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Hot Topics

The Bathtub Curve and Product Failure Behavior
Part Two - Normal Life and Wear-Out

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This paper is adapted with permission from work done while at Hewlett-Packard.

Introduction

Part One of this article (presented in last month's *HotWire*) introduced the concept of the reliability bathtub curve. This is a graphical representation of the lifetime of a population of products, which consists of three key periods. Part One examined the first period of the curve, infant mortality, and also discussed issues related to burn-in, a common practice to reduce the occurrence of this type of failure during the useful life of the product. Part Two (presented here) will address the middle and last periods in the bathtub curve: normal life (or "useful life") and end of life wear-out. The normal life period is characterized by a low, relatively constant failure rate with failures that are considered to be random cases of "stress exceeding strength." The wear-out period is characterized by an increasing failure rate with failures that are caused by the "wear and tear" on the product over time.

Reliability Bathtub Curve Review

As described in more detail in Part One, the bathtub curve, displayed in Figure 1 below, does *not* depict the failure rate of a single item. Instead, the curve describes the relative failure rate of an entire population of products over time. Some individual units will fail relatively early (infant mortality failures), others (we hope most) will last until wear-out, and some will fail during the relatively long period typically called normal life. The first period is characterized by a decreasing failure rate and consists of failures caused by defects and blunders. The second period maintains a low and relatively constant failure rate and consists of random failures typically caused by "stress exceeding strength." The third period exhibits an increasing failure rate and consists of failures caused by wear-out due to fatigue or depletion of materials.
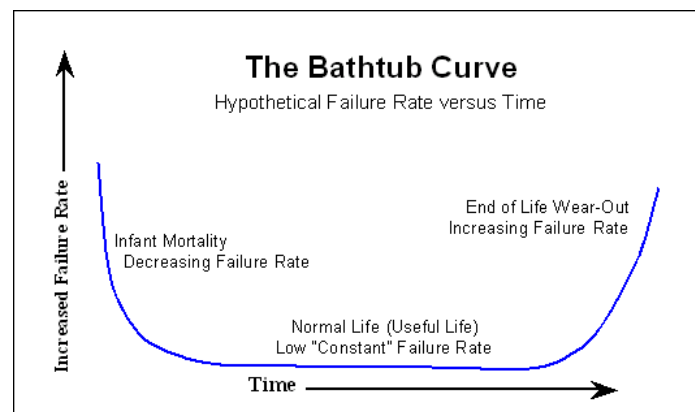

Figure 1: The Bathtub Curve

Normal Life Period Does it Really Exist?

Some reliability specialists like to point out that real products don't exhibit constant failure rates. This is quite true for a mechanical part where wear-out is the primary failure mode. And all kinds of parts, mechanical and electronic, are subject to infant mortality failures from intrinsic defects. But there are common situations where a true random failure potential exists.

Soft Error Rate (SER) is a fact of life for systems using solid state memory chips. And today that includes about any electronic device, from a personal computer to a VCR, microwave oven, digital camera or automotive control module. These errors are caused by two factors: alpha particles and cosmic rays. These errors are random in time and transient. A bit that is "flipped" by one of these factors will be corrected when new data is written to the same memory cell. But if that cell is read before a new write operation takes place, the data read will be erroneous. The effect of the error may be minor (such as a single pixel of a display being the wrong color for one screen refresh cycle) or major (such as crashing a PC). In business-critical computer systems, special error correcting codes are employed to prevent SER from causing any data loss or system malfunctions. However, most electronic products will malfunction in some way from SER.

For SER, the failure mode is a normal life failure. There is an average rate of occurrence but the failures occur "at random." The failures in most cases cause only a minor deviation in operation and are self-correcting. No repair is needed to "fix" a product subject to SER and, in fact, no "fix" can eliminate SER effects. Only a significant design change (using an error correcting design) can eliminate the *effects* of SER, but nothing can eliminate SER.

There are other cases, especially in electronic products, where a "constant" failure rate may be appropriate (although approximate). This is the basis for MIL-STD-217 and other methods to estimate system failure rates from consideration of the types and quantities of components

used. For many electronic components, wear-out is not a practical failure mode. The time that the product is in use is significantly shorter than the time it takes to reach wear-out modes. That leaves infant mortality and normal life failure modes as the causes of all significant failures. As we have already observed, after some time, failures from infant mortality defects get spread out so much that they appear to be approximately random in time. A combination of low level infant mortality failures and some random failures caused by operational stresses (such as power line surges) can result in a product failure distribution that is very close to the classical normal life period. This brings up the question of a much-misunderstood term that applies during the normal life period, MTBF.

MTBF What is it?

A common term used in specifying and marketing products is MTBF, which is a vastly misunderstood (and often misused) term. MTBF historically stands for "Mean Time Between Failures," and as such, applies only when the underlying distribution has a constant failure rate (*e.g.* an exponential distribution). In this case, MTBF is the characteristic life parameter of the exponential distribution, as we will see below. However, use of the term MTBF is confused by the fact that a few reliability practitioners have used it to indicate "Mean Time *Before* Failure," a case where the underlying distribution may be a wear-out mode. Further, to some practitioners the word "between" implies a repairable product while "before" implies a non-repairable product. To make matters worse, vendors of many products use the term MTBF without defining what they mean, sometimes with no concept of reliability issues. In fact, the author has actually seen MTBF explained as "Minimum Time Before Failure," a completely non-statistical and nonsensical concept.

Mean Time Before Failure (often termed Mean Time To Failure, or MTTF) describes the average time to failure of a product, even when failure rate is increasing over time (wear-out mode). Some units will fail before the mean life, *and some will last longer*. Thus, a product specified as having an MTTF of 50,000 hours implies that some units will actually operate longer than 50,000 hours without failure. Note: I'll use MTTF rather than Mean Time Before Failure for the remainder of this article. When I write MTBF, I mean "Mean Time Between Failures," as applies to the exponential distribution.

In recent years, many vendors have started using terminology such as "service life" to describe how long their products may last in use. This is a good trend. However, while writing this article, the author found current a data sheet that indicated "service life" using MTBF, where the MTBF values were in excess of 500,000 hours (this would be 57 years of 24-hour-per-day operation). The products specified would not operate, non-stop, for over 50 years; wear-out modes would kill off most of these products in ten years, at most. The vendor was confusing the normal life **failure rate**, often expressed as an MTBF value, with the wear-out distribution of the product.

How does MTBF describe failure rate? It is quite simple: when the exponential distribution applies (constant failure rate modeled by the flat, bottom of the bathtub curve), MTBF is equal to the inverse of failure rate. For example, a product with an MTBF of 3.5 million hours, used 24 hours per day:

- MTBF = 1 / failure rate
- failure rate = 1 / MTBF = 1 / 3,500,000 hours
- failure rate = 0.000000286 failures / hour
- failure rate = 0.000286 failures / 1000 hours
- failure rate = 0.0286% / 1000 hours - and since there are 8,760 hours in a year
- failure rate = 0.25% / year

Note that 3.5 million hours is 400 years. Do we expect that any of these products will actually operate for 400 years? No! Long before 400 years of use, a wear-out mode will become dominant and the population of products will leave the normal life period of the bathtub and start up the wear-out curve. But during the normal life period, the "constant" failure rate will be 0.25% per year, which can also be expressed as an MTBF of 3.5 million hours.

How does MTBF fit into the equation for the exponential distribution? MTBF is the scale parameter (usually termed eta or

η) that defines the specific model for an exponential distribution. The equation for the density function of an exponential distribution is given by:

$$F(t) = \frac{1}{\eta}\left(e^{\frac{-t}{\eta}}\right)$$

where:

- *F(t)* = probability of failure at time *t*

- η = characteristic life = MTBF (time when 63.2% cumulative failures occur)
- *e* = 2.71828', base of natural logs

Note that many products with very low failure rates during "normal life" will wear out in a few years, so that the Mean Time Before Failure (or MTTF) may be much less than Mean Time Between Failures. Let's look at this graphically.
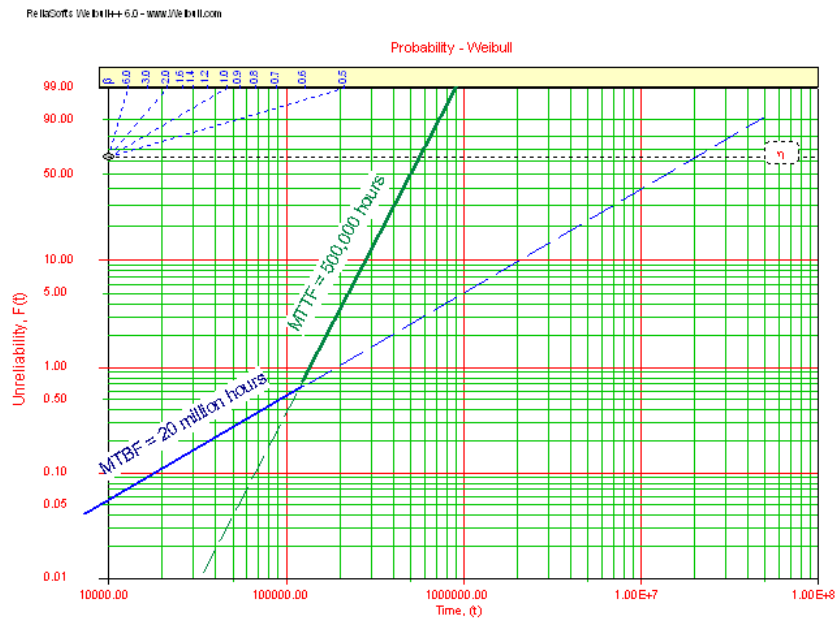
Figure 2: Weibull Plot for Normal Life and Wear-Out Populations

Figure 2 above shows a Weibull probability plot. This plot shows the expected cumulative failures for a product over time, with time shown on the x-axis and cumulative failure percentages (labeled Unreliability) shown on the y-axis. This is one of the most common ways to view failure distributions. The solid blue line is titled "MTBF = 20 million hours" and represents the normal life period shown as a horizontal line on the bathtub curve. It is not horizontal here because this plot shows cumulative failures whereas the bathtub curve shows failure rate. The MTBF of an exponential distribution is equal to the time when 63.2% of the population of units has failed. This level is shown on the plot as a dashed black line labeled

η(eta). In this example, the extension of the "MTBF = 20 million hours" line crosses the 63.2% level at 20 million hours on the x-axis.

The green line, on the other hand, represents a wear-out distribution as depicted on the right side of a bathtub curve. It is not a constant failure rate distribution but a failure rate that increases with time. Note that it crosses the 50% cumulative level at about 500,000 hours. This is a wear-out distribution with an MTTF of 500,000 hours. Note that for betas over 3, MTTF is close to the 50% cumulative failure time - Weibull++ can calculate the actual mean life (MTTF) and median life (50% cumulative failure time) for any Weibull distribution. When beta = 1 (or an exponential distribution is used), the mean life will be the same as Mean Time Between Failures.

Both of these distributions (blue and green lines) apply to the same population of devices. These devices fail primarily according to the constant failure rate model (solid blue MTBF line) until the blue line intercepts the green line. This is when wear-out begins to have a significant effect (a little over 100,000 hours in this example). By 500,000 hours, half of the units will have failed and by 900,000 hours, 99% of the units will have failed. None of them will ever reach the 20 million hour MTBF time because the wear-out mode dominates after about 100,000 hours of operation. Note that the true overall cumulative failures will be the sum of the two distributions shown on this plot. However, because the y-axis is a log-log scale, the sum of the two distributions is very close to the two straight lines except around the area where they intercept.

MTBF Summary

As we have seen here, it is logical that a device can have an MTBF that is much greater than its wear-out time because MTBF is only a projection of the normal lifetime failures to a cumulative level of 63.2%. Most, if not all, devices will have failed due to wear-out modes long before the MTBF time.

A major problem for many people with the term *Mean Time Between Failures* is that it is expressed as "time" when it is really used to indicate failure rate during the normal life period. To further confuse the issue, some people use the term MTBF to indicate *Mean Time Before Failure*, a case when it applies to wear-out modes and really does relate to service life. And, as I noted above, some people don't know what they are talking about and claim service life is equal to "Mean Time Between Failures"!

Good news is that recent data sheets from some vendors (particularly those making electronic assemblies) show MTBF under the heading of "reliability" and a separate value for service life. In this case, the vendor has described both the expected failure rate during the normal life period of the bathtub (*e.g.* "MTBF = 3.5 million hours") and the point in time at which the product is expected to start up the wear-out part of the bathtub curve (*e.g.* "service life greater than 8 years"). Bad news is that some vendors, even major technology firms, still don't understand reliability concepts, at least as expressed in their data sheets.

When you are specifying components for a product and want to understand how long it might operate and what the failure rate might be during normal life, be sure to find out what the vendor means by "MTBF." And if he thinks it means "Minimum Time Before Failure" calculated from MIL-HDBK-217, be careful!

Everything Eventually Wears Out

In the long run, everything wears out. For many electronic designs, wear-out will occur after a long, reasonable use-life. Inexpensive electronic watches, radios, televisions and other such products usually last for years, and people are not too upset if they finally fail. There are usually newer products with better features that they want to buy after a few years.

For many mechanical assemblies, the wear-out time will be less than the desired operational life of the whole product and replacement of failed assemblies can be used to extend the operational life of the product. With some items, wear-out is expected and replacement is a normal routine. For example, inkjet cartridges run out of ink after so much ink has been squirted. This is not normally thought of as a failure. However, if a newly replaced cartridge runs out of ink after a short period of use, then we do consider it a failure. On the other hand, there are mechanical and electro-mechanical devices that only last for months or years of use in a product expected to last for decades. Relays,

generators, switching devices, engine parts and hydraulic components in aircraft are replaced on a periodic basis, usually before they fail, to enable the aircraft to fly for many years of safe operation. Tires and brake components are replaced several times over the period of time that the automobile is in use.

The wear-out period does not occur at one time for all components. The shortest-lived component will determine the location of the wear-out time in a given product. In designing a product, the engineer must assure that the shortest-lived component lasts long enough to provide a useful service life. If the component is easily replaced, such as tires, replacement may be expected and will not degrade the perception of the product's reliability. If the component is not easily replaced and not expected to fail, failure will cause customer dissatisfaction.

In order to assess wear-out time of a component, long-term testing may be required. In some cases, a 100% duty cycle (running tires in a road wear simulator 24 hours a day) may provide useful lifetime testing in months. In other cases, actual product use may be 24 hours a day and there is no way to accelerate the duty cycle. High level physical stresses may need to be applied to shorten the test time. This is an emerging technique of reliability assessment termed QALT (Quantitative Accelerated Life Testing) that requires consideration of the physics and engineering of the materials being tested.

Properly applied, QALT can provide useful information from tests much shorter in length than the expected operating time of a design. However, much care must be taken to assure that all possible failure modes have been investigated. Running a quantitative accelerated life test without considering all possible failure modes and their accelerating stress types may miss a significant failure mode and invalidate the conclusions. As appropriate, mechanics, electronics, physics and chemistry must all be considered when designing a QALT.

Note that "MTBF" testing, using many units in parallel to shorten test times, is a popular method of life testing. It does not apply to testing for wear-out! It can apply to testing for normal life failures, but the results of such testing should never be extrapolated to times longer than were used for the test itself.

Conclusion

As demonstrated in Parts One and Two of this article, the traditional bathtub curve is a reasonable, qualitative illustration of the key kinds of failure modes that can affect a product. Quantitative models such as the Weibull distribution can be used to assess actual designs and determine if observed failures are decreasing, constant or increasing over time so that appropriate actions can be taken. The exponential distribution and the related Mean Time Between Failures (MTBF) metric are appropriate for analyzing data for a product in the "normal life" period, which is characterized by a constant failure rate. But be careful - many people have "imposed" a constant failure rate model on products that should be characterized by increasing or decreasing failure rates, just because the exponential distribution is an easy model to use.

Do not assume that a product will exhibit a constant failure rate. Use life testing and/or field data and life distribution analysis to determine how your product behaves over its expected lifetime. In addition to traditional life data analysis models (such as the Weibull distribution), quantitative accelerated life testing (QALT) may be a valuable technique to better understand failure distributions of highly reliable products with reduced testing time, in a cost-effective manner. Without a QALT approach to testing, there is no way to accurately assess the long-term reliability of a product in a short time. If you need to understand the reliability of a device for a one-year use-life, a non-accelerated test of 12 units for one month will not do it. It will only provide information on one month of use. Projection to one year will be invalid if a wear-out mode occurs, for example, in six months. The only way to find a wear-out mode is to test long enough to observe it, with or without a QALT approach. When dealing with vendors and their claims of reliability for components you wish to use, be sure you understand how they determined these figures and how well they understand the consequences of the bathtub curve.

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