DOI: 10.1007/s12541-013-0282-9

# Reliability Estimation of Pneumatic Cylinders using Performance Degradation Data

**Mu Seong Chang[1], Jung Hun Shin[1], Young Il Kwon[2], Byung Oh Choi[1], Choong Sung Lee[1], and Bo Sik Kang[1,#]**

1 Reliability Assessment Center, Korea Institute of Machinery & Materials, 171 Jang-dong, Yuseong-gu, Daejeon, South Korea, 305-343
2 Department of Industrial Engineering, Cheongju University, 36 Naedeok-dong, Sangdang-gu, Cheongju, South Korea, 360-764
# Corresponding Author / E-mail: kbs668@kimm.re.kr, TEL: +82-42-868-7156, FAX: +82-42-868-7082

KEYWORDS: Degradation test, Performance degradation data, Pneumatic cylinder, Pseudo lifetime, Reliability estimation

*The time allowed for life testing to assess the reliability of a product is continuously reduced and the test at normal use conditions often yields few or no failures. This situation especially occurs in testing products with long lifetime such as pneumatic cylinders. Performance degradation data often provide more accurate estimates on product reliability than those from failure time data. This paper presents a method for estimating parameters of lifetime distribution using the performance degradation data of pneumatic cylinders at normal use conditions. For this purpose, degradation analysis was carried out and the estimates from performance degradation data were compared with those from failure time data. According to the results, when considering test time and an uncertainty of reliability estimates, degradation analysis was strongly recommended rather than failure time analysis with censored data for the pneumatic cylinder.*

Manuscript received: February 17, 2013 / Accepted: September 12, 2013

## NOMENCLATURE

$Y_t$ = performance degradation at time t
a, b = parameters of degradation model
$\beta$ = shape parameter of Weibull distribution
$\eta$ = scale parameter of Weibull distribution / characteristic life
R = reliability
$B_{10}$ life = life at which 10% of the population is predicted to fail
MTTF = mean time to failure

## 1. Introduction

Increasing global competition has placed great pressure on manufacturers to deliver products with more features and higher reliability at a lower cost and in less time.[1] With short product development period, reliability testing often should be conducted with severe time constraints. Sometimes, no failure occurs during the test. Thus it is difficult to assess reliability with traditional life test method that records only failure times.[2] In that instance, accelerated life test (ALT) can be used to shorten test time, but the failure mechanism can be changed in the case of applying too severe stress conditions. That is, failure mechanisms of normal use condition and an accelerated condition may be different. As an alternative to traditional life test and ALT, degradation test can be used in assessing product reliability when measurements of performance degradation leading to failure can be observed. Degradation test allows reliability to be estimated even before a test sample fails. A relationship between failure time and performance degradation data makes it possible to estimate product reliability.

The number of studies on degradation test has increased quickly in the past two decades and many of them have targeted specific products and their degradation characteristics, which indicate the growing interest of using degradation test to assess product reliability in both industry and academia.[3] Nelson[4] and Meeker and Escobar[5] reviewed the degradation literature, survey applications and described basic analytical methods on the accelerated degradation test (ADT) models. Meeker and Escobar[2] also provided a practical guide for ADT modeling based on transformed linear degradation models along with standard ALT formulas. Practical studies using degradation data include the test of LEDs,[3,6] fluorescent lamps,[7] computer disks and compact discs,[8] power supplies,[9] and metalized film pulse capacitor.[10]

Pneumatic cylinder is one of major mechanical components which are widely used in various industries such as automobile production line and semiconductor inspection device because of its low contamination and low maintenance cost.[11] Most of existing studies on reliability assessment of pneumatic cylinders have mainly focused on accelerated life test to reduce product test time.[12-14]

The main purpose of this paper is to provide a method of reliability estimation for pneumatic cylinders based on performance degradation data obtained before a failure. For this purpose, degradation analysis was carried out and comparison analysis between performance degradation data and failure time data is also performed. Section 2 introduces the configuration of pneumatic cylinder, its degradation mechanism, and the measurement method of the degradation. Section 3 presents simple degradation analysis methods. Section 4 presents methods of estimating Weibull parameters of pneumatic cylinders using failure time data and performance degradation data, and performs comparison analysis between performance degradation data and failure time data. Section 5 discusses some concluding remarks.

## 2. Degradation Mechanism of Pneumatic Cylinder

Mechanical component failure has rather complicated aspects since it is composed of several parts which contact with each other or move relatively. First of all, engineers who perform failure analysis should define what the failure is and decide how they can observe it. Major failure modes of pneumatic cylinders are excessive leakage or severe break-out friction in its elastomeric seals. It is also well known that most friction of pneumatic cylinder is generated in piston seals rather than rod seals.[15] Proper test samples are selected and investigated whose failures occurred in their piston seals to verify the failure mechanism of pneumatic cylinders. Fig. 1 shows the pneumatic cylinder using lip piston seals. When compressive air alternately flows into and out of cylinder volumes in both sides, the piston and rod with some mass translates cyclically to the left and then to the right. Piston/cylinder wall is the most crucial sliding part in the cylinder. Accordingly well-made dynamic seals such as lip seals should be used at that part. The seal is installed with initial deformation and loaded by air pressure to provide sealing stiffness. During operation, lubricant

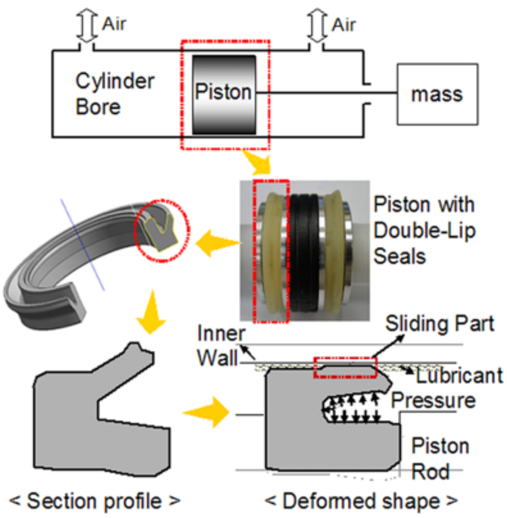


Fig. 1 Pneumatic cylinder and piston seal

(normally grease) should always exist between piston and cylinder wall so that it separates two sliding surfaces. Kang et al.[11] asserted that the sealing failure results from lubricant degradation. This paper also conformed to the results of Kang et al.[11] Fig. 2 shows damaged piston part just after reliability test was finished. A large quantity of sludge was observed which indicated lubricant degradation, and the area of physical degradation in sliding surfaces was small which indicates that adhesive wear occurred due to local lubricant run-out. Once lubrication failures arise, friction starts to increase due to both sludge obstacles and adhesive resistance. The sign of the lubrication failure can be observed by measuring the increase in minimum operating pressure (MOP) at which cylinders break out moving. ISO 19973-3[16] specifies that the MOP should be lower than 120 kPa (1.2 bars) at normal use condition. MOP could be measured after each period of the cyclic test. MOP has a tendency to increase linearly over time. Besides, excessive leakage could occur very few before the increase of friction and so this failure mode was excluded in this paper.

## 3. Degradation Analysis

A degradation test is a useful technique to provide information about lifetime of highly reliable products. In some cases, it is possible to measure physical degradation data as a function of time. In other applications, actual physical degradation cannot be observed directly, instead, measures of product performance degradation may be available. Both kinds of data are generically referred to as degradation data.[2] Performance degradation data is mainly used in this paper. Depending on the product, performance degradation data may be available continuously or at specific points in time where measurements are taken.

In most reliability tests, performance degradation data have several practical advantages over failure time data. Reliability analysis using performance degradation data directly relates reliability to physical characteristics. This enables product reliability to be estimated even before a test sample fails and thus greatly shortens the test time.[1] Degradation analysis often provides more accurate estimates than those from lifetime data analysis especially when lifetime data are highly censored. In degradation tests, performance degradation is measured continuously or periodically and pre-specified threshold value is utilized to define the failure of a product.

Once performance degradation data has been recorded, extrapolation is used to predict the failure time, i.e., time to reach the threshold value. In this sense, predicted failure time obtained here is a pseudo lifetime.[1] The extrapolation is generally performed using linear, exponential, or logarithmic model. These models assume the following relationships


Fig. 2 Seal surface in a failed cylinder

between the test time t and the degradation $Y_t$:

Linear: $Y_t = a + bt$ (1)

Exponential: $Y_t = a \exp(bt)$ (2)

Logarithmic: $Y_t = a + b \ln(t),\ t \geq 1$ (3)

where a and b are model parameters to be solved for and ln( ) is the natural (base e) logarithm. In the case of logarithmic model, test time t should be more than or equal 1 so that $Y_t$ has a positive value. Once the estimates a, b are obtained, we can calculate the pseudo lifetime using the assumed relationships.

## 4. Reliability Estimation of a Pneumatic Cylinder

### 4.1 Analysis with failure time data

Eight pneumatic cylinders were tested for about 15 months (24,000,000 cycles) at normal use conditions (630 kPa and 23°C). One cycle is defined as the reciprocating event of piston between both ends of the cylinder bore. The lifetime of pneumatic cylinders is usually given in number of cycles.[16] During the test, MOPs were observed periodically (0 cycles, 1,000,000 cycles and after every 2,000,000 cycles) and a sample is decided to be failed if three point moving average of MOPs exceeds the pre-specified threshold value.[17] From the test, six failure times and two censored times are obtained (Table 1). Failures of six samples were caused by increase in MOP. Six failure data observed here are called interval censored data. Interval censored data reflects uncertainty as to the exact times the products failed within an interval.[18] But in this paper, failure data was called instead of interval censored data for convenience.

Table 1 Failure time data of pneumatic cylinders ($10^4$ cycles)

| Sample No. | Cycles at start of interval during which the failure occurred | Cycles at end of interval during which the failure occurred |
|---|---|---|
| 1 | 2,400 | censored |
| 2 | 2,200 | 2,400 |
| 3 | 1,200 | 1,400 |
| 4 | 1,600 | 1,800 |
| 5 | 2,000 | 2,200 |
| 6 | 1,800 | 2,000 |
| 7 | 2,400 | censored |
| 8 | 2,200 | 2,400 |

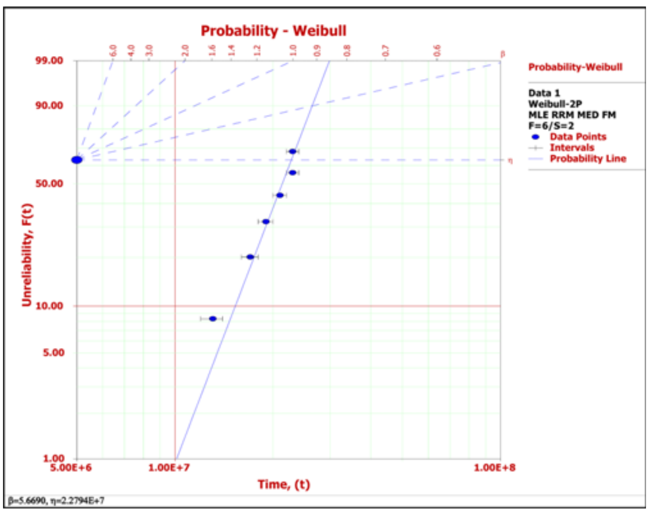


Fig. 3 Weibull probability plot of failure time data (from Weibull++7)

It is well known that Weibull distribution is the most common distribution in mechanical engineering fields.[19] Fig. 3 shows Weibull probability plot of failure data for the pneumatic cylinders. The maximum likelihood estimates of shape and scale parameters were 5.67 and 22,793,961 cycles respectively. The 95% confidence intervals for the shape and scale parameters were (2.78, 11.56) and (19,789,000, 26,255,000). Using the estimates of shape and scale parameters, $B_{10}$ life and MTTF of the cylinders are estimated as follows:

$$B_{10} = \eta \cdot \{-\ln(1-0.1)\}^{\frac{1}{\beta}} = 15{,}325{,}766 \text{ cycles} \quad (4)$$

$$MTTF = \eta \cdot \Gamma\left(1+\frac{1}{\beta}\right) = 21{,}079{,}474 \text{ cycles} \quad (5)$$

The 95% confidence intervals for the $B_{10}$ life and MTTF were (11,195,000, 20,980,000) and (18,124,000, 24,517,000). Statistical analysis and graphical presentation of failure time data were done in Weibull++.

### 4.2 Analysis with performance degradation data

Under normal use conditions, eight pneumatic cylinder samples were tested and MOP data were measured periodically. Degradation analysis was performed by using MOP data until 18,000,000 cycles. Table 2 shows MOP data at each cycle. Two (sample 3 and 4) out of eight samples were actually failed before 18,000,000 cycles. Fig. 4 shows performance degradation data plots of the eight pneumatic cylinders. Each dot represents three point moving average of MOP data. Average plot in the Fig. 4 displays average MOP of eight samples at same cycles. In the Fig. 4, Y-axis is MOP data and X-axis is cycles.

Three models discussed in section 3 were considered for degradation analysis. Table 3 summarizes coefficient of determination $R^2$ and error mean square (MSE) of three degradation models at each sample and average MOP. $R^2$ and MSE are important indicators to evaluate the goodness of fit of the assumed degradation models. $R^2$ is interpreted as the proportion of the variability in the data explained by the degradation model. $R^2$ has $0 \leq R^2 \leq 1$, with larger values being more desirable. MSE measures the average of the squares of the errors. The model with

Table 2 MOP data at each cycle (bars)

| Cycles ($10^4$) \ Sample No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| 200 | 0.790 | 0.847 | 0.863 | 0.910 | 0.740 | 0.877 | 0.620 | 0.857 |
| 400 | 0.927 | 0.953 | 0.947 | 0.910 | 0.733 | 0.923 | 0.623 | 0.913 |
| 600 | 0.993 | 1.000 | 0.963 | 0.850 | 0.710 | 0.900 | 0.713 | 0.990 |
| 800 | 1.070 | 1.027 | 0.947 | 0.897 | 0.880 | 0.830 | 0.810 | 1.027 |
| 1000 | 1.098 | 1.063 | 0.913 | 1.010 | 0.937 | 0.723 | 0.977 | 1.063 |
| 1200 | 1.043 | 1.097 | 1.037 | 1.107 | 1.073 | 0.767 | 0.980 | 1.087 |
| 1600 | 1.103 | 1.097 | 1.240 | 1.120 | 1.070 | 1.030 | 0.937 | 1.073 |
| 1800 | 1.143 | 1.100 | 1.213 | 1.220 | 1.067 | 1.113 | 0.900 | 1.103 |

the smallest MSE is generally interpreted as the best model. Based on the $R^2$ and MSE of Table 3 and characteristic of MOP, a linear model was determined to estimate product reliability.

When the linear model is used to estimate lifetime, some data of sample 6 can increase an error of the model. Thus, some data (displayed in the circles of Fig. 4.) were excluded from the subsequent analysis. Statistical analysis of performance degradation data was done in MINITAB and Weibull++.

Table 4 shows the estimates of a, b in Eq. (1), and predicted failure times of all samples obtained using Eq. (6). The accent * denotes estimate of parameters. The threshold-value of Y = 1.2 (bars) is used to predict the pseudo lifetime (failure time) of a sample. In the case of sample 3 and 4, actual failure time were used for the analysis.

$$\text{Pseudo lifetime} = [\{(Y - a^*) / b^*\} \times 1{,}000{,}000] \quad (6)$$

Fig. 5 shows Weibull probability plot of lifetime data in Table 4. The maximum likelihood estimates of shape and scale parameters were 5.92 and 22,546,820 cycles respectively. The 95% confidence intervals

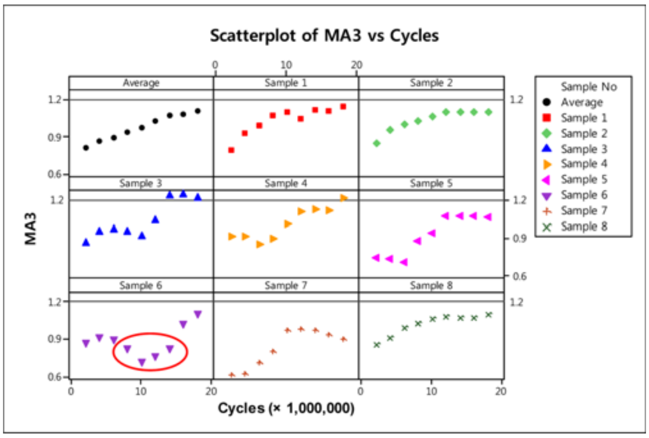


Fig. 4 Performance degradation data plots (from MINITAB16)

Table 3 $R^2$ and MSE of degradation models at each sample and average MOP

| Sample No | Linear | Exponential | Logarithmic |
|---|---|---|---|
| 1 | 76.8%<br>0.003379 | 73.9%<br>0.004142 | 93.2%<br>0.000992 |
| 2 | 81.3%<br>0.001598 | 78.8%<br>0.001886 | 97.2%<br>0.000235 |
| 3 | 79.1%<br>0.00536 | 79.9%<br>0.00457 | 64.4%<br>0.00912 |
| 4 | 84.3%<br>0.00307 | 83.2%<br>0.00316 | 64.0%<br>0.007025 |
| 5 | 85.4%<br>0.00428 | 84.4%<br>0.00579 | 78.3%<br>0.00637 |
| 6 | 16.1%<br>0.01442 | 12.8%<br>0.01823 | 4.8%<br>0.01637 |
| 7 | 69.5%<br>0.00792 | 71.2%<br>0.01202 | 79.0%<br>0.00545 |
| 8 | 82.3%<br>0.001457 | 80.7%<br>0.001664 | 95.9%<br>0.00034 |
| Average | 98.9%<br>0.000139 | 98.3%<br>0.000229 | 92.9%<br>0.000878 |

for the shape and scale parameters were (3.377, 10.38) and (19,933,000, 25,503,000). Estimates of $B_{10}$ life and MTTF were 15,416,902 and 20,901,550 cycles. The 95% confidence intervals for the $B_{10}$ life and MTTF were (11,674,000, 20,361,000) and (18,126,000, 24,102,000). According to the interval estimation results of parameters, $B_{10}$ life and MTTF, the lengths of confidence intervals for performance degradation data were shorter than ones for failure time data.

### 4.3 Comparison analysis of failure time data and performance degradation data

Based on the section 4.1 and 4.2, we can obtain following results.

- In the section 4.1, eight pneumatic cylinders were tested for 24,000,000 cycles and obtained six failure data and two censored data. The estimates of shape and scale parameters for pneumatic cylinders were 5.67 and 22,793,961 cycles.
- In the section 4.2, eight pneumatic cylinders were tested for 18,000,000 life cycles and obtained two failure data and six complete pseudo lifetime using parameter estimates of the linear degradation model. The estimates of shape and scale parameter for pneumatic cylinders were 5.92 and 22,546,820 cycles.
- In analysis with performance degradation data, it could obtain good results with shorter test time (about 4 months decrease) in comparison with failure time data. In addition, the lengths of confidence intervals for performance degradation data were shorter than ones for failure time data.

Table 4 Parameter estimates of the linear model and predicted pseudo lifetimes

| Sample No | a* | b* | Pseudo lifetime (cycles) |
|---|---|---|---|
| 1 | 0.8510 | 0.01808 | 19,298,789 |
| 2 | 0.8889 | 0.01422 | 21,875,264 |
| 3 | | | 12,000,000~14,000,000 |
| 4 | | | 16,000,000~18,000,000 |
| 5 | 0.6505 | 0.02703 | 20,332,248 |
| 6 | 0.8473 | 0.01320 | 26,732,095 |
| 7 | 0.6077 | 0.02297 | 25,783,998 |
| 8 | 0.8798 | 0.01406 | 22,779,596 |

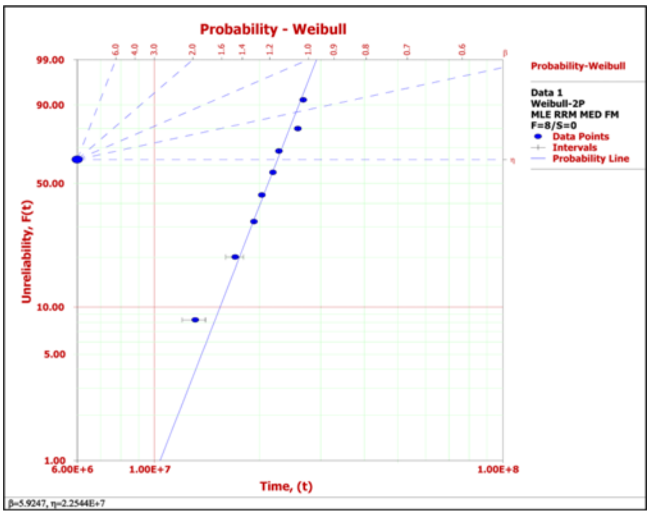


Fig. 5 Weibull probability plot of lifetime data obtained from the degradation model (from Weibull++7)

Comparison test was conducted to validate the degradation analysis results from the failure data analysis. Equality test of parameters between degradation analysis and failure data analysis was used for the comparison. Two hypotheses of equality test include null hypothesis ($H_0$) and alternative hypothesis ($H_1$). The null and alternative hypotheses of equality test are as follows:

$$H_0 : \theta_{\text{degradation data}} = \theta_{\text{failure data}}$$

$$H_1 : \text{Not } H_0$$

where $\theta$ is a parameter (shape or scale parameter) for equality test. The purpose of equality test is to decide whether reject the null hypothesis or not. P value means a probability of the observation under the null hypothesis. The larger p value is, the more difficult it is to reject the null hypothesis. Based on the two analysis results, p values of shape and scale parameters were 0.923 and 0.906 respectively. These p values were calculated by the Wald test. As a result, shape and scale parameters of two analysis results were not significantly different each other. Fig. 6 shows $B_{100p}$ lifetimes estimated from both data types. This figure shows that there is no significant difference between the estimates of $B_{100p}$ lifetime. Thus, when it is possible to obtain some performance degradation data periodically, such data can predict meaningful results before failures. In the case of pneumatic cylinders, degradation analysis could provide good reliability estimates with less test time than failure analysis with censored data.

## 5. Conclusions

In today's competitive business environment, the test time is continuously reduced. In this situation, the degradation analysis enables product reliability to be estimated even before a test sample fails and thus shortens the test time. It also provides more accurate estimates than those from life data analysis when a test is censored.

This paper showed that the degradation of pneumatic cylinders was caused by lubrication failure of the piston part and MOP was selected as a representative performance degradation characteristic. Three point moving average was used for failure criterion of fluctuating MOP data. The maximum likelihood estimates of shape and scale parameter for the failure time data were 5.67 and 22,793,961 cycles. The linear model was chosen to characterize the degradation mechanism of pneumatic

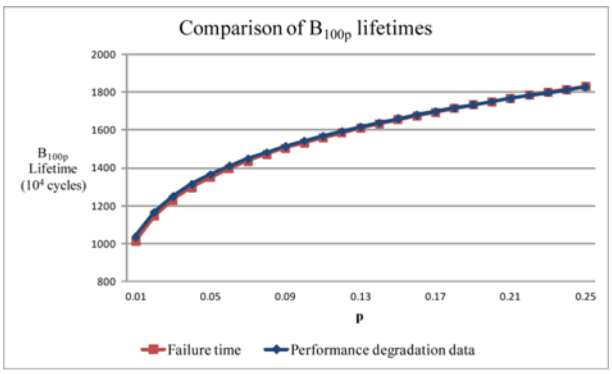


Fig. 6 Comparison of $B_{100p}$ lifetimes estimated from both data types

cylinders. After the estimates of model parameters were obtained, we could calculate the pseudo lifetime. The maximum likelihood estimates of shape and scale parameter for performance degradation data were 5.92 and 22,546,820 life cycles. Comparison analysis of parameters and $B_{100p}$ lifetimes between performance degradation data and failure time data was performed. It drew the result that parameters of both data were not significantly different each other. There was no big difference between the estimates of $B_{100p}$ lifetime of both data types.

In consideration of test time and an uncertainty of reliability estimates, analysis with performance degradation data is strongly recommended as the better method than failure time analysis with censored data for the pneumatic cylinder.

## REFERENCES

1. Yang, G., "Life Cycle Reliability Engineering," Wiley, 2007.
2. Meeker, W. Q. and Escobar, L. A., "Statistical Methods for Reliability Data," Wiley, 1998.
3. Pan, R. and Crispin, T., "A Hierarchical Modeling Approach to Accelerated Degradation Testing Data Analysis: A Case Study," Quality and Reliability Engineering International, Vol. 27, No. 2, pp. 229-237, 2011.
4. Nelson, W., "Accelerated Testing: Statistical Models, Test Plans, and Data Analysis," John Wiley & Sons, 1990.
5. Meeker, W. Q. and Escobar, L. A., "A Review of Recent Research and Current Issues in Accelerated Testing," International Statistical Review, Vol. 61, No. 1, pp. 147-168, 1993.
6. Fukuda, M., "Reliability and Degradation of Semiconductor Lasers and LEDs," Artech House, 1991.
7. Tseng, S. T., Hamada, M., and Chiao, C. H., "Using Degradation Data to Improve Fluorescent Lamp Reliability," Journal of Quality Technology, Vol. 27, No. 4, pp. 333-369, 1995.
8. Murray, W. P., "Accelerated Service Life Predictions of Compact Discs," ASTM Special Technical Publication, Vol. 1202, pp. 263-263, 1994.
9. Chang, D. S., "Analysis of Accelerated Degradation Data in A Two-way Design," Reliability Engineering & System Safety, Vol. 39, No. 1, pp. 65-69, 1993.
10. Zhao, J. and Liu, F., "Reliability Assessment of the Metallized Film Capacitors from Degradation Data," microelectronics Reliability, Vol. 47, No. 2, pp. 434-436, 2007.
11. Kang, B. S., Shin, J. H., and Kim, H., "A Statistical Analysis of Elastomeric Seal Degradation in a Pneumatic Cylinder With Variation of Temperature," Proc. of the ASME/STLE 2011 International Joint Tribology Conference, pp. 195-197, 2011.
12. Han, G. and Fu, Y., "Tri-stress Accelerated Life Test for Cylinders," Procedia Engineering, Vol. 16, pp. 554-563, 2011.
13. Chen, J., Wang, D. Y., Fu, Y. L., and Qi, X. Y., "Double-Crossed

Step-Stress Accelerated Life Testing for Pneumatic Cylinder," Applied Mechanics and Materials, Vol. 121-126, pp. 1274-1278, 2012.

14. Chen, J., Wu, Q., Bai, G., Ma, J., and Wang, Z., "Accelerated Life Testing Design Based on Wear Failure Mechanism for Pneumatic Cylinders," Proc. of Accelerated life testing design based on wear failure mechanism for pneumatic cylinders, pp. 1280-1285, 2009.

15. Muller, H. K. and Nau, B. S., "Fluid Sealing Technology: Principles and Applictions," CRC Press, pp. 161-170, 1998.

16. ISO No. 19973-3, "Pneumatic Fluid Power - Assessment of Component Reliability by Testing - Part 3: Cylinders with piston rod," 2007.

17. ISO No. 19973-1, "Pneumatic Fluid Power - Assessment of Component Reliability by Testing - Part 1: Cylinders with piston rod," 2007.

18. Reliasoft publishing, "Life Data Analysis Reference," 2008.

19. Bertsche, B., "Reliability in Automotive and Mechanical Engineering: Determination of Component and System Reliability," Springer, 2008.