DESIGN PREDICTION FOR LONG TERM STRESS RUPTURE SERVICE OF COMPOSITE PRESSURE VESSELS†

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SUMMARY

Extensive stress rupture studies on glass composites and Kevlar composites were conducted by the Lawrence Radiation Laboratory beginning in the late 60s and extending to about 8 years in some cases. Some of the data from these studies published over the years were incomplete or were tainted by spurious failures, such as grip slippage. These data have been carefully resurveyed by cognizant staff. Updated verified data sets have been defined for both fiberglass and Kevlar composite strand test specimens. These updated data are analyzed in this report by a convenient form of the bivariate Weibull distribution, to establish a consistent set of design prediction charts that may be used as a conservative basis for predicting the stress rupture life of composite pressure vessels.

The updated glass composite data exhibit an invariant Weibull modulus with lifetime. The data are analyzed in terms of homologous service load (referenced to the observed median strength). The equations relating life, homologous load, and probability are given, and corresponding design prediction charts are presented. A similar approach is taken for Kevlar composites, where the updated strand data do show a turndown tendency at long life accompanied by a corresponding change (increase) of the Weibull modulus. This turndown characteristic is not present in stress rupture test data of Kevlar pressure vessels. A modification of the stress rupture equations is presented to incorporate a latent, but limited, strength drop, and design prediction charts are presented that incorporate such behavior.

The methods presented utilize Cartesian plots of the probability distributions (which are a more natural display for the design engineer), based on median normalized data that are independent of statistical parameters and are readily defined for any set of test data. A technique is shown for estimating the Weibull modulus from each observed value. The design prediction equations and the corresponding design prediction charts can be set up to provide selected levels of conservatism in those regions where data are sparse or unavailable. Design values based on these single-end data should be conservative for multiple-end roving and massive composite structures like those on pressure vessels.

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INTRODUCTION

The purpose of this report is to provide a useful engineering tool for estimating stress rupture life of S-glass and Kevlar composites subject to long-term tensile stress. The data base is drawn from the extensive 10 year period test program conducted on S-glass and Kevlar single-end composite strands at the Lawrence Livermore National Laboratory (LLNL).

Previously published results of S-glass exhibited a turndown characteristic at long times. This characteristic, when analyzed by a quadratic maximum likelihood method (Ref. 1), produced unrealistic life prediction extrapolation and did not yield realistic and useful long life predictions. The LLNL S-glass data base has recently been subject to a searching re-examination by the cognizant staff (Refs. 2, 3) to eliminate spurious failures such as grip pullouts. These updated data are analyzed here by the Weibull model and tabulated in Appendix A. These data do not exhibit a turndown and are well approximated by invariant Weibull moduli for the life and strength distributions. It should be noted that the stress rupture analysis will produce straight line probability contours on log stress vs log life coordinates if the Weibull moduli for life and strength are invariant with time. The converse is also true.

Convenient analytical methods based on the Weibull model are presented. These methods allow an estimation of the Weibull modulus based on each ranked observation and allow estimation of the population median life based on partial (censored or incomplete) data. The methods of analysis are simple and straightforward, and may be applied in the same fashion to other stress rupture data. The Weibull modulus for S-glass life is $b = 0.9$, based on the updated stress rupture data presented. LLNL measurements of S-glass composite strand strength show scatter with a representative coefficient of variation CV = 0.48+, corresponding with $m = 24.9$, which is used in the tabulated data and design prediction. These parameters for S-glass are used to produce the design chart of Figure 1.

The LLNL Kevlar composite strand data (Ref. 2) are presented in Appendix B. These data show a turndown trend. Kevlar spherical vessel data (Ref. 4) do not show this trend. The Weibull model was modified, as discussed later, to incorporate a strength degradation that develops later in time according to a first-order reaction rate (Ref. 5) with a specific time constant. This model predicts that within the time period where degradation is expected, the Weibull modulus for life should show an apparent increase. That is exactly what the Kevlar strand data show, and this modified form is used to construct a rational design chart that includes a partial degradation ($f = 0.3$) with a time constant $t_c \approx 120{,}000$ hours. The Weibull modulus for Kevlar composite strand life is also $b = 0.9$, while the Weibull modulus for strength is $m \approx 30$, reflecting a typically slightly lower scatter (CV = 0.04) for Kevlar composite strands than for the S-glass strands. The resulting design chart is shown in Figure 2. Over-plotted on this chart are the pressure vessel data, which do not exhibit the turndown and show greater life at the same homologous load.

Published data for carbon fiber composite strands are very sparse (Ref. 6) and extend to shorter times than the S-glass and Kevlar data. Figure 3 is a preliminary design chart, constructed using the indicated parameters, and should be useful for first-order life estimates of carbon composite pressure vessel stress rupture life.

DISCUSSION

The Bivariate Weibull Distribution

An expression for the stress rupture (Ref. 7) of a multifilament strand is given by

$$S = \mathrm{Exp}\, -H\{R,t\}$$

where H is a function of the applied load and time. Assuming the function to be separable and of exponential (power-law) form, it can be expressed as a bivariate form of the well known Weibull distribution function (Ref. 7).

The two-parameter form of the Weibull distribution is given by

$$S = \mathrm{Exp}\ -\{X/X_o\}^m$$

As a matter of convenience, the function is normalized here to the median value X_m, or to any other percentile S_r, X_r, which may be appropriate, as in the case of a partial sample where the median has not yet been reached in the experimental program and is unknown:

$$S = \mathrm{Exp}\ -\ \{\ln(1/S_r)\ (X/X_r)^m\}$$

If the median is known, then $S_r = 0.5$ and the distribution scale parameter becomes the median. From a design engineer's point of view, this is intuitively more meaningful than the Weibull scale parameter X_o, which corresponds with the 63% quantile. Forms of the Weibull distribution that use mean normalized data are more awkward because the quantile of the mean value involves a gamma function of the Weibull modulus (shape parameter):

$$S = \mathrm{Exp}\ -\{\Gamma(1+1/m)(X/X_{avg})\}^m$$

The bivariate Weibull form, normalized to median strength and life, is given by

$$S = \mathrm{Exp}\ -\{\ln(2)\ (R_m)^m (t/t_m)^b\}$$

The symbol R is the homologous load referenced to the median value. This form is used in subsequent discussions for the analysis of the composite stress rupture data.

From Filaments to Composite Structures

The susceptibility of single filaments to stress rupture is invariably more severe than the susceptibility of multifilament strands for several reasons. The filament surface is totally exposed to the surrounding environment; the access of environmental factors such as moisture, air, or radiation is not impeded; and access remains unimpeded throughout the exposure time. The filament failure under these influences is total, i.e., no load can be transmitted after filament failure. The situation is less severe for the multifilament strand, especially if twist is present. Within a multifilament strand, there is some inhibition of diffusion by geometric effects and by the gradual development of internal concentration gradients. Furthermore, individual filament breaks might not lead to load-carrying reduction because frictional coupling and twist act like the matrix of a composite strand. The composite strand is even less susceptible to individual filament rupture failure because the matrix encapsulates the filaments and can offer considerable protection from diffusion and effects of the environments. Consequently, stress rupture experiments show relatively early failure times and turndown characteristics for single filaments and bare strands as compared with composite strands.

When comparing lifetimes at equal homologous loads, still another factor enters that causes the multifilament strands to exhibit longer life. The prevailing stress within the constituent filaments is reduced because the median strength of a multifilament strand is expected to be less than the median strength of single filaments, and the discrepancy increases as the variability of filament strength increases. At the same homologous load, the average filament stress in massive composites is reduced from the single filament or single-end strand.

For these reasons, it is concluded that using single-end composite strands to establish design charts for massive composites, such as filament-wound pressure vessels, will provide an inherently conservative basis for estimation.

ANALYTICAL FORMS

Invariant Weibull Moduli

The median normalized bivariate Weibull equation (Ref. 7) relates load, life, and probability, as shown below:

$$S = \mathrm{Exp} - \left\{ \mathrm{Ln}(2) \left(\frac{\sigma}{\sigma_m} \right)^m \left(\frac{t}{t_m} \right)^b \right\}$$

The equation is the power law form with the underlying linear log-log relation :

$$\left(\frac{\sigma}{\sigma_m} \right)^m \left(\frac{t}{t_m} \right)^b = \left\{ \frac{\mathrm{Ln}\left(\frac{1}{S}\right)}{\mathrm{Ln}(2)} \right\}$$

This relation defines a family of straight lines on log-log coordinates in which the following proportionality holds (where R represents the load fraction of median strength):

$$R^m t^b \ \alpha \ \left\{ \frac{\mathrm{Ln}\left(\frac{1}{S}\right)}{\mathrm{Ln}(2)} \right\}$$

The preceding relations may be used as shown in the following steps to compute desired combinations of load fraction, R, life, t, and survival probability, S. The shape parameters (Weibull moduli) for strength, m, and for life, b, are determined by analysis of experimental strength and life distributions. For example, the LLNL glass data give m = 24.9 and b = 0.9. The procedure to construct the probability, load, life design chart follows.

1. Select a reference set of values from the data or design: R_r , t_r , and S_r (usually S_r = 0.5).
2. Select the load and life Weibull moduli m and b to give desired conservatism for the design chart.
3. Compute the constant K

$$K = \frac{R_r^{\,m} t_r^{\,b} \,\mathrm{Ln}(2)}{\mathrm{Ln}\left(\frac{1}{S_r}\right)}$$

4. Define the general R, t, S relation by

$$R^m t^b = \left[\frac{K \,\mathrm{Ln}\left(\frac{1}{S}\right)}{\mathrm{Ln}(2)} \right]$$

5. Construct the design chart using the log-log form ($S_r = 0.5$)

$$\text{Log}(R) = \text{Log}(R_r) - \frac{b}{m}\text{Log}\left(\frac{t}{t_r}\right) + \left(\frac{1}{m}\right)\text{Log}\left[\frac{\text{Ln}\left(\frac{1}{S}\right)}{\text{Ln}(2)}\right]$$

This equation, representing time invariant Weibull moduli for both strength and life, is typified by the glass design chart of Figure 1.

6. Compute life for particular load fraction, R, and survival probability, S, by

$$t = \left\{\frac{K}{R^m}\left[\frac{\text{Ln}(1/S)}{\text{Ln}(2)}\right]\right\}^{(1/b)}$$

7. Compute load fraction for particular life, t, and survival probability, S, by

$$R = \left\{\frac{K}{t^b}\left[\frac{\text{Ln}(1/S)}{\text{Ln}(2)}\right]\right\}^{(1/m)}$$

8. Compute the survival probability for particular load fraction, R, and life, t, by

$$S = \text{Exp}-\left\{\frac{R^m t^b}{K}\text{Ln}(2)\right\}$$

<u>Single Point Estimates for Median Life and Weibull Modulus</u>

The following equations show how the median life may be estimated, when the shape factor, m, is known, from each early observed failure life at t_r corresponding with the survival probability, S_r, where
$S_r = 1 - (r-0.5)/N$ and r is the rank serial number. The use of (r-0.5) as the effective rank for computing the corresponding probability is a convenience. Alternative formulations are r/N, r/(N+1), (r-0.3)/(n+0.4), as well as probabilistic treatments of the "correct" rank assignments. Extensive computer simulations of Weibull distributions (Ref. 8) show that (r-0.5)/N is an effective and convenient rank assignment. The value of S_r was taken to be 1- (r-0.5)/N in the tabulated computations. The median life value is estimated by the following equations (with m known):

$$S = \text{Exp}-\left\{\text{Ln}(2)\left(\frac{t}{t_m}\right)^m\right\}$$

$$t_{0.5} = t_m = t_r\left(\frac{\text{Ln}(2)}{\text{Ln}\left(\frac{1}{S_r}\right)}\right)^{\frac{1}{m}}$$

The shape factor may also be estimated from a few early observations, and in this case we take as an interim normalizing value the longest observed life t_r, corresponding to survivability S_r, and use the preceding data at lesser life t having survival probability S (greater than S_r) to estimate the Weibull Modulus by the relation:

$$m = \frac{\mathrm{Ln}\left\{\dfrac{\mathrm{Ln}\left(\frac{1}{S}\right)}{\mathrm{Ln}\left(\frac{1}{S_r}\right)}\right\}}{\mathrm{Ln}\left(\frac{t}{t_r}\right)}$$

The two estimators are combined to produce individual median life estimates from each observed value, with t_r as the normalizing life at survival probability, S_r, as shown below

$$t_{0.5} = t_r \left\{\frac{\mathrm{Ln}\,(2)}{\mathrm{Ln}\left(\frac{1}{S_r}\right)}\right\}^{\left\{\dfrac{\mathrm{Ln}\left(\frac{t}{t_r}\right)}{\mathrm{Ln}\left\{\frac{\mathrm{Ln}\left(\frac{1}{S}\right)}{\mathrm{Ln}\left(\frac{1}{S_r}\right)}\right\}}\right\}}$$

These predictions are tabulated in the data appendices.

Degradation and Strength Turndown

The possibility of a latent strength reduction, which may appear after a substantial amount of time under sustained load, was addressed by Christensen (Ref. 5). He showed the effect on stress rupture life of degradation that follows first-order chemical reaction rates, with the strength decreasing progressively until failure:

$$\sigma = \sigma_r \,\mathrm{Exp}\,(-t/t_c)$$

This idea, with some additional constraints, can be used to make a simple and useful modification of the design charts. One can postulate such degradation, which might be related to moisture effects,
and the breakdown of locally susceptible regions in the load-carrying filaments . These locally susceptible regions are finite; after all of them are degraded, the breakdown process will stop. This leads to a fraction, f, of strength lost in accordance with the time constant, t_c, of this assumed reaction

$$\sigma = \sigma_r\left[1 - f\left(1 - \mathrm{Exp}\,(-t/t_c)\right)\right]$$

This fractional strength loss is incorporated into the stress rupture equations as shown below:

$$R = R_r\left(\frac{t_r}{t}\right)^{\frac{b}{m}}\left[\frac{\mathrm{Ln}\left(\frac{1}{S}\right)}{\mathrm{Ln}\,(2)}\right]^{\frac{1}{m}}\left\{1 - f\left[1 - \mathrm{Exp}\left(-\frac{t}{t_c}\right)\right]\right\}$$

The log-log form to be used for plotting the probability contours on the design chart is given by

$$\mathrm{Log}\,(R) = \mathrm{Log}(R_r) - \frac{b}{m}\mathrm{Log}\,\left(\frac{t}{t_r}\right) + \left(\frac{1}{m}\right)\mathrm{Log}\left[\frac{\mathrm{Ln}\left(\frac{1}{S}\right)}{\mathrm{Ln}\,(2)}\right] + \mathrm{Log}\left\{1 - f\left[1 - \mathrm{Exp}\left(-\frac{t}{t_c}\right)\right]\right\}$$

This type of design chart is illustrated by the Kevlar composite strand design chart of Figure 2, although the Kevlar vessel data do not exhibit the turndown.

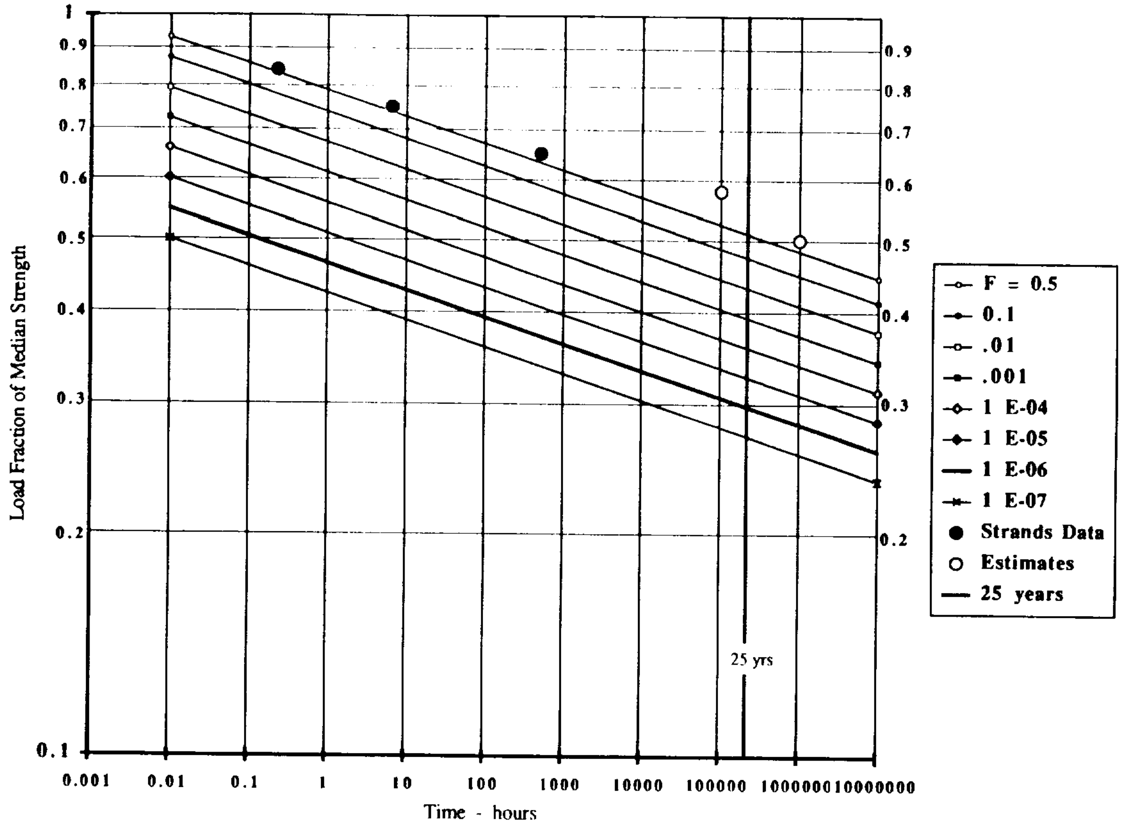

Figure 1. Glass Composite Strand Stress Rupture Design Chart

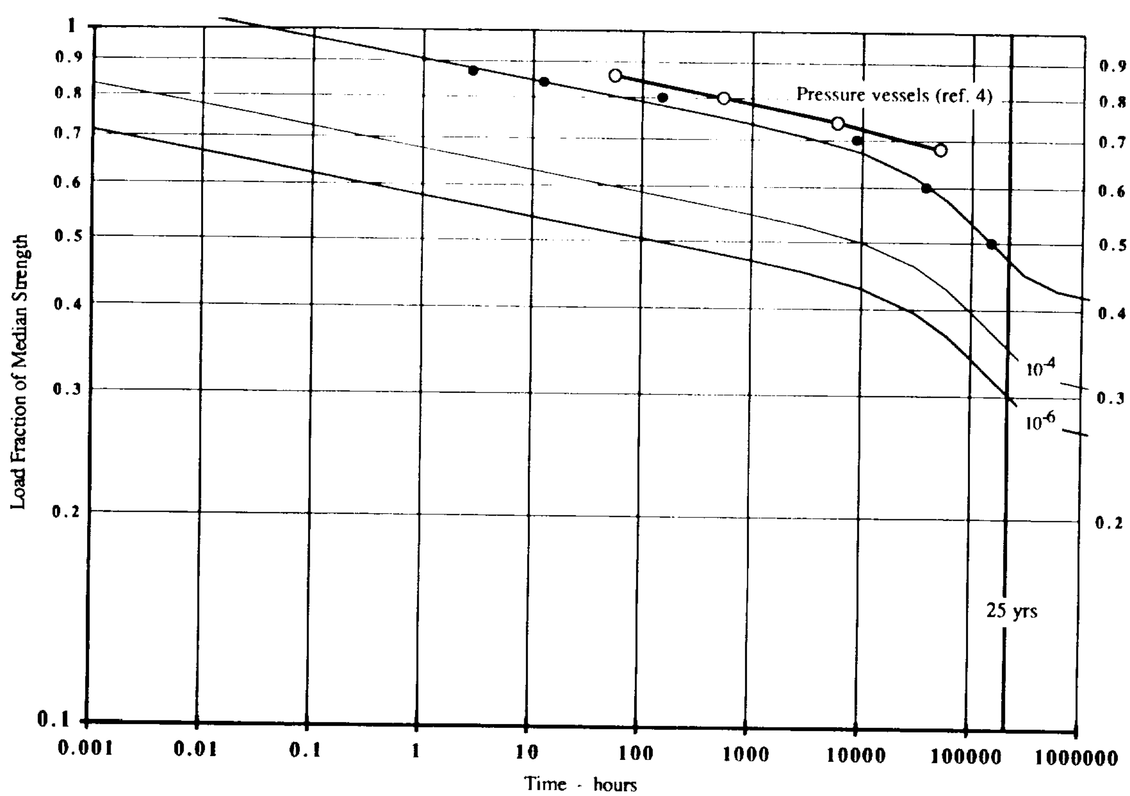

Figure 2. Kevlar Composite Strand Stress Rupture Design Chart
with m = 30 b = 0.9 f = 0.3 Tc = 120000 hrs.

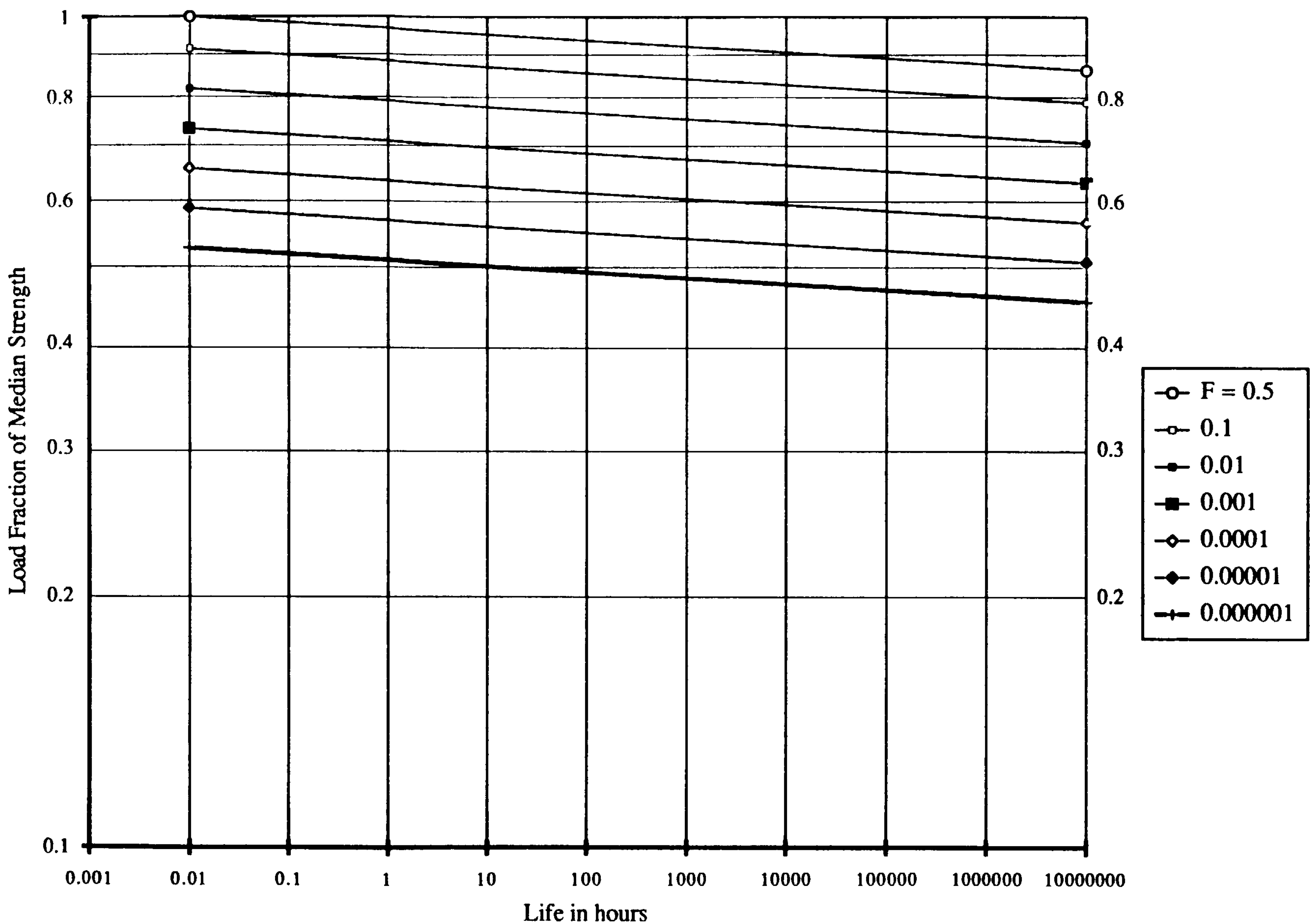

Figure 3. Graphite Composite Stress Rupture Design Chart
with m = 21 b = 0.15

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CONCLUSIONS

Design charts based on the bivariate form of the Weibull distribution are presented for S–glass composites and Kevlar composites, and for carbon composites in preliminary form. The equations are readily modified to accommodate selected values for the life and strength Weibull moduli in order to determine the most consistent and useful fits to the data.

The methods presented may be applied to any type of stress rupture data that exhibit a consistent power law relation between the Weibull moduli for strength and life. A modification of the linear model is presented and used to accommodate the Kevlar strand data turndown tendency at long life.

The underlying analytical models show that if life and strength are Weibull distributions with invariant moduli (shape factors), then log load vs log life will be linear. Conversely, if the log load vs log life is linear, and either the life distribution or the strength distribution is a Weibull, then the other distribution must also be a Weibull.

The data processing by these methods allows each observation to be used for estimating the Weibull modulus, giving a valuable perspective for engineering approximations that seek a single conservative design reference value. Methods for estimating median life from incomplete data are also shown.

A notable point is the dramatic difference seen in stress rupture life between S-glass and Kevlar composite rupture data on the one hand, and the carbon data on the other hand. The carbon data seem to exhibit very little stress rupture degradation, and therefore offer very high homologous stresses in operation. Such high stress potential (and high performance) may not be a practically usable characteristic. The lower design stresses required for the glass and Kevlar also provide a certain amount of damage tolerance during the service life. In addition, both S-glass and Kevlar are inherently resistant to moderate impact and casual damage. Carbon composites, on the other hand, are notorious for susceptibility to physical damage and abuse. Such susceptibility, coupled with very high operating stresses, could lead to premature or catastrophic failures in cases of casual damage to a carbon composite vessel operating so close to its expected strength.

The design of S-glass and Kevlar pressure vessels is controlled by stress rupture characteristics for long-term service. The design of carbon composite pressure vessels for long term service is controlled by the amount and type of damage in the operating environment. The carbon composite pressure vessels must be protected from environmental damage or designed to resist and tolerate the service environment.

Acknowledgement

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SYMBOLS

S,F	Cumulative survival and failure probabilities.
m	Weibull modul (shape factor) for strength; subscript designates median.
b	Weibull modulus for life.
R	Homologous load (referenced to the median strength).
H, X	Function of load and time, and generic variable.
t	Time, life.
r	Subscript for reference value of load and time; also rank number for sorted data.
f,t_c	Strength fraction lost in first-order degradation reaction, with characteristic time, t_c.
σ	Stress or strength.

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APPENDIX A

S-Glass Composite Strand Data Tables and Plots
Based on LLNL Data Update

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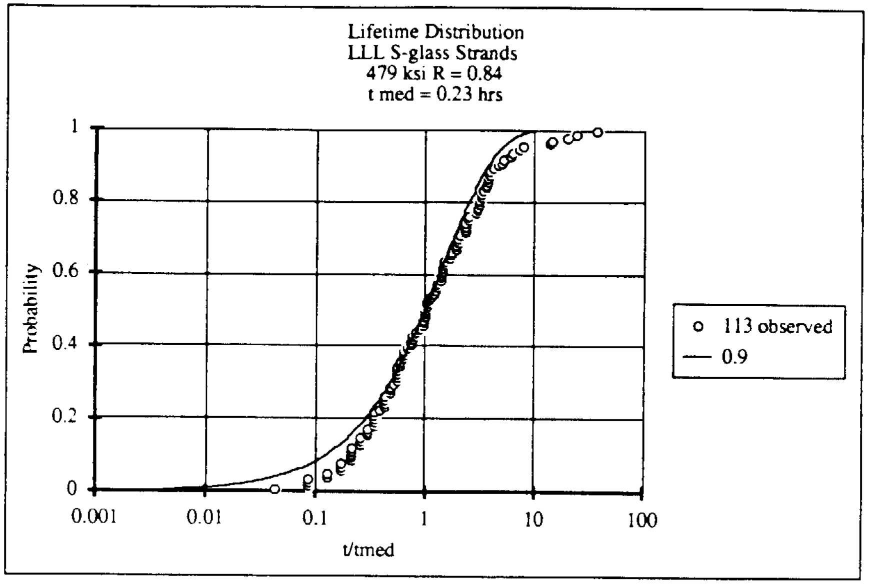
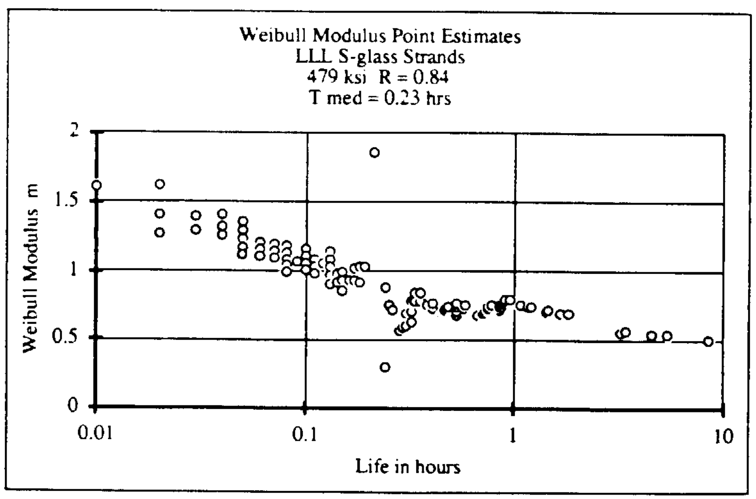




LLL S-glass

Stress = 479

R = 0.84

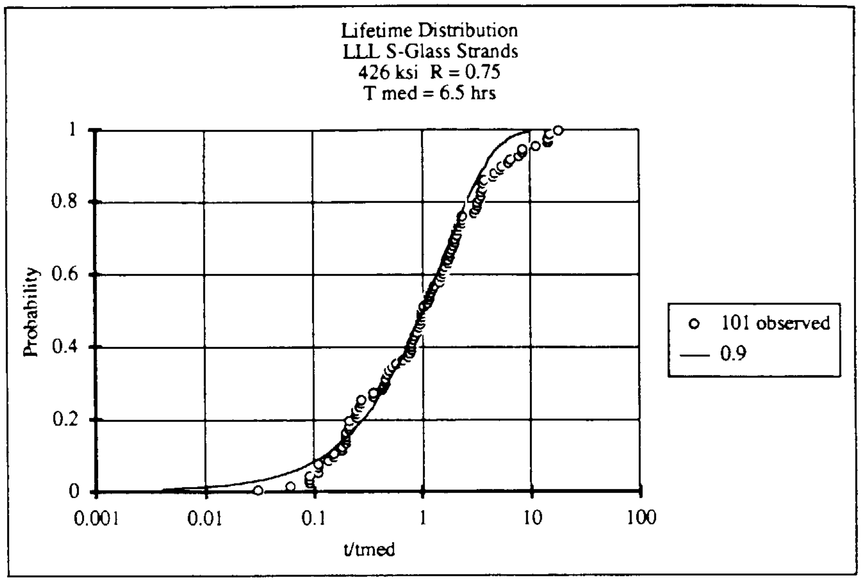
N = 113

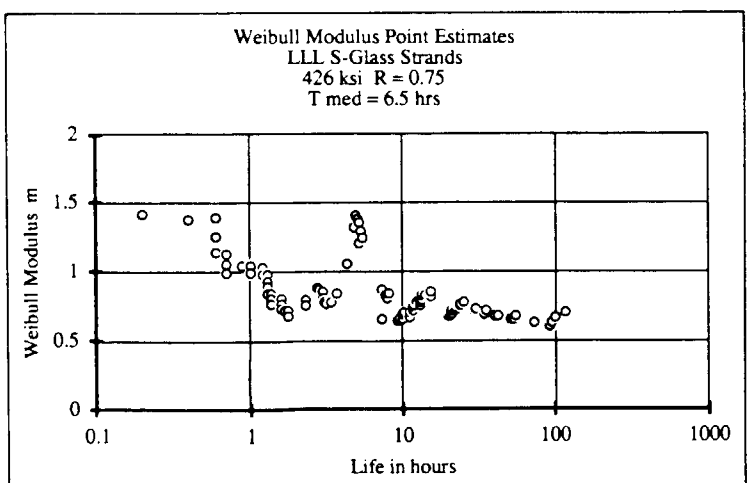
Median = 0.23

Specimen
type 1
(572)
sgl end

Rank r	Life t hrs	Normal t/tmed	Prob F	est b	fit b=0.9	Rank r	Life t hrs	Normal t/tmed	Prob F	est b	fit b=0.9
1	0.01	0.043	0.004	1.6	0.004	58	0.24	1.043	0.509	0.6	1.029
2	0.02	0.087	0.013	1.6	0.012	59	0.24	1.043	0.518	1.2	1.058
3	0.02	0.087	0.022	1.4	0.022	60	0.25	1.087	0.527	0.9	1.088
4	0.02	0.087	0.031	1.3	0.032	61	0.26	1.130	0.535	0.8	1.118
5	0.03	0.130	0.040	1.4	0.043	62	0.28	1.217	0.544	0.6	1.150
6	0.03	0.130	0.049	1.3	0.054	63	0.29	1.261	0.553	0.6	1.182
7	0.04	0.174	0.058	1.4	0.065	64	0.3	1.304	0.562	0.7	1.214
8	0.04	0.174	0.066	1.3	0.077	65	0.3	1.304	0.571	0.7	1.248
9	0.04	0.174	0.075	1.2	0.089	66	0.32	1.391	0.580	0.7	1.282
10	0.05	0.217	0.084	1.4	0.101	67	0.32	1.391	0.588	0.7	1.317
11	0.05	0.217	0.093	1.3	0.113	68	0.32	1.391	0.597	0.8	1.353
12	0.05	0.217	0.102	1.2	0.126	69	0.33	1.435	0.606	0.8	1.389
13	0.05	0.217	0.111	1.2	0.139	70	0.33	1.435	0.615	0.9	1.427
14	0.05	0.217	0.119	1.1	0.152	71	0.35	1.522	0.624	0.8	1.466
15	0.06	0.261	0.128	1.2	0.166	72	0.35	1.522	0.633	0.9	1.505
16	0.06	0.261	0.137	1.2	0.179	73	0.38	1.652	0.642	0.8	1.546
17	0.06	0.261	0.146	1.1	0.193	74	0.4	1.739	0.650	0.8	1.588
18	0.07	0.304	0.155	1.2	0.207	75	0.4	1.739	0.659	0.8	1.631
19	0.07	0.304	0.164	1.1	0.222	76	0.44	1.913	0.668	0.7	1.676
20	0.07	0.304	0.173	1.1	0.237	77	0.45	1.957	0.677	0.7	1.721
21	0.08	0.348	0.181	1.2	0.252	78	0.46	2.000	0.686	0.7	1.768
22	0.08	0.348	0.190	1.1	0.267	79	0.47	2.043	0.695	0.8	1.817
23	0.08	0.348	0.199	1.1	0.282	80	0.48	2.087	0.704	0.8	1.867
24	0.08	0.348	0.208	1.0	0.298	81	0.53	2.304	0.712	0.7	1.919
25	0.08	0.348	0.217	1.0	0.314	82	0.53	2.304	0.721	0.7	1.972
26	0.09	0.391	0.226	1.1	0.330	83	0.53	2.304	0.730	0.8	2.028
27	0.1	0.435	0.235	1.1	0.347	84	0.53	2.304	0.739	0.8	2.085
28	0.1	0.435	0.243	1.1	0.364	85	0.57	2.478	0.748	0.8	2.145
29	0.1	0.435	0.252	1.0	0.381	86	0.58	2.522	0.757	0.8	2.207
30	0.1	0.435	0.261	1.0	0.398	87	0.66	2.870	0.765	0.7	2.271
31	0.11	0.478	0.270	1.1	0.416	88	0.69	3.000	0.774	0.7	2.338
32	0.11	0.478	0.279	1.0	0.434	89	0.7	3.043	0.783	0.7	2.408
33	0.11	0.478	0.288	1.0	0.452	90	0.71	3.087	0.792	0.7	2.481
34	0.12	0.522	0.296	1.0	0.470	91	0.73	3.174	0.801	0.7	2.558
35	0.13	0.565	0.305	1.1	0.489	92	0.74	3.217	0.810	0.7	2.638
36	0.13	0.565	0.314	1.1	0.508	93	0.75	3.261	0.819	0.8	2.722
37	0.13	0.565	0.323	1.0	0.528	94	0.77	3.348	0.827	0.8	2.811
38	0.13	0.565	0.332	0.9	0.548	95	0.85	3.696	0.836	0.7	2.904
39	0.13	0.565	0.341	0.9	0.568	96	0.85	3.696	0.845	0.8	3.004
40	0.14	0.609	0.350	1.0	0.588	97	0.87	3.783	0.854	0.8	3.109
41	0.14	0.609	0.358	0.9	0.609	98	0.87	3.783	0.863	0.8	3.222
42	0.15	0.652	0.367	1.0	0.631	99	0.89	3.870	0.872	0.8	3.342
43	0.15	0.652	0.376	0.9	0.652	100	0.9	3.913	0.881	0.8	3.472
44	0.15	0.652	0.385	0.8	0.674	101	0.96	4.174	0.889	0.8	3.612
45	0.16	0.696	0.394	0.9	0.696	102	1.07	4.652	0.898	0.8	3.764
46	0.17	0.739	0.403	1.0	0.719	103	1.16	5.043	0.907	0.8	3.931
47	0.17	0.739	0.412	0.9	0.742	104	1.2	5.217	0.916	0.8	4.115
48	0.18	0.783	0.420	1.0	0.766	105	1.42	6.174	0.925	0.7	4.321
49	0.18	0.783	0.429	0.9	0.790	106	1.46	6.348	0.934	0.7	4.554
50	0.19	0.826	0.438	1.0	0.815	107	1.67	7.261	0.942	0.7	4.822
51	0.21	0.913	0.447	1.7	0.840	108	1.79	7.783	0.951	0.7	5.136
52	0.22	0.957	0.456		0.865	109	3.21	13.957	0.960	0.6	5.516
53	0.22	0.957	0.465		0.891	110	3.38	14.696	0.969	0.6	5.996
54	0.22	0.957	0.473		0.917	111	4.47	19.435	0.978	0.6	6.645
55	0.23	1.000	0.482		0.944	112	5.38	23.391	0.987	0.6	7.641
56	0.23	1.000	0.491		0.972	113	8.55	37.174	0.996	0.6	9.828
57	0.23	1.000	0.500		1.000						

1603





LLL S-glass

Stress = 426

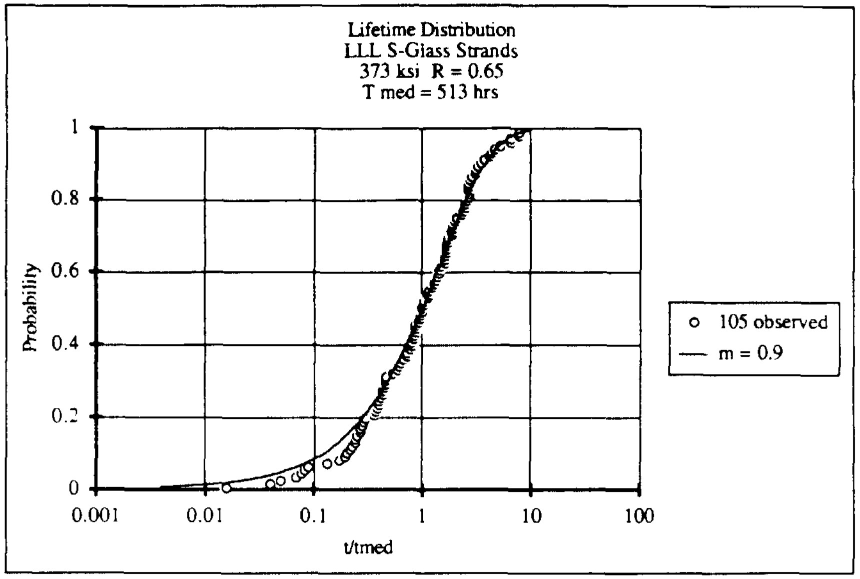
R = 0.75

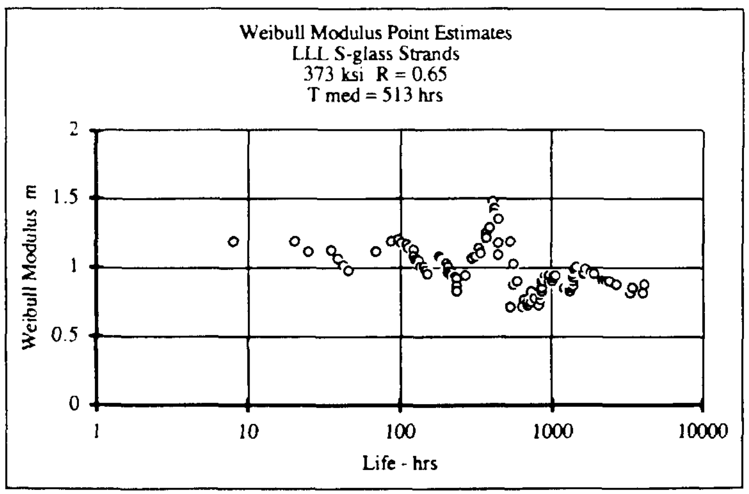
N = 101

Median = 6.5

Type 1 (572)
sgl end

Rank r	Life t hrs	Normal t/tmed	Prob F	est b	fit b=0.9	Rank r	Life t hrs	Normal t/tmed	Prob F	est b	fit b=0.9
1	0.2	0.031	0.005	1.4	0.004	52	6.6	1.015	0.510		1.032
2	0.4	0.062	0.015	1.4	0.014	53	7.3	1.123	0.520		1.065
3	0.6	0.092	0.025	1.4	0.025	54	7.4	1.138	0.530	0.7	1.099
4	0.6	0.092	0.035	1.2	0.037	55	7.4	1.138	0.540	0.9	1.133
5	0.6	0.092	0.045	1.1	0.049	56	7.7	1.185	0.550	0.8	1.168
6	0.7	0.108	0.054	1.1	0.061	57	8	1.231	0.559	0.8	1.205
7	0.7	0.108	0.064	1.1	0.074	58	8.2	1.262	0.569	0.8	1.242
8	0.7	0.108	0.074	1.0	0.087	59	9.2	1.415	0.579	0.6	1.280
9	0.9	0.138	0.084	1.0	0.101	60	9.5	1.462	0.589	0.7	1.319
10	1	0.154	0.094	1.0	0.115	61	9.9	1.523	0.599	0.7	1.359
11	1	0.154	0.104	1.0	0.129	62	10.1	1.554	0.609	0.7	1.401
12	1.2	0.185	0.114	1.0	0.144	63	10.4	1.600	0.619	0.7	1.443
13	1.2	0.185	0.124	1.0	0.159	64	11.1	1.708	0.629	0.7	1.487
14	1.3	0.200	0.134	1.0	0.174	65	11.2	1.723	0.639	0.7	1.532
15	1.3	0.200	0.144	0.9	0.189	66	11.6	1.785	0.649	0.7	1.579
16	1.3	0.200	0.153	0.9	0.205	67	11.7	1.800	0.658	0.7	1.627
17	1.3	0.200	0.163	0.8	0.221	68	12.1	1.862	0.668	0.7	1.677
18	1.4	0.215	0.173	0.8	0.238	69	12.3	1.892	0.678	0.8	1.728
19	1.4	0.215	0.183	0.8	0.255	70	12.9	1.985	0.688	0.8	1.781
20	1.4	0.215	0.193	0.8	0.272	71	13.1	2.015	0.698	0.8	1.836
21	1.6	0.246	0.203	0.8	0.289	72	13.4	2.062	0.708	0.8	1.893
22	1.6	0.246	0.213	0.8	0.307	73	13.4	2.062	0.718	0.8	1.952
23	1.6	0.246	0.223	0.7	0.325	74	13.9	2.138	0.728	0.8	2.013
24	1.7	0.262	0.233	0.7	0.343	75	14.8	2.277	0.738	0.8	2.077
25	1.8	0.277	0.243	0.7	0.362	76	15.1	2.323	0.748	0.8	2.143
26	1.8	0.277	0.252	0.7	0.381	77	15.1	2.323	0.757	0.8	2.212
27	2.3	0.354	0.262	0.8	0.401	78	19.5	3.000	0.767	0.7	2.285
28	2.3	0.354	0.272	0.8	0.420	79	20.2	3.108	0.777	0.7	2.361
29	2.8	0.431	0.282	0.9	0.441	80	20.7	3.185	0.787	0.7	2.440
30	2.9	0.446	0.292	0.9	0.461	81	20.9	3.215	0.797	0.7	2.524
31	3	0.462	0.302	0.8	0.482	82	21.7	3.338	0.807	0.7	2.612
32	3	0.462	0.312	0.8	0.504	83	22.2	3.415	0.817	0.7	2.705
33	3.1	0.477	0.322	0.8	0.525	84	22.8	3.508	0.827	0.7	2.804
34	3.2	0.492	0.332	0.8	0.547	85	23.5	3.615	0.837	0.7	2.908
35	3.4	0.523	0.342	0.8	0.570	86	23.7	3.646	0.847	0.8	3.020
36	3.7	0.569	0.351	0.8	0.593	87	24.6	3.785	0.856	0.8	3.140
37	4.3	0.662	0.361	1.1	0.616	88	28.8	4.431	0.866	0.7	3.268
38	4.8	0.738	0.371	1.3	0.640	89	29.8	4.585	0.876	0.7	3.408
39	5	0.769	0.381	1.4	0.665	90	34	5.231	0.886	0.7	3.559
40	5.1	0.785	0.391	1.4	0.690	91	34.6	5.323	0.896	0.7	3.725
41	5.2	0.800	0.401	1.4	0.715	92	40	6.154	0.906	0.7	3.908
42	5.2	0.800	0.411	1.2	0.741	93	42.1	6.477	0.916	0.7	4.113
43	5.4	0.831	0.421	1.3	0.767	94	50.3	7.738	0.926	0.6	4.345
44	5.5	0.846	0.431	1.2	0.794	95	53.5	8.231	0.936	0.7	4.611
45	5.8	0.892	0.441		0.822	96	55	8.462	0.946	0.7	4.924
46	6	0.923	0.450		0.850	97	72	11.077	0.955	0.6	5.303
47	6.1	0.938	0.460		0.879	98	92.3	14.200	0.965	0.6	5.781
48	6.2	0.954	0.470		0.908	99	92.7	14.262	0.975	0.6	6.428
49	6.4	0.985	0.480		0.938	100	99.3	15.277	0.985	0.7	7.421
50	6.5	1.000	0.490		0.969	101	115.7	17.800	0.995	0.7	9.602
51	6.5	1.000	0.500		1.000						





LLL S-glass

Stress = 373

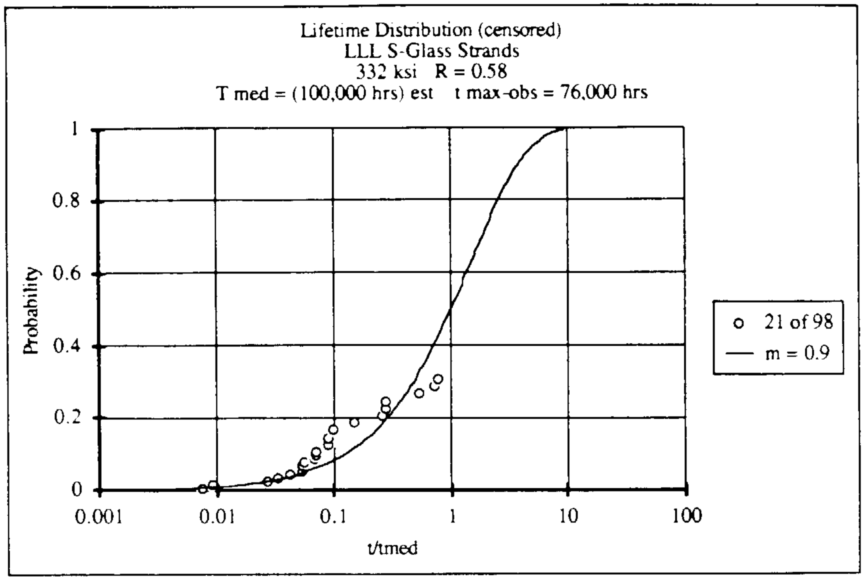
R = 0.65

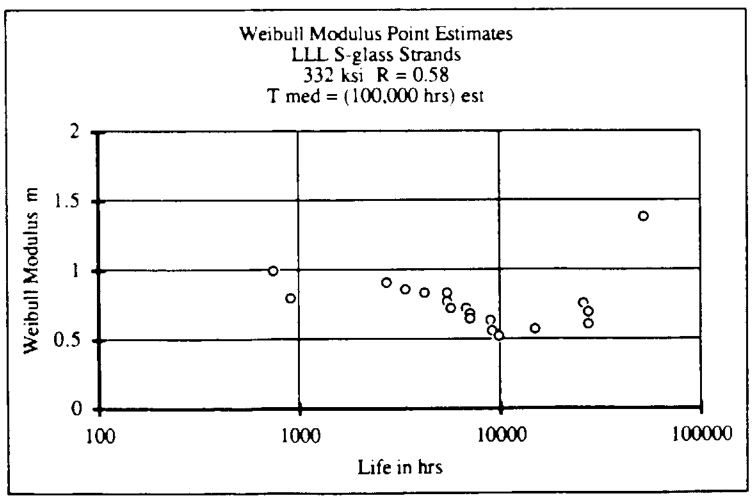
N = 105

Median = 513

Type 1 (572)

Rank r	Life t hrs	Normal t/tmed	Prob F	est b	fit b=0.9	Rank r	Life t hrs	Normal t/tmed	Prob F	est b	fit b=0.9
1	8	0.016	0.005	1.2	0.004	54	533	1.039	0.510	0.7	1.031
2	20	0.039	0.014	1.2	0.013	55	537	1.047	0.519	1.2	1.062
3	25	0.049	0.024	1.1	0.024	56	563	1.097	0.529	0.9	1.095
4	35	0.068	0.033	1.1	0.035	57	570	1.111	0.538	1.0	1.128
5	39	0.076	0.043	1.1	0.046	58	596	1.162	0.548	0.9	1.162
6	42	0.082	0.052	1.0	0.058	59	643	1.253	0.557	0.7	1.196
7	45	0.088	0.062	1.0	0.071	60	655	1.277	0.567	0.8	1.232
8	69	0.135	0.071	1.1	0.083	61	690	1.345	0.576	0.7	1.268
9	87	0.170	0.081	1.2	0.096	62	707	1.378	0.586	0.7	1.306
10	98	0.191	0.090	1.2	0.110	63	729	1.421	0.595	0.8	1.344
11	103	0.201	0.100	1.2	0.123	64	730	1.423	0.605	0.8	1.383
12	110	0.214	0.110	1.2	0.137	65	770	1.501	0.614	0.8	1.424
13	115	0.224	0.119	1.1	0.151	66	823	1.604	0.624	0.7	1.465
14	123	0.240	0.129	1.1	0.166	67	830	1.618	0.633	0.8	1.508
15	123	0.240	0.138	1.1	0.181	68	842	1.641	0.643	0.8	1.552
16	127	0.248	0.148	1.1	0.196	69	855	1.667	0.652	0.8	1.598
17	135	0.263	0.157	1.0	0.211	70	865	1.686	0.662	0.9	1.644
18	136	0.265	0.167	1.0	0.227	71	866	1.688	0.671	0.9	1.692
19	144	0.281	0.176	1.0	0.243	72	891	1.737	0.681	0.9	1.742
20	149	0.290	0.186	1.0	0.259	73	900	1.754	0.690	0.9	1.794
21	153	0.298	0.195	1.0	0.275	74	945	1.842	0.700	0.9	1.847
22	183	0.357	0.205	1.1	0.292	75	948	1.848	0.710	0.9	1.902
23	190	0.370	0.214	1.1	0.309	76	1004	1.957	0.719	0.9	1.959
24	196	0.382	0.224	1.0	0.327	77	1011	1.971	0.729	0.9	2.018
25	202	0.394	0.233	1.0	0.345	78	1029	2.006	0.738	0.9	2.080
26	206	0.402	0.243	1.0	0.363	79	1063	2.072	0.748	0.9	2.144
27	209	0.407	0.252	1.0	0.381	80	1205	2.349	0.757	0.8	2.210
28	218	0.425	0.262	1.0	0.400	81	1226	2.390	0.767	0.9	2.280
29	222	0.433	0.271	0.9	0.419	82	1297	2.528	0.776	0.8	2.353
30	231	0.450	0.281	0.9	0.438	83	1308	2.550	0.786	0.9	2.429
31	237	0.462	0.290	0.9	0.458	84	1334	2.600	0.795	0.9	2.508
32	238	0.464	0.300	0.9	0.478	85	1374	2.678	0.805	0.9	2.592
33	240	0.468	0.310	0.8	0.498	86	1379	2.688	0.814	0.9	2.681
34	274	0.534	0.319	0.9	0.519	87	1381	2.692	0.824	0.9	2.774
35	305	0.595	0.329	1.1	0.540	88	1391	2.712	0.833	1.0	2.873
36	318	0.620	0.338	1.1	0.562	89	1403	2.735	0.843	1.0	2.978
37	335	0.653	0.348	1.1	0.584	90	1434	2.795	0.852	1.0	3.090
38	341	0.665	0.357	1.1	0.606	91	1467	2.860	0.862	1.0	3.210
39	368	0.717	0.367	1.3	0.629	92	1600	3.119	0.871	1.0	3.339
40	374	0.729	0.376	1.2	0.652	93	1630	3.177	0.881	1.0	3.478
41	391	0.762	0.386	1.3	0.676	94	1648	3.212	0.890	1.0	3.630
42	413	0.805	0.395	1.5	0.700	95	1786	3.481	0.900	1.0	3.796
43	419	0.817	0.405	1.4	0.725	96	1894	3.692	0.910	1.0	3.980
44	426	0.830	0.414	1.4	0.750	97	2152	4.195	0.919	0.9	4.185
45	434	0.846	0.424	1.4	0.775	98	2262	4.409	0.929	0.9	4.417
46	443	0.864	0.433	1.4	0.801	99	2395	4.669	0.938	0.9	4.684
47	444	0.865	0.443	1.2	0.828	100	2673	5.211	0.948	0.9	4.998
48	451	0.879	0.452	1.1	0.855	101	3321	6.474	0.957	0.8	5.377
49	475	0.926	0.462		0.883	102	3357	6.544	0.967	0.8	5.855
50	499	0.973	0.471		0.911	103	3996	7.789	0.976	0.8	6.503
51	504	0.982	0.481		0.940	104	4033	7.862	0.986	0.9	7.497
52	507	0.988	0.490		0.970	105	4194	8.175	0.995	1.0	9.680
53	513	1.000	0.500		1.000						





LLL S-glass

Stress = 332 ksi

R = 58%

N = 98

Normal t = 76032
S_{norm} = 0.5929

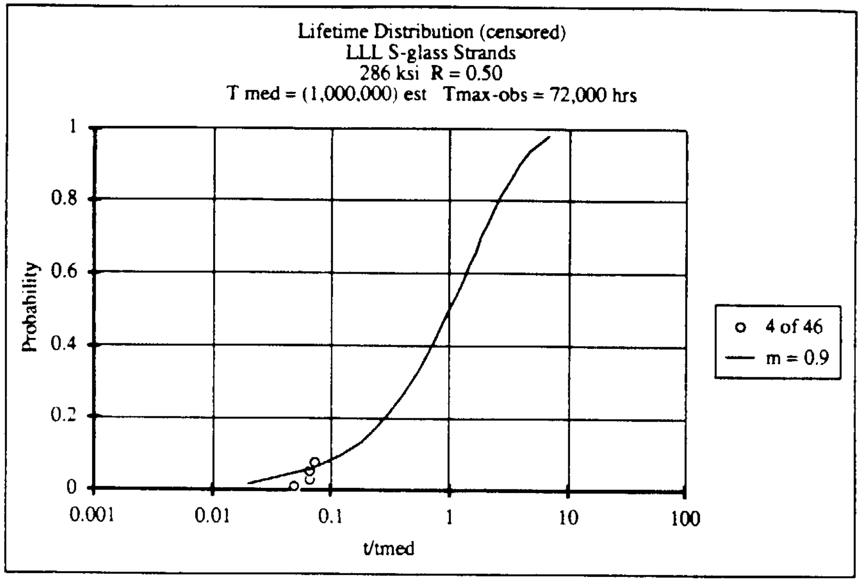
Remaining:
N_1 = 50
t_1 = 7200 hr
ΔF = 0.02

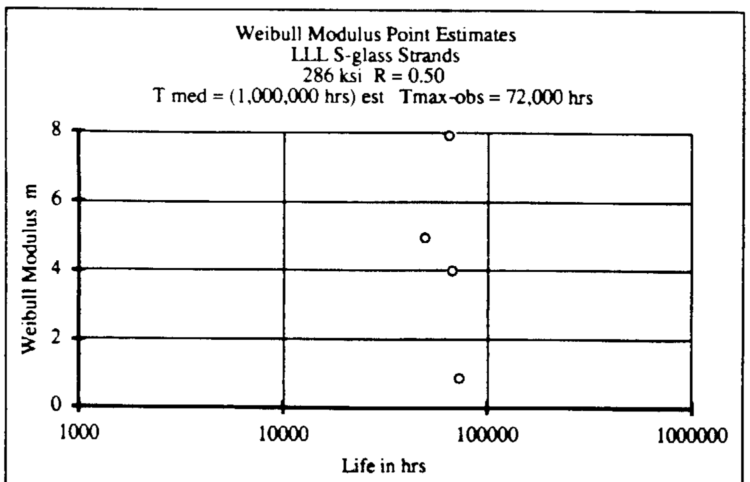
Rank r	Life t hrs	Normal t/t_{norm}	Prob F	est b	fit b=0.9	est med sample	Med Norm 100000
1	745	0.010	0.0051	1.0	0.004	100811	0.007
2	914	0.012	0.0153	0.8	0.015	108338	0.009
3	2712	0.036	0.0255	0.9	0.026	103955	0.027
4	3384	0.045	0.0357	0.9	0.038	105702	0.034
5	4211	0.055	0.0459	0.8	0.050	106709	0.042
6	5376	0.071	0.0561	0.8	0.063	106753	0.054
7	5400	0.071	0.0663	0.8	0.077	109807	0.054
8	5640	0.074	0.0765	0.7	0.090	112304	0.056
9	6816	0.090	0.0867	0.7	0.104	112145	0.068
10	6984	0.092	0.0969	0.7	0.119	114818	0.070
11	7080	0.093	0.1071	0.6	0.134	117839	0.071
12	9000	0.118	0.1271	0.6	0.164	118907	0.090
13	9096	0.120	0.1471	0.6	0.195	125840	0.091
14	9840	0.129	0.1671	0.5	0.228	131705	0.098
15	14928	0.196	0.1871	0.6	0.261	124906	0.149
16	25968	0.342	0.2071	0.8	0.297	110449	0.260
17	27504	0.362	0.2271	0.7	0.333	114063	0.275
18	27792	0.366	0.2471	0.6	0.371	121063	0.278
19	52176	0.686	0.2671	1.4	0.410	93272	0.522
20	71328	0.938	0.2871		0.451		0.713
21	76032	1.000	0.3071		0.493		0.760
					USE	100000	

1605

1606

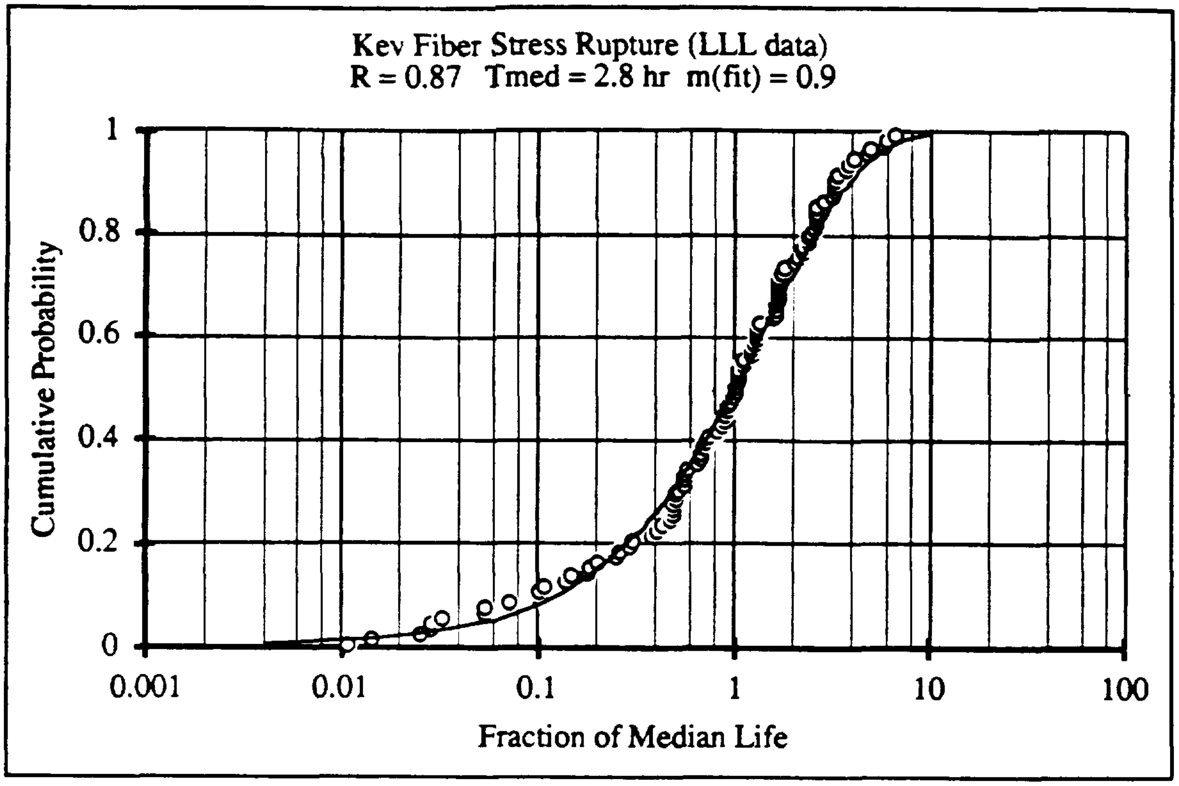
LLL S-glass		Rank r	Life t hrs	Normal t/t_{norm}	Prob F	est m	est med life	est med life 0.9	Life est at 1e-06	med Norm by 1E06
Stress =	286	1	48792	0.672	0.011	5.0	112443	4907270	7514	0.049
R =	0.5	2	65112	0.896	0.033	7.9	95516	1908427	17534	0.065
N =	46	3	66600	0.917	0.054	4.0	125193	1092816	4301	0.067
Normal t =	72648	4	72648	1.000	0.076	0.9		809811	0.26	0.073
S_{norm} =	0.924						(Use)	1000000	and m = 0.9	
Type 1	(572)									

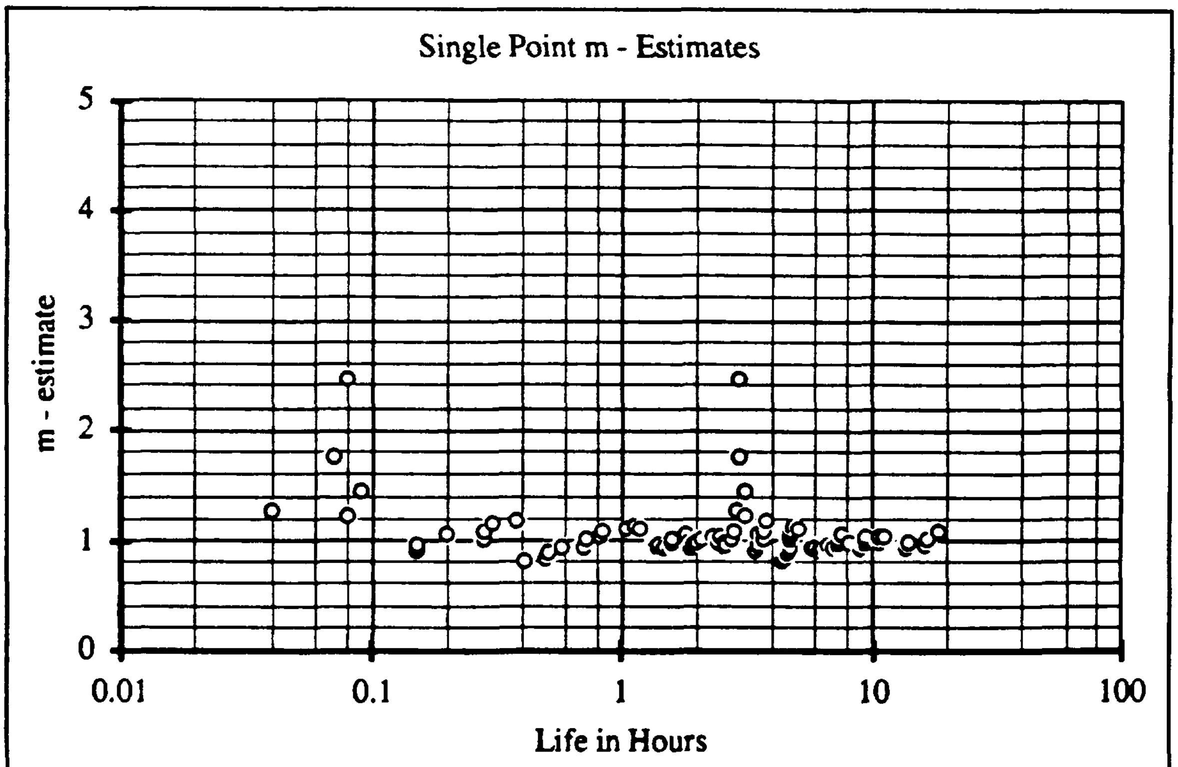




APPENDIX B

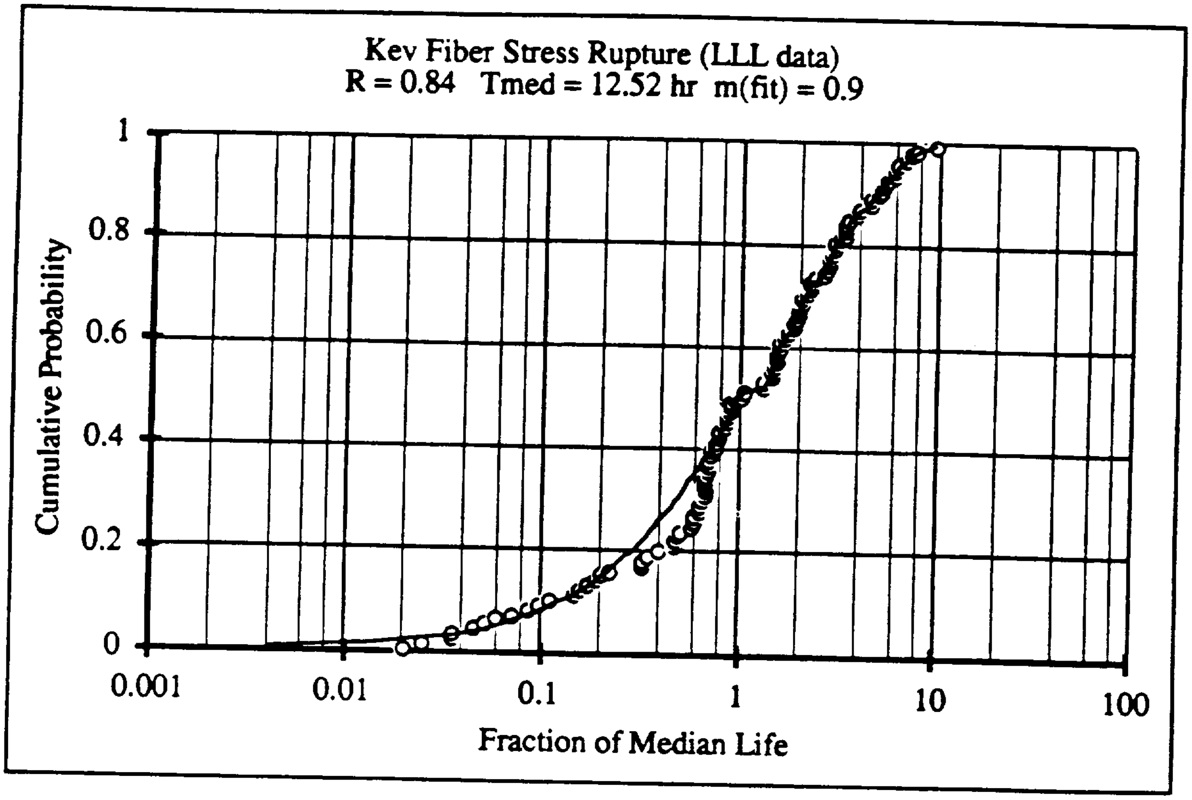
Kevlar Composite Strand Data Tables and Plots
Based on Reference 2

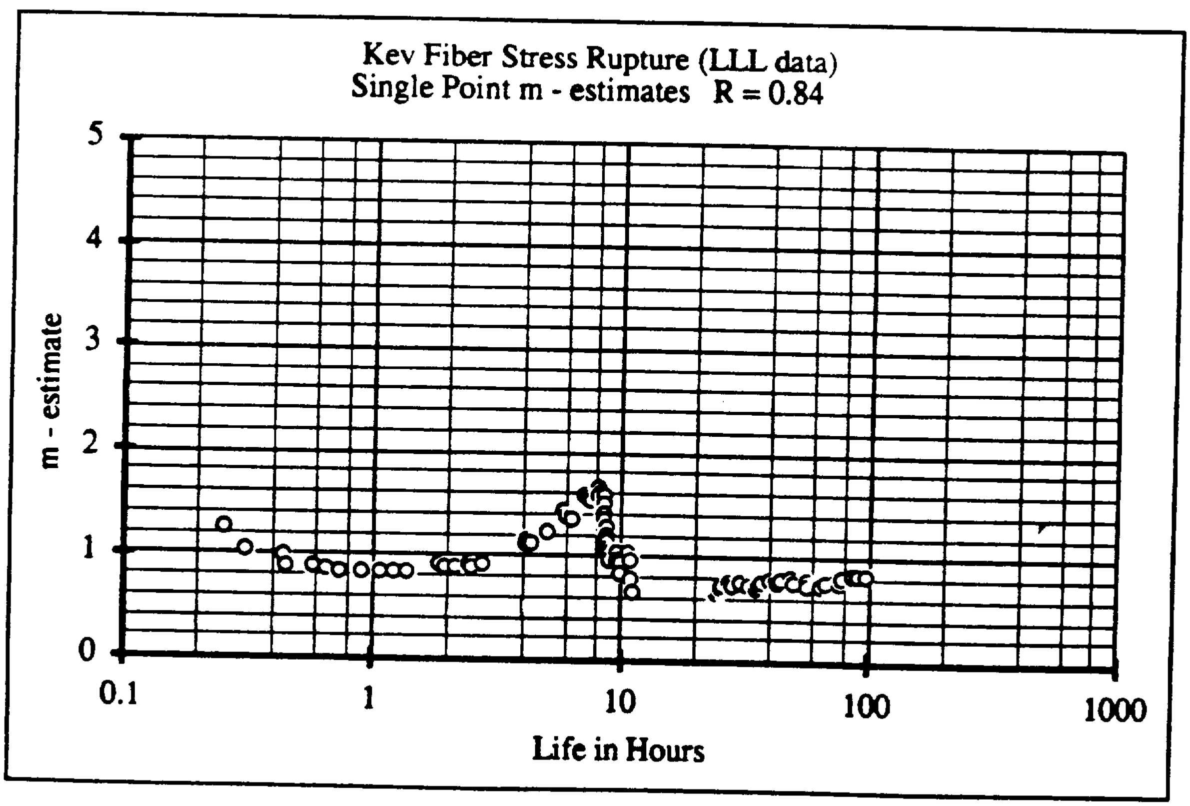

Kev Fiber Stress Rupture (LLL data)
R = 0.87 Tmed = 2.8 hr m(fit) = 0.9
Cumulative Probability
0
0.2
0.4
0.6
0.8
1
0.001
0.01
0.1
1
10
100
Fraction of Median Life


Single Point m - Estimates
m - estimate
0
1
2
3
4
5
0.01
0.1
1
10
100
Life in Hours

UCID 19849	r	Life - hrs	t/tmed	F = (r-1/2)/N	1-F	b est	pred t/tmed
440 ksi 0.87	1	0.03	0.011	0.005	0.995	1.09	0.004
N = 100	2	0.04	0.014	0.015	0.985	0.90	0.014
Med = 2.795	3	0.07	0.025	0.025	0.975	0.90	0.025
	4	0.08	0.029	0.035	0.965	0.84	0.037
	5	0.08	0.029	0.045	0.955	0.76	0.049
	6	0.09	0.032	0.055	0.945	0.73	0.062
	7	0.15	0.054	0.065	0.935	0.80	0.075
	8	0.15	0.054	0.075	0.925	0.75	0.088
	9	0.20	0.072	0.085	0.915	0.78	0.102
	10	0.28	0.100	0.095	0.905	0.84	0.116
	11	0.28	0.100	0.105	0.895	0.80	0.131
	12	0.30	0.107	0.115	0.885	0.78	0.145
	13	0.38	0.136	0.125	0.875	0.83	0.160
	14	0.41	0.147	0.135	0.865	0.81	0.176
	15	0.50	0.179	0.145	0.855	0.86	0.192
	16	0.51	0.182	0.155	0.845	0.83	0.208
	17	0.57	0.204	0.165	0.835	0.85	0.224
	18	0.70	0.250	0.175	0.825	0.93	0.241
	19	0.72	0.258	0.185	0.815	0.90	0.258
	20	0.82	0.293	0.195	0.805	0.95	0.275
	21	0.84	0.301	0.205	0.795	0.92	0.293
	22	1.05	0.376	0.215	0.785	1.07	0.311
	23	1.13	0.404	0.225	0.775	1.10	0.329
	24	1.19	0.426	0.235	0.765	1.11	0.348
	25	1.32	0.472	0.245	0.755	1.20	0.367
	26	1.35	0.483	0.255	0.745	1.18	0.386
	27	1.35	0.483	0.265	0.735	1.12	0.406
	28	1.36	0.487	0.275	0.725	1.07	0.426
	29	1.39	0.497	0.285	0.715	1.04	0.446
	30	1.40	0.501	0.295	0.705	0.99	0.467
	31	1.48	0.530	0.305	0.695	1.01	0.489
	32	1.55	0.555	0.315	0.685	1.03	0.510
	33	1.56	0.558	0.325	0.675	0.97	0.532
	34	1.57	0.562	0.335	0.665	0.92	0.555
	35	1.59	0.569	0.345	0.655	0.88	0.578
	36	1.80	0.644	0.355	0.645	1.04	0.601
	37	1.85	0.662	0.365	0.635	1.02	0.625
	38	1.86	0.665	0.375	0.625	0.95	0.649
	39	1.92	0.687	0.385	0.615	0.94	0.674
	40	2.00	0.716	0.395	0.605	0.96	0.700
	41	2.08	0.744	0.405	0.595	0.98	0.725
	42	2.27	0.812	0.415	0.585	1.23	0.752
	43	2.38	0.852	0.425	0.575	1.40	0.779
	44	2.46	0.880	0.435	0.565	1.52	0.806
	45	2.49	0.891	0.445	0.555	1.41	0.834
	46	2.61	0.934	0.455	0.545	1.94	0.863
	47	2.61	0.934	0.465	0.535	1.50	0.892
	48	2.62	0.937	0.475	0.525	1.13	0.922
	49	2.74	0.980	0.485	0.515	2.19	0.953
more	50	2.79	0.998	0.495	0.505		0.984

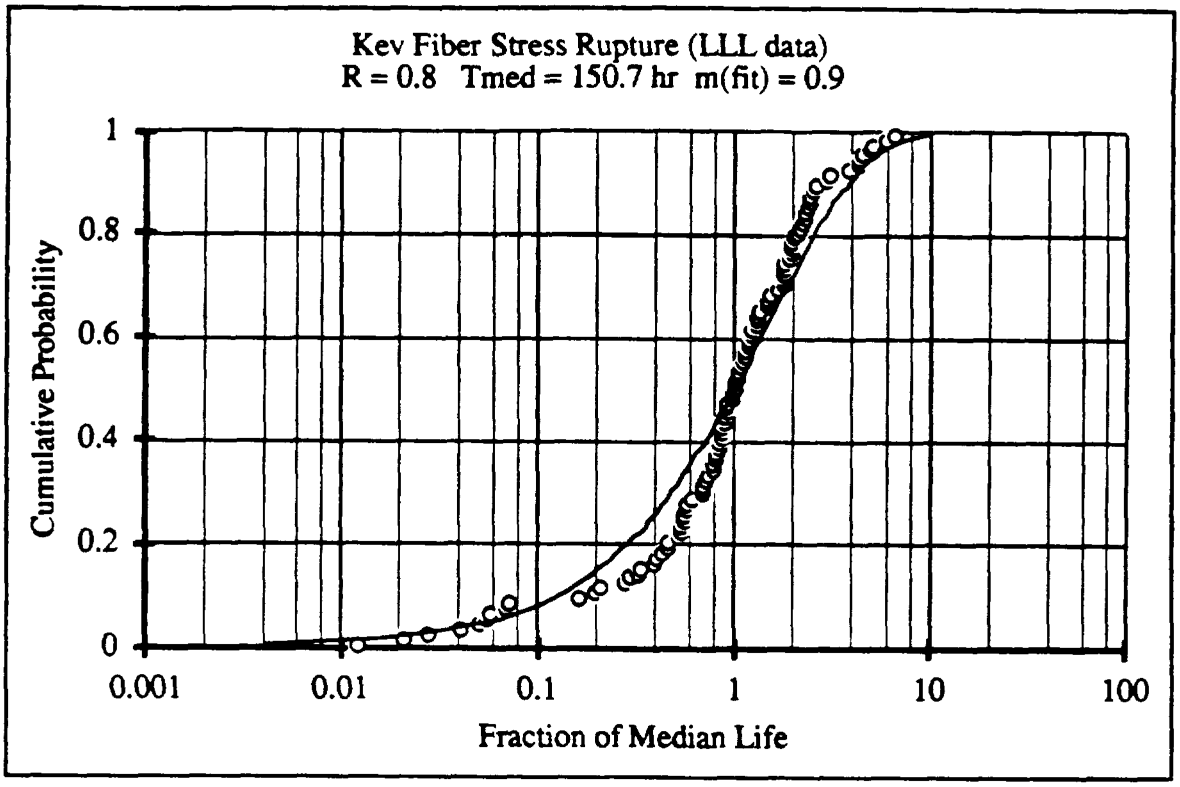
UCID 19849	r	Life - hrs	t/tmed	F = (r-1/2)/N	1-F	b est	pred t/tmed
440 ksi 0.87							
N = 100	51	2.80	1.002	0.505	0.495		1.016
Med = 2.795	52	2.89	1.034	0.515	0.485	1.29	1.049
	53	2.91	1.041	0.525	0.475	1.77	1.083
	54	2.91	1.041	0.535	0.465	2.47	1.117
	55	3.10	1.109	0.545	0.455	1.23	1.152
	56	3.11	1.113	0.555	0.445	1.46	1.188
	57	3.42	1.224	0.565	0.435	0.91	1.226
	58	3.47	1.242	0.575	0.425	0.97	1.264
	59	3.50	1.252	0.585	0.415	1.06	1.303
	60	3.64	1.302	0.595	0.405	1.00	1.343
	61	3.67	1.313	0.605	0.395	1.07	1.384
	62	3.68	1.317	0.615	0.385	1.16	1.427
	63	3.75	1.342	0.625	0.375	1.18	1.471
	64	4.39	1.571	0.635	0.365	0.83	1.516
	65	4.50	1.610	0.645	0.355	0.84	1.562
	66	4.53	1.621	0.655	0.345	0.89	1.610
	67	4.53	1.621	0.665	0.335	0.94	1.660
	68	4.65	1.664	0.675	0.325	0.95	1.711
	69	4.65	1.664	0.685	0.315	1.00	1.764
	70	4.69	1.678	0.695	0.305	1.04	1.819
	71	4.70	1.682	0.705	0.295	1.09	1.876
	72	4.75	1.699	0.715	0.285	1.12	1.934
	73	4.84	1.732	0.725	0.275	1.13	1.996
	74	5.01	1.792	0.735	0.265	1.11	2.059
	75	5.71	2.043	0.745	0.255	0.95	2.126
	76	5.92	2.118	0.755	0.245	0.94	2.195
	77	6.19	2.215	0.765	0.235	0.93	2.268
	78	6.33	2.265	0.775	0.225	0.94	2.343
	79	6.59	2.358	0.785	0.215	0.93	2.423
	80	6.62	2.369	0.795	0.205	0.96	2.506
	81	6.94	2.483	0.805	0.195	0.94	2.594
	82	7.16	2.562	0.815	0.185	0.95	2.687
	83	7.29	2.608	0.825	0.175	0.96	2.786
	84	7.36	2.633	0.835	0.165	0.99	2.891
	85	7.38	2.640	0.845	0.155	1.02	3.002
	86	7.42	2.655	0.855	0.145	1.05	3.122
	87	8.09	2.894	0.865	0.135	1.00	3.250
	88	8.88	3.177	0.875	0.125	0.95	3.389
	89	9.05	3.238	0.885	0.115	0.97	3.541
	90	9.25	3.309	0.895	0.105	0.99	3.707
	91	9.26	3.313	0.905	0.095	1.02	3.890
	92	9.47	3.388	0.915	0.085	1.04	4.095
	93	10.50	3.757	0.925	0.075	1.00	4.326
	94	10.57	3.782	0.935	0.065	1.03	4.593
	95	11.25	4.025	0.945	0.055	1.03	4.906
	96	13.49	4.826	0.955	0.045	0.95	5.284
	97	13.78	4.930	0.965	0.035	0.99	5.762
	98	16.15	5.778	0.975	0.025	0.95	6.408
	99	16.59	5.936	0.985	0.015	1.01	7.402
	100	18.16	6.497	0.995	0.005	1.09	9.582

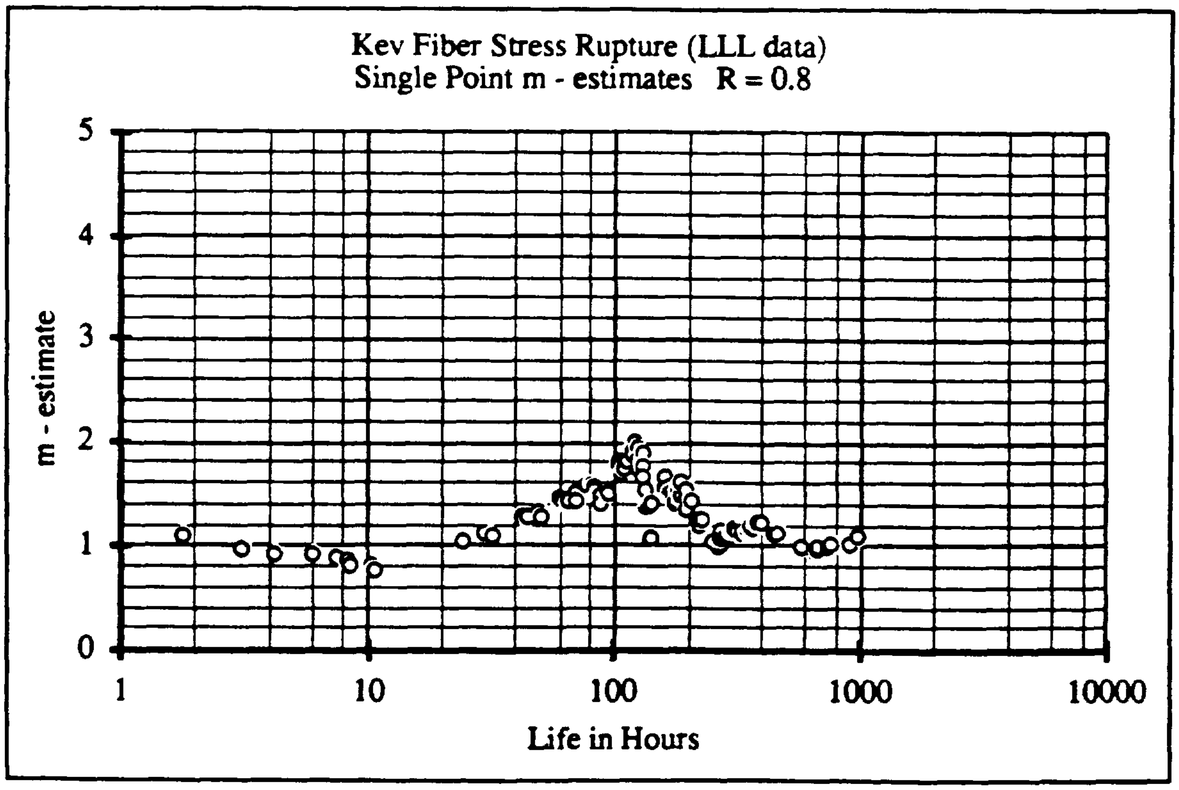

Kev Fiber Stress Rupture (LLL data)
R = 0.84 Tmed = 12.52 hr m(fit) = 0.9
Cumulative Probability
1
0.8
0.6
0.4
0.2
0
0.001
0.01
0.1
1
10
100
Fraction of Median Life


Kev Fiber Stress Rupture (LLL data)
Single Point m - estimates R = 0.84
m - estimate
5
4
3
2
1
0
0.1
1
10
100
1000
Life in Hours

	r	Life - hrs	t/tmed	F = (r-1/2)/N	S = 1-F	b est	b=0.9 pred
UCID 19849	1	0.25	0.020	0.005	0.995	1.27	0.004
424.8 ksi 0.84	2	0.31	0.025	0.015	0.985	1.04	0.014
N = 103	3	0.44	0.035	0.024	0.976	1.00	0.024
Med = 12.52	4	0.45	0.036	0.034	0.966	0.90	0.036
	5	0.57	0.046	0.044	0.956	0.89	0.048
	6	0.65	0.052	0.053	0.947	0.86	0.060
	7	0.73	0.058	0.063	0.937	0.83	0.072
	8	0.89	0.071	0.073	0.927	0.84	0.085
	9	1.06	0.085	0.083	0.917	0.84	0.099
	10	1.22	0.097	0.092	0.908	0.85	0.112
	11	1.37	0.109	0.102	0.898	0.84	0.126
	12	1.83	0.146	0.112	0.888	0.92	0.140
	13	1.96	0.157	0.121	0.879	0.91	0.155
	14	2.15	0.172	0.131	0.869	0.91	0.170
	15	2.40	0.192	0.141	0.859	0.92	0.185
	16	2.51	0.200	0.150	0.850	0.90	0.200
	17	2.77	0.221	0.160	0.840	0.91	0.216
	18	4.05	0.323	0.170	0.830	1.16	0.232
	19	4.07	0.325	0.180	0.820	1.12	0.248
	20	4.34	0.347	0.189	0.811	1.13	0.265
	21	4.98	0.398	0.199	0.801	1.24	0.282
	22	5.86	0.468	0.209	0.791	1.43	0.299
	23	5.90	0.471	0.218	0.782	1.37	0.317
	24	6.18	0.494	0.228	0.772	1.39	0.335
	25	6.30	0.503	0.238	0.762	1.36	0.353
	26	7.14	0.570	0.248	0.752	1.59	0.372
	27	7.32	0.585	0.257	0.743	1.58	0.391
	28	7.45	0.595	0.267	0.733	1.55	0.410
	29	7.92	0.633	0.277	0.723	1.66	0.429
	30	7.99	0.638	0.286	0.714	1.60	0.449
	31	8.22	0.657	0.296	0.704	1.62	0.470
	32	8.35	0.667	0.306	0.694	1.58	0.490
	33	8.38	0.669	0.316	0.684	1.50	0.511
	34	8.39	0.670	0.325	0.675	1.42	0.533
	35	8.45	0.675	0.335	0.665	1.35	0.555
	36	8.53	0.681	0.345	0.655	1.29	0.577
	37	8.55	0.683	0.354	0.646	1.21	0.600
	38	8.64	0.690	0.364	0.636	1.15	0.623
	39	8.68	0.693	0.374	0.626	1.07	0.646
	40	8.92	0.712	0.383	0.617	1.06	0.670
	41	8.93	0.713	0.393	0.607	0.97	0.695
	42	9.45	0.755	0.403	0.597	1.05	0.720
	43	9.57	0.764	0.413	0.587	0.98	0.745
	44	9.80	0.783	0.422	0.578	0.95	0.771
	45	9.83	0.785	0.432	0.568	0.84	0.798
	46	10.60	0.847	0.442	0.558	1.04	0.825
	47	10.82	0.864	0.451	0.549	0.98	0.853
	48	10.83	0.865	0.461	0.539	0.79	0.881
	49	11.03	0.881	0.471	0.529	0.67	0.910
more	50	11.12	0.888	0.481	0.519		0.939

	r	Life - hrs	t/tmed	F = (r-1/2)/N	1-F	b est	pred t/tmed
UCID 19849							
424.8 ksi 0.84							
N = 103	51	11.13	0.889	0.490	0.510		0.969
Med = 12.52	52	12.52	1.000	0.500	0.500		1.000
	53	12.94	1.034	0.510	0.490		1.031
	54	16.42	1.312	0.519	0.481		1.064
	55	16.47	1.315	0.529	0.471		1.097
	56	17.68	1.412	0.539	0.461		1.130
	57	17.79	1.421	0.549	0.451		1.165
	58	18.45	1.474	0.558	0.442		1.200
	59	18.95	1.514	0.568	0.432		1.237
	60	19.07	1.523	0.578	0.422		1.274
	61	19.40	1.550	0.587	0.413		1.312
	62	19.62	1.567	0.597	0.403		1.352
	63	19.86	1.586	0.607	0.393		1.392
	64	20.76	1.658	0.617	0.383		1.433
	65	21.38	1.708	0.626	0.374		1.476
	66	23.03	1.839	0.636	0.364		1.520
	67	23.10	1.845	0.646	0.354	0.66	1.565
	68	23.83	1.903	0.655	0.345	0.67	1.612
	69	24.46	1.954	0.665	0.335	0.68	1.660
	70	24.81	1.982	0.675	0.325	0.71	1.710
	71	25.15	2.009	0.684	0.316	0.73	1.761
	72	25.18	2.011	0.694	0.306	0.77	1.814
	73	26.96	2.153	0.704	0.296	0.73	1.869
	74	27.53	2.199	0.714	0.286	0.75	1.926
	75	27.86	2.225	0.723	0.277	0.77	1.985
	76	29.89	2.387	0.733	0.267	0.74	2.047
	77	32.55	2.600	0.743	0.257	0.70	2.110
	78	33.95	2.712	0.752	0.248	0.70	2.177
	79	34.51	2.756	0.762	0.238	0.72	2.246
	80	34.74	2.775	0.772	0.228	0.74	2.319
	81	35.63	2.846	0.782	0.218	0.75	2.395
	82	36.84	2.942	0.791	0.209	0.76	2.475
	83	36.97	2.953	0.801	0.199	0.78	2.558
	84	39.17	3.129	0.811	0.189	0.77	2.647
	85	41.54	3.318	0.820	0.180	0.76	2.740
	86	42.32	3.380	0.830	0.170	0.77	2.838
	87	42.53	3.397	0.840	0.160	0.79	2.943
	88	43.61	3.483	0.850	0.150	0.81	3.055
	89	48.54	3.877	0.859	0.141	0.77	3.175
	90	49.02	3.915	0.869	0.131	0.79	3.304
	91	55.20	4.409	0.879	0.121	0.75	3.443
	92	55.99	4.472	0.888	0.112	0.77	3.595
	93	61.37	4.902	0.898	0.102	0.75	3.761
	94	63.17	5.046	0.908	0.092	0.76	3.944
	95	66.48	5.310	0.917	0.083	0.77	4.149
	96	67.06	5.356	0.927	0.073	0.79	4.381
	97	74.01	5.911	0.937	0.063	0.78	4.648
	98	74.61	5.959	0.947	0.053	0.81	4.961
	99	76.46	6.107	0.956	0.044	0.83	5.340
	100	84.26	6.730	0.966	0.034	0.83	5.819
	101	89.87	7.178	0.976	0.024	0.85	6.465
	102	97.37	7.777	0.985	0.015	0.88	7.460
	103	119.09	9.512	0.995	0.005	0.91	9.641


Kev Fiber Stress Rupture (LLL data)
R = 0.8 Tmed = 150.7 hr m(fit) = 0.9
Cumulative Probability
1
0.8
0.6
0.4
0.2
0
0.001
0.01
0.1
1
10
100
Fraction of Median Life


Kev Fiber Stress Rupture (LLL data)
Single Point m - estimates R = 0.8
m - estimate
5
4
3
2
1
0
1
10
100
1000
10000
Life in Hours

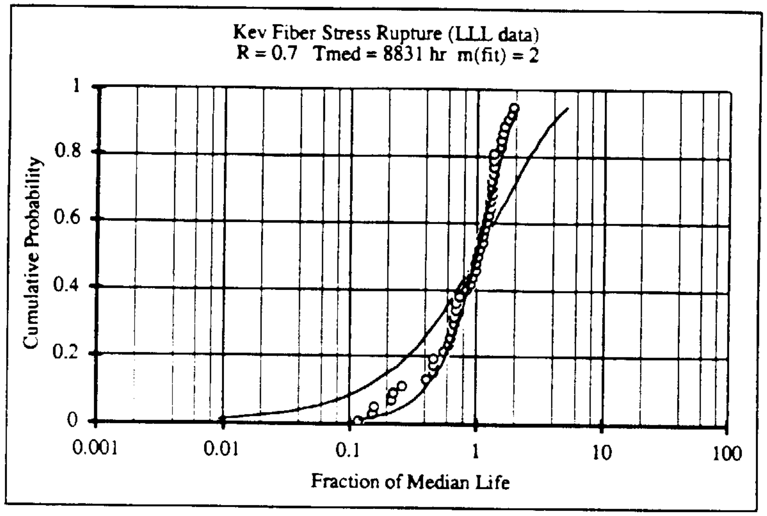
UCID 19849
404.6 ksi 0.8
N = 100
Med = 150.7 hr

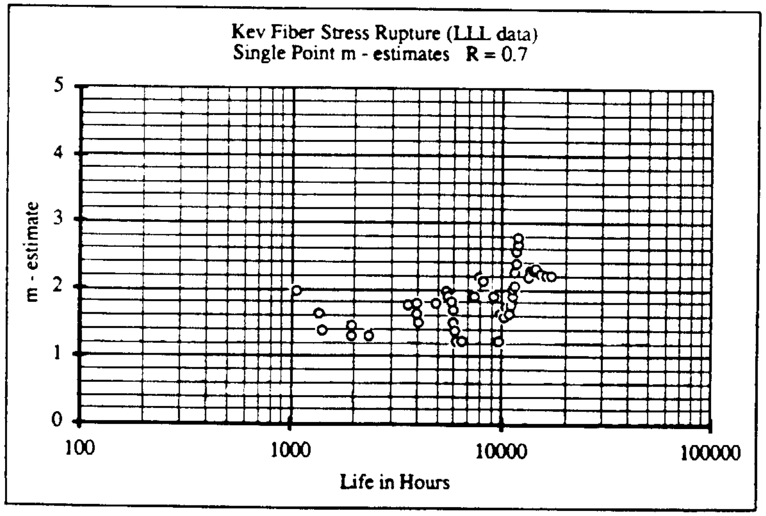
r	Life - hrs	t/tmed	F = (r-1/2)/N	S = 1-F	m est	m = 0.9 fit
1	1.80	0.012	0.005	0.995	1.11	0.004
2	3.10	0.021	0.015	0.985	0.99	0.014
3	4.20	0.028	0.025	0.975	0.92	0.025
4	6.00	0.040	0.035	0.965	0.92	0.037
5	7.50	0.050	0.045	0.955	0.90	0.049
6	8.20	0.054	0.055	0.945	0.86	0.062
7	8.50	0.056	0.065	0.935	0.81	0.075
8	10.30	0.068	0.075	0.925	0.81	0.088
9	10.60	0.070	0.085	0.915	0.77	0.102
10	24.20	0.161	0.095	0.905	1.06	0.116
11	29.60	0.196	0.105	0.895	1.13	0.131
12	31.70	0.210	0.115	0.885	1.11	0.145
13	41.90	0.278	0.125	0.875	1.29	0.160
14	44.10	0.293	0.135	0.865	1.27	0.176
15	49.50	0.328	0.145	0.855	1.34	0.192
16	50.10	0.332	0.155	0.845	1.28	0.208
17	59.70	0.396	0.165	0.835	1.45	0.224
18	61.70	0.409	0.175	0.825	1.44	0.241
19	64.40	0.427	0.185	0.815	1.44	0.258
20	69.70	0.463	0.195	0.805	1.51	0.275
21	70.00	0.464	0.205	0.795	1.44	0.293
22	77.80	0.516	0.215	0.785	1.59	0.311
23	80.50	0.534	0.225	0.775	1.60	0.329
24	82.30	0.546	0.235	0.765	1.57	0.348
25	83.50	0.554	0.245	0.755	1.53	0.367
26	84.20	0.559	0.255	0.745	1.47	0.386
27	87.10	0.578	0.265	0.735	1.48	0.406
28	87.30	0.579	0.275	0.725	1.41	0.426
29	93.20	0.618	0.285	0.715	1.51	0.446
30	103.40	0.686	0.295	0.705	1.82	0.467
31	104.60	0.694	0.305	0.695	1.77	0.489
32	105.50	0.700	0.315	0.685	1.70	0.510
33	108.80	0.722	0.325	0.675	1.74	0.532
34	112.60	0.747	0.335	0.665	1.82	0.555
35	116.80	0.775	0.345	0.655	1.94	0.578
36	118.00	0.783	0.355	0.645	1.87	0.601
37	122.00	0.810	0.365	0.635	2.00	0.625
38	123.50	0.820	0.375	0.625	1.95	0.649
39	124.40	0.825	0.385	0.615	1.85	0.674
40	125.40	0.832	0.395	0.605	1.75	0.700
41	129.50	0.859	0.405	0.595	1.91	0.725
42	130.40	0.865	0.415	0.585	1.78	0.752
43	131.60	0.873	0.425	0.575	1.66	0.779
44	132.80	0.881	0.435	0.565	1.53	0.806
45	133.80	0.888	0.445	0.555	1.37	0.834
46	137.00	0.909	0.455	0.545	1.39	0.863
47	140.20	0.930	0.465	0.535	1.42	0.892
48	140.90	0.935	0.475	0.525	1.09	0.922
49	148.50	0.985	0.485	0.515		0.953
50	149.20	0.990	0.495	0.505		0.984

UCID 19849
404.6 ksi 0.8
N = 100
Med = 150.7 hr

r	Life - hrs	t/tmed	F = (r-1/2)/N	S = 1-F	b est	b=0.9 pred
51	152.20	1.010	0.505	0.495		1.016
52	152.80	1.014	0.515	0.485		1.049
53	157.70	1.046	0.525	0.475	1.57	1.083
54	160.00	1.062	0.535	0.465	1.66	1.117
55	163.60	1.086	0.545	0.455	1.55	1.152
56	166.90	1.107	0.555	0.445	1.52	1.188
57	170.50	1.131	0.565	0.435	1.48	1.226
58	174.90	1.161	0.575	0.425	1.41	1.264
59	177.70	1.179	0.585	0.415	1.44	1.303
60	179.20	1.189	0.595	0.405	1.53	1.343
61	183.60	1.218	0.605	0.395	1.48	1.384
62	183.80	1.220	0.615	0.385	1.61	1.427
63	194.30	1.289	0.625	0.375	1.37	1.471
64	195.10	1.295	0.635	0.365	1.45	1.516
65	195.30	1.296	0.645	0.355	1.55	1.562
66	202.60	1.344	0.655	0.345	1.45	1.610
67	220.20	1.461	0.665	0.335	1.20	1.660
68	221.30	1.468	0.675	0.325	1.26	1.711
69	227.20	1.508	0.685	0.315	1.24	1.764
70	251.00	1.666	0.695	0.305	1.06	1.819
71	266.50	1.768	0.705	0.295	0.99	1.876
72	267.90	1.778	0.715	0.285	1.03	1.934
73	269.20	1.786	0.725	0.275	1.07	1.996
74	270.40	1.794	0.735	0.265	1.11	2.059
75	272.50	1.808	0.745	0.255	1.15	2.126
76	285.90	1.897	0.755	0.245	1.11	2.195
77	292.60	1.942	0.765	0.235	1.11	2.268
78	295.10	1.958	0.775	0.225	1.14	2.343
79	301.10	1.998	0.785	0.215	1.15	2.423
80	304.30	2.019	0.795	0.205	1.18	2.506
81	316.80	2.102	0.805	0.195	1.15	2.594
82	329.80	2.188	0.815	0.185	1.14	2.687
83	334.10	2.217	0.825	0.175	1.16	2.786
84	346.20	2.297	0.835	0.165	1.15	2.891
85	351.20	2.330	0.845	0.155	1.17	3.002
86	353.30	2.344	0.855	0.145	1.20	3.122
87	369.30	2.451	0.865	0.135	1.18	3.250
88	372.30	2.470	0.875	0.125	1.21	3.389
89	381.30	2.530	0.885	0.115	1.23	3.541
90	393.50	2.611	0.895	0.105	1.23	3.707
91	451.30	2.995	0.905	0.095	1.11	3.890
92	461.50	3.062	0.915	0.085	1.13	4.095
93	574.20	3.810	0.925	0.075	0.99	4.326
94	653.30	4.335	0.935	0.065	0.94	4.593
95	663.00	4.399	0.945	0.055	0.97	4.906
96	669.80	4.445	0.955	0.045	1.00	5.284
97	739.70	4.908	0.965	0.035	0.99	5.762
98	759.60	5.040	0.975	0.025	1.03	6.408
99	894.70	5.937	0.985	0.015	1.01	7.402
100	974.90	6.469	0.995	0.005	1.09	9.582

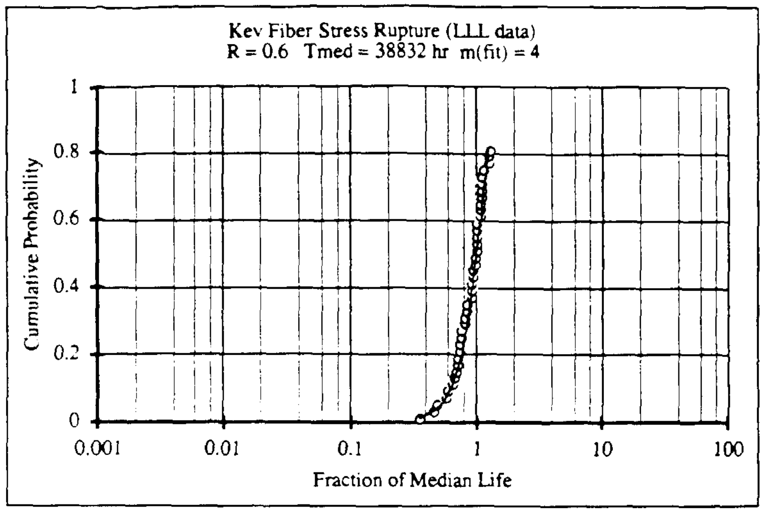
1614

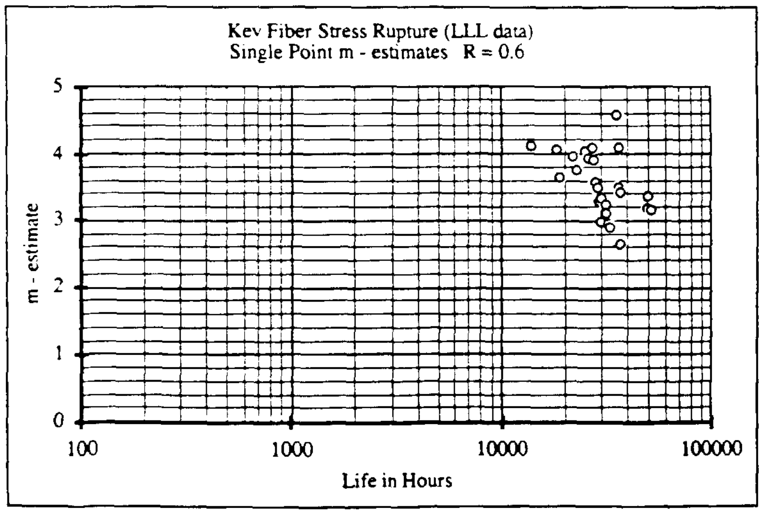




UCID 19849
354 ksi 0.7
N = 49
Med = 8831 hr

r	Life - hrs	t/tmed	F = (r-1/2)/N	S = 1-F	m est	m = 0.9 fit	m = 1.5	m = 2
1	1051	0.119	0.010	0.990	1.98	0.009	0.060	0.122
2	1337	0.151	0.031	0.969	1.64	0.032	0.109	0.212
3	1389	0.157	0.051	0.949	1.40	0.057	0.158	0.275
4	1921	0.218	0.071	0.929	1.47	0.083	0.203	0.327
5	1942	0.220	0.092	0.908	1.30	0.112	0.244	0.373
6	2322	0.263	0.112	0.888	1.32	0.141	0.284	0.414
7	3629	0.411	0.133	0.867	1.78	0.172	0.323	0.453
8	4006	0.454	0.153	0.847	1.81	0.204	0.360	0.490
9	4012	0.454	0.173	0.827	1.64	0.238	0.398	0.524
10	4063	0.460	0.194	0.806	1.50	0.273	0.434	0.558
11	4921	0.557	0.214	0.786	1.81	0.309	0.470	0.590
12	5445	0.617	0.235	0.765	1.97	0.347	0.507	0.621
13	5620	0.636	0.255	0.745	1.89	0.386	0.543	0.652
14	5817	0.659	0.276	0.724	1.83	0.427	0.579	0.682
15	5905	0.669	0.296	0.704	1.69	0.469	0.615	0.711
16	5956	0.674	0.316	0.684	1.52	0.513	0.651	0.741
17	6068	0.687	0.337	0.663	1.40	0.559	0.688	0.770
18	6121	0.693	0.357	0.643	1.23	0.606	0.725	0.798
19	6473	0.733	0.378	0.622	1.22	0.656	0.762	0.827
20	7501	0.849	0.398	0.602	1.91	0.707	0.800	0.856
21	7886	0.893	0.418	0.582	2.17	0.761	0.839	0.884
22	8105	0.918	0.439	0.561	2.13	0.817	0.878	0.913
23	8546	0.968	0.459	0.541		0.875	0.918	0.942
24	8666	0.981	0.480	0.520		0.936	0.958	0.971
25	8831	1.000	0.500	0.500		1.000	1.000	1.000
26	9106	1.031	0.520	0.480	1.90	1.067	1.043	1.030
27	9711	1.100	0.541	0.459	1.22	1.137	1.086	1.060
28	9806	1.110	0.561	0.439	1.65	1.211	1.131	1.090
29	10205	1.156	0.582	0.418	1.58	1.290	1.178	1.121
30	10396	1.177	0.602	0.398	1.74	1.372	1.225	1.153
31	10861	1.230	0.622	0.378	1.64	1.459	1.275	1.185
32	11026	1.249	0.643	0.357	1.78	1.552	1.327	1.219
33	11214	1.270	0.663	0.337	1.89	1.651	1.380	1.253
34	11362	1.287	0.684	0.316	2.01	1.757	1.437	1.289
35	11604	1.314	0.704	0.296	2.06	1.870	1.496	1.325
36	11608	1.314	0.724	0.276	2.27	1.993	1.558	1.364
37	11745	1.330	0.745	0.255	2.38	2.125	1.624	1.404
38	11762	1.332	0.765	0.235	2.57	2.270	1.694	1.446
39	11895	1.347	0.786	0.214	2.68	2.429	1.769	1.491
40	12044	1.364	0.806	0.194	2.78	2.605	1.850	1.538
41	13520	1.531	0.827	0.173	2.18	2.801	1.939	1.590
42	13670	1.548	0.847	0.153	2.28	3.025	2.037	1.646
43	14110	1.598	0.867	0.133	2.28	3.282	2.147	1.707
44	14496	1.641	0.888	0.112	2.32	3.585	2.272	1.776
45	15395	1.743	0.908	0.092	2.23	3.952	2.419	1.856
46	16179	1.832	0.929	0.071	2.21	4.417	2.599	1.951
47	17092	1.935	0.949	0.051	2.21	5.047	2.831	2.072





UCID 19849	r	Life - hrs	t/tmed	F = (r-1/2)/N	S = 1-F	b est	b = 4 fit
303.5 ksi 0.6	1	13872	0.357	0.010	0.990	4.11	0.347
N = 50	2	18024	0.464	0.030	0.970	4.07	0.458
Med = 38832 hr	3	19008	0.489	0.050	0.950	3.64	0.522
	4	21960	0.566	0.070	0.930	3.96	0.569
	5	22872	0.589	0.090	0.910	3.77	0.607
	6	25008	0.644	0.110	0.890	4.05	0.640
	7	25848	0.666	0.130	0.870	3.94	0.670
	8	27216	0.701	0.150	0.850	4.08	0.696
	9	27744	0.714	0.170	0.830	3.91	0.720
	10	27840	0.717	0.190	0.810	3.58	0.743
	11	28512	0.734	0.210	0.790	3.49	0.764
	12	28896	0.744	0.230	0.770	3.30	0.784
	13	29832	0.768	0.250	0.750	3.34	0.803
	14	29832	0.768	0.270	0.730	2.99	0.821
	15	31224	0.804	0.290	0.710	3.23	0.838
	16	31752	0.818	0.310	0.690	3.10	0.855
	17	32232	0.830	0.330	0.670	2.94	0.872
	18	32976	0.849	0.350	0.650	2.91	0.888
	19	35544	0.915	0.370	0.630	4.58	0.904
	20	35760	0.921	0.390	0.610	4.10	0.919
	21	35928	0.925	0.410	0.590	3.51	0.934
	22	36528	0.941	0.430	0.570	3.43	0.949
	23	36720	0.946	0.450	0.550	2.65	0.964
	24	38592	0.994	0.470	0.530		0.978
repeat *	25	38592	0.994	0.490	0.510		0.993
	26	39072	1.006	0.510	0.490		1.007
	27	39240	1.011	0.530	0.470		1.022
	28	39576	1.019	0.550	0.450		1.036
	29	39744	1.023	0.570	0.430		1.050
repeat *	30	39744	1.023	0.590	0.410		1.065
	31	41592	1.071	0.610	0.390		1.080
	32	41760	1.075	0.630	0.370		1.094
repeat *	33	41760	1.075	0.650	0.350		1.109
	34	42600	1.097	0.670	0.330		1.125
repeat *	35	42600	1.097	0.690	0.310		1.140
	36	42960	1.106	0.710	0.290		1.156
	37	43176	1.112	0.730	0.270		1.172
	38	44664	1.150	0.750	0.250		1.189
	39	49176	1.266	0.770	0.230	3.18	1.207
	40	49440	1.273	0.790	0.210	3.36	1.225
	41	51192	1.318	0.810	0.190	3.16	1.244

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UCID 19849	r	Life - hrs	t/t4	F = (r-1/2)/N	S = 1-p	m est	Est Median	t /med	m fit	m =
252 ksi 0.5	1	31344	0.475	0.010	0.990	2.65	154536	0.209	0.244	3.000
N = 50	2	32376	0.490	0.030	0.970	1.22	420866	0.216	0.353	
r=4 life = 66024	3	58056	0.879	0.050	0.950	2.70	152386	0.387	0.420	
	4	66024	1.000	0.070	0.930			0.440	0.471	
							(150,000)