Special Topics for Consideration in a Design for Reliability Process

Georgios Sarakakis, ReliaSoft Corporation
Athanasios Gerokostopoulos, ReliaSoft Corporation
Adamantios Mettas, ReliaSoft Corporation

Key Words: Design for Reliability

SUMMARY & CONCLUSIONS

In this paper, we look at certain areas of the Design For Reliability (DFR) process where missteps or misapplications are common due to misunderstood “common practices” or due to attempts to either oversimplify the process or introduce unnecessary complexity. We show how these practices can have detrimental effects on the reliability of a product and identify what the areas of improvement are.

We identify three major areas where missteps most commonly occur. The first of these is during the early stage of the DFR process, including the practices of setting requirements and specifications. We explore the importance of understanding usage and environmental conditions and discuss issues such as using Mean Time Between Failures as a sole metric, or mean estimates without associated confidence bounds. The second area prone to missteps is during the DFR stage where the reliability of a product is quantified; here, we discuss problems such as testing for failure modes that don’t correlate with actual usage, using inappropriate life-stress relationship models or modeling the failure rate behavior incorrectly. The third time problems are likely is during the DFR stage that addresses the assurance and sustaining of reliability; here, we present missteps related to setting up demonstration tests without statistical significance, not colleting the appropriate data for warranty analysis and either ignoring suspensions or assuming that units have survived beyond the warranty period.

1 INTRODUCTION

DFR is a process that describes the entire set of tools that support the effort to increase a product’s reliability and are applied from the early concept stage of a design all the way through to product obsolescence. The success of a DFR process is directly related to the selection of the appropriate reliability tools for each phase of the product development and the correct implementation of those tools.

In this paper, we present the most common missteps during the DFR process, as we have collectively observed them from interactions with customers during consulting projects, training seminars and our experience of how reliability engineering software tools are used in the industry.

The paper is divided in three sections.

In the first section we look at the early stage of the DFR process and the practices of setting requirements and specifications. We present and analyze the most frequent examples of missteps at this stage.

In the second section we look at the DFR stage where the reliability of a product is quantified. We focus on practices that occur during the testing and life data analysis of the components of the product.

In the third section we focus on the DFR stage that addresses the assurance, monitoring and controlling of reliability during the manufacturing, shipping and support of fielded products.

2 DEFINING RELIABILITY OBJECTIVES

The early stages of a DFR process can have a significant effect on the success of the process. Understanding the usage conditions and defining the appropriate reliability requirements will drive the design efforts of a product and assure that the product is designed with reliability in mind. In this section we present some missteps that are common during this stage.

2.1 Reliability Requirements

Setting well-defined and meaningful reliability requirements is one of the most important steps in a DFR process.

Mean Time Between Failures (MTBF) is an example of a reliability requirement that is a standard in many industries, yet is often misused and is inappropriate in most cases. Note that when referring to non-repairable systems, the most appropriate term is Mean Time To Failure (MTTF), but these terms are often interchangeable in practice. Here we will use the more common term MTBF. The use of an MTBF as a sole reliability requirement implies a constant failure rate, which is not the case for most systems or components. Even if the assumption of a constant failure rate is not made, the MTBF does not tell the whole story about reliability. For example, consider three components whose life is modeled using the Weibull distribution, each of which has the exact same MTBF. The fact that the MTBF of the three components is the same does not necessarily imply that their reliability at any given time will be the same. Figure 1 shows the reliability functions of three such components.

Although the MTBF is the same for all three components,

978-1-4244-8855-1/11/$26.00 ©2011 IEEE

the corresponding reliabilities at different times vary considerably. Therefore, the use of a reliability requirement instead of simply an MTBF can be more descriptive of the expected life of a component.

Another example of an inadequate reliability requirement is the use of a mean estimate with the absence of confidence bounds. Confidence bounds are crucial, especially when setting reliability requirements for suppliers, in order to ensure that the reliability value claimed by the supplier has been demonstrated properly. For example, consider a case where two vendors are evaluated in terms of the reliability of their components and suppose that they both claim that their reliability is 95%. Given that information, one would expect that the decision should be made solely on price, since the reliabilities are the same. However, suppose that through further investigation it was found that one vendor tested 100 components while the other tested only 5. Given that, it can be determined that the 90% lower confidence bound on reliability for the first vendor is 93%, while for the second vendor it is 78%. Thus, the basis for choosing the best vendor has changed. This simple example demonstrates that unless there is a lower confidence level attached to the specifications, there is no way to evaluate the validity of the vendors' claims and make comparisons.

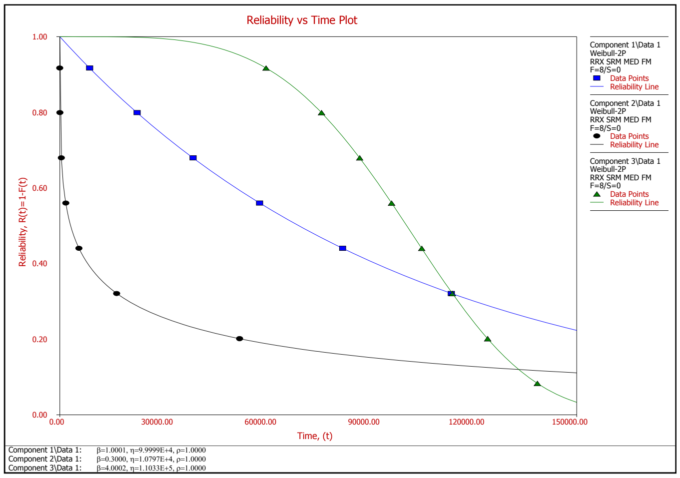

Figure 1 – Reliability Function for the three components

2.2 Usage and Environmental Conditions

The core definition of reliability – the probability that the component or product will perform its intended function for a specific mission duration under specified conditions – suggests the need to clearly map out and understand usage and environmental conditions. We have observed that many of the DFR challenges that organizations face are due to lack of understanding or poor understanding of usage and environmental conditions.

The way the product will be used in the hands of the customer should be considered in the design phase. Understanding what constitutes normal use or abuse can help with making the right design choices and selecting the right tests to simulate actual usage conditions when planning in-house testing. Technical directions in a user's manual are, in most cases, not enough to protect a product from aggressive usage: "Wait until the engine has warmed up to operate," "switch from 4x4 to 2x4 when driving above 55mph," etc. are frequently ignored in real usage. If the tests do not account for aggressive usage, then the disconnect between in-house test reliability and field reliability is usually very high.

Usage can also be expressed in terms of understanding the distribution of customers that will reach a certain design life. For example, suppose a printer is designed to last five years, but it is also designed to last one million pages. Understanding the distribution of pages printed during five years can make a big difference in design decisions. Any reliability requirement is complete when it has an associated percentile user; for example, a requirement to prove a certain level of reliability for a component of a printer for a 99th percentile user would mean proving that reliability for a specific number of pages printed.

Environmental conditions are also critical in making the right design choices to support reliability. Often products are tested in a very narrow range of environmental conditions, but they are used in a broader spectrum of conditions in the field. Using the same example of a printer, one can design a printer that will work without failures and paper jams in Arizona, but will fail to operate in Florida, where the relative humidity is so high that it induces new failure modes not observed in the previous environment tested. In this case, the paper in the trays curls from the high humidity environment and causes the printer to jam frequently. Up-front work needs to be done to clearly define the range of environmental conditions for which the product will operate, and testing needs to simulate various profiles of those environmental conditions in order to expose failure modes that would not show up in "ambient" conditions.

Temperature and humidity are only two of the major environmental conditions that can significantly affect product reliability. Depending on the specific application, solar load, water quality, rain, wind, snow, sand, dust, mud, hail, thermal cycling, voltage input stability and many other environmental factors can be key factors that affect the product's life. Major effort should be made up front in the DFR process in order to identify the environmental conditions. The goal is to incorporate environmental concerns into the design early on, and also to be able to design tests that will reflect the actual environmental conditions to which the product will be exposed.

3 QUANITFYING RELIABILITY

The quantification of reliability during the DFR process involves all the activities of modeling the system, testing and analyzing test data to understand component and system reliability. It also involves prediction of the reliability of the end product. In this section we present some common missteps during this stage.

3.1 Preparation Before Testing

Reliability tests play an integral role in a DFR process, since they provide the means to quantify reliability. In general, a lot of money, effort and resources can be saved through thorough preparation before reliability testing.

For example, accelerated tests are often performed with a large number of stresses. That can result in very expensive tests or even unsuccessful tests that yield failure modes that are not expected to be seen in practice. If sufficient effort is spent in planning the test, the process will yield the same results in a much more efficient way. A best practice in this case would be to use Design of Experiments methodologies in order to screen the most significant stresses that will be used in the accelerated tests. That way, by performing small experiments to determine the few important stresses, the overall cost of the test will be decreased significantly. Furthermore, the data collected from those experiments can be used for planning the accelerated test so that the available samples are optimally allocated across the different stress levels.

3.2 Execution and Analysis of Accelerated Tests

Accelerated testing provides the benefit of uncovering failures in a short time for components that have very high life expectancy. However, it is important to take care that the principles of accelerated testing and the assumptions of the models used are not violated.

When deciding on the levels of the stresses applied during the test, one must consider the design limits of the component being tested. When the applied stress goes beyond those limits, then new failure modes that will not be seen in the field are introduced and the results of the test are not valid. Besides engineering judgment, contour plots can be a useful tool in determining whether the component is failing the same way across all stress levels. For example, consider the contour plots shown in Figure 2, which represent data sets obtained at three different stress levels. The contour on the far left of Figure 2 represents the highest stress, the contour in the middle represents the middle stress and the contour on the far right the lowest stress level. The Weibull distribution was used to model the data. When the Weibull distribution is used, the assumption is that the component will show the same failure behavior across all stress levels and therefore the beta parameter remains the same.. As shown in Figure 2, the beta parameter is significantly different for the data set obtained from the highest stress level at the 90% significance level, indicating that at this stress level the failure behavior has changed. Moreover, even if the stress levels are not beyond the design limits, it should be considered that the further away the stress level is from the usage conditions, the more error is introduced to results of the analysis. In many cases, in an effort to minimize the duration and cost of a test, engineers fail to consider those principles, resulting in tests that offer no value to the analysis.

Another area that requires careful attention is the analysis of the data. The most important part of the analysis, with the greatest effect on the results, is choosing the appropriate model to describe the life-stress relationship. There are a number of models that have been suggested to describe life-stress relationships and the appropriateness of each model depends on the applied stress. For example, the Arrhenius model is commonly used when the stress is temperature, while the inverse power law is often used when the stress is mechanical [1]. Therefore, when a practitioner chooses a model, he should carefully consider the applied stress and the physics of failure of the component.

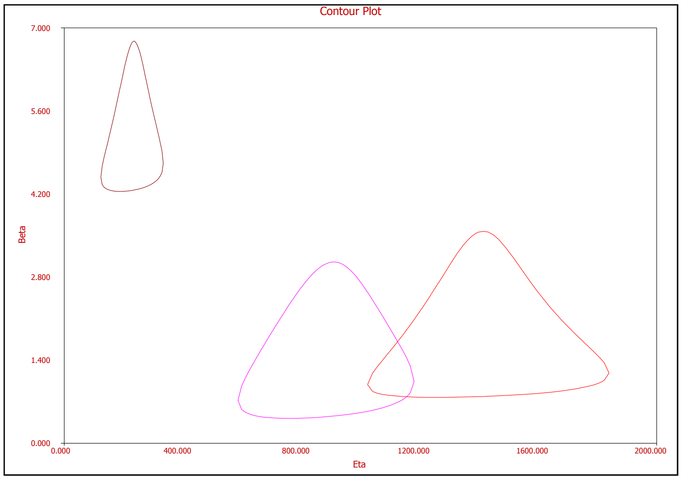

Figure 2 – Contour Plots

A common characteristic of most of the available models of the life-stress relationships is that they are monotonic, meaning that as the stress increases, the life decreases. We have observed many cases where this assumption is violated. One such scenario is illustrated in Figure 3 for life vs. stress data. In this specific scenario, the stress applied was temperature. At a specific temperature range, a chemical reaction kicked in and reversed the trend. In other words, starting at a specific temperature, product life improved as temperature increased to a certain point; once the upper limit of that particular temperature range was reached, however, the trend reversed and product life then began to decrease as temperature rose. This is illustrated in Figure 3, where two different Arrhenius life models were applied to the data. We can see that moving from the lowest stress level to the middle stress level, life is increasing when stress is increasing; on the other hand, moving from the middle stress level to the highest stress level, life is decreasing when stress is increasing. This type of life-stress relationship is non-monotonic and most models that assume a monotonic relationship, such as the Arrhenius in this case, cannot be used to predict life at usage conditions.

3.3 Understanding Failure Rate Behavior

One of the most important aspects of reliability engineering activities is to be able to characterize the failure rate behavior of components and systems. DFR activities are used to design out decreasing failure rate behavior (aka infant mortality) at the start of the life of the product; increase margins and robustness and reduce variation during the useful life; and extend wear-out beyond the designed life or institute preventive maintenance before wear-out if it makes economic sense.

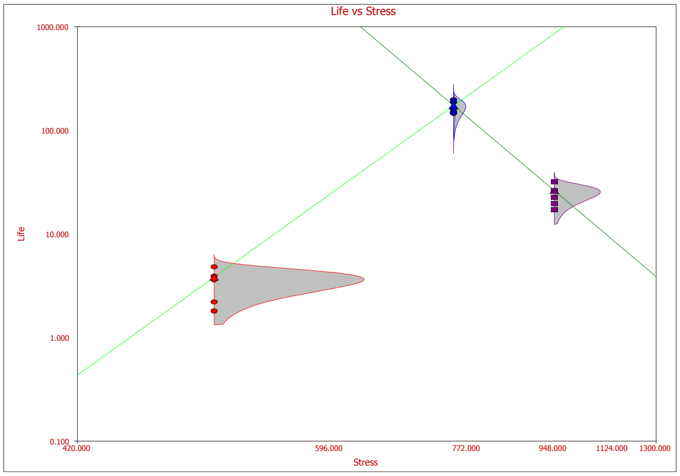

Figure 3 – Non-monotonic life-stress relationship

Using inappropriate models or assumptions can lead to erroneous conclusions about the failure rate behavior of a component or system. One of the most typical missteps is the assumption of an exponential distribution as the underlying lifetime distribution for reliability data. The exponential distribution implies a constant failure rate and superimposes that behavior on the modeled data. As a result, the analyst misses the signals that can indicate infant mortality or wear-out mechanisms, or a mix of these as subpopulations in the data. This very often leads to poor design decisions concerning the reliability behavior of products, inaccurate estimation of warranty costs and many surprises after the product is fielded.

One of the most common scenarios that we observe when working with customers in various industries is the following: The reliability team needs to understand the suppliers' reliability so it requests reliability information for components from suppliers. Many suppliers provide a single estimate as MTTF, without associated confidence bounds. In most cases, these numbers are generated by testing units for a short time, so the parameters are estimated based on a lot of suspensions and very few failure points; at the same time, an exponential distribution is often assumed. This can create overly optimistic reliability estimates. If the same test were continued longer and a flexible distribution such as a two-parameter Weibull distribution were used, the same test would provide a more pessimistic estimation of reliability. The same scenario occurs with accelerated life data when key parameters are superimposed instead of being calculated from the data. A good example of this is to superimpose the activation energy in an Arrhenius model. The choice of that value can drastically affect the acceleration factors assumed and, as a result, the reliability projection back to usage conditions can be adjusted easily to a wide range of values [2].

4 ASSURING AND SUSTAINING RELIABILITY

The assuring and sustaining phase of the DFR process is as important as the early phases of the process because if the tools and practices of this phases are not applied correctly, then all the effort of designing reliability into the product will not be as effective. Therefore, missteps in this phase can influence the overall effectiveness of the DFR process and be detrimental to the overall reliability of the product.

4.1 Demonstration Tests

Reliability Demonstration Tests are a common practice right before a product goes into mass production in order to assure that the reliability target has been met. The importance of these tests is that they provide a final validation of the redesigns and the reliability tests that took place during the design phase. Therefore, the proper application of those tests is critical in the DFR process before a product goes into production and out in the field, where dealing with reliability issues is much more costly.

A common misstep takes place when planning for Reliability Demonstration Tests. Most commonly when designing those tests the binomial equation is used [3,4], where with a reliability goal at a given confidence level and the allowable number of failures, one can compute the required number of units to be tested for a given test time or the test time required for the given number of units. However, as we have observed in many cases, the design of such tests may be driven solely by the resource constraints of available time or samples without considering the statistical references. As a result, the tests provide no statistical significance in terms of achieved reliability. In other words, time and money are spent without proving that the reliability goals have been met.

Another common misstep takes place in the execution of these tests. Usually the tests are designed to be "zero failure tests," meaning that no failures should be observed in the sample for the given test duration. However, when the first failure occurs, the test becomes a "one failure test" and the necessary time is recalculated; then when the second failure occurs, the test becomes a "two failure test" and the test time is recalculated; and so on. Of course, this practice usually leads to a situation where the reliability engineer is essentially chasing his tail, with no useful results. When a failure occurs, one should go back and reevaluate the design from a reliability perspective instead of spending valuable resources to make the demonstration test succeed.

4.2 Effects of Manufacturing

Well-done DFR tasks still need to be supported by manufacturing reliability tasks to ensure that the inherent design reliability is not degraded or unstable. Manufacturing introduces variations in material, processes, manufacturing sites, human operators, contamination, etc. [5]. A common misstep is to assume that the reliability of a product out of the manufacturing line will automatically match the test results of the fine-tuned prototype units. Meeker and Escobar [6] identify differences in cleanliness & care, materials & parts and highly trained technicians vs. factory workers. A lot of effort has to be spent investigating the effects of manufacturing on product reliability to assure that problematic steps are identified and addressed. Not paying attention to manufacturing issues can result in units showing infant mortality, which is usually the result of misassembly, inappropriate transfer or storage, the line being unable to conform to designed specifications, or uncontrolled key product characteristics. The best approach is to pay attention to manufacturing issues through activities such as PFMEA, manufacturing control, screening and monitoring plans and others, so that manufacturing issues are addressed and designed out. Burn-in testing can be used to address infant mortality, but this is not the preferred choice, since the ideal goal is to design out infant mortality [7, 8].

Variation in manufacturing is not resolved as soon as the first product out the door is reliable. Variation in terms of supplier material, processes, machinery, personnel skills and other factors can influence the reliability characteristics of the produced products. A common misstep is to assume that verifying the reliability of the products through a single demonstration test is adequate. A thorough DFR process examines the reliability characteristics of the produced products at regular intervals over time to understand what changed. The solution here is two-fold and includes mostly quality control approaches, such as statistical process control for key characteristics that can influence product reliability, but can also include "ongoing reliability tests," a common industry term. These tests can also address the impact of current product engineering changes on product reliability. For example, a firmware upgrade can cause unexpected interactions that can lead to altered reliability characteristics. This and similar issues can be identified through an ongoing reliability test.

4.3 Warranty Analysis

Warranty analysis is a key step in a DFR process in order to assure reliability monitoring throughout the product's lifecycle. DFR does not stop when the product ships; a warranty tracking and analysis process should be built into the plan in order to assure field reliability.

One seemingly trivial and very common misstep during this stage is failing to implement the infrastructure that allows capturing of times-to-failure in the field. A simple Nevada chart requires the knowledge of when units were shipped and when they were returned in order to apply Weibull analysis methodologies. However, it is very common that due to lack of infrastructure, rush to market, or overly complex supply chain processes, times-to-failure are not available for the product, so warranty analysis cannot be thoroughly conducted or the data set contains too much noise.

The next misstep during the warranty stage is to ignore suspended units when analyzing reliability data from the field. Suspension information is of as much value as failure information and ignoring it will lead to erroneous results. Consider this example: A company has just launched its new product and started to track reliability failures in the field. Every month, 500 new products enter service. Table 1 shows the Nevada chart of returns during the first six months of service.

	Jun-10	Jul-10	Aug-10	Sep-10	Oct-10	Nov-10
May-10	0	1	2	0	1	2
Jun-10		0	2	0	1	0
Jul-10			1	1	0	2
Aug-10				2	2	0
Sep-10					3	1
Oct-10						2

Table 1– Warranty return data

The reliability analyst builds a Weibull model based on the times-to-failure, by adding the diagonals of the Nevada chart for each month, as shown in Table 2.

State	Number of units	Time to Failure (months)
Failed	8	1
Failed	7	2
Failed	2	3
Failed	3	4
Failed	1	5
Failed	2	6

Table 2– Times-to-Failure data

The analyst uses Maximum Likelihood Estimation and fits a two-parameter Weibull distribution. The calculated parameters are β=1.6851 and η=2.7986 months. The prediction for the reliability at the warranty time of 36 months is almost zero.

The correct approach to predict reliability is to also consider all the suspended units as shown in Table 3. The analyst again uses Maximum Likelihood Estimation and fits a two-parameter Weibull distribution. The calculated parameters are β=1.3621 and η=130.3 months. The prediction for the reliability at the warranty time of 36 months is now $R(36)$=84%.

State	Number of units	Time to Failure (months)
Failed	8	1
Suspended	498	1
Failed	7	2
Suspended	496	2
Failed	2	3
Suspended	496	3
Failed	3	4
Suspended	496	4
Failed	1	5
Suspended	497	5
Failed	2	6
Suspended	494	6

Table 3– Times-to-Failure data with Suspensions

The last example clearly illustrates the vast difference in reliability estimation during warranty when considering or ignoring suspensions, and suggests to always include suspensions for accurate warranty analysis. However, another common misstep is the extreme application of this rule, considering suspensions when in reality there is no information at all on whether the units have survived or not. This is a common scenario in fielded systems analysis beyond warranty life. In this case, there is no reliable way to track if the unit is operating or not beyond warranty time, but the analyst is assuming that the unit is still operating, unless there is definite knowledge that it failed. Without a robust way to know the state of the fielded units, using the assumption that the units are still operating leads to overly optimistic reliability estimations. Warranty analysis needs to rely on good data and true knowledge of the state of fielded units, which can be very challenging.

5 CONCLUDING REMARKS

In this paper, we have outlined some special topics for consideration during the DFR process. Extra care and focus need to be used when deploying the DFR process so that these issues do not hinder the progress of aiming for, growing, achieving and sustaining reliability. Although the list is by no means comprehensive, the underlying idea is that some DFR activities require special attention for successful and meaningful execution. Otherwise, they become a checkmark in a long list of activities, but do not truly contribute to the reliability efforts. We hope that practitioners can benefit from this material and focus on improving the quality of key DFR activities in their organization. With product development becoming more dynamic and complex every year, designing for reliability is becoming the only way to quickly meet reliability goals and the new extreme time to market requirements.

REFERENCES

1. W. Nelson, *Accelerated Testing: Statistical Models, Test Plans, and Data Analysis*, New York, Wiley, 1990.
2. D. J. Groebel, A. Mettas, F. B. Sun, "Determination and Interpretation of Activation Energy Using Accelerated-Test Data," *Proc. Ann. Reliability & Maintainability Symp*., (Jan.) 2001.
3. D. Kececioglu, *Reliability & Life Testing Handbook*, vol. 2, New Jersey, Prentice-Hall, Inc., 1994.
4. L. M. Leemis, "Lower System Reliability Bounds From Binary Failure Data Using Bootstrapping," *Journal of Quality Technology*, 38(1), 2006, pp 2-13.
5. C. Carlson, G. Sarakakis, D. Groebel, A. Mettas, "Best Practices for Effective Reliability Program Plans," *Proc. Ann. Reliability & Maintainability Symp*., (Jan.) 2010.
6. W. Q. Meeker, L. A. Escobar, "Pitfalls of Accelerated Testing," *IEEE Trans. Reliability,* vol. 47, (June) 1998, pp 114-118.
7. W. Q. Meeker, L. A. Escobar, *Statistical Methods for Reliability Data*, New York, John Wiley & Sons, Inc., 1998, pp 520-522.
8. W.Q. Meeker, M. Hamada, "Statistical tools for the rapid development and evaluation of high-reliability products," *IEEE Trans. Reliability,* vol. 44, (June) 1995, pp 187-198.

BIOGRAPHIES

Georgios Sarakakis
ReliaSoft Corporation
1450 S. Eastside Loop
Tucson, AZ 85710-6703, USA

e-mail: Georgios.Sarakakis@ReliaSoft.com

Georgios Sarakakis is a Research Scientist at ReliaSoft Corporation. His research and consulting interests include reliability and quality management and the development of reliability program plans. Mr. Sarakakis received his M.S. in Reliability Engineering from the University of Arizona. He is a Certified Reliability Engineer, Certified Project Management Professional and Certified Six Sigma Black Belt. Prior to joining ReliaSoft, he worked as a Reliability Engineer at Hewlett-Packard.

Athanasios Gerokostopoulos
ReliaSoft Corporation
1450 S. Eastside Loop
Tucson, AZ 85710-6703, USA

e-mail: Athanasios.Gerokostopoulos@ReliaSoft.com

Athanasios Gerokostopoulos is a Research Scientist at ReliaSoft Corporation.. His areas of interest include Reliability Program Plans, Design for Reliability, System Reliability and Reliability Growth Analysis. Mr. Gerokostopoulos holds an M.S. degree in Reliability Engineering from the University of Arizona and an MBA from Eller College of Management at the University of Arizona.

Adamantios Mettas
ReliaSoft Corporation
1450 S. Eastside Loop
Tucson, AZ 85710-6703, USA

e-mail: Adamantios.Mettas@ReliaSoft.com

Adamantios Mettas is the VP of Product Development at ReliaSoft Corporation, spearheading ReliaSoft's innovative product development group. In his previous position as ReliaSoft's Senior Scientist, he played a key role in the development of ReliaSoft's software by deriving statistical formulations and models and developing numerical methods for solving them. Mr. Mettas has trained more than 2,000 engineers throughout the world on the subjects of Life Data Analysis, FMEA, Warranty Analysis, System Reliability, RCM, DOE and Design for Reliability, as well as Accelerated Testing, Repairable Systems and Reliability Growth. He has published numerous papers on these topics. Mr. Mettas is also part of ReliaSoft's consulting arm and has been involved in various projects across different industries, including Oil & Gas, Power Generation, Automotive, Semiconductor, Defense and Aerospace. Mr. Mettas holds an M.S. in Reliability Engineering from the University of Arizona and he is a Certified Reliability Professional (CRP).