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Standard Guide for Statistical Analysis of Accelerated Service Life Data[1]

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1. Scope

1.1 This guide describes general statistical methods for analyses of accelerated service life data. It provides a common terminology and a common methodology for calculating a quantitative estimate of functional service life.

1.2 This guide covers the application of two general models for determining service life distribution at usage condition. The Arrhenius model serves as a general model where a single stress variable, specifically temperature, affects the service life. It also covers the Eyring Model for applications where multiple stress variables act simultaneously to affect the service life.

1.3 This guide emphasizes the use of the Weibull life distribution and is written to be used in combination with Guide G166.

1.4 The uncertainty and reliability of every accelerated service life model becomes more critical as the number of stress variables increases and the extent of extrapolation from the accelerated stress levels to the usage level increases, or both. The models and methodology used in this guide are to provide examples of data analysis techniques only. The fundamental requirements of proper variable selection and measurement must still be met by the users for a meaningful model to result.

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

G166 Guide for Statistical Analysis of Service Life Data

3. Terminology

3.1 *Terms Commonly Used in Service Life Estimation:*

3.1.1 *accelerated stress, n*—a stress variable, such as temperature or irradiance, applied to the test material at levels intensified over those encountered in the service environment.

3.1.2 *F(t), n*—the probability that a random unit drawn from the population will fail by time (t).

3.1.2.1 *Discussion*—Also $F(t)$ = the decimal fraction of units in the population that will fail by time (t). The decimal fraction multiplied by 100 is numerically equal to the percent failure by time (t).

3.1.3 *usage stress, n*—the level of the experimental variable that is considered to represent the stress occurring in normal use.

3.1.3.1 *Discussion*—This value must be determined quantitatively for accurate estimates to be made. In actual practice, usage stress may be highly variable, such as those encountered in outdoor environments.

3.1.4 *Weibull distribution, n*—for the purposes of this guide, the Weibull distribution is represented by the equation:

$$F(t) = 1 - e^{-\left(\frac{t}{c}\right)^b} \tag{1}$$

where:

$F(t)$ = probability of failure by time (t) as defined in 3.1.2,
t = units of time used for service life,
c = scale parameter, and
b = shape parameter.

3.1.4.1 *Discussion*—The shape parameter (b), 3.1.4, is so called because this parameter determines the overall shape of the curve. Examples of the effect of this parameter on the distribution curve are shown in Fig. 1.

3.1.4.2 *Discussion*—The scale parameter (c), 3.1.4, is so called because it positions the distribution along the scale of the time axis. It is equal to the time for 63.2 % failure.

NOTE 1—This is arrived at by allowing t to equal c in Eq 1. This then reduces to Failure Probability = $1 - e^{-1}$, which further reduces to equal 1 – 0.368 or 0.632.

4. Significance and Use

4.1 The nature of accelerated service life estimation normally requires that stresses higher than those experienced during service conditions are applied to the material being

[1] This guide is under the jurisdiction of ASTM Committee G03 on Weathering and Durability and is the direct responsibility of Subcommittee G03.08 on Service Life Prediction.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

Distribution Curves for Various Values of Shape Parameters

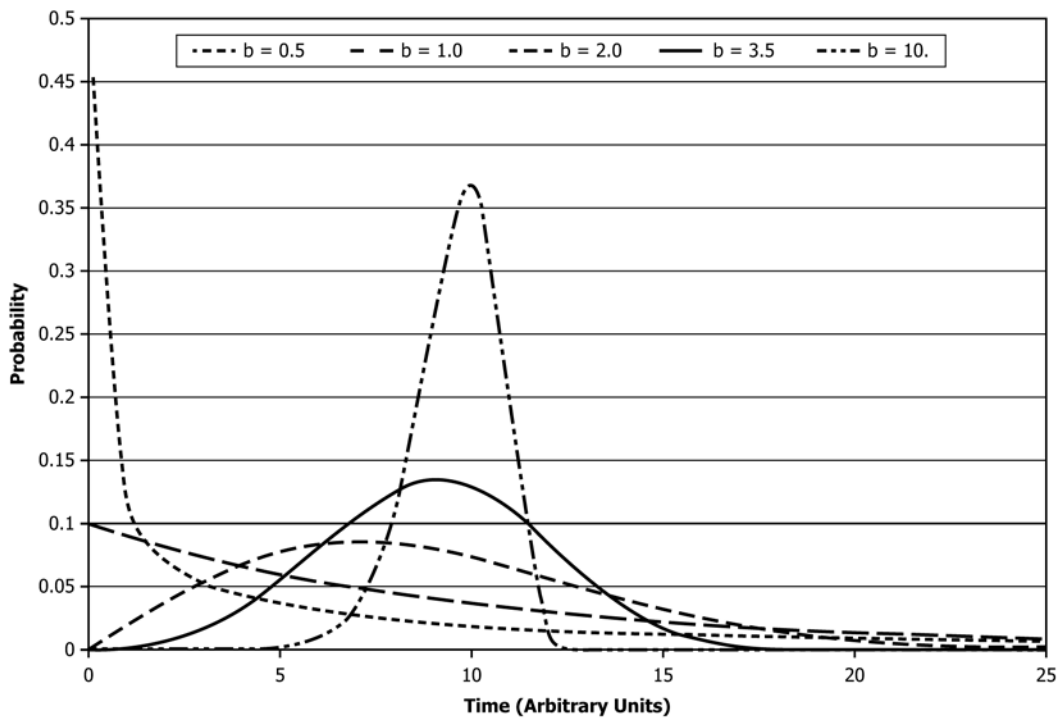

FIG. 1 Effect of the Shape Parameter (b) on the Weibull Probability Density

evaluated. For non-constant use stress, such as experienced by time varying weather outdoors, it may in fact be useful to choose an accelerated stress fixed at a level slightly lower than (say 90 % of) the maximum experienced outdoors. By controlling all variables other than the one used for accelerating degradation, one may model the expected effect of that variable at normal, or usage conditions. If laboratory accelerated test devices are used, it is essential to provide precise control of the variables used in order to obtain useful information for service life prediction. It is assumed that the same failure mechanism operating at the higher stress is also the life determining mechanism at the usage stress. It must be noted that the validity of this assumption is crucial to the validity of the final estimate.

4.2 Accelerated service life test data often show different distribution shapes than many other types of data. This is due to the effects of measurement error (typically normally distributed), combined with those unique effects which skew service life data towards early failure time (infant mortality failures) or late failure times (aging or wear-out failures). Applications of the principles in this guide can be helpful in allowing investigators to interpret such data.

4.3 The choice and use of a particular acceleration model and life distribution model should be based primarily on how well it fits the data and whether it leads to reasonable projections when extrapolating beyond the range of data. Further justification for selecting models should be based on theoretical considerations.

NOTE 2—Accelerated service life or reliability data analysis packages are becoming more readily available in common computer software packages. This makes data reduction and analyses more directly accessible to a growing number of investigators. This is not necessarily a good thing as the ability to perform the mathematical calculation, without the fundamental understanding of the mechanics may produce some serious errors.[3]

5. Data Analysis

5.1 *Overview*—It is critical to the accuracy of Service Life Prediction estimates based on accelerated tests that the failure mechanism operating at the accelerated stress be the same as that acting at usage stress. Increasing stress(es), such as temperature, to high levels may introduce errors due to several factors. These include, but are not limited to, a change of failure mechanism; changes in physical state, such as change from the solid to glassy state; separation of homogenous materials into two or more components; migration of stabilizers or plasticisers within the material; thermal decomposition of unstable components; and formation of new materials which may react differently from the original material.

5.2 A variety of factors act to produce deviations from the expected values. These factors may be of purely a random nature and act to either increase or decrease service life depending on the magnitude and nature of the effect of the factor. The purity of a lubricant is an example of one such factor. An oil clean and free of abrasives and corrosive materials would be expected to prolong the service life of a moving part subject to wear. A contaminated oil might prove to be harmful and thereby shorten service life. Purely random variation in an aging factor that can either help or harm a

[3] Hahn, G. J., and Meeker, W. Q., "Pitfalls and Practical Considerations in Product Life Analysis—Part I: Basics Concepts and Dangers of Extrapolation," *Journal of Quality Technology*, Vol 14, July 1982, pp. 144-152.

service life might lead to a normal, or gaussian, distribution. Such distributions are symmetrical about a central tendency, usually the mean.

5.2.1 Some non-random factors act to skew service life distributions. Defects are generally thought of as factors that can only decrease service life (that is, monotonically decreasing performance). Thin spots in protective coatings, nicks in extruded wires, and chemical contamination in thin metallic films are examples of such defects that can cause an overall failure even though the bulk of the material is far from failure. These factors skew the service life distribution towards early failure times.

5.2.2 Factors that skew service life towards greater times also exist. Preventive maintenance on a test material, high quality raw materials, reduced impurities, and inhibitors or other additives are such factors. These factors produce lifetime distributions shifted towards increased longevity and are those typically found in products having a relatively long production history.

5.3 *Failure Distribution*—There are two main elements to the data analysis for Accelerated Service Life Predictions. The first element is determining a mathematical description of the life time distribution as a function of time. The Weibull distribution has been found to be the most generally useful. As Weibull parameter estimations are treated in some detail in Guide G166, they will not be covered in depth here. It is the intention of this guide that it be used in conjunction with Guide G166. The methodology presented herein demonstrates how to integrate the information from Guide G166 with accelerated test data. This integration permits estimates of service life to be made with greater precision and accuracy as well as in less time than would be required if the effect of stress were not accelerated. Confirmation of the accelerated model should be made from field data or data collected at typical usage conditions.

5.3.1 Establishing, in an accelerated time frame, a description of the distribution of frequency (or probability) of failure versus time in service is the objective of this guide. Determination of the shape of this distribution as well as its position along the time scale axis is the principal criteria for estimating service life.

5.4 *Acceleration Model*—The most common model for single variable accelerations is the Arrhenius model. It was determined empirically from observations made by the Swedish scientist S. A. Arrhenius. As it is one that is often encountered in accelerated testing, it will be used as the fundamental model for single variables accelerations in this guide.

5.4.1 Although the Arrhenius model is commonly used, it should not be considered to be a basic scientific law, nor to necessarily apply to all systems. Application of the principles of this guide will increase the confidence of the data analyst regarding the suitability of such a model. There are many instances where its suitability is questionable. Biological systems are not expected to fit this model, nor are systems that undergo a change of phase or a change of mechanism between the usage and some experimental levels.

5.4.2 The Arrhenius model has, however, been found to be of widespread utility and the accuracy has been verified in some systems. Wherever possible, confirmation of the accuracy of the accelerated model should be verified by actual usage data. The form of the equation most often encountered is:

$$\text{Rate} = Ae^{-\Delta H/kT} \tag{2}$$

where:

A = pre-exponential factor and is characteristic of the product failure mechanism and test conditions,
T = absolute temperature in Kelvin (K),
ΔH = activation energy. For the sake of consistency with many references contained in this guide, the symbol ΔH is used. In other recent texts, it has become a common practice to use E for the activation energy parameter. Either symbol is correct, and
k = Boltzmann's constant. Any of several different equivalent values for this constant can be used depending on the units appropriate for the specific situation. Three commonly used values are: (*1*) 8.617×10^{-5} eV/K, (*2*) 1.380×10^{-18} ergs/K, and (*3*) 0.002 kcal/mole·K.

5.4.3 The rate may be that of any reasonable parameter that one wishes to model at accelerated conditions and relate to usage conditions. It could be the rate in color change units per month, gloss loss units per year, crack growth in mm's per year, degree of chalking per year, and so forth. It could also be the amount of corrosion penetration per hour, or byte error growth rate on data storage disks.

5.4.4 Because the purpose of this guide is to model service life, the Eq 2 may be rewritten to express the Arrhenius model in terms of time rather than rate. As time and rate are inversely related, the new expression is formed by changing the sign of the exponent so that the time, *t*, is:

$$\text{Time} = A'e^{\Delta H/kT} \tag{3}$$

5.4.5 The time element used in the Eq 3 is arbitrary. It can be the time for the first 5 % failure, time for average failure, time for 63.2 % failure, time for 95 % failure, or any other representation that would suit the particular application.

5.4.6 Because Guide G166 emphasizes the utility of the Weibull distribution model, it will be used for the rest of the discussion in this guide as well. Should a different distribution model fit a particular application, simple adjustments permit their use. Therefore, by setting the value for time in the above expression to be the time for 63.3 % failure, the model will predict the scale parameter for the Weibull distribution at the usage stress.

5.4.7 The Weibull model, as given in Eq 1, is also expressed as a function of time. We can, therefore, relate the Weibull distribution model to the Arrhenius acceleration model by:

$$1 - e^{-\left(\frac{t}{c}\right)^b} = Ae^{\Delta H/kT} = F(t) \tag{4}$$

5.4.8 By determining the Weibull shape and scale parameters at temperatures above the expected service temperature, and relating these parameters with the Arrhenius model, one may determine an expression to estimate these parameters at usage condition. This integration of the Weibull parameters and an acceleration model such as Arrhenius forms the fundamental structure of this guide.

6. Accelerated Service Life Model—Single Variable

6.1 For the purposes of this discussion, the accelerating stress variable is assumed to be temperature. This is generally true for most systems and is the stress most frequently used in the Arrhenius model. Other ones, such as voltage, may work as well.

6.2 *Temperature Selection*—One of the critical points used in Accelerated Service Life modeling is the choice of the number and levels of the accelerating stress. Theoretically, it takes only two levels of stress to develop a linear model and extrapolate to usage conditions. This does not provide any insight into the degree of linearity, or goodness of fit, of the model. At least three levels of the accelerating stress are necessary to determine an estimate of linearity. These should be chosen such that one can reasonably expect to obtain good estimates for the shape and scale parameters of the Weibull model at the lowest stress temperature and within the allowable time for the experiment.

6.2.1 If the service life of the material is expected to be on the order of years at 25 °C, and the time available to collect supporting data is on the order of months, then the lowest temperature chosen might be 60 °C. This would reasonably be expected to produce sufficient failures to model the Weibull distribution within the allotted time frame. This is only used as an example. The temperature is system dependent and will vary for each material evaluated.

6.2.2 The highest temperature chosen is one that should allow one to accurately measure the time to failure of each specimen under test. If the selected upper temperature is too high, then all or nearly all of the test specimens may fail before the first test measurement interval. More importantly, if the highest temperature level produces a change in degradation mechanism, the model is not valid.

6.3 *Specimen Distribution*—Whenever the cost of specimens or the cost of analysis is a significant factor, a non-uniform distribution of specimens is recommended over having the same number of specimens at each temperature. The reasons for this are:

6.3.1 Use of more specimens at lower temperatures, compared to the number used at higher temperatures, increases the chance of obtaining sufficient failures within the allotted time for the experiment and improves the accuracy of extrapolation to the usage condition.

6.3.2 If three evenly spaced temperatures are chosen for the number of stress levels, and there are *x* specimens available for the experiment then place x/7 at the high temperature, 2x/7 at the mid temperature, and 4x/7 at the lowest temperature. This is only a first order guide.[4] If the cost of specimens and analysis are not significant, then a more even distribution among the stress conditions may be appropriate.

7. Service Life Estimation

7.1 Guide G166 may be consulted for methods which may be employed to estimate the service life of a material.

[4] Meeker, W. Q., and Hahn, G. J., "How to Plan an Accelerated Life Test," *ASQC Basic References*, 10, 1985.

8. Example Calculations—Single Accelerating Variable of Temperature, Weibull Distribution

8.1 Determine Weibull scale and shape parameters for failure times at each accelerated temperature.

8.1.1 Consider a hypothetical case where 55 adhesive coated strips are placed on test. This particular adhesive is one that exhibits a characteristic of thermal degradation resulting in sudden failure from stress. The specimens are divided into three groups with one group being placed in an oven at 80 °C, the second group in an oven at 70 °C, and the third group into an oven at 60 °C. The first group contains 10 specimens, the second group contains 15 specimens, and the third group contains 30 specimens. This approximates the 1X, 2X, 4X ratio cited above.

TABLE 1 Failure Times for Experimental Adhesive, h

80 °C	70 °C	60 °C	
1465	2375	2407	3590
1384	2259	2521	3703
1177	2399	2727	3764
1857	2062	2820	3806
1998	1773	2903	4018
1244	2367	2954	4087
1506	2606	3102	4210
1424	2348	3122	4230
1595	1869	3221	4254
947	2194	3237	4407
	2115	3239	4560
	3240	3398	4525
	1411	3440	4650
	1707	3524	4680
	2522	3557	4850

8.1.2 The time to failure for this application is defined as the time at which the adhesive strip will no longer support a 5 lb load. The test apparatus is constructed with one end of each strip adhered to a test panel and the other end suspending a 5 lb weight. Optical proximity sensors are used to detect when the strip releases from the panel. The times to fail for each individual strip are recorded electronically to the nearest hour. Table 1 is a summary of the times to fail for each individual strip, by temperature.

8.1.3 From these three sets of data, three sets of Weibull parameters are calculated, one for each temperature. Refer to Guide G166 for detailed examples for these calculations. The values determined from the above sets of data are shown in Table 2.

TABLE 2 Summary of Weibull Parameters for the Accelerated Data in Table 1

	80 °C	70 °C	60 °C
Weibull Scale	1580.8	2391.1	3932.9
Weibull Shape	5.39	5.45	6.10

8.2 Plot data on one common Weibull graph.

8.2.1 Graphically display the data before proceeding further with analysis. This simple step allows the analyst to detect abnormal trends, outliers, and any other anomalous behavior of the data. The graph in Fig. 2 shows the three sets of accelerated data displayed on one Weibull axis.

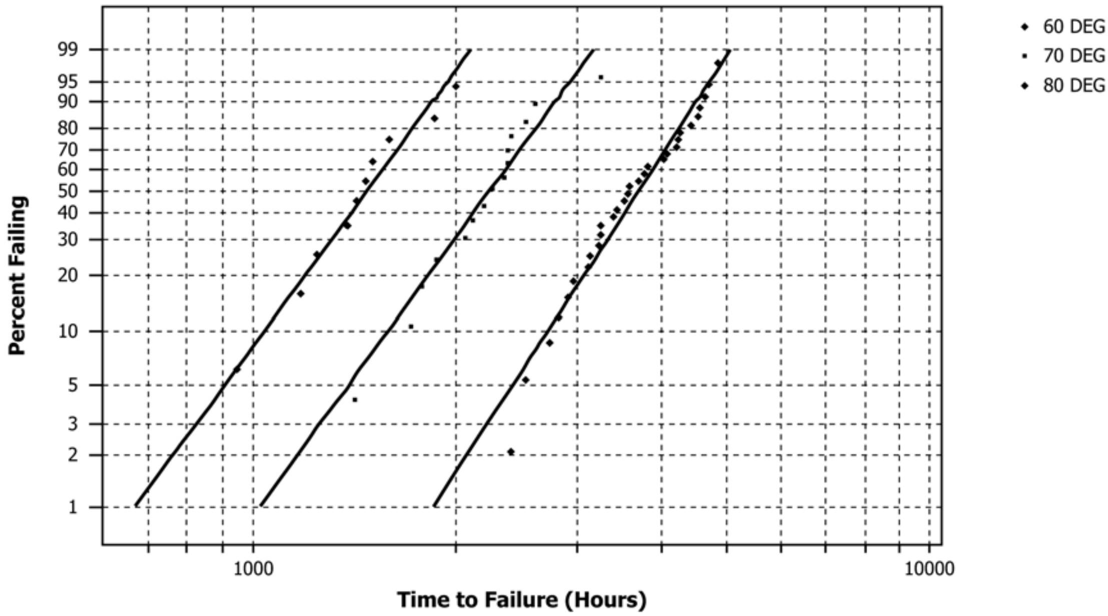

FIG. 2 Weibull Probability Plots for 80 °C, 70 °C, and 60 °C Experimental Adhesive Failure Times, h

8.2.2 From inspection of the graphical display above and the numerical values of the shape parameters in Table 2, it may be seen that the Weibull shapes (slopes of the line) are essentially the same. A significant difference among the shapes may indicate a change in degradation mechanism has occurred. If the shapes are essentially the same, then it is safer to assume that the same mechanism operates at all of the experimental temperatures.

8.2.3 The Weibull scale parameters show a clear trend toward higher values as the temperature decreases. This is what is to be expected if the samples fail sooner at higher temperatures.

8.3 Estimate the Weibull scale parameter at the usage condition.

8.3.1 For the sake of this example, it is assumed that the usage temperature for this tape application is 25 °C. We need then to regress the Weibull scale parameters versus temperature to estimate what the scale would be at 25 °C. To do this, we use Eq 4, which relates the Arrhenius equation to the Weibull scale parameter. By taking the natural logarithm of both sides of the equation, the following is produced:

$$\ln(A') + \Delta H/k \cdot (1/T) = \ln[F(t)] \quad (5)$$

NOTE 3—It doesn't matter whether natural logarithms (ln) or base 10 logarithms (log) are used, only that one is consistent throughout a calculation. Natural logarithms (ln) are chosen here to be consistent with Guide G166.

8.3.2 In this form, we now have the equation for a straight line ($Y = a_{(1)}X + a_{(2)}$) with ln [$F(t)$] representing the dependent variable (Y), $\Delta H/k$ as the slope of the line ($a_{(1)}$), $1/T$ as the independent variable (X), and ln (A') as the intercept ($a_{(2)}$). Simple linear regression of ln [$F(t)$] and $1/T$ will allow us to solve for the slope and intercept. As we have three equations, and only two unknowns, there is ample information for the solution to be found.

8.3.3 *Convert °C to K*—In order to convert °C to K, the constant 273.1 is added to each centigrade temperature. Thus 80 °C becomes 353.1 K, 70 °C becomes 343.1 K, and 60 °C becomes 333.1 K.

8.3.4 *Regression*—Calculation of the reciprocals of Kelvin temperature and the natural logarithm of the Weibull Scale parameters produces the values shown in Table 3.

TABLE 3 Summary of Estimated Weibull Scale Parameters for Experimental Adhesive

Temp. K	1/K	Weibull Scale, h	ln, (Scale, h)
353.1	0.0028321	1580.8	7.3657
343.1	0.0029146	2391.1	7.7795
333.1	0.0030021	3932.9	8.2771

8.3.4.1 Linear regression of the ln (Scale) versus the reciprocal Kelvin temperature produces the following:

ln Scale = −7.83 + 5363 (1/*T* K)

8.3.4.2 As we wish to calculate the Weibull scale parameter at 298.1 K (25 °C) we simply substitute 298.1 for *T* K and solve for ln (Scale). This becomes:

ln (Scale) = −7.83 + 5363 (1/298.1)
ln (Scale) = −7.83 + 17.9906
ln (Scale) = 10.1606
Scale = 25864 h

8.3.4.3 This then translates to the estimate that 63.2 % of the adhesive strips will release by 2.95 years if exposed at 25 °C temperature.

8.3.4.4 A graphical display of the ln(Weibull Scale) versus 1/Temperature K is shown in Fig. 3. It may be seen that the three ln(Weibull Scale) values lie along a straight line when plotted against the reciprocal of the temperature in K. It may

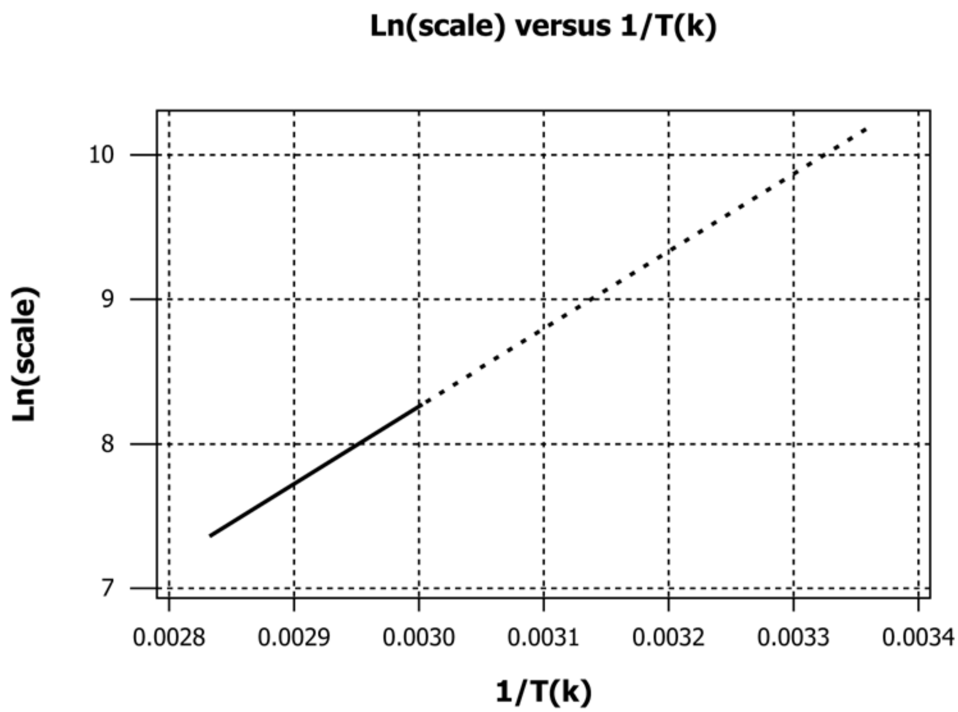

FIG. 3 ln (Weibull Scale) versus 1/T °K for Experimental Adhesive

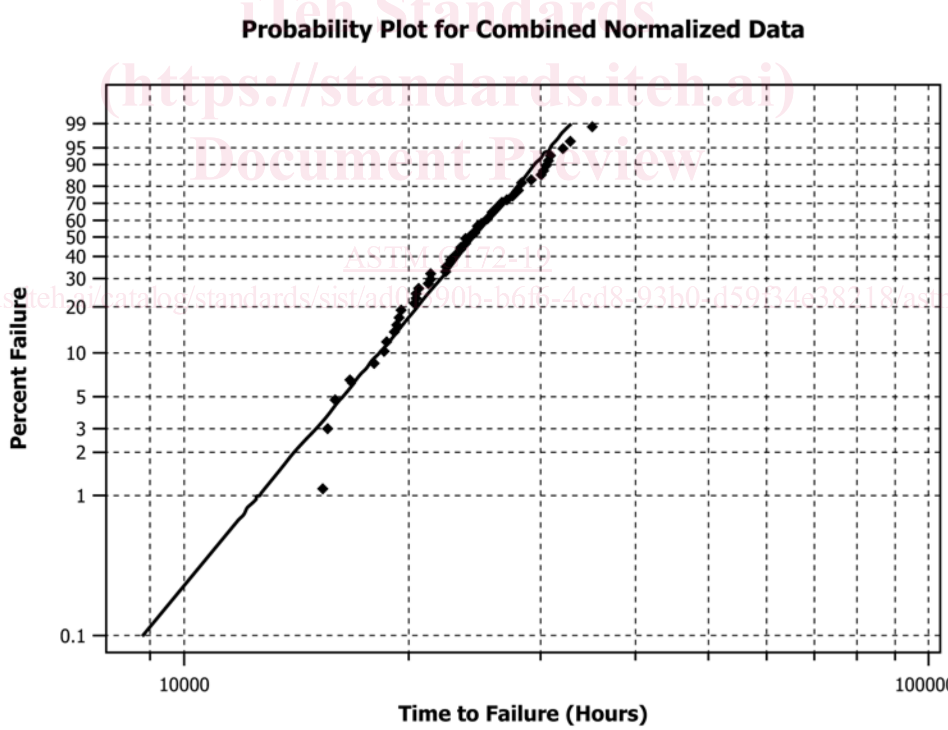

FIG. 4 Combined Normalized Data Plotted on a Single Probability Plot

also be seen that at the value for 1/*T* K for 25 °C (0.003354) the ln(Scale) agrees with the calculated value of 10.1606 above.

8.3.5 *Acceleration Factor*—Acceleration factors must be used with extreme caution. They apply only to the system where the specific data sets have been analyzed. They do not extend to other systems. To calculate the acceleration factor for the example data one needs only to ratio the scale factors. The scale factor at 25 °C is assigned the acceleration factor value of 1 as it is, by definition for this case, the usage condition. By dividing the scale factor at the usage condition by the scale factor at the accelerated condition, the amount of acceleration provided by the higher temperature may be determined. The result of this operation for the example data is shown in Table 4.