Time-Varying Multi-Stress ALT for Modeling Life of Outdoor Optical Products

Chung F. Lam, Corning Cable Systems
Huairui Guo, Ph.D., ReliaSoft Corporation
Lance Larson, ReliaSoft Corporation

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SUMMARY & CONCLUSIONS

The long-term performance prediction of optical products deployed outdoors is very important. The accuracy of the prediction directly affects the warranty cost calculations. In the indoor environment, products are usually operated under the controlled temperature and humidity. However, in the outdoors, products usually experience multiple stresses that continuously vary with time. An outdoor use optical product, such as a fiber distribution hub cabinet with splitters, connectors and fan-outs built-in, will experience temperature cycling effects plus varying humidity. In unusual circumstances, it will also experience vibration and shock. Therefore, the time varying temperature and humidity are considered as the major stresses acting on the outdoor use optical products. In this paper, a practical method which uses Design of Experiment (DOE) techniques and Generalized Log–Linear (GLL) life-stress relationship to predict the life of outdoor optical products is proposed. Considerations are made to include the mating and un-mating of connectors, and environmental vibration.

The temperature effect is defined by the following settings. 1) High temperature, 2) Low temperature, 3) Ramp rates, 4) Cycle length and 5) Dwell time at high and low temperatures. These settings are used in the accelerated testing to mimic the temperature cycle in the outdoor environment. Humidity is also applied during the test. The individual effect of each stress and their interactions is studied by using multiple levels of each stress, analyzed using DOE methods. Using the accelerated testing results obtained from the laboratory, the relationship between stresses and product life is established, and the life distribution model can be constructed. Subsequently, the 20-year reliability of the products under different outdoor environments is predicted. Since the temperature and humidity change seasonally, the weighted probabilities are used in the calculation of the 20-year reliability. Based on the predicted reliability, the warranty costs can be easily calculated.

1 INTRODUCTION

The main objective of this study is to calculate the warranty and other logistics costs for passive optical products operating in an outdoor field environment, based on the predicted product reliability. It can be difficult to predict failure rates using the field-return data with high levels of confidence. Hence, laboratory simulation tests are needed for the reliability modeling to predict the life in the field.

Many methods of predicting product life under indoor environments through constant stress accelerated life testing have been proposed (Ref. 1-3). Few, however, discuss how to conduct time varying, multi-stress accelerated life testing to predict the outdoor performance (Ref. 4-6). Most research work has been in the prediction of the life of optical products assuming that the products are deployed in central offices with controlled temperature and humidity, i.e. time-independent. Few have predicted the life times of products deployed in an outside plant (OSP) environment, with stresses that vary with time.

For OSP optical products, the most predominant stresses are temperature and humidity. Some may also consider vibration and shock in the environment, however, with this study it was assumed that the vibration and shock are not the major concern for the optical products as they are enclosed in cabinets that are protected, isolated and situated far away from such stresses. If field vibration is found to be a significant input factor, it may be considered to be independent of temperature and humidity since it normally occurs in a random and transient way. Independent tests can be performed to establish the reliability of the product due to vibration and to include it in the final reliability of the products. There are many ways to approach a problem. This proposed method addresses only a few aspects and is presented in a discussion and comment format. Simulated data is included to illustrate the methodology. In this paper, a method is proposed which integrates DOE techniques and a commonly used accelerated life test model to predict the life of outdoor optical products.

2 DESIGN of EXPERIMENT

Environmental time-varying temperature can be considered to be cycling from high to low within a day. In considering time-varying stresses, one is more interested in the time-to-failure (TTF) which can be calculated based on the number of cycles to failure. The time-varying temperature cycle can approximately be described by:

- highest temperature
- temperature range

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- percentage of dwell at high temperature in 1 cycle
- thermal cycle frequency

Environmental humidity also varies with time. However, for some optical products that we are considering, humidity is a major factor only when combined with high temperature. Ramp rates are usually considered insignificant. In a passive optical device, the combination of temperature and humidity may weaken the epoxy holding the packaging together, and moisture may ingress more rapidly into the inside of the hermetically sealed package. So one may consider worst case and control humidity only at the high temperatures during the test. An example is shown in Figure 1.

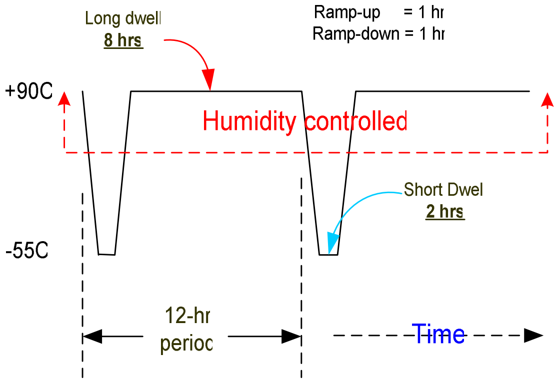

Figure 1 - Example of a temperature cycle

Other factors such as "% dwell at high temperature" and the "cycle frequency" may also affect the product life. Cycle frequency is defined as number of test cycles in a day. Therefore, we should consider them in the test. The definitions of the input factors and possible values of the high and low levels are shown in Table 1.

Factor Name	Factor Definition	Factor High Level	Factor Low Level
Highest Temp	A (X1)	90°C	70°C
Temp Range	B (X2)	135°C	105°C
Humidity	C (X3)	90%	70%
% dwell at High Temp	D (X4)	60%	40%
Cycle Frequency	E (X5)	2 /day	3/day

Table 1 - Factor Definition

X_i is used to denote the value or the transformed value of each factor. For some products, the highest temperatures, temperature range, and humidity are the major factors. The interaction between the humidity and the highest temperature (factors A, C) is normally significant. Interaction between humidity and the temperature range (factors B, C) may be significant but is substituted by factor D. This action reduces the number of test runs but at the cost of having confounded results. However, all interactions are accounted for as input factors in the ALTA 6 PRO folio during the data analysis process. It can be postulated that the three-factor interaction is also not a significant interaction (ABC) and it can be replaced by the cycle frequency. Note that factors D and E do not have significant interactions with other factors and one can tolerate that their main effects are confounded with other small interactions. One can then choose factor generators as: D=BC and E=ABC to design a 2^{5-2} DOE design which is described in Table 2.

.Run	Highest Temp (HT)	Temp Range (DT)	Relative Humidity (RH)	% Dwell at High Temp (DW)	Cycle Frequency (CF)
	A (X1)	B(X2)	C (X3)	D(X4)	E(X5)
1	-1	-1	-1	1	-1
2	1	-1	-1	1	1
3	-1	1	-1	-1	1
4	1	1	-1	-1	-1
5	-1	-1	1	-1	1
6	1	-1	1	-1	-1
7	-1	1	1	1	-1
8	1	1	1	1	1

Table 2 - DOE Test Profiles

Using the above 2^{5-2}, the following alias structure can be obtained.

I + ADE + BCD

A + DE + BCE + ABCD
B + CD + ACE + ABDE
C + BD + ABE + ACDE
D + AE + BC + ABCDE
E + AD + ABC + BCDE
AB + CE + ACD + BDE
AC + BE + ABD + CDE

From the above alias structure of the design, it can be seen that all the main effects are not confounded with each other. The major interactions of AB and AC are not confounded with any main effect. Therefore, this design can be used to estimate the main effects and the two major interaction effects of interest.

3 *RELIABILITY PREDICTION MODEL*

For three or more stresses, the Generalized Log-Linear (GLL) model with transformation for each stress is normally used. In this study, the ReliaSoft's ALTA-6 PRO software was used for all the data analysis and model predictions. The GLL model can be expressed as:

$$L(X) = e^{\alpha_0 + \sum_{j=1}^{n} \alpha_j X_j} \qquad (1)$$

where $L(X)$ = life of the product under all stresses

α_0 = constant

X_j = j^{th} stress or the interaction of the stresses.

In the life distribution model the Weibull distribution was used for fitting the test data. A Weibull probability density function is expressed as follows:

$$f(T) = \frac{\beta}{\eta}\left(\frac{T}{\eta}\right)^{\beta-1} e^{-\left(\frac{T}{\eta}\right)^{\beta}} \qquad (2)$$

where $f(T)$ = probability density function
T = time
β = shape parameter
η = scale parameter

In combination, for example, the Generalized Log Linear (GLL) – Weibull model is expressed as:

$$f(T,X) = \beta t^{\beta-1} e^{-\beta\left(\alpha_0+\sum_{j=1}^{n}\alpha_j X_j\right)} e^{-t^{\beta} e^{-\beta\left(\alpha_0+\sum_{j=1}^{n}\alpha_j X_j\right)}} \qquad (3)$$

The adequacy of the model is judged using the goodness-of-fit approach by comparing the likelihood functions calculated for GLL and Weibull, Lognormal or the Exponential models. Outliers in the data can be observed from the residual plots (e.g. Cox-Snell and Standard Residual plots). Details of these models and techniques can be found in Ref. 7.

When all the possible iterations are conducted and the best model is selected, the reliability and unreliability across time can be plotted for the product with assigned confidence bounds.

In "quantitative" life tests for optical products, some tests may take relatively long time to complete because normally the experimenters may not want to test at temperatures exceeding the epoxy glass transition temperatures. This is because at much higher temperatures, the failure mechanisms may not correlate well with that found at the normal operating conditions.

To illustrate the points at hand, some simulated plots are included in this paper. In generating these simulated reliability plots, the simulated TTF for each sample is entered into the data folio of the Reliasoft ALTA 6 PRO software, for each case (test run) as described in Table 2 above. Note that simulated data may not be close to the real data but the methodology of processing and analyzing the data is demonstrated.

Besides two main factors, temperature and humidity, vibration and usage rate of the connectors will also affect the product reliability. Therefore, if the products have connectors and encounter significant field vibration, the effective reliability is the product of the reliabilities due to (1) temperature humidity cycling, (2) connect and reconnect, (3) field vibration. In this paper, the primary focus was on the failure modes related with temperature and humidity. An example of how to use GLL model to predict the field reliability is given in the following section.

4 CASE STUDIES

Before entering the simulated data into ALTA 6, a DOE analysis was conducted to test the significant of the seven (7) effects list under Table 2. By performing a DOE analysis, one can screen out the non-significant effects and only the important effects will be included in the later more advanced ALTA 6 analysis. The data format for DOE analysis is presented in Table 3.

Using the logarithmic transform of the failure times as responses, the results of the DOE analysis are given in Table 4.

Failure Time	HT (A)	DT (B)	RH (C)	DW (D)	CY (E)
4500	-1	-1	-1	1	1
6000	-1	-1	-1	1	1
7000	-1	-1	-1	1	1
8000	-1	-1	-1	1	1
9000	-1	-1	-1	1	1
10100	-1	-1	-1	1	1
...	...	...	...	...	...

Table 3 - Data Format for DOE Analysis

Term	Coef	Standard Error of Coef	T	P
Constant	8.35	0.049	169.36	0
A (HT)	-0.101	0.049	-2.07	0.04
B(DT)	-0.34	0.046	-7.31	0
C(RH)	-0.35	0.06	-5.75	0
D(DW)	-0.12	0.05	-2.69	0.01
E(CF)	-0.14	0.05	-3.03	0.003
AB(HT*DT)	0.054	0.05	1.17	0.244
AC(HT*RH)	0.13	0.06	2.22	0.03

Table 4 - DOE Analysis Results

From the P values, we found out the AB effect, which is the interaction of the highest temperature and the temperature range, is not significant. As such, it was excluded from further analyzed in ALTA.

Instead of using the code values which is -1 and +1 of each factor, the actual values are used in the ALTA. According to the commonly used Coffin-Manson Model and Temperature-Humidity Model (Generalized Eyring Model) (Ref. 8), the following transforms for each stress are used:

Temperature: Reciprocal Transform
Humidity: Reciprocal Transform
Temperature Range: Logarithmic Transform
Cycle Frequency: Logarithmic Transform

For the "% dwell at high temperature," no transform was used. The data format used in ALTA analysis is shown in Table 5.

The last column in Table 5 is the product of column HT and RH. This column represents the interaction effect of the highest temperature and humidity. First, we include all the seven effects in the model. From the analysis results and the engineering knowledge, we will use step-wise method to find out the best model. The results for the full model are included in Table 6.

From Table 6 it was found that the uncertainty of the effect A and AC was relatively large because the variance to mean ratio is very high.

To reduce the uncertainty, one way is to increase the test sample size. Another way is to reduce the number of model parameters. Therefore, removing the AC interaction term from the model provides the result shown in Table 7:

Failure Time	HT	DT	RH	DW	CY	HT*RH
4500	343	105	0.7	0.6	3	204.1
6000	343	105	0.7	0.6	3	204.1
7000	343	105	0.7	0.6	3	204.1
8000	343	105	0.7	0.6	3	204.1
9000	343	105	0.7	0.6	3	204.1
10100	343	105	0.7	0.6	3	204.1
...	...	...	...	...	...	...

Table 5 - ALTA Input Data Format

Parameters	Mean Value	Variance	Variance to Mean Ratio	Lower Bound	Upper Bound
Beta	3.7	0.1	0.03	3.2	4.3
Constant	47.71	116.5	2.4	29.95	65.5
A (HT)	-1.37E4	1.47E7	-1072	-2.01E4	-7422
B(DT)	-0.02	0.00	-0.0003	-0.03	-0.02
C(RH)	-31.3	85.6	-2.74	-46.5	-16.03
D(DW)	-0.5	0.03	-0.06	-0.81	-0.24
E(CF)	-0.7	0.03	-0.04	-0.97	-0.42
AC (HT*RH)	11779	1.04E7	880.23	6481.5	1.71E4

Table 6 - Full Model Results

Parameters	Mean Value	Variance	Variance to Mean Ratio	Lower Bound	Upper Bound
Beta	3.40	0.08	0.024	2.96	3.91
Constant	8.48	1.77	0.21	6.3	10.7
A (HT)	136	233314	1711	-658	931
B(DT)	-0.026	6.23E-6	-0.0002	-0.03	-0.022
C(RH)	2.66	0.07	0.03	2.22	3.1
D(DW)	-0.31	0.03	-0.09	-0.59	-0.04
E(CF)	-0.88	0.03	-0.036	-1.2	-0.59

Table 7 - Updated Results without AC Interaction

From Table 7, it is apparent that the uncertainty of the temperature is still large. Moreover, the range of its bound includes 0. Therefore, one can still reduce the model complexity by deleting the highest temperature from the model. One reason factor A is not significant relates to the fact that in the test of optical products, the highest temperature is still relatively low. Another possible reason is that the difference of the high level and low level of the factor A is not large enough. Since the goal is to use the model to predict the warranty returns, a model with less uncertainty should be used. As such, factor A was deleted from the model and those results are shown in Table 8.

From Table 8, one finds that the variance to mean ratio is small and no parameter bounds include 0. Therefore, this model is used as the final model. The standard residuals are plotted in Figure 2.

Parameters	Mean Value	Variance	Variance to Mean Ratio	Lower Bound	Upper Bound
Beta	3.41	0.08	0.024	2.97	3.9
Constant	9.4	0.16	0.02	8.7	10
B(DT)	367	1216	3.3	310	425
C(RH)	-4.29	0.125	-0.03	-4.9	-3.7
D(DW)	0.15	6.48E3	0.04	0.02	0.28
E(CF)	-0.89	3.07E-2	-0.035	-1.18	-0.6

Table 8 - Updated Results Without Factor A

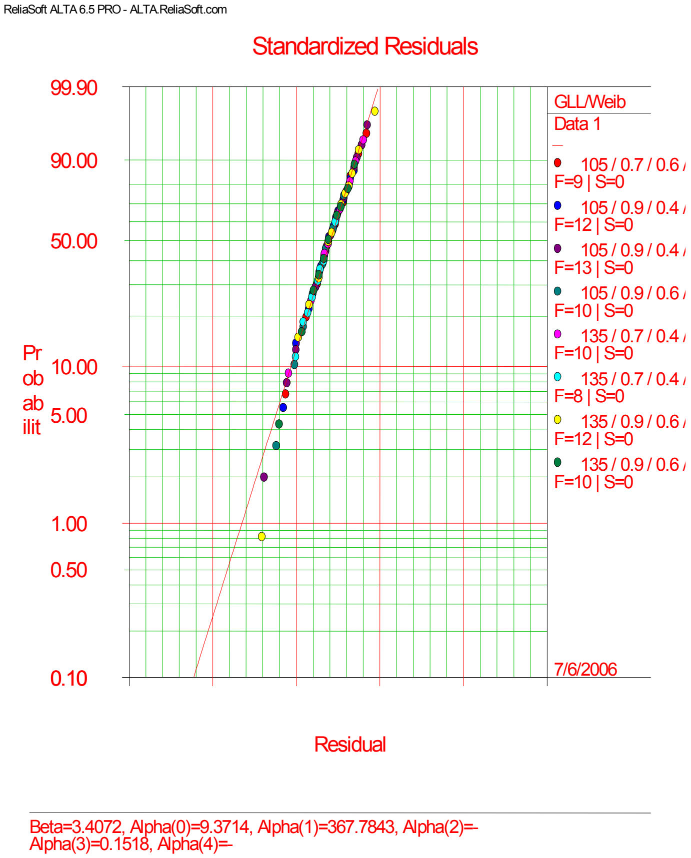

Figure 2 - Standard Residual plot of the GLL-Weibull model

The probability plot under the test stress is given in Figure 3. Figure 4 shows the unreliability versus time simulation plot, with two-side 90% confidence bounds. Note that this is a 5 input factors design of experiment and the data can be complicated and the analysis of the data may be very involving. It is from this figure that the failure percentage of the life cycle can be drawn. Figure 5 shows life versus the relative humidity at use-level stress. Similar plots can be for life versus other input stresses such as temperature range, percentage dwell at high temperature and cycle frequency. Note that in the use level, the cycle frequency is always one because there is only 1 cycle per day.

From Figure 5, we can see the bound is relative wide. In order to reduce the estimation uncertainty, more samples at each run should be tested.

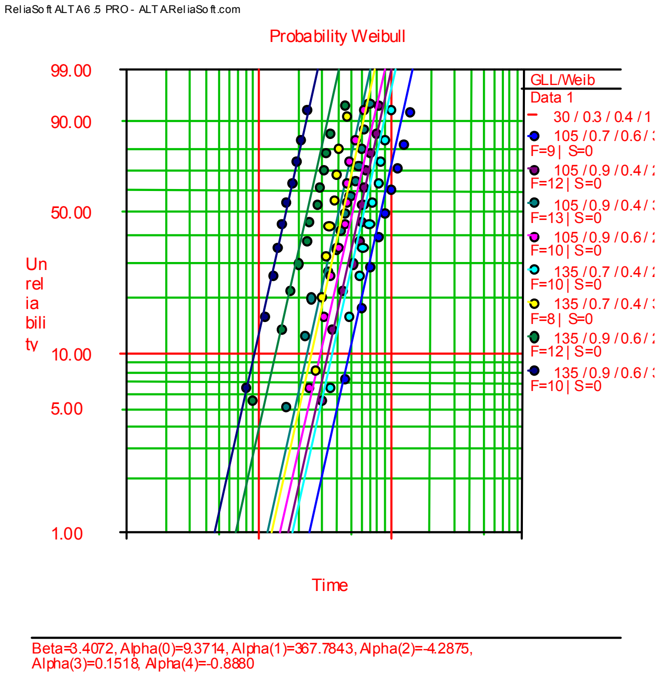

Figure 3 - Probability GLL-Weibull Model

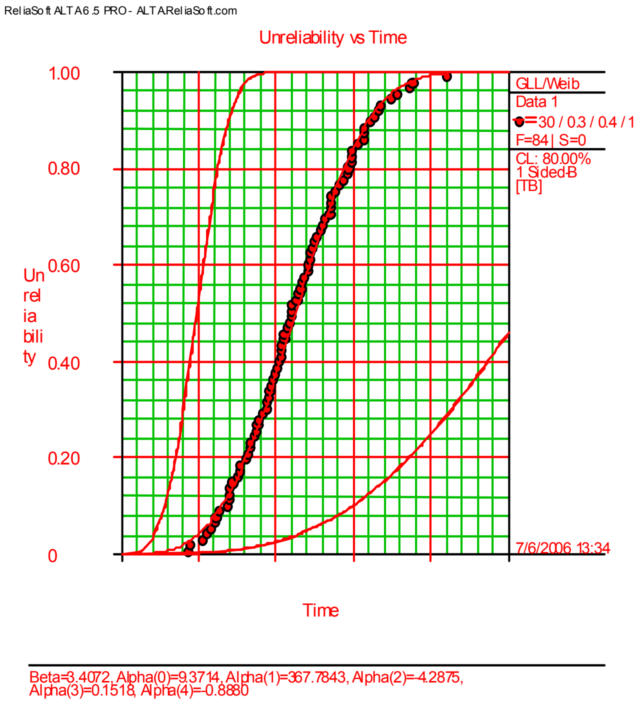

Figure 4 - Unreliability vs. time for the GLL-Weibull Model

5 WARRANTY CALCULATIONS

In use conditions, a product deployed in an outdoor environment is exposed to time-varying temperatures and humidity throughout the year. One will need to determine the values of each stress at use conditions in the modeling. To simplify calculations, one may consider average temperature range and average humidity for spring, summer, autumn and winter at the location that the product is deployed, for the warranty calculations. The cycle period is 24 hours and the percentage highest temperature dwell can be figured out from weather patterns when the information is available.

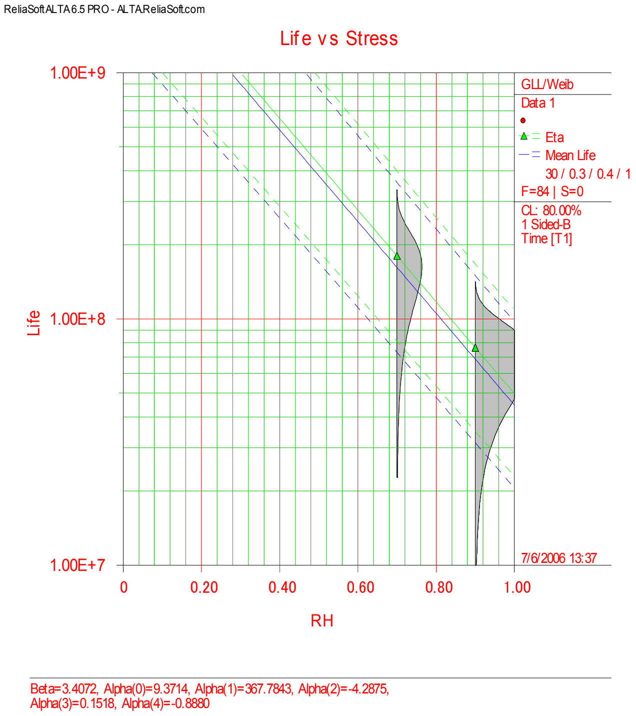

Figure 5 - Life versus relative humidity at use level

Once the parametric regression on the equation (3) is complete, the unreliability (i.e. cumulative density function of failure in percentage, for the design life of say 20 years) versus time can be plotted under various use conditions. For example, for the summer, each of the values of the stress can be determined and the unreliability versus time plotted with say a 90% confidence level and the unreliability (in percentage failure) in the 20th year can be determined from the plot. Let it be denoted by F_{summer}. Hence the effective percentage failure F is expressed as:

$$F = 0.25*(F_{summer} + F_{autumn} + F_{winter} + F_{spring}) \qquad (4)$$

One may take the average of the failure percentage for each year as 0.05*F.

6 CONCLUSIONS

In this paper, a practical multi-stress accelerated test methodology was given. DOE method was used to help the analysis of the acceleration test data. Procedures of how to transform the stress value, how to select suitable model for reliability prediction were discussed. A case study using the simulated data for an optical product was presented to illustrate the proposed method. The method proposed in this paper is a general method and can be extended to other products.

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BIOGRAPHIES

Chung F. Lam
Corning Cable Systems, LLC,
9275 Denton Highway,
Keller, Texas, 76248, U.S.A.

e-mail: chung.lam@corning.com

Chung F. Lam is currently the Reliability Engineering Supervisor at Corning Cable Systems in Keller, Texas. Before joining Corning, he worked for LIGHTCONNECT Incorporated as Manager of Reliability, Failure Analysis and Quality Assurance for four years. Prior to that, he was named Reliability Team Leader and ESD Program Manager at READ-RITE Corporation for five years. In his earlier career, he held various Product Development, Design and Manufacturing Engineering positions at IBM Corporation (San Jose, CA) for thirteen years. His reliability, testing and quality experiences have been in both the fiber optics and disk-drive industries. His current interests include design for reliability, ongoing reliability testing to assure product performances in the field, and in the practical applications of statistics and reliability theories to model and predict product lifetimes. He holds five issued patents and has published more than 10 papers. He earned a B.S. degree in Mechanical Engineering from Oregon State University and a M.S. degree, also in Mechanical Engineering, from the University of Washington. He is a member of ASQ and A.S.M.E.

Huairui Guo, Ph.D.
Senior Research Scientist,
ReliaSoft Corporation,
ReliaSoft Plaza,
115 South Sherwood Village Drive,
Tucson, Arizona 85710, U.S.A.

e-mail: Harry.Guo@ReliaSoft.com

Huairui Guo is a Senior Research Scientist at ReliaSoft Corporation. He received his Ph.D. in Systems and Industrial Engineering from the University of Arizona. He also received his M.S. in Manufacturing (2002) from the National University of Singapore in Singapore and M.S. (2004) in Reliability and Quality Engineering from the University of Arizona. His publications address Quality Engineering areas such as SPC, ANOVA and DOE and Reliability Engineering areas. His current research interests include Reliability Prediction, Accelerated Life/Degradation Testing, Warranty Data Analysis, and Robust Optimization.

Lance Larson,
Technical Support Specialist,
ReliaSoft Corporation,
ReliaSoft Plaza,
115 South Sherwood Village Drive,
Tucson, Arizona 85710, U.S.A.

E-MAIL: Lance.Larson@ReliaSoft.com

Lance Larson is a Technical Support Specialist at ReliaSoft Corporation in Tucson, Arizona. For the past several years, he has helped analyze and provide solutions for various unique customer needs using most of ReliaSoft's software solutions, including ALTA, BlockSim, RCM++, RGA, Weibull++ and Xfmea. Mr. Larson attended the University of Arizona and he is a member of ASQ.