Life Data Analysis Using the Competing Failure Modes Technique

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SUMMARY & CONCLUSIONS

As demand for highly reliable complex systems increases, engineers are being forced to consider the risk implications of design decisions earlier in the conceptual phase of projects and with greater accuracy. Standard probabilistic risk assessments (PRA) usually employed to verify that a product meets requirements are too resource intensive and too slow to keep up with the speed at which the design is maturing; while classical qualitative methods do not provide the level of detail and granularity required by the designers to make high-quality risk informed decisions.

Every company is dependent on some type of asset that keeps the business *in* business – be it a computer, a centrifuge or a megawatt transformer. In a large enterprise, reducing costs related to asset maintenance, repair and ultimate replacement is at the top of management concerns [1]. Downtime in any network, manufacturing or computer system ultimately results not only in high repair costs, but in customer dissatisfaction and lower potential sales. In response to these concerns, this paper presents a methodology for using Life Data Analysis (LDA) techniques for evaluating new product innovation and projecting product performance due to several failure modes. The paper presents an application for a brake design where the technique was used in determining the right failure mode based on failure mechanisms.

1.0 ACCELETATED LIFE TEST METHODS

Accelerated degradation testing is an emerging technique for effectively estimating the reliability of many products. Traditionally, an accelerated life test is usually employed to estimate the product life distribution at the design stress level. To do the test, we sample a number of units and divide them into two or more groups. Each group is subjected to an elevated stress level. The life data obtained at higher stress levels are extrapolated to estimate the reliability at the design stress level. The methods for life data analysis are effective and easy to use when sufficient life data is available. However, in today's competitive business environment, the time allowed for testing is continuously reduced, and thus the tests at low stress levels often yield few or no failures. This is especially the case when we test high-reliability products. In these situations, it is difficult or impossible to analyze the life data and make meaningful inferences about product reliability.

In accelerated life testing, we consider products to have a binary state: success or failure.

In practice, many products experience gradual performance degradation over time. For these products, a failure is said to have occurred when a performance characteristic reaches a pre-specified threshold. In accelerated testing, we can measure their performance characteristics at various time intervals. Such a test is often referred to as an *accelerated degradation test*. The measurement data contain credible and much useful information about product reliability. Therefore, it is possible to infer reliability by analyzing the degradation data.

2*.0 ACCELETATED LIFE TEST (ALT) AND LIFE MODELS*

The primary purpose of an ALT is to estimate the reliability of a product at the design condition in a shorter time. To achieve this, we sample a number of units and divide the sample into two or more groups. Each group is tested at a different accelerating condition. The life data of all groups are combined to estimate the reliability at the design condition.

In an ALT, the selection of acceleration methods is important in effectively reducing test time and yielding the relevant life data. Basically, there are four types of acceleration methods: overstressing, increasing usage rate, changing level of a control factor and tightening the failure threshold [2]. These methods may be further classified, as shown in Figure 1..

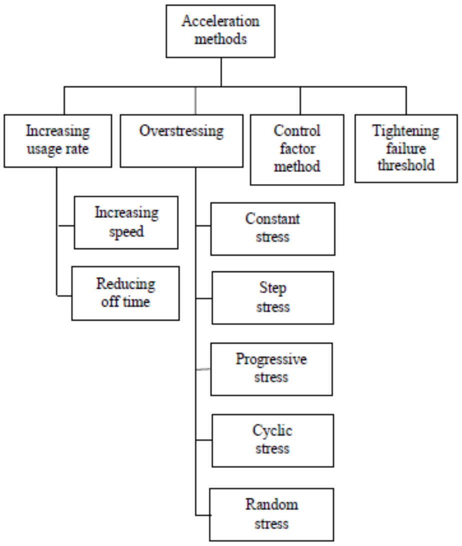

Figure1 - Life Test Acceleration Methods

In practice, constant stress testing is most commonly used

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because of the simplicity in stress application and subsequent data analysis. Most accelerated degradation tests also use this test method

In a constant-stress ALT, the stress level of each group is held constant over time. The test at a stress level continues until either all units fail or until a pre-specified time or number of failures is reached. Using an acceleration relationship between life and stress, the life data obtained at higher stress levels are combined to estimate the life distribution at the design stress level.

Many products fail because their performance characteristics degrade to an unacceptable level. Such failure is called *soft failure*. This is in contrast to *hard failure*, meaning that the function of a product ceases catastrophically and completely. For a product that is subject to soft failure, it is possible to measure its performance characteristics during testing. The performance degradation signifies the reliability deterioration and the measurement data indicates the level of reliability.

Therefore, the measurements of performance characteristics can be used to estimate the reliability of the product. However, in most situations, the degradation rate is very small at the design stress level. A degradation test at the design stress level usually yields a small amount of degradation in a reasonable length of time. Insufficient degradation certainly results in biased reliability estimates [3].

In the analysis of non-repairable systems, one of three techniques, namely the time to failure, stress-strength or condition-based approach, is generally adopted. While the stress-strength and condition-based approaches are appropriate in certain situations, they both tend to be rather limited in their practical application [1]. As a consequence, it is the time to failure (TTF) method which will be focused upon here, In this approach, the random variable 'time to failure', TTF, is fundamental. The reliability can be fully defined in terms of the (probability) distribution of this random variable. Six numerical measures are generally used, namely the Failure function, Reliability function, Expected time to failure, Mission success and Hazard function.

Weibull and lognormal are the two frequently used probability distributions functions for reliability modeling of non-repairable systems.

The lognormal distribution has been used successfully for modeling material fatigue failures and failures due to crack propagation [2. The lognormal distribution is defined as

$$f(t) = \frac{1}{t\sigma'\sqrt{2\pi}} * exp^{\left[-\frac{1}{2}\left(\frac{t'-\mu'}{\sigma'}\right)^2\right]} \quad (1)$$

where $\sigma' = ln(\sigma)$; $\mu' = \ln(\mu)$. and σ is the standard deviation and μ is the mean value of the data set.

The Weibull distribution can be used to model failures caused by degradation processes such as fatigue, corrosion, diffusion and mechanical abrasion such as the failure of ball bearings. The 2-parameter Weibull distribution is:

$$f(t) = \frac{\beta}{n}\left(\frac{t}{n}\right)^{\beta-1} e^{-\left(\frac{t}{n}\right)^{\beta}} \quad (2)$$

where β is the shape parameter and n is the scale parameter or characteristic life.

3.0 ACCELERATED LIFE TEST FOR INNOVATION

There are other cases, especially during innovation of new technology or new product applications of existing technology, where actual failure modes are not clearly understood in order to design an effective accelerated life test. The only information the design team has at this point is the understanding of how the customer will use a new product based on focus groups or expected product utilization levels.

In this case a test replicating the actual utilization profile can help to define which one are the failure modes expected in the field. Risk based assessments like Failure Mode and Effects Analysis (FMEA) as well as an understanding of operational profiles can help define the test strategy to be followed.

4.0 APPLICATION

To demonstrate the technique this paper focuses on the Hydraulic Parking Brake components/subsystem for an automotive application to be used in a new operational environment. The new technology application is reviewed with the customer and an operational profile is defined. The test objective is to determine what could be the potential issues as well as to define the potential failure modes associated with the new application.

4.1 Reliability Test Strategy

The critical question is how to evaluate the potential failure mechanisms and the risks associated with each of them.

The team started by using a Boundary and Phase diagram to facilitate the generation of the Design Failure Mode and Effects Analysis (DFMEA). Based on the risks identified during the DFMEA the team decided to proceed with a test that replicated the operational and environmental conditions in order to determine the expected reliability of the product.

In practice defining potential failure modes/mechanisms and determining the best test strategy alternative is by using Design of Experiments (DOE) to define the actual factors affecting the product degradation. Once the critical factors are identified, an accelerated life testing can be used to demonstrate product reliability under specific operational conditions.

For the parking brake the team defined the key functional requirements as follows:

- When the parking brake is engaged it must hold the machine from drifting on a grade (the parking brake cylinder is retracted).
- When the parking brake is disengaged, the parking brake releases from the disk allowing the machine to drive (the parking brake cylinder is extended with hydraulic pressure).
- The parking brake piston operates freely for both hydraulic extended and spring return.
- The parking brake cylinder shall be capable of being operated in very dirty environments with no scheduled

maintenance.

- The minimum operating pressure is 170psi and maximum operating pressure is 270psi.
- 10 year design life @100,000 cycles (27+ cycles/day @365 days/year).

4.2 Cycle Test Plan

The test objective is to place the parking brake in an environment and cycle it for the expected life of the system. The operational test environment is a replica of the expected customer application in a time compression format.

The number of cycles defining life of the systems and stress levels is equivalent to 2,500 days of operation.

The operational test environment combines cleaning with operational cycles. A cleaning cycle is applied every 4-hour intervals.

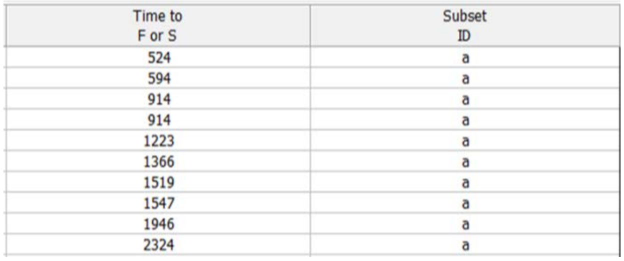
The test bench replicated the position of the parking brake by having the parking brake in the same orientation as it will be mounted on the field application. The bench allowed for water spray over the parking brake cylinder, rod and excluder cap for a period of 4 hours. After 4 hours dirt was placed in the same area as the water spray. Then the parking brake cylinder was cycled for 4 hours.

At the end of the test the cylinder was torn down and inspected for signs of water/dirt ingress into the cylinder as well any other degradation associated with the failure mechanisms observed.

4.3 Results and AnalysisS

The failure data is shown in Figures 2 and 3. Type “a” failures are due to wear degradation of the seals and type “b” degradation is a failure in the hydraulic system of the brake.

When performing a competing failure mode (CFM) analysis the data should reflect the fact that failing in one failure mode type means that the component still has capacity to survive other failure modes.

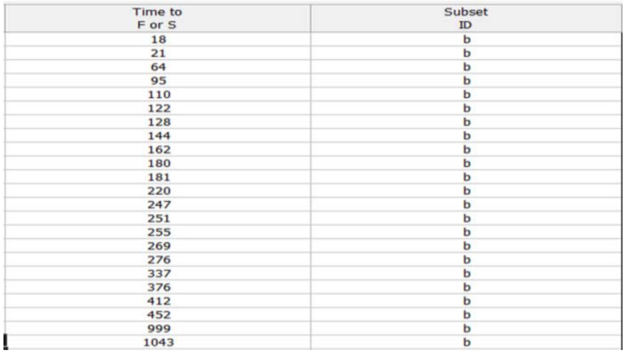


Time to F or S	Subset ID
524	a
594	a
914	a
914	a
1223	a
1366	a
1519	a
1547	a
1946	a
2324	a

Figure 2 – Time to failure for Mode A

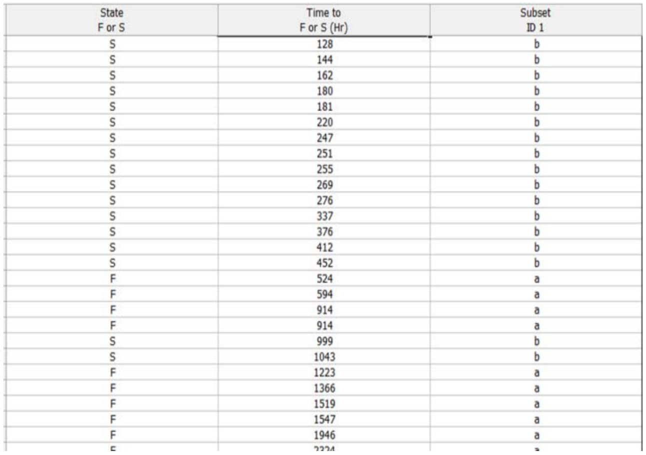
Therefore when performing analysis for one type of failure, the other failure modes should be considered censored or suspension data [6]. For example, in the case of the failure type “a” being analyzed the failure mode “b” is considered as a suspension (see Figure 4).

Statistical analysis of the data indicated that failure modes observed during the test can be modeled either using a Weibull or lognormal distribution since the likelihood values were close in value.



Time to F or S	Subset ID
18	b
21	b
64	b
95	b
110	b
122	b
128	b
144	b
162	b
180	b
181	b
220	b
247	b
251	b
255	b
269	b
276	b
337	b
376	b
412	b
452	b
999	b
1043	b

Figure 3- Time to failure for Mode B



State F or S	Time to F or S (Hr)	Subset ID 1
S	128	b
S	144	b
S	162	b
S	180	b
S	181	b
S	220	b
S	247	b
S	251	b
S	255	b
S	269	b
S	276	b
S	337	b
S	376	b
S	412	b
S	452	b
F	524	a
F	594	a
F	914	a
F	914	a
S	999	b
S	1043	b
F	1223	a
F	1366	a
F	1519	a
F	1547	a
F	1946	a

Figure 4 – Data for type “a” analysis

The failure mode behavior in relation to the probability distribution model used is critical when the objective is to project the potential reliability performance of the product. Therefore a set of analysis were performed to select the final distribution to be used for product life prediction.

The first analysis was performed assuming both distributions use a 2-parameter Weibull (see Figure 5).

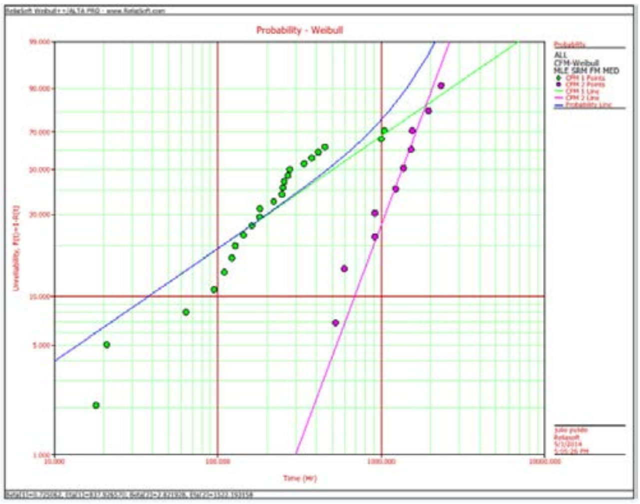


Figure 5 CFM with A and B with 2-parameter Weibull

The second analysis was performed assuming that both distributions use a lognormal model (see Figure 6).

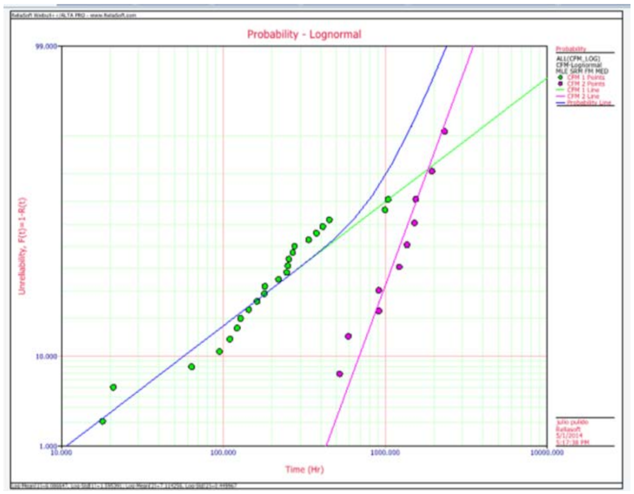


Figure 6 – CFM with A and B a Lognormal

The next step is to better understand from both distributions which of the functions can better represent the performance of the product in the field.

The reliability R(t) versus time graph of both reliability functions for type “a” and “b” using the Weibull and lognormal probability distribution functions are shown in Figure 7. The graph shows that both functions have a very similar behavior [4].

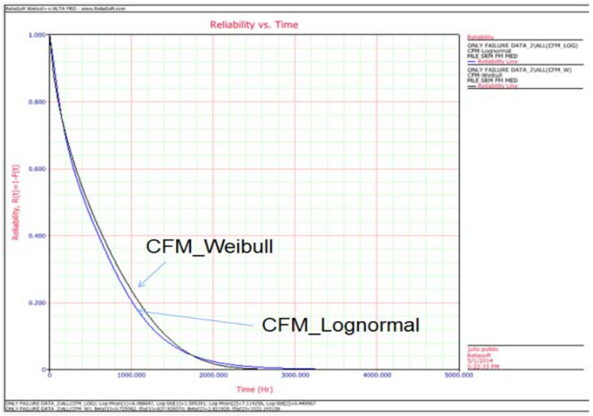


Figure 7 – R(t) for both pdf

When comparing the Weibull and the lognormal probability distribution functions for the data set using a two sided 90 confidence level; both analyses showed that the reliability values are similar (see Figure 8). Therefore the results showed that either analysis can be used for modeling.

Further evaluation showed that failure rates were different for both functions as shown in Figure 9.

Contour plots can be used for comparing data sets especially in determining if the failure mechanisms are independent statistically.

Consider the two data sets “a” and “b”, and you would like to determine whether the two failure modes are significantly different, and at what confidence. By plotting the contour plots of each data set in a multiple plot, you can determine the confidence at which the two sets are significantly different (see Figure 10). Note that the same distribution must be fitted to each data set.

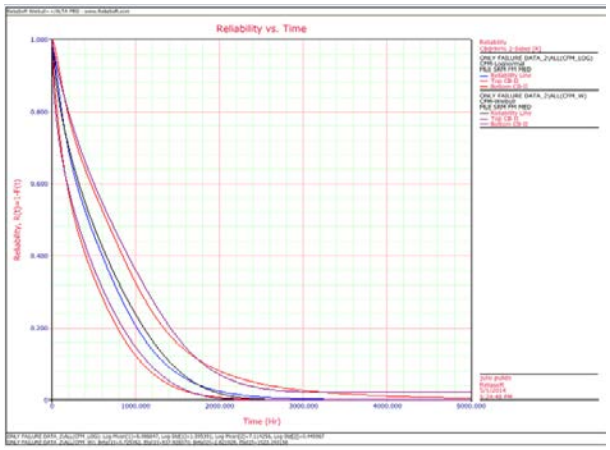


Figure 8 – R(t) with both side 90% c.l.

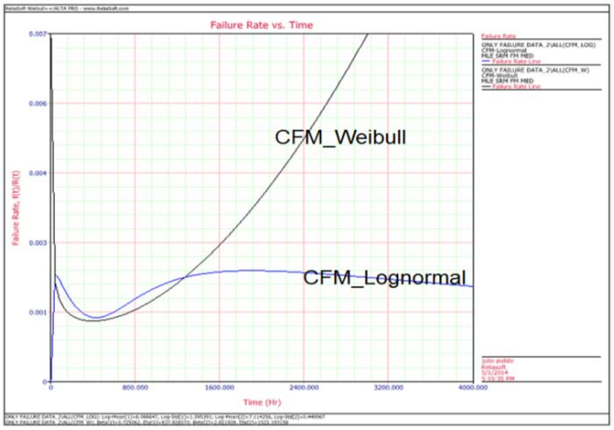


Figure 9 – Failure rate

If, for example, there is no overlap between the two 90% contours, (i.e., the two plots do not intersect); then the two data sets (“a” and “b”) are significantly different with a 90% confidence. If there is an overlap between the two 95% contours, then the two designs are not significantly different at the 95% confidence level [2,6].

Since both failure modes are independent the next step is to represent each failure mode by the failure distribution that best models the failure behavior (see Figure 11). The R(t) of the component can then be calculated by considering a series model [5]. The R(t) for a series system is

$$R(t) = R_1(t)R_2(t) \tag{3}$$

where:

- R(t) is the reliability of the component to both failures.
- $R_1(t)$ is the reliability of the component to failure “a”.
- $R_2(t)$ is the reliability of the component to failure “b”.

The failure mode type “b” occurs in the early part of the operation of the component while the failure mode “a” occurs toward the end of the life of the component.

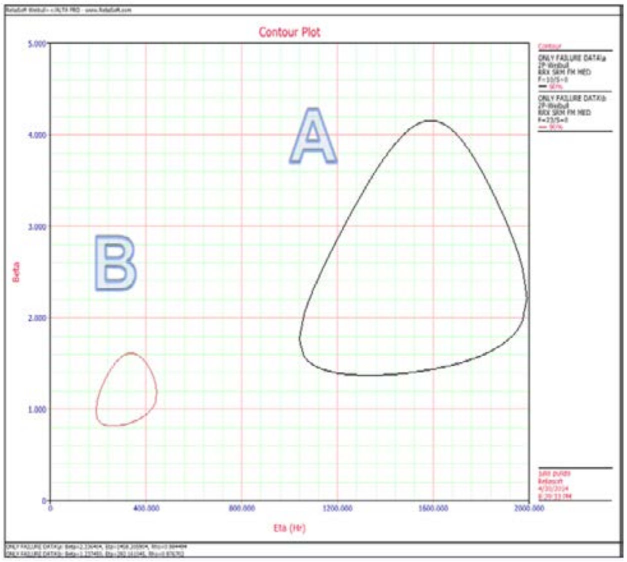


Figure 10 – Contour Plot for a 2-parameter Weibull

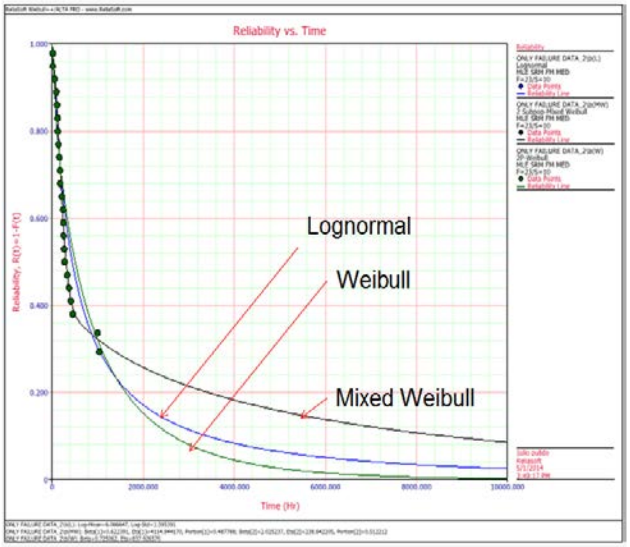


Figure 11 – Model Comparison for mechanism “b”

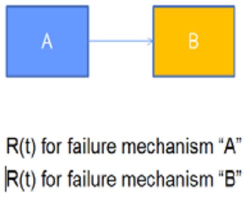


Figure 12 – Graphical Representation of a Series Model

For failure mode “a” the Weibull distribution was the best fit model with $\beta = 2.82$ and n =1522.19. The failure rate is shown below (see Figure 13).

The failure analysis of failure mode “b” showed infant mortality events due to manufacturing variability as well as actual degradation events. Therefore a mixed Weibull distribution was selected as a better representation of the data behavior (see Figures 11 and 14).

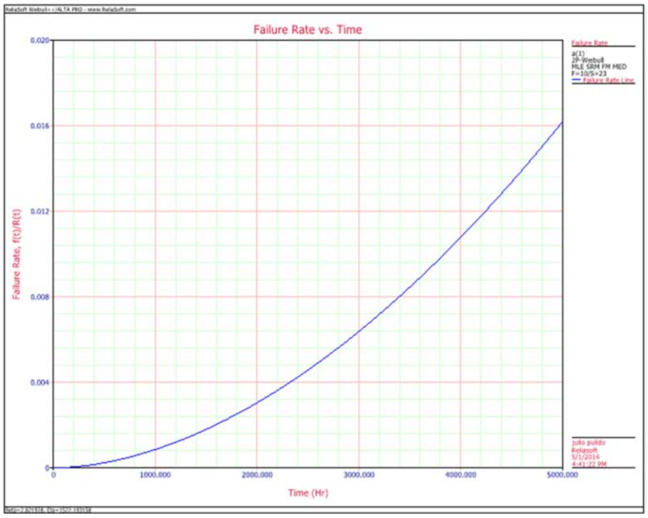


Figure 13- Failure rate for failure mode “a”

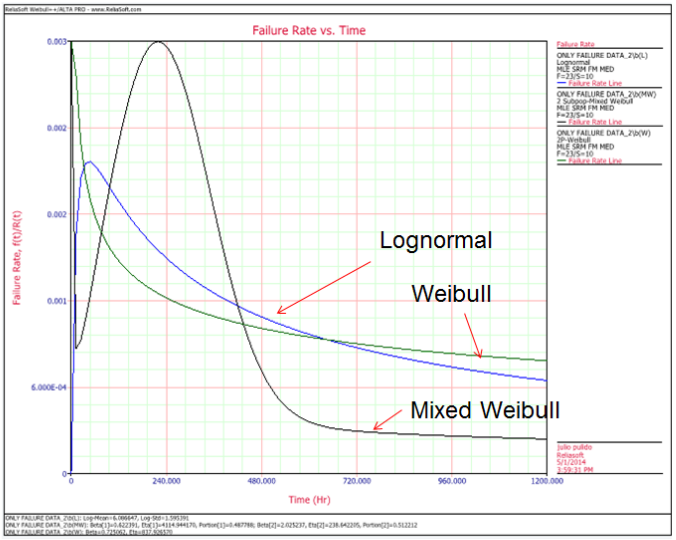


Figure 14 – Failure rate of mode “b” for different pdfs

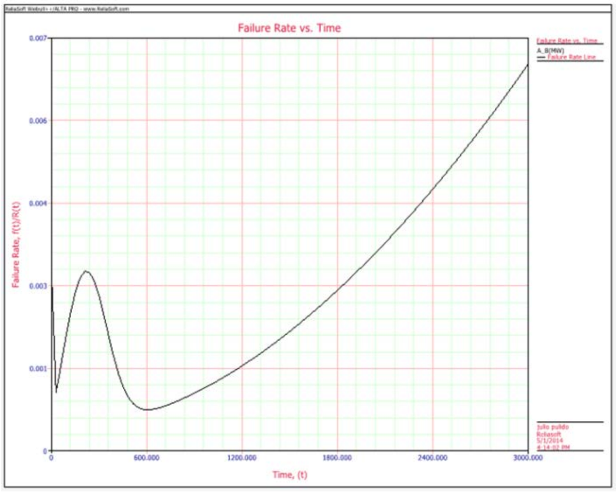


Figure 15 – Final Failure rate for mode “a”+”b”

5.0 CONCLUSION

Based on the analysis described, the following conclusions can be reached:

When selecting a probability distribution function it is important to consider the how the data fits a given distribution as well as the physics of failure associated with the failure modes found during testing. Reliability test loading needs to replicate the environment as well as the duty cycle associated with the operation of the component in the field after a year of product release.

To improve the accuracy of the results it is recommended to collect the historical inspection measurements after product release to demonstrate product utilization. The challenge relates to failure modes that show after the warranty period of the part. A Design for Reliability (DFR) programs should account for ways to collect data after warranty programs. This could be a challenging activity but necessary to demonstrate potential long term failure modes.

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