintegration, while radiation damage can cause a severe degradation of a material's properties. These failure modes, and spalling, wear, brinelling, and thermal shock are described throughout this article.

Wear

Wear is a general term describing the deterioration of a material's surface caused by frictional forces generated by contact between two surfaces moving in relation to one another. Temperature has an effect on the wear rate (rate at which a material deteriorates under frictional forces) because friction generates heat, which in turn can affect the microstructure of the material making it more susceptible to deterioration.

Components such as bearings, cams, and gears are often susceptible to wear. There are several different types of wear, including adhesive wear, abrasive wear, corrosive wear, surface fatigue wear, impact wear, and fretting wear. Most of these will be discussed in some detail in the following sections.

Minimizing or protecting a material's surface from wear can be accomplished through several methods including the use of lubricants and surface treatments (Reference 3). Selecting a material that is resistant to wear, such as one having high hardness (e.g., ceramics), is also a good method to prevent excessive wear. Alternatively, hard coatings such as tungsten-carbide-cobalt can be used to augment the hardness of a component having a relatively soft surface. Surface or heat treatments can also be used to increase the hardness or smoothness of the surface. Examples include carburizing and superfinishing, which is described in Reference 4.

Adhesive Wear

Adhesive wear occurs between two surfaces in relative motion as the result of high contact stresses, which are generated because of the inherent roughness of material surfaces. No matter how finely polished a surface is, two materials in contact with each other do not mate completely. This allows localized areas on the surface to sustain a greater percentage of a mechanical load, while the areas that are not in contact with the opposing surface absorb none of the mechanical load. In adhesive wear, the peaks on the adjacent surfaces that do come into contact will plastically deform under pressure and form atomic bonds at the interface (in some cases this is considered solid-phase welding). As the relative motion between the surfaces continues, the shear stress at the now atomically bonded contact point increases until the shear strength limit of one of the materials is reached and the contact point is broken bringing with it a piece of the opposing surface. The broken material can then either be released as debris or remain bonded to the other material's surface. This process is demonstrated in Figure 1. Adhesive wear is also known as scoring, scuffing, galling or seizing (galling and seizure are described briefly below) (References 3 and 5).

High hardness and low strength are desirable properties for applications requiring resistance to adhesive wear. However, these properties are somewhat mutually exclusive, which makes composite materials desirable for such applications. Examples of resistant monolithic materials include low strength, high ductility polymers, and high hardness, low density ceramics. Sintered copper infiltrated with polytetrafluoroethylene (Teflon™) and lead particle reinforced bronze materials are specific examples of composite materials that are highly resistant to adhesive wear (Reference 3).

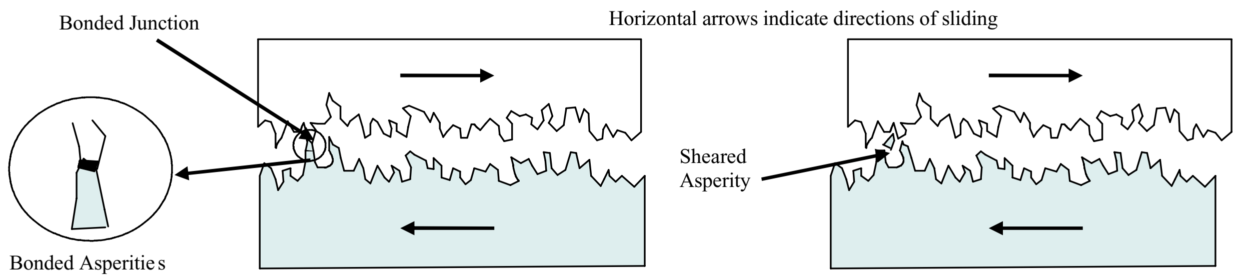

Figure 1. Illustration of Adhesive Wear Mechanism (Reference 3)

(Continued on page 10)

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analysis (FMEA), fault tree analysis (FTA), thermal analysis, reliability centered maintenance (RCM) analysis, testability analysis, human factors analysis, spares analysis, life cycle cost analysis, and maintenance task analysis. SRC develops on-site RMS training programs to facilitate analysis tasks in a hands-on, team-based environment. SRC engineers also develop industry standards for completing RMS analysis tasks (e.g., PRISM®).

- **Reliability Maturity Assessment:** SRC has developed a systematic approach for independently assessing the maturity of an organization's process. In addition to providing a numerical rating of an organization's current reliability maturity, SRC provides an improvement roadmap for moving the organization forward to higher levels of maturity. SRC's Reliability Maturity Assessment typically produces results in less than 30 days.
- **Maintenance Optimization:** The Alion SRC assesses maintenance and reliability data to determine the optimum time for replacement of components before failure. The SRC team uses analytical techniques to determine the optimal mix of corrective and preventive maintenance activities needed to sustain the desired level of operational reliability of systems while ensuring their safe and economical operation and support.
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A Brief Tutorial on Impact, ... (Continued from page 5)

Abrasive Wear

Gouging, grinding and scratching are examples of abrasive wear, which occurs when a solid surface experiences the displacement or removal of material as a result of a forceful interaction with another surface or particle. Particles can become trapped in between the two surfaces in contact, and the relative motion between them results in abrasion (displacement and removal of surface material) of the surface that has a lower hardness. This process is demonstrated in Figure 2. Sources of particles can include foreign contaminants (particles originating outside the system), wear debris, or solid constituents suspended in a fluid. Alternatively, abrasive wear can occur in the absence of loose particles when the roughness of one surface causes abrasion and/or removal of material from the other surface. This wear mechanism differs from adhesive wear in that there is no atomic bonding between the two surfaces. Abrasive erosion occurs when a fluid carrying solid particles is traveling in a direction parallel (as opposed to perpendicular which is impact wear) to the surface, and the particles gradually deteriorate the material's surface.

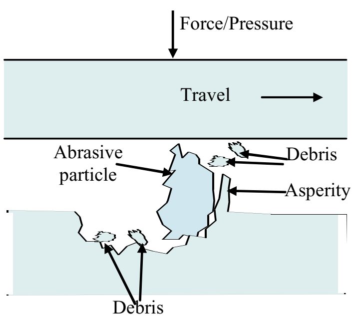

Figure 2. Illustration of Abrasive Wear Mechanism (Reference 3)

Galling and Seizure

Galling is an extreme form of adhesive wear that involves excessive friction between the two surfaces resulting in localized solid-phase welding and subsequent spalling of the mated parts. This process causes significant damage to the surface of one or both materials. Seizure is even more extreme in that the two surfaces experience a sufficient amount of solid-phase welding such that the two components can no longer move.

Material hardness is a critical factor in the abrasive wear rate of the surface, as higher hardness results in a lower wear rate. Moreover, if the hardness of the material's surface is higher than the hardness of the abrading particles, then little wear is observed and the particles are likely to be broken into smaller pieces. Materials with high hardness and toughness properties are well-suited to prevent or minimize abrasive wear. Examples of materials that are inherently resistant to abrasive wear include high hardness or surface hardened steels, cobalt alloys and ceramics. (Reference 3)

Corrosive Wear

When the effects of corrosion and wear are combined, a more rapid degradation of the material's surface may occur. This process is known as corrosive wear. Films or coatings are often used to protect a base metal or alloy from harsh environments that would otherwise cause it to corrode. If such a coating were subjected to abrasive or adhesive wear causing a loss of coating from the material's surface, for instance, the base metal or alloy could be exposed and consequently corroded. Alternatively, a surface that is corroded or oxidized may be mechanically weakened and more likely to wear at an increased rate. Furthermore, corrosion products including oxide particles that are dislodged from the material's surface can subsequently act as abrasive particles.

Surface Fatigue Wear

Surface or contact fatigue occurs when two material surfaces that are in contact with each other in a rolling or combined rolling and sliding motion create an alternating force or stress oriented in a direction normal to the surface. The contact stress initiates the formation of cracks slightly beneath the surface, which then grow back toward the surface causing pits to form, as particles of the material are ejected or worn away. This form of fatigue is common in applications where an object repeatedly rolls across the surface of a material resulting in a high concentration of stress at each point along the surface. For example, rolling-element bearings, gears, and railroad wheels commonly exhibit surface fatigue (References 3 and 6). Figure 3 illustrates an example of the surface fatigue mechanism.

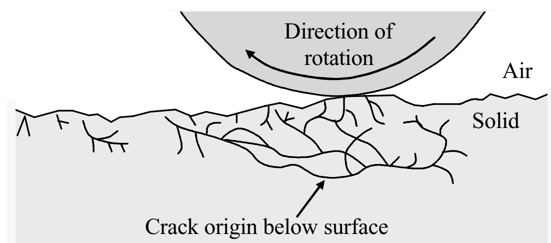

Figure 3. Illustration of Surface Fatigue Mechanism (Reference 3)

Impact Wear

Impact wear is discussed in the section addressing impact failure modes.

Fretting Wear

Surfaces that are in intimate contact with each other and are subject to a small amplitude relative motion that is cyclic in nature, such as vibration, tend to incur wear. Fretting wear is normally accompanied by the corrosion or oxidization of the debris and worn surface. Unlike normal wear mechanisms only a small amount of the debris is lost from the system; instead the debris remains within the conjoined surfaces. The mated surfaces essentially exhibit adhesion through mechanical bonding, and the oscillatory motion causes the surface to fragment, thereby creating oxidized debris. If the debris becomes embedded in the surface of the softer metal, the wear rate may be reduced. If the debris remains free at the interface between the two materials the wear rate may be increased. Fatigue cracks also have a tendency to form in the region of wear, resulting in a further degradation of the material's surface. Liquid or solid lubricants (e.g., surface treatments, coatings, etc.), residual stresses (e.g., through shot or laser peening), surface grooving (e.g., to enable the release of debris), and/or appropriate material selection for the material pair can help to reduce the effects or prevent the occurrence of fretting wear (Reference 7).

Brinelling

Brinelling can be very basically defined as denting. When a localized area of a material's surface is repeatedly impacted or is subjected to a static load that overcomes the material's yield strength causing it to permanently deform, it is considered to have undergone brinelling. Bearings are often susceptible to failure by brinelling since an indentation can cause an increase in vibration, noise, and heating (Reference 7). Brinelling failures can be caused by improper handling, such as forcing a bearing into a housing, by dropping the bearing, or by severe vibrations, such as those produced during ultrasonic cleaning (Reference 8). Selecting a material with a high hardness or taking extra care during handling and cleaning can help prevent brinelling.

Thermal Shock

Thermal shock is a failure mechanism that occurs in materials that exhibit a significant temperature gradient (indicating a sudden and dramatic change in temperature has occurred). For instance, if the temperature gradient is so large that the material experiences thermal stresses (or strains) great enough to overcome its strength, it may lead to fracture, especially if the material is constrained. An example of the consequence of thermal shock is shown in Figure 4. Awareness of a system or component's operating conditions when selecting materials is important in order to prevent thermal shock failure from occurring. The designer should choose a material that has an appropriate thermal conductivity and heat capacity for the intended environmental conditions. In addition, residual stresses (from shot or laser peening, for example) can help accommodate thermal stresses that are generated during thermal shock, thereby potentially protecting the material from fracture.

Figure 4. Brittle Fracture of a Ductile Weld Material that Is Constrained – Caused by High Stresses Induced from a Rapid 1000°F Change in Temperature (Photo Courtesy of Sachs, Salvaterra & Associates, Inc.)

Radiation Damage

The space environment is very unfriendly to most materials due to an array of harsh conditions that can easily and rapidly degrade the material and/or its properties. Degradation of an exposed material often comes as a result of the different types of radiation present in space. Radiation is not limited to the space environment, however, as there are a number of environments and specific applications that subject materials to this damaging energy (Figure 5).

Figure 5. CO2 Laser Used to Study the Energy Incident on the Effects of Radiation on Materials (Reference 9)

High-energy radiation, such as neutrons in a nuclear reactor, can damage almost any material including metals, ceramics, and polymers (Reference 3). Typically, when a material is subjected to high-energy radiation its properties are altered through structural mutation in order to absorb some of the energy that is incident on the material. For instance, when a metal is exposed to neutron radiation from a nuclear reactor, atoms in the metal are displaced resulting in the creation of defects. These defects can diffuse and coalesce to create crack initiation sites or can simply leave the metal brittle and susceptible to failure through another mechanism. Another portion of metal is absorbed and converted to heat. Metals are often better suited to withstand radiation energy than are ceramics. Typically, the ductility, thermal conductivity, and electrical conductivity are negatively impacted when a metal is exposed to radiation (Reference 3). Ceramics are affected by radiation to varying extents depending on the type of inherent bonding (i.e., covalent or ionic). Ionically-bonded ceramics experience decreases in ductility, thermal conductivity, and optical properties, but the damage can be reversed with proper heat treatment (similar to metals). Covalently-bonded ceramics experience similar damage; however the damage is somewhat permanent (Reference 3).

Polymers are especially susceptible to radiation even at low energy levels, such as UV radiation. Damage from radiation in polymers usually manifests itself as cracking. For this reason, polymers have been known for their cracking problems in outdoor applications, where they are constantly exposed to UV radiation. UV blockers, absorbers, and stabilizers are often added to polymers used for outdoor applications to augment their ability to withstand incident radiation energy.

Corrosion

Corrosion is the deterioration of a metal or alloy and its properties due to a chemical or electrochemical reaction with the surrounding environment. The most serious result of corrosion is a system or component failure. Material failure can occur either

(Continued on page 13)

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by sufficient material property degradation such that the material is rendered unable to perform its intended function, or by fracture that originates from or propagated by corrosive effects.

Uniform/General Corrosion

Uniform corrosion is a generalized corrosive attack that occurs over a large surface area of a material. The result is a thinning of the material until failure occurs. Uniform corrosion can also lead to changes in surface properties such as increased surface roughness and friction, which may cause component failure especially in the case of moving parts that require lubricity.

In most cases corrosion is inevitable. Therefore, mitigating the effects of corrosion or reducing the corrosion rate is essential to ensuring material longevity. Protecting against uniform corrosion can often be accomplished through selection of a material that is best suited for the anticipated environment. The selection of materials for uniform corrosion resistance should simply take into consideration the susceptibility of the metal to the type of environment that will be encountered.

Aside from selecting a uniform corrosion resistant material, protection schemes such as barrier coatings can be implemented. Organic or metallic coatings should be used wherever feasible. When coatings are not used, surface treatments that artificially produce the metal oxide layer prior to exposure to the environment will result in a more uniform oxide layer with a controlled thickness. There are also surface treatments where additional elements are incorporated for corrosion resistance, such as chromium. Also, vapor phase inhibitors may be used in such applications as boilers to combat corrosive elements and adjust the pH level of the environment.

Galvanic Corrosion

Galvanic corrosion is a form of corrosive attack that occurs when two dissimilar metals (e.g., stainless steel and magnesium) are electrically connected, either through physically touching each other or through an electrically conducting medium, such as an electrolyte. When this occurs, an electrochemical cell can be established, resulting in an increased rate of oxidation of the more anodic material (lower electrical potential). The opposing metal, the cathode, will consequently receive a boost in its resistance to corrosion. Galvanic corrosion (shown in Figure 6) is usually observed to be greatest near the surface where the two dissimilar metals are in contact.

Figure 6. Galvanic Corrosion between a Stainless Steel Screw and Aluminum (Reference 10)

There are a number of driving forces that influence the occurrence of galvanic corrosion and the rate at which it occurs. Among these influencing factors are the difference in the electrical potentials of the coupled metals, the relative area of each metal, and the system geometry, and the environment to which the system is exposed.

In most cases, galvanic corrosion can be easily avoided if proper attention is given to the selection of materials during design of a system. It is often beneficial for performance and operational reasons for a system to utilize more than one type of metal, but this may introduce a potential galvanic corrosion problem. Therefore, sufficient consideration should be given to material selection with regard to the electrical potential differences of the metals. Cathodic protection, electrical insulation, or coatings can also help protect materials from galvanic corrosion.

Crevice Corrosion

Crevice corrosion occurs as a result of water or other liquids getting trapped in a localized stagnant areas creating an enclosed corrosive environment. This commonly occurs under fasteners, gaskets, washers, and in joints or other components with small gaps. Crevice corrosion can also occur under debris built up on surfaces, sometimes referred to as "poultice corrosion." Poultice corrosion can be quite severe due to an increasing acidity in the crevice area.

Table 1 provides a brief list of guidelines that can help minimize galvanic corrosion.

Table 1. Guidelines for Minimizing Galvanic Corrosion (Reference 11)

- Use one material to fabricate electrically isolated systems or components where practical.
- If mixed metal systems are used, select combinations of metals as close together as possible in the galvanic series, or select metals that are galvanically compatible.
- Avoid the unfavorable area effect of a small anode and large cathode. Small parts or critical components such as fasteners should be the more noble metal.
- Apply coatings with caution. Keep the coatings in good repair, particularly the one on the anodic member.
- Insulate dissimilar metals wherever practical [for example, by using a gasket]. It is important to insulate completely if possible.
- Add inhibitors, if possible, to decrease the aggressiveness of the environment.
- Avoid threaded joints for materials far apart in the series.
- Design for the use of readily replaceable anodic parts or make them thicker for longer life.
- Install a third metal that is anodic to both metals in the galvanic contact.

Crevice Corrosion

Crevice corrosion occurs as a result of water or other liquids getting trapped in localized stagnant areas creating an enclosed corrosive environment. This commonly occurs under fasteners, gaskets, washers and in joints or in other components with small gaps. Crevice corrosion can also occur under debris built up on surfaces, sometimes referred to as "poultice corrosion." Poultice corrosion can be quite severe, due to an increasing acidity in the crevice area.

Several factors including crevice gap, depth, and the surface ratios of materials affect the severity or rate of crevice corrosion. Tighter gaps, for example, have been known to increase the rate of crevice corrosion of stainless steels in chloride environments. The larger crevice depth and greater surface area of metals will generally increase the rate of corrosion.

Materials typically susceptible to crevice corrosion include aluminum alloys and stainless steels. Titanium alloys normally have good resistance to crevice corrosion. However, they may become susceptible in elevated temperature and acidic environments containing chlorides. Copper alloys can also experience crevice corrosion in seawater environments.

To protect against problems with crevice corrosion, systems should be designed to minimize areas likely to trap moisture, other liquids, or debris. For example, welded joints can be used instead of fastened joints to eliminate a possible crevice. Where crevices are unavoidable, metals with a greater resistance to crevice corrosion in the intended environment should be selected. Avoid the use of hydrophilic materials (strong affinity for water) in fastening systems and gaskets. Crevice areas should be sealed to prevent the ingress of water. Also, a regular cleaning schedule should be implemented to remove any debris build up.

Pitting Corrosion

Pitting corrosion, also simply known as pitting, is an extremely localized form of corrosion that occurs when a corrosive medium attacks a metal at specific points causing small holes or pits to form (see Figure 7). This usually happens when a protective coating or oxide film is perforated, due to mechanical damage or chemical degradation. Pitting can be one of the most dangerous forms of corrosion because it is difficult to anticipate and prevent, relatively difficult to detect, occurs very rapidly, and penetrates a metal without causing it to lose a significant amount of weight. Failure of a metal due to the effects of pitting corrosion can occur very suddenly. Pitting can have side effects too, for example, cracks may initiate at the edge of a pit due to an increase in the local stress. In addition, pits can coalesce underneath the surface, which can weaken the material considerably.

Figure 7. Pitting Corrosion of Stainless Steel Tubing

Stainless steels tend to be the most susceptible to pitting corrosion among metals and alloys. Polishing the surface of stainless steels can increase the resistance to pitting corrosion compared to etching or grinding the surface. Alloying can have a significant impact on the pitting resistance of stainless steels. Conventional steel has a greater resistance to pitting corrosion than stainless steels, but is still susceptible, especially when unprotected. Aluminum in an environment containing chlorides and aluminum brass (Cu-20Zn-2Al) in contaminated or polluted water are usually susceptible to pitting. Titanium is strongly resistant to pitting corrosion.

Proper material selection is very effective in preventing the occurrence of pitting corrosion. Another option for protecting against pitting is to mitigate aggressive environments and environmental components (e.g., chloride ions, low pH, etc.). Inhibitors may sometimes stop pitting corrosion completely. Further efforts during design of the system can aid in preventing pitting corrosion, for example, by eliminating stagnant solutions or by the inclusion of cathodic protection. In some cases, protective coatings can provide an effective solution to the problem of pitting corrosion. However, they can also accelerate the corrosion process at locations where the coating has been breached and the base metal is left exposed to the corrosive environment.

Intergranular Corrosion

Intergranular corrosion attacks the interior of metals along grain boundaries. It is associated with impurities which tend to deposit at grain boundaries and/or a difference in crystallographic phase precipitated at grain boundaries. Heating of some metals can cause a "sensitization" or an increase in the level of inhomogeneity at grain boundaries. Therefore, some heat treatments and weldments can result in a propensity for intergranular corrosion. Susceptible materials may also become sensitized if used in operation at a high enough temperature environment to cause such changes in internal crystallographic structure.

Intergranular corrosion can occur in many alloys. The most predominant susceptibilities have been observed in stainless steels and some aluminum and nickel-based alloys. Stainless steels, especially ferritic stainless steels, have been found to become sensitized, particularly after welding. Aluminum alloys also suffer intergranular attack as a result of precipitates at grain boundaries that are more active. Exfoliation corrosion (shown in Figure 8 is considered a type of intergranular corrosion in materials that have been mechanically worked to produce elongated grains in one direction. High nickel alloys can be susceptible by precipitation of intermetallic phases at grain boundaries.

Methods to limit intergranular corrosion include:

- Keep impurity levels to a minimum.
- Proper selection of heat treatments to reduce precipitation at grain boundaries.
- Specifically for stainless steels, reduce the carbon content, and add stabilizing elements (Ti, Nb, Ta) which preferentially form more stable carbides than chromium carbide.

Figure 8. Exfoliation of an Aluminum Alloy in a Marine Environment

Selective Leaching/Dealloying

Dealloying, also called selective leaching, is a rare form of corrosion where one element is targeted and consequently extracted from a metal alloy, leaving behind an altered structure. The most common form of selective leaching is dezincification (shown in Figure 9), where zinc is extracted from brass alloys or other alloys containing significant zinc content. Left behind are structures that have experienced little or no dimensional change, but whose parent material is weakened, porous and brittle. Dealloying is a dangerous form of corrosion because it reduces a strong, ductile metal to one that is weak, brittle and subsequently susceptible to failure. Since there is little change in the metal's dimensions dealloying may go undetected, and failure can occur suddenly. Moreover, the porous structure is open to the penetration of liquids and gases deep into the metal, which can result in further degradation. Selective leaching often occurs in acidic environments.

Figure 9. Dezincification of Brass Containing a High Zinc Content (Reference 12)

Reducing the aggressive nature of the atmosphere by removing oxygen and avoiding stagnant solutions/debris buildup can prevent dezincification. Cathodic protection can also be used for prevention. However, the best alternative, economically, may be to use a more resistant material such as red brass, which only contains 15% Zn. Adding tin to brass also provides an improvement in the resistance to dezincification. Additionally, inhibiting elements, such as arsenic, antimony and phosphorous can be added in small amounts to the metal to provide further improvement. Avoiding the use of a copper metal containing a significant amount of zinc altogether may be necessary in systems exposed to severe dezincification environments.

Erosion Corrosion

Erosion corrosion is a form of attack resulting from the interaction of an electrolytic solution in motion relative to a metal surface. It has typically been thought of as involving small solid particles dispersed within a liquid stream. The fluid motion causes wear and abrasion, increasing rates of corrosion over uniform (non-motion) corrosion under the same conditions. Erosion corrosion is evident in pipelines, cooling systems, valves, boiler systems, propellers, impellers, as well as numerous other components. Specialized types of erosion corrosion occur as a result of impingement and cavitation. Impingement refers to a directional change of the solution whereby a greater force is exhibited on a surface such as the outside curve of an elbow joint. Cavitation is the phenomenon of collapsing vapor bubbles which can cause surface damage if they repeatedly hit one particular location on a metal.

There are several factors that influence the resistance of a material to erosion corrosion including hardness, surface smoothness, fluid velocity, fluid density, angle of impact, and the general corrosion resistance of the material to the environment are other properties that factor in. Materials with higher hardness values typically resist erosion corrosion better than those that have a lower value.

There are some design techniques that can be used to limit erosion corrosion as follow:

- Avoid turbulent flow.
- Add deflector plates where flow impinges on a wall.
- Add plates to protect welded areas from the fluid stream. Put piping of concentrate additions vertically into the center of a vessel.

Hydrogen Damage

There are a number of different ways that hydrogen can damage metallic materials, resulting from the combined factors of hydrogen and residual or tensile stresses. Hydrogen damage can result in cracking, embrittlement, loss of ductility, blistering and flaking, and also microperforation.

Hydrogen induced cracking (HIC) refers to the cracking of a ductile alloy when under constant stress and where hydrogen gas is present. Hydrogen is absorbed into areas of high triaxial stress producing the observed damage. A related phenomenon, hydrogen embrittlement is the brittle fracture of a ductile alloy during plastic deformation in a hydrogen gas containing environment. In both cases, a loss of tensile ductility occurs with metals exposed to hydrogen which results in a significant decrease in elongation and reduction in area. It is most often observed in low strength alloys and has been witnessed in steels, stainless steels, aluminum alloys, nickel alloys, and titanium alloys.

High pressure hydrogen will attack carbon and low-alloy steels at high temperatures. The hydrogen will diffuse into the metal and react with carbon resulting in the formation of methane. This in turn results in decarburization of the alloy and possibly cracks formation.

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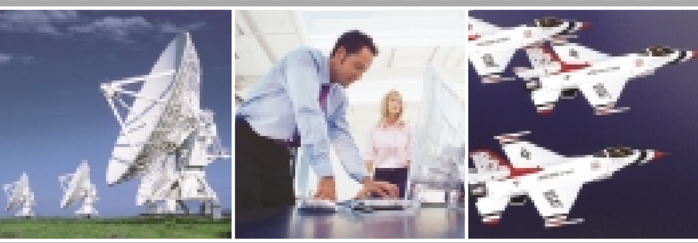

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A Brief Tutorial on Impact, ... (Continued from page 15)

Methods to deter hydrogen damage are to:

- Limit hydrogen introduced into the metal during processing.
- Limit hydrogen in the operating environment.
- Structural designs to reduce stresses (below threshold for subcritical crack growth in a given environment)
- Use barrier coatings
- Use low hydrogen welding rods

Biological Corrosion

Microbiological corrosion is the acceleration of corrosion due to the growth or existence of microorganisms in contact with a material. This form of corrosion can appear in any environment capable of supporting the life of microorganisms and is usually a localized effect on the metal. Microorganisms may accelerate or impede corrosion which is attributed to the oxygen concentration and pH level of the microenvironment. Two types of bacteria known to increase corrosion rates are sulfate-reducing bacteria and sulfate-oxidizing bacteria. Sulfate-reducing bacteria convert sulfates to sulfides which in turn create the metal sulfide corrosion product. Sulfate-oxidizing bacteria convert sulfate ions to produce sulfuric acid leading to a decrease in pH level. There are also many other bacteria capable of producing reduction and oxidation type reactions that will affect metals.

Methods to combat microbiological corrosion include:

- Inhibitors/coatings that deter growth of microorganisms.
- Preventive maintenance to remove microorganisms.

Stress Corrosion Cracking

Stress corrosion cracking (SCC) is an environmentally induced cracking phenomenon that sometimes occurs when a metal is subjected to a tensile stress and a corrosive environment simultaneously. This is not to be confused with similar phenomena such as hydrogen embrittlement, in which the metal is embrittled by hydrogen, often resulting in the formation of cracks. Moreover, SCC is not defined as the cause of cracking that occurs when the surface of the metal is corroded resulting in the creation of a nucleating point for a crack. Rather, it is a synergistic effort of a corrosive agent and a modest, static stress.

Another form of corrosion similar to SCC, although with a subtle difference, is corrosion fatigue. The key difference is that SCC occurs with a static stress, while corrosion fatigue requires a dynamic or cyclic stress.

SCC is a process that takes place within the material, where the cracks propagate through the internal structure, usually leaving the surface unharmed. Aside from an applied mechanical stress, a residual, thermal, or welding stress along with the appropriate corrosive agent may also be sufficient to promote SCC. Pitting corrosion, especially in notch-sensitive metals, has been found to be one cause for the initiation of SCC. SCC is a dangerous form of corrosion because it can be difficult to detect, and it can occur at stress levels which fall within the range that the metal is designed to handle.

Stress corrosion cracking is dependent on the environment based on a number of factors including temperature, solution, metallic structure and composition, and stress (Reference 13). However, certain types of alloys are more susceptible to SCC in particular environments, while other alloys are more resistant to that same environment. Increasing the temperature of a system often works to accelerate the rate of SCC. The presence of chlorides or oxygen in the environment can also significantly influence the occurrence and rate of SCC. SCC is a concern in alloys that produce a surface film in certain environments, since the film may protect the alloy from other forms of corrosion, but not SCC.

There are several methods that may be used to minimize the risk of SCC. Some of these methods include:

- Choose a material that is resistant to SCC.
- Employ proper design features for the anticipated forms of corrosion (e.g., avoid crevices or include drainage holes).
- Minimize stresses including thermal stresses.
- Environment modifications (pH, oxygen content).
- Use surface treatments (shot peening, laser shock peening) which increase the surface resistance to SCC.
- Any barrier coatings will deter SCC as long as it remains intact.
- Reduce exposure of end grains (i.e., end grains can act as initiation sites for cracking because of preferential corrosion and/or a local stress concentration).

Corrosion Fatigue

Corrosion fatigue was discussed in the section addressing fatigue failure modes.

Failure Prevention

In general, the most effective ways to prevent a material from failing is proper and accurate design, routine and appropriate maintenance, and frequent inspection for defects and abnormalities. Each of these general methods will be described in further detail.

Proper design of a system should include a thorough materials selection process in order to eliminate materials that could potentially be incompatible with the operating environment and to select the material that is most appropriate for the operating and peak conditions of the system. If a material is selected based only on its ability to meet mechanical property requirements, for instance, it may fail due to incompatibility with the operating environment. Therefore, all performance requirements, operating conditions, and potential failure modes must be considered when selecting an appropriate material for the system.

Routine maintenance will lessen the possibility of a material failure due to extreme operating environments. For example, a material that is susceptible to corrosion in a marine environment could be sustained longer if the salt is periodically washed off. It is generally a good idea to develop a maintenance plan before the system is in service.

Finally, routine inspections can sometimes help identify if a material is at the beginning stages of failure. If inspections are performed in a routine fashion then it is more likely to prevent it from failing while the system is in-service.

Conclusion

A number of material failure modes were introduced in this article including impact, spalling, wear, brinelling, thermal shock, and radiation damage. These mechanisms can affect metals, polymers, ceramics, and composites in various applications and in many different environments. Thus, it is important to take these failure modes into consideration during the design phases of a component or system in order to make appropriate materials selection decisions.

From a research standpoint, researchers must consider all material failure modes when developing and maturing a new material or when ‘evolving’ an old material. However, material failure can often be the result of inadequate material selection by the design engineer or their incomplete understanding of the consequences for placing specific types of materials in certain environments.

Education and understanding of the nature of materials and how they fail are essential to preventing it from occurring. Simple fracture or breaking into two pieces is not all-inclusive in terms of failure, because materials also fail by being stretched, dented or worn away. If potential failure modes are understood, then critical systems can be designed with redundancy or with fail-safe features to prevent a catastrophic failure of the system. Furthermore, if appropriate effort is given to understanding the environment and operating loads, keeping in mind potential failure modes, then a system can be designed to be better suited to resist failure.

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(Continued on page 21)

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- SPIDR includes all "raw data". SPIDR develops data summaries based on a user search. Previous data products provided predefined data results reducing flexibility of searches and ease of product and data updates.
- Separate failure mode data resources exist in SPIDR for test and field data.
- SPIDR provides additional details regarding component usage. For example SPIDR includes the system application and the usage environment associated with field and failure mode data.
- ESD susceptibility data for parts tested and manufactured after 1995 are included in SPIDR which more than doubles the amount of ESD susceptibility data contained by VZAP-95.
- Improved software interface. Multiple search capabilities allow users to find reliability data more efficiently and quickly.
- SPIDR will be updated annually. Prior products were updated sporadically.

The cost of SPIDR is $1,995 and data updates are provided annually to maintenance subscribers. The SPIDR software includes a user manual and on-line help to assist the user in understanding the software capabilities. Visit the SPIDR web site to order your copy today and take advantage of the complimentary 1 year of maintenance for all SPIDR purchases before June 30, 2006! <http://src.alionscience.com/spidr/>.

If you have additional questions, feel free to contact the SPIDR program manager at 315.339.7055 or by E-mail at <ddylis@alionscience.com>.

The iFR Method for Early Prediction of Annualized Failure Rate in Fielded Products

By: Bill Lycette, Agilent Technologies

Introduction

As with many manufacturers of complex electronic equipment, Agilent Technologies uses a non-parametric AFR (Annualized Failure Rate) metric for reporting product reliability. However, the AFR metric can be very sluggish in responding to changes in customer-experienced reliability. When investments to improve reliability culminate in the implementation of an engineering change, it can take as many as 9 to 12 months before the improvement is observed in the AFR. Equally important, degradation in reliability may be quickly detected by customers but it may take several months before a change is observed in the manufacturer's internal AFR measures.

The "instant Failure Rate" (iFR) is a parametric-based measure developed for the express purpose of providing much quicker feedback of changes in a product's reliability. This paper explains the iFR Method through analysis of actual field failure data and demonstrates how a balance is struck between selecting iFR variables that yield the best possible combination of quick reliability feedback, effective AFR predictive power, and narrow confidence bounds.

Note: The term "iFR" as used in this paper should not be confused with the reliability hazard rate (Reference 1), given by

$$h(t) = \frac{f(t)}{R(t)}$$

where *h(t)* is the true instantaneous failure rate, *f(t)* is the frequency of failures function, and *R(t)* is the reliability function

(Continued on page 23)

The iFR Method for ... (Continued from page 21)

representing the probability that the product will survive until time *t*. In this paper, "iFR" is meant to signify a metric that is much more responsive than the non-parametric AFR in measuring the reliability of products currently being shipped.

Annualized Failure Rate Metrics

A widely-used method for measuring reliability of electronic equipment is calculating field failure rates using the Annualized Failure Rate (AFR). There are countless different variations on such non-parametric methods as explained in Reference 2, but they generally rely upon simple calculations involving the number of failures and the size of the installed base (Reference 3).

The advantages of such methods are their simplicity and ease of understanding. No special software or graphing paper is required to make the calculation. The computation is straightforward and can be performed by someone unfamiliar with reliability statistics. The calculation is quick, simple and can be easily explained to the layperson. For these reasons, AFR is widely used in industry to measure the reliability of electronic equipment.

The disadvantages of such AFR methods are several. These methods do not allow for quantification of confidence bounds. Additionally, many of such metrics make the potentially false assumption that the underlying failure rate is constant over time. These methods also do not allow for conditional probability calculations.

Finally, a major disadvantage of AFR methods is that they can be sluggish to respond to changes in product reliability (both degradation and improvement) during the product's manufacturing life cycle. The iFR Method provides a solution to sluggish response time.

The iFR Method

The method is based on parametric techniques involving reliability statistics and principles. Reliability statistics are well documented in textbooks and the literature (References 4, 5, and 6).

By using the iFR Method, changes in the reliability of complex electronic measurement equipment can be detected by as many as four to six months earlier than would be otherwise possible using some conventional AFR methods.

<u>Keys to Success</u>

The keys to the success of the iFR Method include selecting a shipment evaluation window that strikes the optimum balance among the following.

1. Providing timely feedback of reliability changes,
2. Detecting the occurrence of new failure mechanisms,
3. Providing acceptable confidence bounds,
4. Minimizing reliability false alarms, and
5. Providing useful predictive power for anticipating eventual changes in AFR.

Through analysis of shipment and failure data associated with more than a dozen different products involving complex microwave/RF measurement equipment, the iFR Method has effectively predicted future AFR trends by using a shipment evaluation window in the range of four to six months.

Complex electronic measurement equipment is characterized by having between a few thousand electronic components and more than 10,000 electronic components, while at the same time having relatively few mechanical components. With the advancement in design and manufacturing technology over the past 10-20 years, electronic components have the distinguishing feature of typically exhibiting constant failure rates or improving failure rates (so-called "infant mortality") over time. Eventually these parts will enter a wear-out phase which is marked by a rapidly increasing fail rate; however for electronic components, this phase is generally well beyond the normal expected operating life of the end product. Therefore owners of complex electronic measurement equipment will rarely experience such electronic component failures.

Mechanical parts are susceptible to wear-out failure mechanisms. However, their relatively low numbers in electronic measurement equipment and recent advances in their reliability have resulted in products where customer-experienced failure of mechanical parts is fairly small over the expected operating life.

These observations, coupled with the selection of an optimum iFR data analysis shipment window, mean that it is possible to predict changes in traditional AFR reliability metrics by as many as six months earlier than when the AFR metric would show the change.

<u>Description of the iFR Method</u>

1. The Shipment Evaluation Window is defined to be the number of consecutive months containing product shipments that the reliability analyst wishes to consider in the failure rate prediction.
2. The iFR Reporting Month is defined to be the last month of the Shipment Evaluation Window.
3. Data processing and metric calculation begins one month after the end of the Shipment Evaluation Window, referred to as the Calculation Date (CD).
4. On the CD, qualifying shipment records are collected from the specified Shipment Evaluation Window.
5. On the CD failure records (namely failure age) are collected from qualifying shipments records.
6. Ages of qualifying shipments that have not yet failed as of the CD are calculated.
7. Ages of failed products and unfailed products are entered into a parametric reliability data analysis tool.
8. The life data distribution that best fits the data is selected. For distributions that equally fit the data, selecting the distribution that yields the lowest fail rate generally provides the best predictive result.
9. The percent of failed products expected after one year of operation is calculated. This is the iFR for that Reporting Month.

10. The iFR by Reporting Month is plotted over time and the trend line used to predict changes in the AFR.

Refer to Figure 1 for a timeline of iFR Method events.

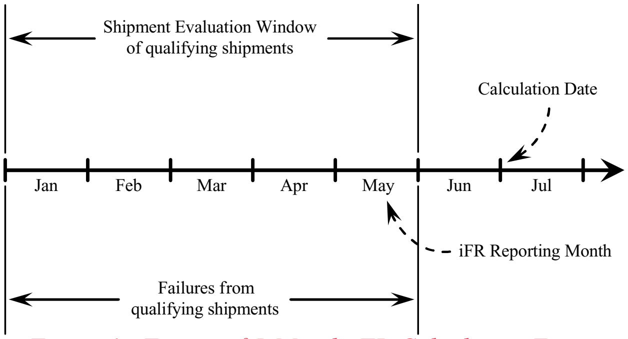

Figure 1. Timing of 5-Month iFR Calculation Events

Data Analysis Results

Agilent Technologies designs and manufactures complex microwave/RF test and measurement equipment. It is common for such equipment to have 10,000 or more electronic components. Typically the equipment is constructed of several digital and analog printed circuit assemblies, hybrid microcircuit assemblies, power supply, disk drive, CD-ROM, keypad assembly and display. While the equipment does contain some mechanical parts, the vast majority of components are electronic.

The paragraphs that follow illustrate the iFR Method using actual fielded data of a complex measurement system. The data presented here has been disguised but the results and conclusions are the same.

Field failure data spanning more than three years was studied using the iFR Method. Shipment windows consisting of six different sizes were initially analyzed: two months, four months, six months, eight months, ten months, and twelve months. Utilizing parametric methods, the iFR was calculated for 30 successive reporting months. These data points were plotted to evaluate the relationship between the calculated iFR and the product's eventual AFR.

Impact of Shipment Window Size

In looking at Figure 2, at the one extreme we see that using a wide 12-month shipment evaluation window results in an iFR that is an excellent predictor of the eventual AFR. However, the disadvantage of the 12-month shipment window is that one must wait a full year before making the calculation. As a result, such a wide evaluation window makes this choice of little value.

At the other the extreme shown in Figure 3, we see that a narrow 2-month shipment evaluation window yields a very responsive metric that can be calculated with very little delay. Unfortunately, such a short evaluation window can result in some wild month-over-month fluctuations, numerous false alarms and a generally poor predictor of the eventual AFR (as will be discussed later in this article).

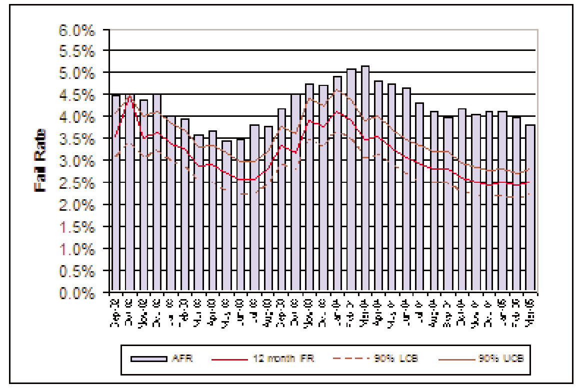

Figure 2. 12-Month Shipment Evaluation Window

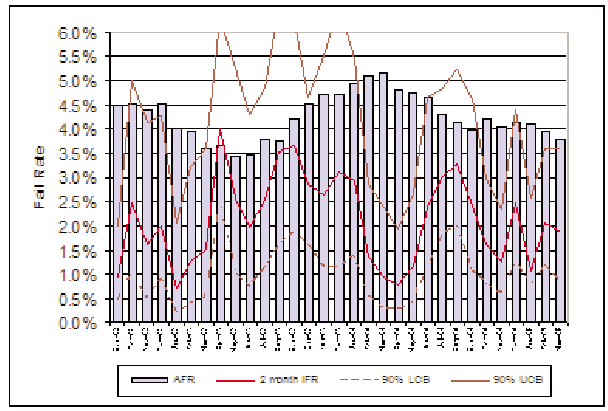

Figure 3. 2-Month Shipment Evaluation Window

In examining the other shipment evaluation windows as shown in Figures 4 through 6, we see that an evaluation window between four and six months seems to offer the best balance between predictive power of the iFR, stability and shortest delay in the making the iFR calculation. The iFR for a 10-month shipment evaluation window was calculated but is not presented here for brevity; its shape is very similar to that of the 8-month shipment evaluation window.

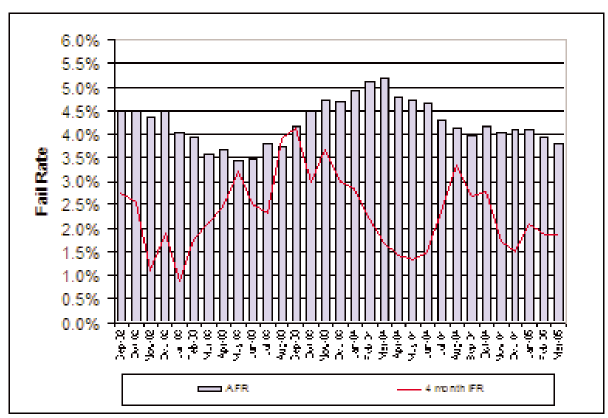

Figure 4. 4-Month Shipment Evaluation Window

The graphs show a steep decrease in iFR at the end of 2002. Earlier in 2002, the engineering team discovered that one of the components in an attenuator assembly degraded over time. After evaluating alternative components, an improved device was selected and implemented in mid-2002. To the engineering team's relief, the AFR subsequently dropped as predicted by the iFR and the design change was affirmed.

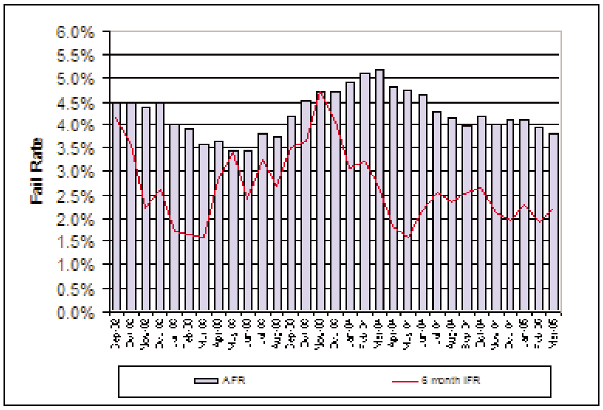

Figure 5. 6-Month Shipment Evaluation Window

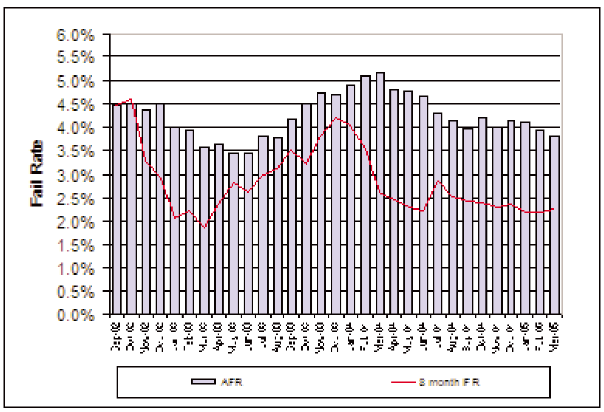

Figure 6. 8-Month Shipment Evaluation Window

The initial increase in iFR throughout the first half of 2003 accurately predicted an associated increase in AFR during the second half of 2003. A Pareto analysis of failed assemblies showed increasing failure rates of several printed circuit assemblies (PCA). Failure analysis of the PCAs revealed a fabrication problem with tantalum capacitors purchased from the same supplier. Other suppliers' components were evaluated and devices with improved reliability implemented later in 2003. The iFR gave advance notice of the problem and confirmed that the solution would be effective.

To further optimize predictive results, the iFR Method was refined by calculating failure rates using a 5-month shipment evaluation window. The results are shown in Figure 7.

Confidence Bounds

Another important aspect when considering what size of evaluation period to select is the width of the iFR confidence bounds. Confidence bounds on failure rates are inversely proportional to the number of field failures observed.

Consequently, narrowest confidence bounds will occur with the largest shipment evaluation windows.

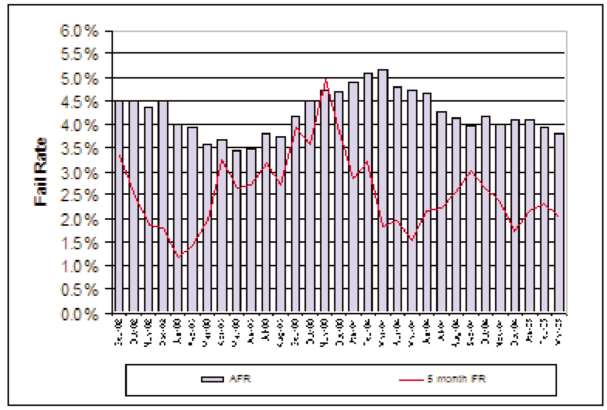

Figure 7. 5-Month Shipment Evaluation Window

For a failure process that follows the exponential distribution, the two-sided upper limit on the failure rate is:

$$\lambda_U = \frac{\chi_{\alpha,2r+2}}{2T}$$

where χ is the Chi square distribution, α is the significance level, $2r+2$ is the degrees of freedom (r is the number of failures observed) and T is the total product exposure time.[4]

The two-sided lower limit on the failure rate is given by:

$$\lambda_L = \frac{\chi_{1-\alpha,2r}}{2T}$$

Larger shipment evaluation windows will provide greater precision in the metric. Again, we have the tradeoff between using small shipment windows (quick reliability feedback) and larger shipment windows. The effect of evaluation window size on confidence bounds can be seen in Figures 2 and 3.

The confidence bounds for shipment evaluation windows of four months, five months and six months were also calculated (not presented here for brevity). These confidence bounds were all roughly the same and therefore did not play a significant factor in selecting the optimum shipment evaluation window.

iFR Predictive Power

We want a shipment evaluation period that affords the best possible predictive power (using iFR to predict the eventual AFR) while at the same time minimizing calculation delay time and confidence bound widths. A correlation analysis using linear regression was performed where iFR and eventual AFR were compared using the previously described shipment evaluation windows. For each shipment evaluation window, correlation coefficients were calculated using five different iFR lead times. iFR lead time represents the amount of advance notice that the iFR metric provides with respect to predicting the eventual AFR number. Analysis results are shown in Table 1.

Similar to a long range weather forecast, iFR predictive accuracy declines as we attempt to predict further into the future about what the AFR will eventually be. We also see that the iFR predictive power improves with larger shipment evaluation windows. Larger evaluation windows tend to yield better results because 1) greater customer-use time (i.e., exposure time) provides for more latent failure mechanisms to manifest themselves, and 2) larger data sets drive smaller random variation (confidence bounds) in the calculated iFR.

Table 1. Correlation Coefficients to Assess the Predictive Power of the iFR

Shipment Window Size (in Months)	AFR Advance Warning Lead Time (in months)								
	0	1	2	3	4	5	6	7	8
2	-	-	-	-	0.48	0.57	0.59	0.47	0.34
4	-	-	-	0.53	0.67	0.68	0.65	0.53	-
5	-	-	0.55	0.74	0.79	0.70	0.60	-	-
6	-	0.39	0.60	0.71	0.68	0.53	-	-	-
8	0.45	0.58	0.70	0.64	0.49	-	-	-	-
10	0.71	0.69	0.72	0.62	-	-	-	-	-
12	0.71	0.67	0.61	-	-	-	-	-	-

It would make little sense to use a shipment evaluation window of 10 or 12 months because one would have to wait for nearly one year in order to make an accurate statement about what the AFR is likely to do in the following month.

In this example, we see that the sweet spot for predicting AFR (highest predictive power, shortest iFR calculation delay and acceptable confidence bounds) is achieved by selecting a five month shipment evaluation window. This results in an optimum AFR lead time indicator of four months. Slightly inferior, but nevertheless useful, results can be obtained with four and six month shipment evaluation windows.

Limitations

Methods for predicting field failure rates are based on failure mechanisms that have already manifested themselves. If a specific failure mechanism, e.g., the wear out of a disk drive bearing, has not already presented itself in the data, then such methods have no way of knowing that the failure mechanism can occur. As such, predictive methods would not be effective on products that have failure mechanisms occurring beyond the edge of the shipment evaluation window.

While complex electronic measurement equipment is typically constructed of electronic components that exhibit constant or decreasing failure rates, there are occasions when such components may exhibit an increasing failure rate during the product's normal expected operating life. Likewise, one of the product's handful of mechanical parts may enter a wear out phase unexpectedly early. Either of these two scenarios would likely not provide for an accurate AFR prediction based on only a few months of early field data used in the iFR Method.

Conclusions

Reliability metrics such as the widely used Annualized Failure Rate can be extremely sluggish to respond to changes in the product's reliability over the course of its manufacturing life cycle. The iFR Method described in this paper has been shown to be effective in providing a more responsive leading indicator of customer-experienced reliability in complex electronic equipment.

Waiting six, nine or even 12 months for a reliability problem to be reflected in traditional AFR metrics represents a huge delay in solving the root cause of the problem. In the mean time, shipments of the problem continue thus increasing the installed base and associated exposure to higher warranty costs, greater customer dissatisfaction and lost future sales. Additionally, it is costly and frustrating to wait long periods of time to determine if a recently-implemented fix was actually successful. Metrics such as AFR are slow to reflect the effectiveness of such a fix, and several months of patiently monitoring the AFR may give way to making costly, unnecessary investments in additional reliability improvements.

The iFR Method provides timely, valuable feedback to manufacturers thus enabling them to 1) quickly take action in response to degradation in product reliability, and 2) avoid costly, unnecessary engineering changes when recent improvements are judged to be effective and adequate.

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About the Author

Bill Lycette is a Senior Reliability Engineer with Agilent Technologies. He has 25 years of engineering experience with Hewlett-Packard and Agilent Technologies, including positions in reliability and quality engineering, process engineering, and manufacturing engineering of microelectronics, printed circuit assemblies and system-level products. Mr. Lycette is an ASQ Certified Reliability Engineer and Certified Quality Engineer.

From the Editor

How Did I Get Here!

I've heard it said that life is a funny dog. It takes some twists and turns that we can neither plan nor expect. So in looking back on one's career, it is not surprising that we find our careers have taken a twisty path.

I did not choose to be a reliability engineer – that career path sort of chose me. While I was a First Lieutenant in the United States Air Force, stationed at Wright-Patterson AFB and working on test bed modifications, I was centrally selected for the Systems Engineering-Reliability Master's Degree program at the Air Force Institute of Technology. At the time, I had never heard of reliability and had planned to get my Master's Degree in the same area as my Bachelor's Degree – Mechanical Engineering. However, a Master's Degree at Government expense is nothing to turn down. So I accepted the opportunity.

That was nearly 37 years ago. In those three plus decades, I have come to be an avid and enthusiastic supporter of the reliability and related disciplines. Like my colleagues in the field, I know that understanding the causes of failure and taking action to mitigate or prevent those failures, first through design changes and later through improvements in production, operation, or maintenance, is vital to the defense of our country and the economic vitality of our economy.

Like many of my colleagues, I also have come to realize that reliability is not consistently or even readily embraced by managers and those holding the purse strings. In part, this reluctance to accept reliability as a necessary performance parameter is due to the probabilistic nature of reliability and our inability to forecast precisely when a failure will occur or how many failures will occur in a given interval of time.

Another reason reliability is not a top priority with managers is that the benefits of a robust reliability program are long term and not seen until after a product is sold or a system is fielded. The costs, however, are immediate. Training, reliability software tools, growth testing, redesign, data collection, root cause failure analysis, and other essential reliability tasks require resources today, not tomorrow.

Consequently, as a result of these two reasons and a third which I will touch upon in a minute, much of my reliability career, and those of many of my colleagues, has been spent in trying to "sell" reliability to management. As a proponent, I have expounded on the long-term benefits of reliability and the costs and risks incurred by ignoring reliability. I have worked to educate managers and engineers in the reliability discipline, trying to dispel the many myths that surround the subject. I have had some success but not nearly as much as I would have liked or I think is needed.

Ned H. Criscimagna

Those who know me well know my third reason for this unsatisfactory level of success in making reliability a part of every program. They know that I lay the blame on our society's penchant for immediate gratification. Whether it be adult stockholders or teenage children, members of our society seem unable to look much beyond tomorrow. Why save for the future when we can spend today, even if it means living on credit? Why invest in our companies to help ensure their future and that of the employees when we can make huge profits today to keep the stockholders happy?

Reliability requires looking to the future, not dwelling on the present. Reliability requires that one recognizes that "you must pay now or pay even more later." Many a system has required considerable investment of resources to achieve a reasonable level of availability during its operational life, simply because little or no attention was devoted to reliability during acquisition and production.

Perhaps some of our readers have similar stories and perceptions regarding their career in reliability. And despite the times that we have failed to convince managers to spend money now to save money, reduce risks, and increase performance later, we persevere. We persevere because we believe in what we are doing. We persevere because we have seen the dire consequences of neglecting a basic part of system engineering. These consequences are, unfortunately, not limited to higher costs. They include loss of life, injury, unsuccessful military missions, and gut-wrenching scenes of a space vehicle self-destructing in the clear blue skies over Florida.

Many may regard the passion that reliability engineers bring to their job as overdone or excessive. We are too focused, they complain, and too zealous. Perhaps. But I think that everyone whose life depends on the reliable operation of a system may see us in a different light.

Reliability engineers may not receive the recognition or credit given to those in other branches of engineering. However, recognition and credit are not the reasons I have stayed in the profession and I doubt they are what motivate my colleagues.

I may have started down the path of reliability engineering by accident. But I have stayed the course on purpose. I have taken and continue to take great pride in the work that my colleagues and I do. I know how I got here and I know why I stayed.

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