# USING DEGRADATION DATA FROM A FRACTIONAL FACTORIAL EXPERIMENT TO IMPROVE FLUORESCENT LAMP RELIABILITY

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# USING DEGRADATION DATA FROM A FRACTIONAL FACTORIAL EXPERIMENT TO IMPROVE FLUORESCENT LAMP RELIABILITY

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## ABSTRACT

While statistically designed experiments have been employed extensively to improve a product's or process' quality, they have been underused for improving reliability. In this paper, we present a case study which used an experiment to improve the reliability (or lifetime) of fluorescent lamps. The effect of three factors from among many potentially important manufacturing factors was investigated using a fractional factorial design. For fluorescent lamps, failures occur when their luminosity or light intensity fall below a certain level. An interesting feature of this experiment is the periodic monitoring of the luminosity. The paper demonstrates how the luminosity's degradation over time provides a practical way to improve fluorescent lamps which are already highly reliable. Recommendations based on the experiment's results suggest that nearly 70% improvement can be realized.

*Key words: Case Study, Recommended Factor Settings.*

## Introduction

In the 1980's, industry rediscovered statistically designed experiments as an efficient tool for improving quality of products and processes. While many documented case studies (e.g., *Symposia on Taguchi Methods* 1984-1993) demonstrate the success of using experiments for improving quality, few discuss their use for improving reliability. In this paper, we present such an experiment conducted at the Taiwan Fluorescent Lamp Company to improve the reliability of the fluorescent lamps it manufactures. Because of a competitive market, one of a manufacturer's most important goals is to improve the reliability of an already highly reliable product. Using designed experiments provides a proactive means by identifying important factors that affect the product's reliability; the influential factors can then be set at levels which give reliability gains.

In designing an appropriate experiment, the fact that the product is already highly reliable presents certain challenges. For example, testing units until failure is not feasible. The use of censoring also offers little help because no failures are likely to occur in a reasonable amount of time. An alternative is to accelerate the failures by testing at high levels of stress such as elevated temperatures or voltages. For highly reliable hybrid electronic components, however, suitable accelerating factors cannot easily be found. The same holds for commercial fluorescent lamps.

If there are product characteristics whose degradation over time can be related to reliability, then collecting "degradation data" can provide information about product reliability. Nelson (1990 Chapter 11) surveys the scant literature on the subject and documented applications. Lu and Meeker (1993) give an updated literature survey and provide methods which use the degradation data to estimate the failure time distribution. For fluorescent lamps, failure has been traditionally defined in terms of the amount of degradation in their luminosity or luminous flux. Consequently, collecting degradation data is a natural approach to take. Note that the literature has focused on estimating existing reliability rather than improving it as is presented in this paper.

This paper's main purpose is to describe how a designed experiment which collected degradation data was used to improve the reliability of fluorescent lamps. The paper is organized as follows. First, we provide some background information. A description of the manufacturing process shows that there are potentially many factors that can affect the fluorescent lamp reliability. A discussion of the modeling and use of degradation is given next. Details of the experimental plan are then given which include the design for the experimental factors and the inspection plan for collecting the degradation data. The experimental data are analyzed next to identify the important factors affecting reliability. Recommendations based on the experiment's results suggest that nearly a 70% improvement can be realized. The paper concludes with a discussion.

## Background

First, we describe the components of a fluorescent lamp and then the manufacturing process that produces it. Fluorescent lamps consist of the following components as illustrated in Figure 1:

- Source of electric discharge which includes a stem, exhaustive vent, filament (cathode) and auxiliary anode.
- A luminous frame which includes a fluorescent tube, base and base pins.
- The mercury vapor and argon which fills the fluorescent tube.

*** Figure 1 about here ***

Fluorescent lamps work on the principle of electric-luminescence. That is, light is generated as follows: (1) The filament discharges electrons when current is applied. (2) The kinetic energy generated by electrons excites the mercury vapor and argon which releases ultraviolet light. There are many different kinds of ultraviolet light such as 1048 Å (Ångströms), 1067 Å and 2537 Å etc., all of which are invisible. (3) The ultraviolet light excites the fluorescent material adhered to the inside of the fluorescent tube which releases visible light ( 3600 Å $\sim$ 7200 Å ).

The manufacturing process of fluorescent lamps is a well-known technology and consists of seven main steps (Lin 1976):

1. Glass Tube Production

   This step fabricates the fluorescent tube made out of soda-lime glass and the stem and exhaustive vent which are both made out of lead glass.

2. Coating and Baking Processes

   The fluorescent tube is coated with a mixture of solid fluorescent material and a water soluble binder. The baking process removes the binder leaving the solid adhered to the inside of the tube.

3. Production of the Electric Discharge Mechanism

   The electric discharge mechanism consists of a stem tube, exhaustive tube, lead wire, filament and an electric discharge material (e.g., of Barium oxide ($BaO$) is often used). A mounting machine assembles the mount consisting of a filament, exhaustive vent and lead wires. The electric discharge material, which assists the filament in exciting electrons, cannot be adhered directly to the filament, however. In this step, the filament is coated with Barium Carbonate ($BaCO_3$); $BaO$ is obtained in the next step.

4. Exhaustive Process

   An electric current is passed through the filament which elevates the temperature around the filament referred to as the exhaustive temperature. Under the exhaustive temperature which is controlled entirely by the amount of electric current, $CO_2$ is removed from the $BaCO_3$ coating leaving the oxide $BaO$.

5. Mercury Dispenser Coating Process

   The auxiliary anode is coated with a mercury dispenser. The dispenser, heated from outside the fluorescent tube, releases mercury vapor which completely fills the fluorescent tube. The mercury vapor excites ultraviolet light which at 2537 Å is the most efficient exciting light for the fluorescent material.

6. Argon Filling Process

   The final step fills the fluorescent tube with argon. The argon assists the filament in discharging electricity, thereby preventing excessive electricity to build up. Also, the argon helps to prevent the $BaO$ from wearing out.

7. Inspection Process
   All finished lamps are inspected. A lamp after 100 hours use is declared non-defective if its output luminous flux under an input voltage of 110 volts exceeds 2500 lumen.

## The Use and Modeling of Luminosity Degradation

A key quality characteristic of fluorescent lamps is its luminosity or luminous flux measured in lumens. Because it degrades over time as the fluorescent material darkens, failure has traditionally been defined in terms of the amount of degradation in the luminous flux. More specifically, a lamp fails at time $t$ when the luminous flux $\Lambda(t)$ falls below 60% of luminous flux after 100 hours of use or aging, i.e., $0.6\Lambda(100)$.

Based on Lin (1976), a model for luminous flux $\Lambda(t)$ at time $t$ is:

$$\ln \Lambda(t) = \theta + \lambda t \tag{1}$$

The parameters $\theta$ and $\lambda$ are the initial luminous flux and rate of degradation, respectively. Using Equation (1), the failure time $t$ is:

$$(\ln 0.6/\lambda) + 100 \ . \tag{2}$$

See Figure 2a which depicts the luminous flux degradation path for a single lamp as given by the dotted line. The solid horizontal line at $\ln(0.6\Lambda(100))$ is the amount of luminous flux at failure (on the log scale) whose failure time of 18651 is indicated by the dashed vertical line.

***Figure 2 about here ***

Since all lamps do not fail at the same time, i.e., the failure times follow some distribution, Equation (2) implies that the rate of degradation $\lambda$ must be a random variable. As in Lu and Meeker (1993) who derive the distribution under various models, it can be shown that if $\lambda$ has a lognormal distribution then the failure time $T$ also has a lognormal distribution, one of the commonly used failure time distributions. Figure 2b shows the degradation paths of 100 randomly sampled lamps with a lognormally distributed $\lambda$ and constant $\theta$ which are plotted until failure. Figure 2c presents a histogram of the 100 lognormally distributed failure times which shows the skewness of the lognormal distribution.

To see that the model in Equation (1) might be reasonable for fluorescent lamps, see Figure 3 which displays the sample luminous flux degradation paths of four groups of five lamps tested in the experiment which will described next.

***Figure 3 about here ***

## The Experimental Plan

The previous section discussed the relation between the failure of fluorescent lamps and their degradation of luminous flux associated with the darkening of the fluorescent material. Three explanations for the darkening are: (1) the electric discharge material wears out; (2) oxidation of the electric discharge material and (3) diffusion of impurities arising in the manufacturing process. From the description of the seven-step manufacturing process, there are many factors that could potentially affect the reliability of fluorescent lamps. Based on the project engineer's experience, the following factors were chosen to be studied in the experiment:

- the amount of electric current (*Factor A*) in the exhaustive process
- the concentration of the mercury dispenser (*Factor B*) in the mercury dispenser coating process
- the concentration of argon (*Factor C*) in the argon filling process

It was then decided to study each factor at two levels denoted by $(-, +)$ and referred to as the (low, high) settings. The two settings represent: the range in which the electric current in amperes is typically controlled; the region in which the concentration of the mercury dispenser in milligrams is usually set and the range in which the ideal concentration of argon in Torrs is thought to be. The actual settings are not given here because they are proprietary information.

In order to study three two-level factors completely, a $2^3$ full factorial design with eight runs (experiments) is required. Because of limited resources allocated to the study, however, only four runs could be done so that the $2^{(3-1)}$ fractional factorial design given in Table 1 was chosen as the design for the experimental factors. Thus, four different types of lamps were manufactured for the study.

Table 1. $2^{(3-1)}$ Fractional Factorial Design for the Fluorescent Lamp Experiment

| | Factors | | |
|---|---|---|---|
| | *A* | *B* | *C* |
| Run | Current | Mercury | Argon |
| 1 | − | − | − |
| 2 | − | + | + |
| 3 | + | − | + |
| 4 | + | + | − |

From a production run of each lamp type, five lamps were randomly selected for testing. The luminous flux (in lumens) of each of the 20 lamps was recorded by an engineer at 100, 500, 1000, 2000, 3000, 40000, 5000 and 6000 hours. The readings were recorded by the same engineer using the same test equipment. Note that fluorescent lamps require a 100 hour burn-in (about 4 days) based on the Chinese National Standard for fluorescent lamps. The reading at 500 hours is useful to detect "abnormal variation". Theoretically, the output luminous flux should degrade stably after 1000 hours used. Therefore, the readings were recorded only at 1000 hour intervals up to 6000 hours. Because of the testing equipment's availability, readings for lamps from Runs 2 and 4 continued to be taken up to 12000 hours at 1000 hours interval. Figure 3 displays the luminous flux measurements of the five lamps for each of the four runs in the experiment.

## Analysis of the Data

The analysis of the data consisted of two parts:

(I) For each lamp, the luminous flux degradation was modeled and used to to predict the lamp's failure time.

(II) The predicted failure times from (I) were analyzed to identify which of experimental factors are important. Then settings for the important factors that give reliability gains were recommended.

### Modeling Degradation

Using the observed luminous flux readings $L(t)$ as shown in Figure 3, the degradation path for each lamp is fit using the following model based on the model for $\Lambda(t)$ from Equation (1):

$$\ln L(t) = \ln \Lambda(t) + \varepsilon = \theta + \lambda t + \varepsilon \ , \qquad (3)$$

where $\varepsilon$ is the measurement error term assumed to follow a normal distribution $N(0, \sigma_\varepsilon^2)$. This simple linear regression model (3) is fit to the measurements after 1000 hours since Figure 3 shows a more stable degradation pattern after that time. The maximum likelihood estimates (MLEs) (which are the same as least squares estimates) for $\theta$ and $\lambda$ are presented in Table 2, columns 3 and 4. Residual plots (not given here) show that the model fits well and the normality assumption is reasonable. More importantly, the residual standard errors of the 20 lamps do not exceed 0.007, which indicates the measurement error is very small.

Because of the small measurement error, we simply predict the lifetime of each lamp using the MLEs of $\theta$ and $\lambda$ as follows:

$$\hat{t_{ij}} = \frac{1}{\hat{\lambda}}(\ln(0.6L(100)) - \hat{\theta}) \qquad (4)$$

Equation (1) was used directly instead of Equation (2) since the model in Equation (3) was fit to the measurements after 1000 hours. The predicted lifetimes for the 20 lamps are given in column 5 of Table 2 which are denoted by $\hat{t_{ij}}$, where i indicates the run and j the lamp number.

Table 2. MLEs of Degradation Model, Predicted Lifetimes and Location-Scale Parameters of the Log Lifetime Distribution

| Run | Lamp No. | $\hat{\theta}$ | $-\hat{\lambda}$ $(10^{-5})$ | $\hat{t}_{ij}$ | $\hat{\mu}_i$ | $\hat{\sigma}_i$ $(10^{-2})$ |
|---|---|---|---|---|---|---|
|  | 1 | 7.8440 | 3.10 | 14762.98 |  |  |
|  | 2 | 7.8279 | 2.68 | 16145.74 |  |  |
| 1 | 3 | 7.8490 | 3.38 | 13429.86 | 9.53 | 10.07 |
|  | 4 | 7.8375 | 3.34 | 12941.79 |  |  |
|  | 5 | 7.8697 | 3.75 | 12127.27 |  |  |
|  | 6 | 7.8488 | 1.66 | 26380.14 |  |  |
|  | 7 | 7.8565 | 1.84 | 22860.88 |  |  |
| 2 | 8 | 7.8374 | 1.64 | 24436.63 | 10.04 | 9.70 |
|  | 9 | 7.8408 | 2.04 | 20694.20 |  |  |
|  | 10 | 7.8497 | 2.16 | 20468.02 |  |  |
|  | 11 | 7.8865 | 3.28 | 15028.19 |  |  |
|  | 12 | 7.8578 | 2.99 | 15914.50 |  |  |
| 3 | 13 | 7.8786 | 3.46 | 13708.69 | 9.67 | 9.18 |
|  | 14 | 7.8657 | 2.73 | 17285.64 |  |  |
|  | 15 | 7.8722 | 2.66 | 17578.56 |  |  |
|  | 16 | 7.8691 | 2.05 | 20349.38 |  |  |
|  | 17 | 7.8456 | 3.01 | 15000.83 |  |  |
| 4 | 18 | 7.9387 | 2.61 | 17600.54 | 9.81 | 10.56 |
|  | 19 | 7.9218 | 2.34 | 19395.51 |  |  |
|  | 20 | 7.9265 | 2.45 | 18746.54 |  |  |

### Identifying the Important Factors

Next we use the predicted lifetimes $\hat{t}_{ij}$ to identify the important manufacturing factors that affect lamp reliability. Previously, a rationale was given for the lifetimes being lognormally distributed. The lognormal probability plot in Figure 4 shows that the the lognormal distribution reasonably fits the predicted lifetimes, i.e., the logged lifetimes follow a normal distribution. For convenience, let $(\mu_i, \sigma_i)$ denote the normal location and scale parameters of the logged lifetimes at run i. Columns 6 and 7 of Table 2 give the MLEs $(\hat{\mu}_i, \hat{\sigma}_i)$. Using Bartlett's test, the hypothesis of equal $\sigma's$ $(H_0 : \sigma = \sigma_1 = \sigma_2 = \sigma_3 = \sigma_4)$ is not rejected at a significance level of 0.05. Consequently, standard methods for analyzing fractional factorial designs can be applied to the logged predicted lifetimes to identify the important factors.

*** Figure 4 about here ***

Table 3 summarizes the information from Tables 1 and 2 and presents estimates and 95% confidence intervals (CIs) for the three main effects of factors $A$, $B$ and $C$. These results suggest that only factors $B$ and $C$ are important and that reliability can be improved by setting them to their high levels (+,+). $A$ is set at its low level (-), the factor's original setting. The estimated mean lifetime at these recommended levels is 23000 hours. The estimated mean lifetime at the original process settings (all at their low levels) is 13800 hours, so that reliability can be improved by 67% at the recommended settings. The unit manufacturing cost at the recommended settings will increase about 10%, however.

Table 3. Main Effects Estimates and 95% Confidence Intervals

| Run | $A$ | $B$ | $C$ | $\hat{\mu}_i$ |
|---|---|---|---|---|
| 1 | − | − | − | 9.533 |
| 2 | − | + | + | 10.037 |
| 3 | + | − | + | 9.670 |
| 4 | + | + | − | 9.805 |
| Main effect | − 0.0477 | 0.3193 | 0.1846 | |
| (95% CI) | (-0.1526,0.0572) | (0.2144,0.4242) | (0.0797,0.2895) | |

## Discussion

"Reliability improvement" is an effective strategy for enhancing a product's competitive position in the market. This case study illustrates how designed experiments can be used proactively to improve reliability. Degradation data is an interesting feature of the experiment which was collected out of necessity. For an already highly reliable product, collecting failure time data is infeasible. When testing was stopped, which required a considerable amount of time, none of the units had failed and none were close to failing. The analysis of the degradation in this case was relatively simple because the measurement error was so small that it could be ignored in analyzing the predicted lifetimes. When the opposite is true, the methods in Lu and Meeker (1993) can be applied. Also, the logged predicted lifetimes had a normal distribution with constant standard deviation so that standard methods for analyzing fractional factorial experiments could be used. This case study shows how the results from a simple four run design can be used to improve reliability. The recommended settings are different than the original settings and have now been implemented. Of course, it will take some time to confirm the experiment's findings. This approach can be easily extended to other high technology products such as Light Emitting Diodes (LED) and Liquid Crystal Display (LCD), etc.

## Acknowledgements

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## List of Figures and Titles

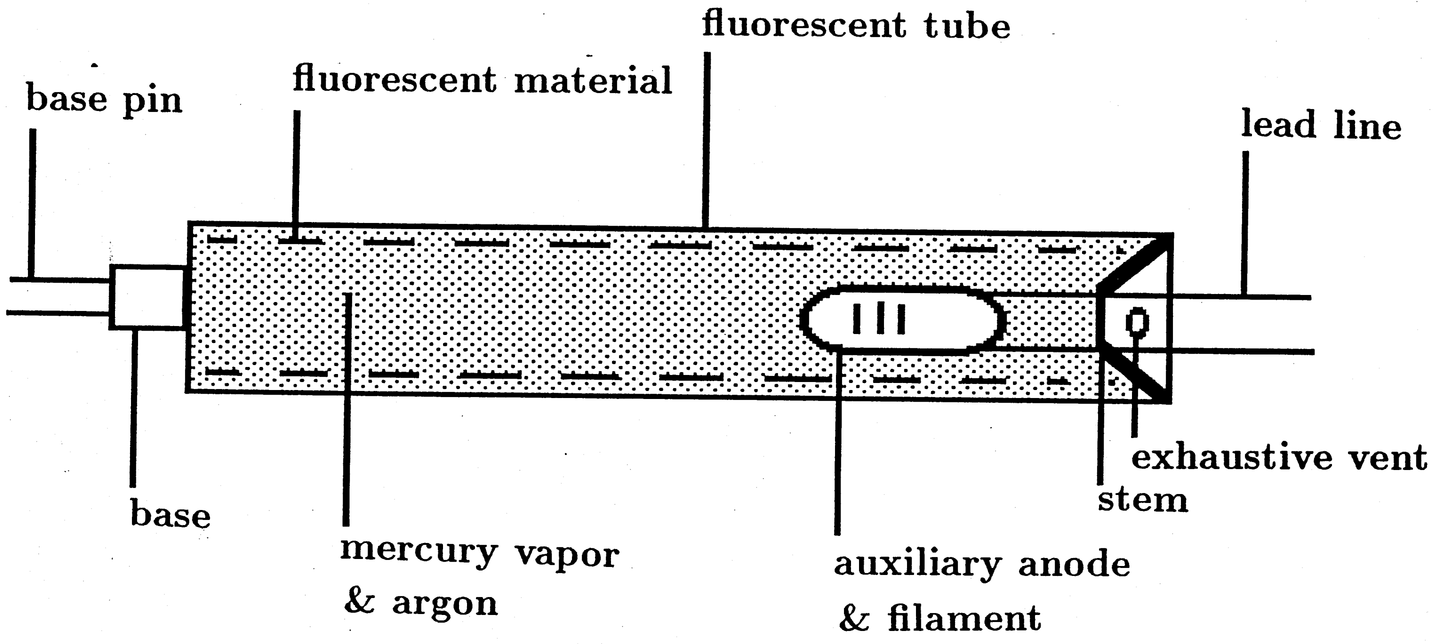
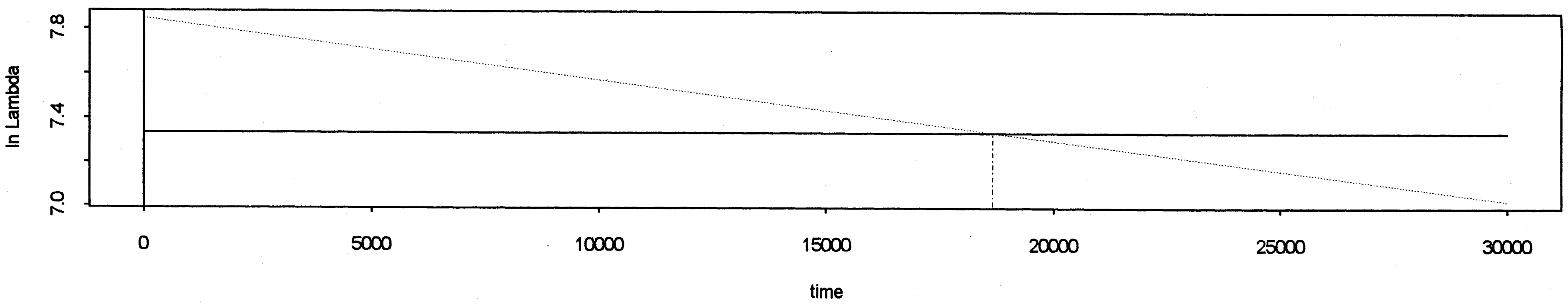
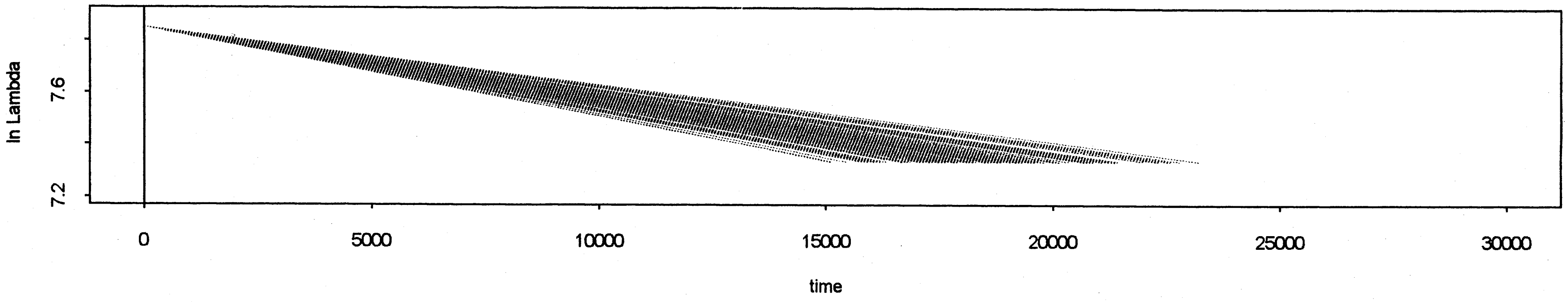


Figure 1. The Fluorescent Lamp Assembly

(a) Lifetime for a Single Lamp



(b) Lifetimes for 100 Lamps



(c) Histogram of 100 Lamp Lifetimes

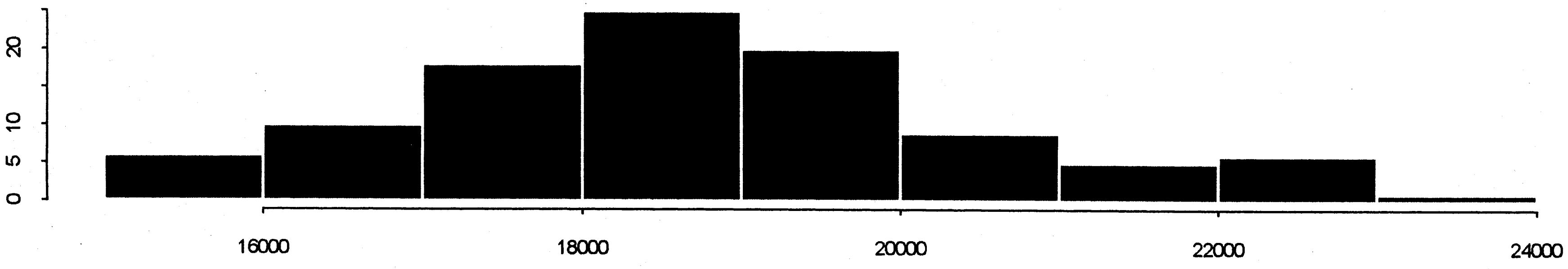


Figure 2. The Relationship between Degradation and Failure Time

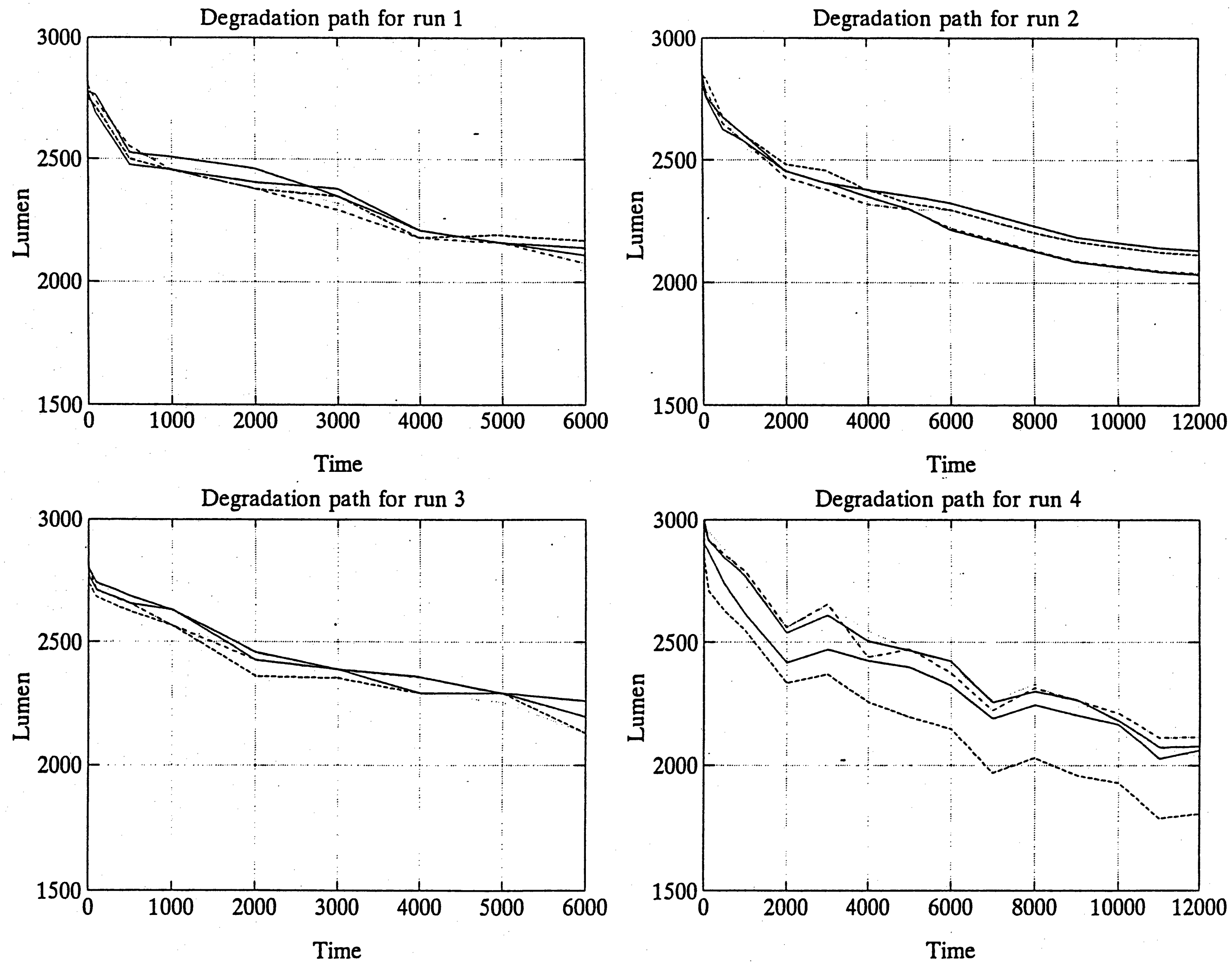


Figure 3. Sample Degradation Paths from Fluorescent Lamp Experiment

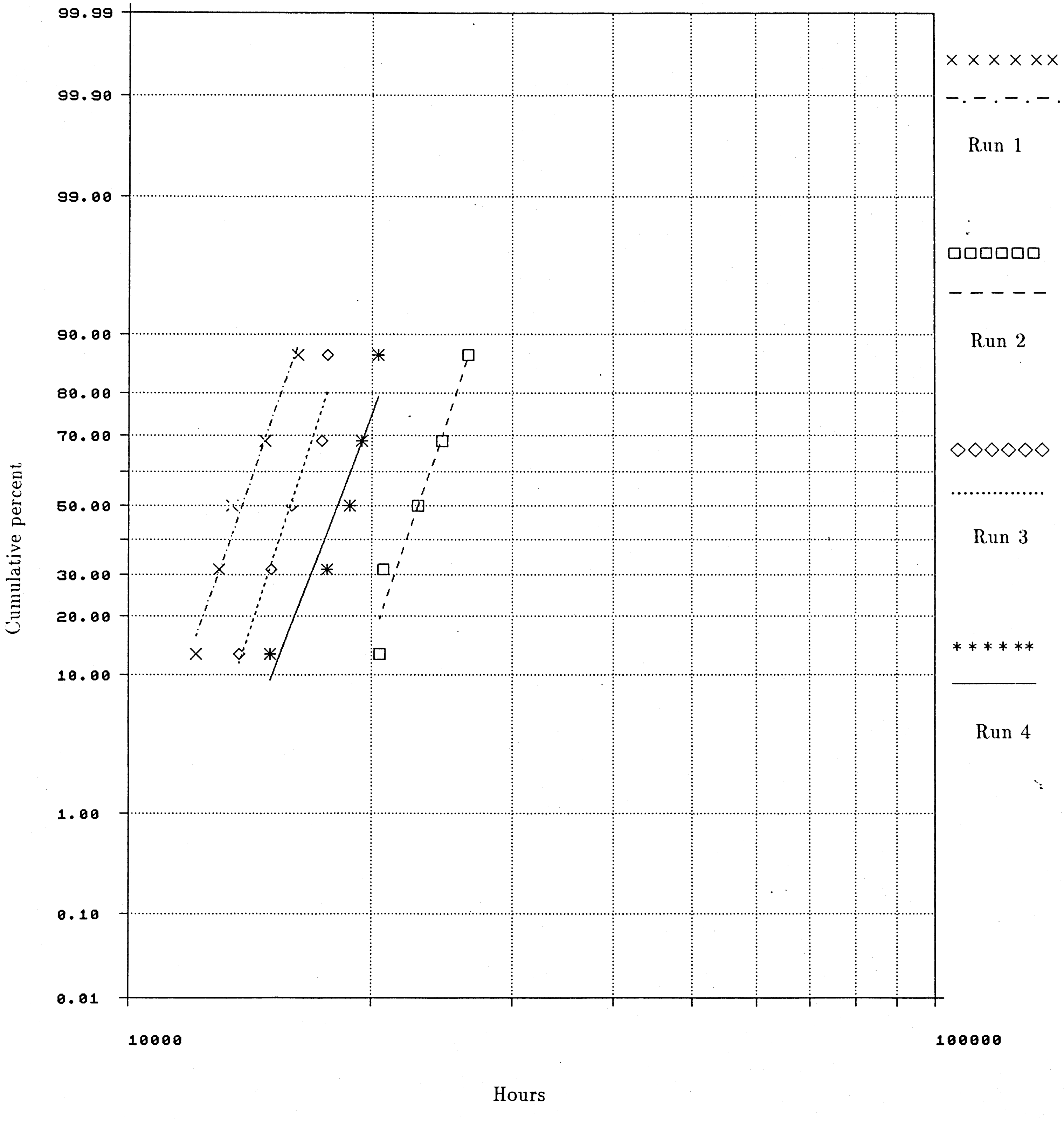


**Figure 4. Lognormal Probability Plot of Predicted Lifetimes**