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# EXAMINATION OF THE TENSILE STRENGTH OF GRAPHITE FIBERS

ELIZABETH C. GOEKE and SHUN-CHIN CHOU
MATERIALS DYNAMICS BRANCH

February 1989

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## ABSTRACT

The Single Fiber Graphite Tester was developed to measure the failure load and fiber diameter of graphite fibers. Data have been taken on a number of commercially available fibers with the tester. These data have been examined in order to understand the dispersion in these properties and the correlation between them.

Keywords: tensile strength; carbon fibers; (AT)

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## INTRODUCTION

This is a study undertaken to explore the dispersion observed in the failure loads and diameters of a variety of types of single filament graphite fibers. In order to be able to measure diameter and tensile properties on the same fiber, a new testing apparatus was developed for the study, the Single Fiber Graphite Tester. This tester is similar to the one developed by Dr. Wu at the Naval Postgraduate School.*

## BACKGROUND

The motivation for this study can be found in the effort reported by Wu and Chou.[1] They observed that the characterization of composite laminates is complex and expensive. However, if composites are to be used in structures, data on their properties is essential. Fiber manufacturers are improving production techniques and developing new fibers on an ongoing basis. Therefore, there is a continuing demand to test candidate composite materials.

A considerable body of literature exists describing the properties of "brittle" fibers in terms of Weibull statistics and exploring the fit of graphite fibers to this description (e.g., Watson and Smith).[2] Wu and Chou postulated that if a correlation could be found in the Weibull description of the tensile properties of single fibers, impregnated strands, and unidirectional coupons, the task of evaluating fibers could be simplified by testing fibers rather than coupons. One would then use the established relationship to translate the fiber properties into expected composite properties. Wu and Chou tested a set of single fibers, strands, and coupons. They found a consistent trend in the dispersion characteristics that indicated a useful tool could be developed.

A large percentage of the single fiber tensile data for graphite fibers in the literature is based on testing where the failure loads are recorded for a group of fibers, then a mean diameter measured on another group of fibers is used to convert the loads to stresses (e.g., Kowalski).[3] This technique assumes there is no correlation between the failure load and the diameter of the fiber. This study intended to explore this assumption. This requires that the diameter and failure load for each individual fiber be measured. The small size of the fibers makes the handling of them difficult. Because "brittle" materials have large variability in their properties, a large number of measurements are needed to characterize them. In the past, these two conditions have inhibited other workers from studies of individual fiber properties.

## EXPERIMENTAL TECHNIQUE

When the Single Fiber Graphite Tester was assembled, one of the objectives was to minimize the handling of the fibers measured. To this end, the diameter measurements and the tensile loading were done with the fibers held in the same load frame. The fibers were mounted in frames cut from graph paper with cellulosic glue as shown in Figure 1a. Before measurement, the frame was burned out and tension applied to the fiber. A gage length of about 1.75 inches was prescribed by the equipment configuration. Figure 1b shows the paper frame mounted in the aluminum load frame. Figure 1c shows the tester without the personal computer, x-y recorder, and position recorder that are used to process the readings. ASTM D 3379[4] served as a guide when designing the equipment.

*WU, E. M., KUNKEL, J. S., and STORCH, M. *Reliability of Composites Through Fiber Statistics and Automated Laser Diffraction Implementation.* Technical Report, Naval Postgraduate School, 1988, to be published.


1. WU, E. M., and CHOU, S. *Statistical Strength Comparison of Metal Matrix and Polymeric Matrix Composites.* U.S. Army Materials Technology Laboratory, MTL TR 86-11, April 1986.
2. WATSON, A. S., and SMITH, R. L. *An Examination of Statistical Theories for Fibrous Materials in the Light of Experimental Data.* Journal of Material Science, v. 20, 1985, p. 3260.
3. KOWALSKI, I. *Composite Materials: Testing and Design (Eighth Conference)*, J. D. Whitcomb, ed., ASTM STP-972, 1988.
4. ASTM D 3379. *Tensile Strength and Young's Modulus for High Modulus Single-Filament Materials.* 1987 Annual Book of ASTM Standards, v. 15.03.

The physical principle from which the diameter measurement derives is the diffraction pattern from a slit. Figure 2 is a schematic of the configuration. A helium laser is used to create the diffraction pattern and cadmium-sulphide detectors to measure it. A beam of light behaves in the identical manner for the mirror image of a slit, a fiber. Thus, a fiber held vertically in the laser beam gives a horizontal diffraction pattern where the distance between the minima of the diffraction pattern is proportional to the diameter of the fiber (assuming the fiber cross section is circular).

The diffraction pattern is measured by moving the detectors across it and finding the minima. The output is a resistance-position plot. During the course of the study, these plots were produced in varying ways. None of these changes was expected to affect the data but to expedite data acquisition. Because the detectors increase their resistance for a decrease in light intensity, the minima in the diffraction pattern appear as maxima in the resistance-position plots. Figure 3 is a typical set of such plots. The peak positions were determined graphically on the plots. During the study, details of the experimental configuration were changed in order to improve the character of the plots.

After the fiber diameter measurement was completed, the fiber was tensile tested using the load cell and constant displacement rate screw mounted in the load frame. Failure loads were taken from the resulting load displacement curves.

Data sets were defined as 50 fibers. Thus, a measurement of a type of fiber consists of about 50 fibers taken from one location in a fiber tow.

The fibers measured in this study were three fibers from Hercules, AS-4, IM-6, and IM-7; Apollo IM, a Courtaulds fiber; and four fibers purchased as a set of tow, impregnated strand, and coupons. These four are Microfil 40, Microfil 55, ACIF-HM, and ACIF-XHT. Repeat measurements were made on AS-4 and IM-6 to explore the reproducibility of the data and the consistency of the testing technique.

Hercules has replaced AS-4 as its recommended fiber, yet a large body of data on its properties exists in the literature. This makes data on it valuable for validation of the test procedure and exploration of interlaboratory variation. Hercules has marketed IM-6 and IM-7 as fibers with improvements. In addition to the tow testing, strand and plate of IM-6 will be tested in the future.

## EXPERIMENTAL RESULTS

Data reduction has two components, calculation and graphical analysis. The details of the fiber diameter calculations are given in Appendix A. The individual failure stresses are calculated from the failure loads and diameters of the fibers.

Two types of graphical analysis have been used, the correlation between fiber diameter and fiber failure, and the description of the data variability by three distribution functions. The MARS code[5] was used for the latter. This fits the data to a normal, a lognormal, and a Weibull distribution. Because diameter is a geometrical property, the expected distribution of its values would be normal. The description of failure distributions by a Weibull function is part of the Wu and Chou analysis. For these reasons, the diameter distributions are presented with the best fit normal curve. The failure load and failure strength distributions are presented with the best fit Weibull curves. Table 1 lists all of these plots. The fiber properties as calculated from the data sets are shown in Table 2.

5. NEAL, D., LENOE, E., and SPIRIDIGTROZZI, L. *Advanced Statistical Design Allowable Code.* Proceedings of the Twenty-Second Automotive Technology Development Contractors Coordination Meeting, SAE Publication T-155, 1984.

Table 1. EXPERIMENTAL RESULTS

| Fiber | Manufacturer | Diameter Correlation | Distribution Description |
|---|---|---|---|
| AS-4 | Hercules | Figure 4 | Figure 5 |
| Microfil 40 | FMI | Figure 6 | Figure 7 |
| Microfil 55 | FMI | Figure 8 | Figure 9 |
| ACIF-HM | Israeli | Figure 10 | Figure 11 |
| ACIF-XHT | Israeli | Figure 12 | Figure 13 |
| Apollo IM | Courtaulds | Figure 14 | Figure 15 |
| IM-6 | Hercules | Figure 16 | Figure 17 |
| IM-7 | Hercules | Figure 18 | Figure 19 |

The precision of the measurements was limited by the equipment. The load cell and the x-y recorder used for readout can be read to the nearest 0.3 gram. Since the failure loads were in the range of 3.5 to 20 grams, this is an uncertainty of 15% or less. From the details of the measurements, the diameter values were concluded to be reproducible to the nearest 0 .1 micron. Since diameter values ranged from 4 to 9 microns, this is an uncertainty of 1% or less. Alternative methods for measuring the failure load or the diameter were not pursued and thus the accuracy of the measurements was not explored.

## ANALYSIS OF DATA

Because the Single Fiber Graphite Tester is a new piece of equipment, the first question was whether the initial data appeared "reasonable." Wu and Chou[1] tested single filament AS-4 and measured a mean failure load of 16 grams and a Weibull shape parameter of 5.8. This is within one sigma of the load value reported herein, 14.2 grams, and does not differ greatly from the shape parameter of 4.9 observed herein. They also tested single filament pitch-based fibers from Union Carbide with resulting Weibull shape parameters of approximately 5. Thus, they observed similar scatter in their data. These comparisons led to the conclusion that the test method is valid. Additional exploration of this conclusion occurred when a second AS-4 data set was measured later in the program. The details of the examination of the second AS-4 data set are given in Appendix B. It was found to have two outlying values. When these were removed, the two AS-4 data sets were definitely from the same population.

The next issue examined was the relationship between fiber diameter and fiber strength observed for the fibers measured. This requires a study of Figures 4, 6, 8, 10, 12, 14, 16, and 18. None of these plots exhibits correlation between either fiber failure load and diameter or fiber failure strength and diameter. The range of fibers studied is probably not sufficient to state that fiber failure strength is not related to fiber diameter for all graphite fibers, but this appears to be true for all fibers measured.

The third issue examined was the variability observed in the diameter, failure load, and failure strength data. The simplest description of this variability is the coefficient of variation. Values for the diameter range from 0.03 to 0.06. Values for failure load range from 0.18 to 0.29, indicating much higher variability for failure load than diameter. An examination of the root mean square error values obtained from the MARS code analysis of the fit of normal, lognormal, and Weibull distributions to the data did not show a consistent pattern for choosing between the distributions. The Weibull shape parameters obtained from the analysis are another measure of observed variability. Its value for the diameter data was in the range of 20 to 35. The parameter for the failure loads and failure strengths was in the range of 3 to 8. This greater dispersion in the failure loads than in the fiber diameters can also be seen in Figure 20. Here, the mean values are plotted with one sigma variation bars.

Table 2. SINGLE FIBER TEST RESULTS

| Fiber | | Diameter (microns) | Failure Load (grams) | Failure Strength (GPa) |
|---|---|---|---|---|
| AS-4 | | | | |
| | Mean | 7.90 | 14.20 | 2.80 |
| | Std. Dev. | 0.36 | 3.11 | 0.59 |
| | Cof. Var. | 0.05 | 0.22 | 0.21 |
| | W. Shape | 24.60 | 4.90 | 5.40 |
| AS-4 (Repeat) | | | | |
| | Mean | 7.80 | 13.60 | 2.90 |
| | Std. Dev. | 0.44 | 3.33 | 1.13 |
| | Cof. Var. | 0.06 | 0.24 | 0.39 |
| | W. Shape | 17.20 | 4.80 | 4.50 |
| Apollo IM | | | | |
| | Mean | 5.50 | 7.10 | 3.00 |
| | Std. Dev. | 0.23 | 1.46 | 0.63 |
| | Cof. Var. | 0.04 | 0.20 | 0.21 |
| | W. Shape | 28.60 | 5.00 | 4.70 |
| ACIF-XHT | | | | |
| | Mean | 7.40 | 10.80 | 2.40 |
| | Std. Dev. | 0.32 | 1.92 | 0.45 |
| | Cof. Var. | 0.04 | 0.18 | 0.19 |
| | W. Shape | 24.40 | 5.40 | 5.60 |
| ACIF-HM | | | | |
| | Mean | 7.40 | 9.20 | 2.10 |
| | Std. Dev. | 0.31 | 2.65 | 0.58 |
| | Cof. Var. | 0.04 | 0.29 | 0.28 |
| | W. Shape | 31.50 | 3.90 | 4.20 |
| M40 | | | | |
| | Mean | 4.80 | 5.60 | 3.00 |
| | Std. Dev. | 0.25 | 1.14 | 0.59 |
| | Cof. Var. | 0.05 | 0.20 | 0.20 |
| | W. Shape | 19.40 | 5.00 | 5.00 |
| M55 | | | | |
| | Mean | 4.70 | 5.00 | 2.80 |
| | Std. Dev. | 0.20 | 0.81 | 0.39 |
| | Cof. Var. | 0.04 | 0.16 | 0.14 |
| | W. Shape | 25.60 | 7.00 | 7.50 |
| IM-6 | | | | |
| | Mean | 5.80 | 6.60 | 2.50 |
| | Std. Dev. | 0.19 | 1.82 | 0.68 |
| | Cof. Var. | 0.03 | 0.28 | 0.28 |
| | W. Shape | 34.20 | 4.00 | 4.00 |
| IM-6-II | | | | |
| | Mean | 5.90 | 7.60 | 2.80 |
| | Std. Dev. | 0.30 | 1.90 | 0.72 |
| | Cof. Var. | 0.05 | 0.25 | 0.26 |
| | W. Shape | 24.00 | 4.10 | 4.10 |
| IM-6-III | | | | |
| | Mean | 5.70 | 8.50 | 3.20 |
| | Std. Dev. | 0.21 | 1.81 | 0.72 |
| | Cof. Var. | 0.04 | 0.21 | 0.21 |
| | W. Shape | 27.00 | 4.80 | 5.10 |
| IM-7 | | | | |
| | Mean | 5.50 | 8.30 | 3.40 |
| | Std. Dev. | 0.20 | 1.62 | 0.61 |
| | Cof. Var. | 0.04 | 0.20 | 0.20 |
| | W. Shape | 32.00 | 4.80 | 5.40 |

NOTE: This data is based on fiber sets of about 50 fibers from one location in the tow. The data for each fiber set is given in Appendix C.

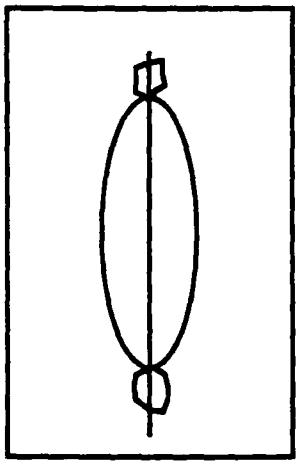
The data is described by the standard deviation, the coefficient of variation and the shape parameter of a Weibull distribution.

## CONCLUSIONS

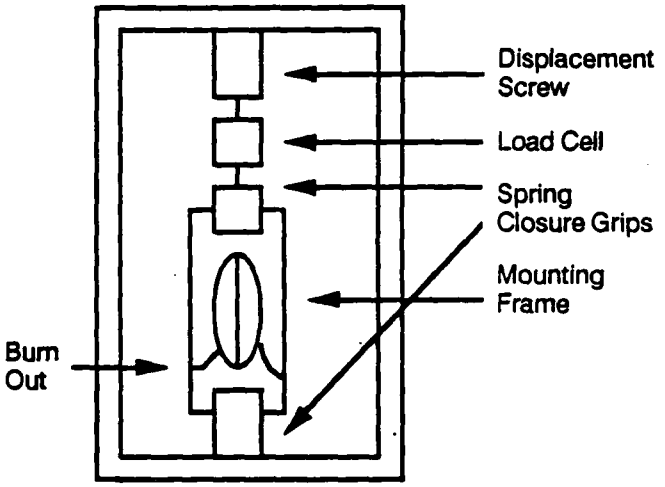
The Single Fiber Graphite Tester has been shown to generate data of interest in the examination of the properties of graphite fibers and their composites. This data consists of fiber diameter and failure load for individual graphite fibers. For the fibers tested, no correlation was found between the fiber diameter and the failure load. This result justifies the use by workers of a mean fiber diameter in determining fiber strength.

The dispersion observed in the fiber diameter and failure load was examined using mathematical models. Further study of this aspect is in progress.

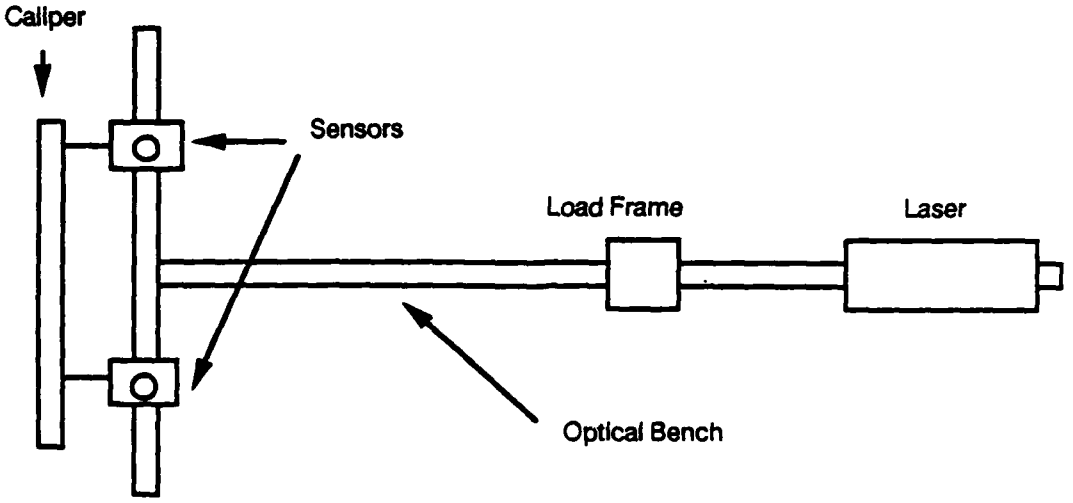
This preliminary work justifies the further development of the equipment and the generation of additional data with the equipment.



(a) Mounting Frame




(b) Aluminum Load Frame




(c) Single Fiber Graphite Tester

Figure 1.

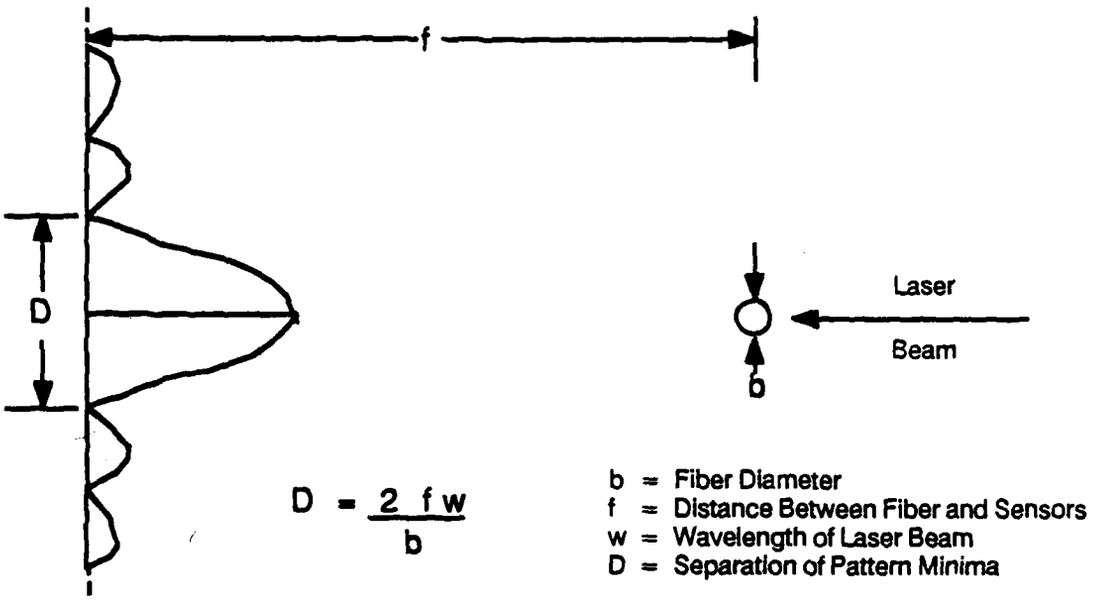
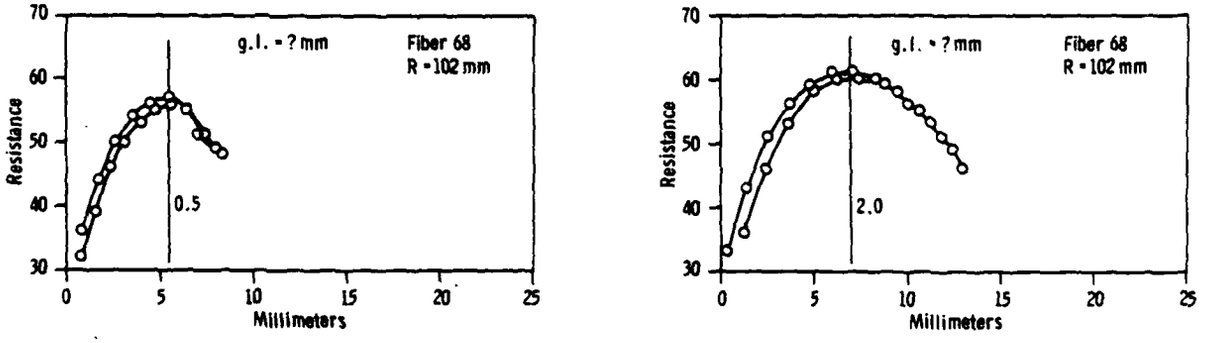


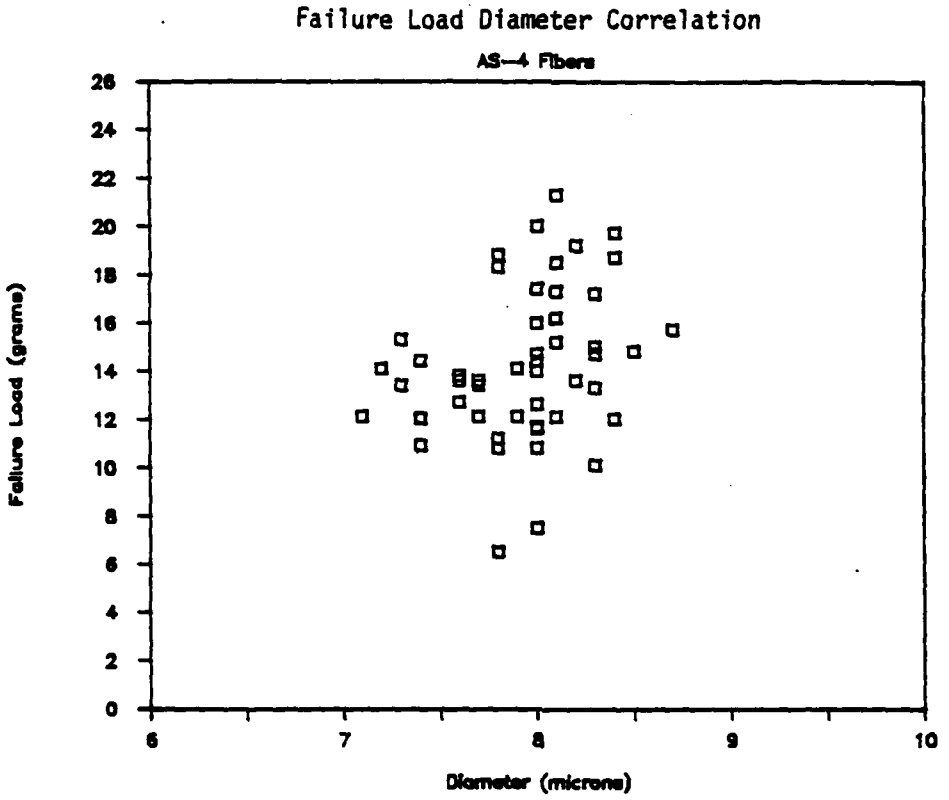

Figure 2. Schematic of diffraction pattern.




(a) Test 747 Left

(b) Test 747 Right

Figure 3.


Failure Load Diameter Correlation
AS-4 Fibers
Failure Load (grams)
Diameter (microns)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
6
7
8
9
10

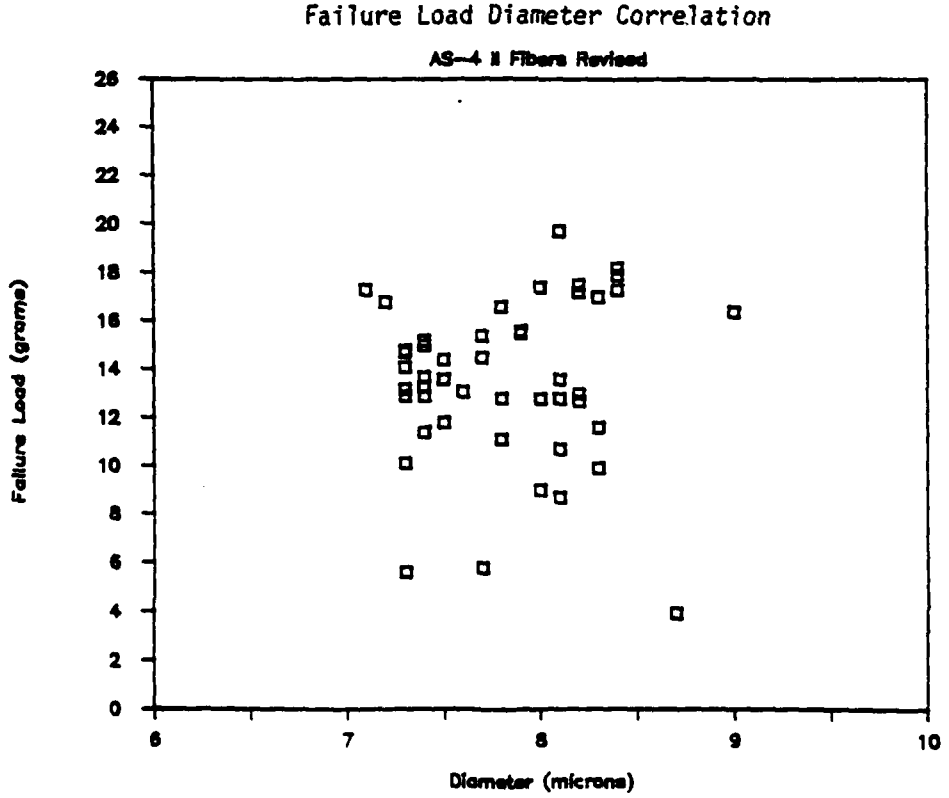
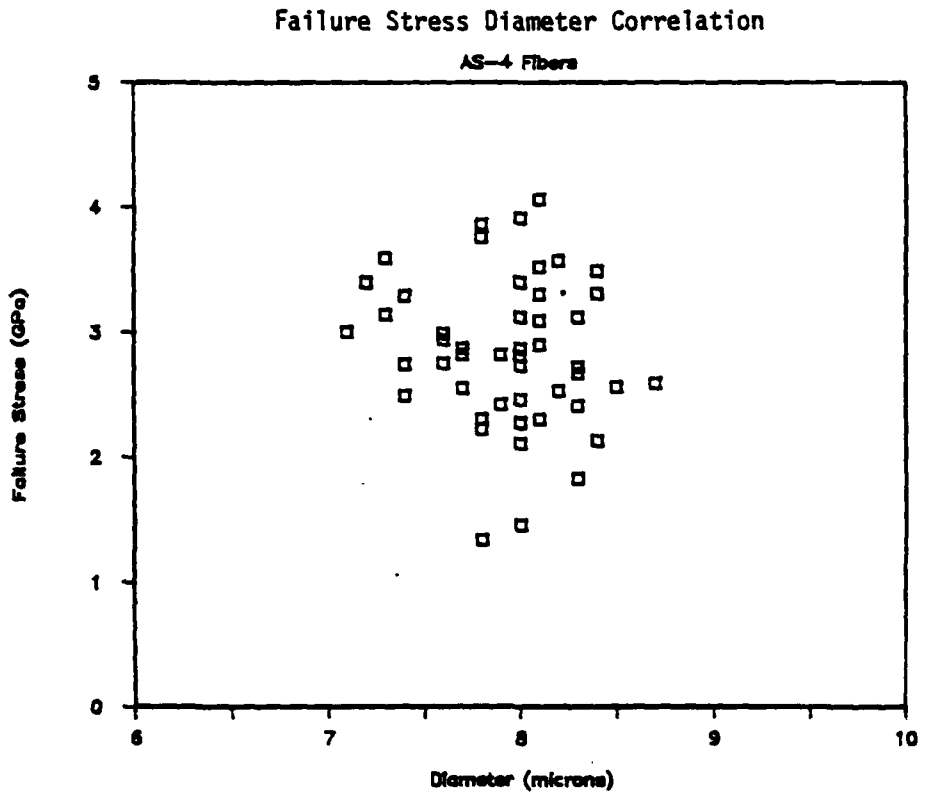

Failure Load Diameter Correlation
AS-4 II Fibers Revised
Failure Load (grams)
Diameter (microns)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
6
7
8
9
10

Figure 4a.


Failure Stress Diameter Correlation
AS-4 Fibers
Failure Stress (GPa)
Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10

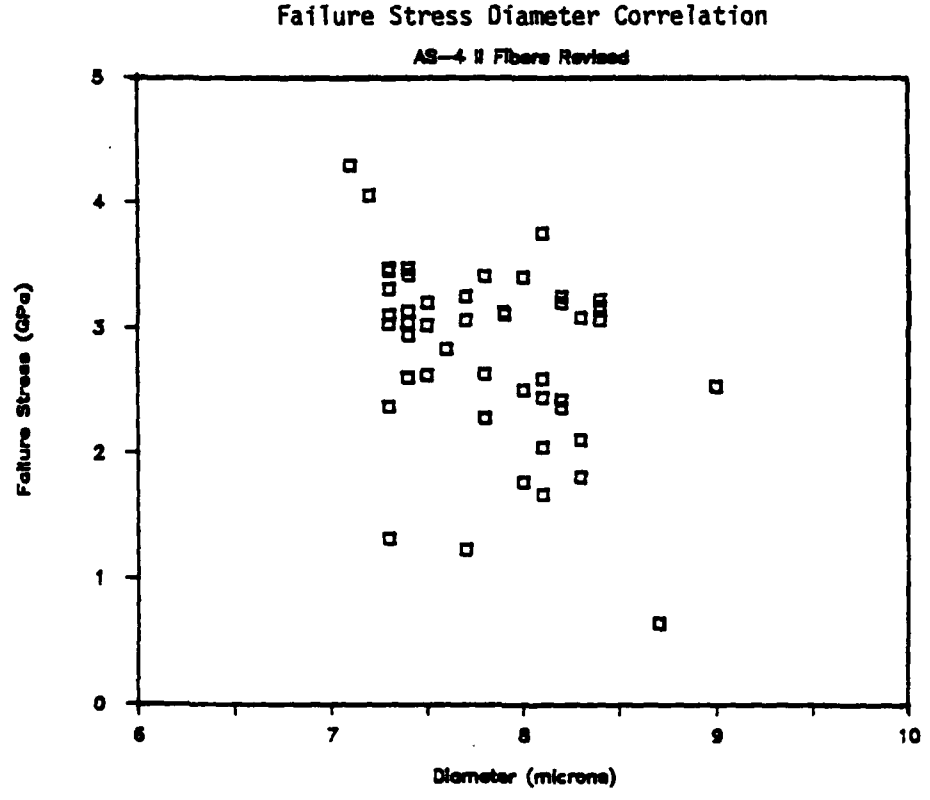

Failure Stress Diameter Correlation
AS-4 II Fibers Revised
Failure Stress (GPa)
Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10

Figure 4b.

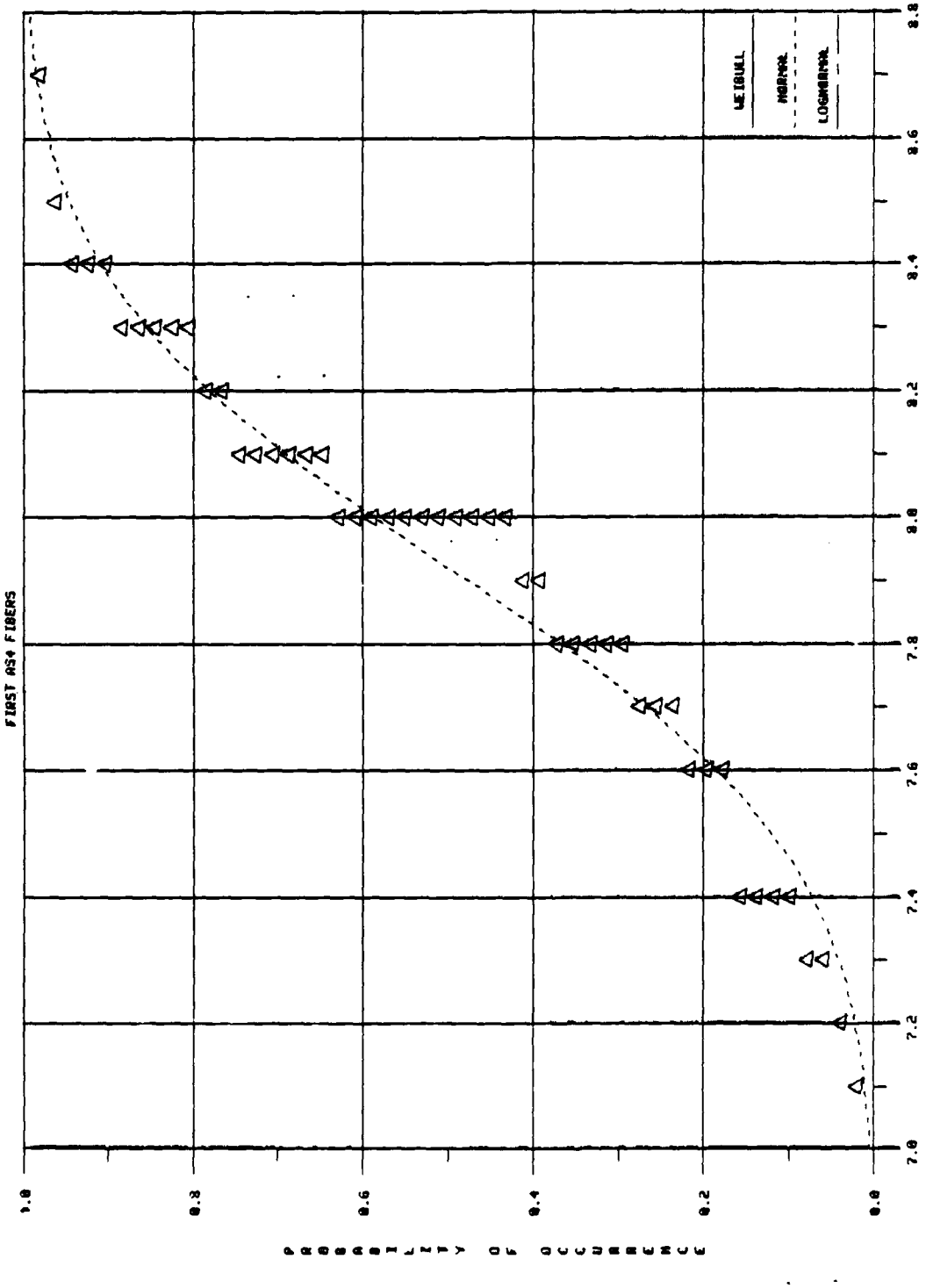

FIRST ASA FIBERS
PROBABILITY OF OCCURRENCE
DIAMETER (MICRONS)
WEIBULL
NORMAL
LOGNORMAL
1.0
0.8
0.6
0.4
0.2
0.0
7.0
7.2
7.4
7.6
7.8
8.0
8.2
8.4
8.6
8.8

Figure 5a.

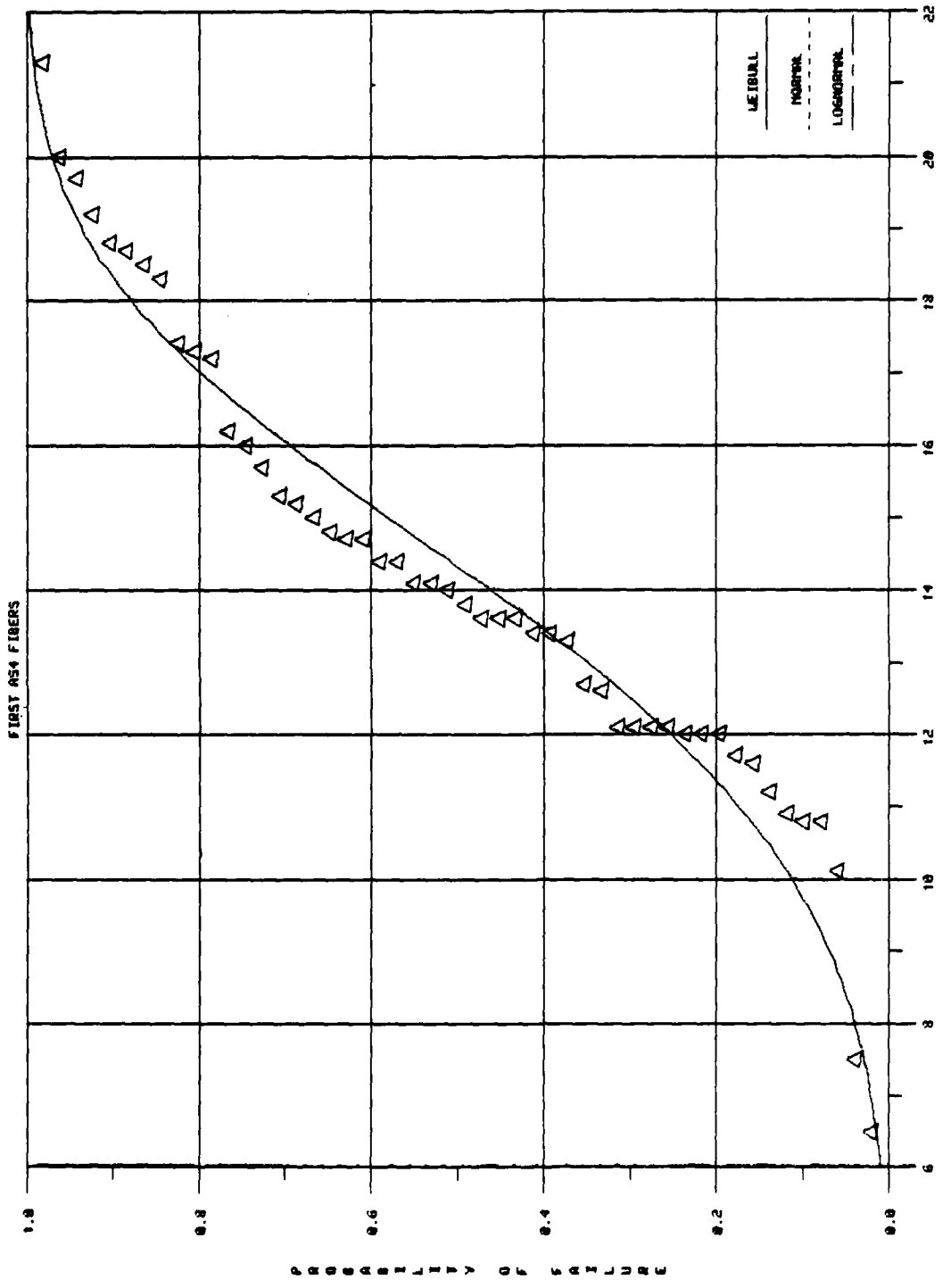

FIRST AS4 FIBERS
PROBABILITY OF FAILURE
FAILURE LOAD (GRAMS)
WEIBULL
NORMAL
LOGNORMAL
0.0
0.2
0.4
0.6
0.8
1.0
6
8
10
12
14
16
18
20
22

Figure 5b.

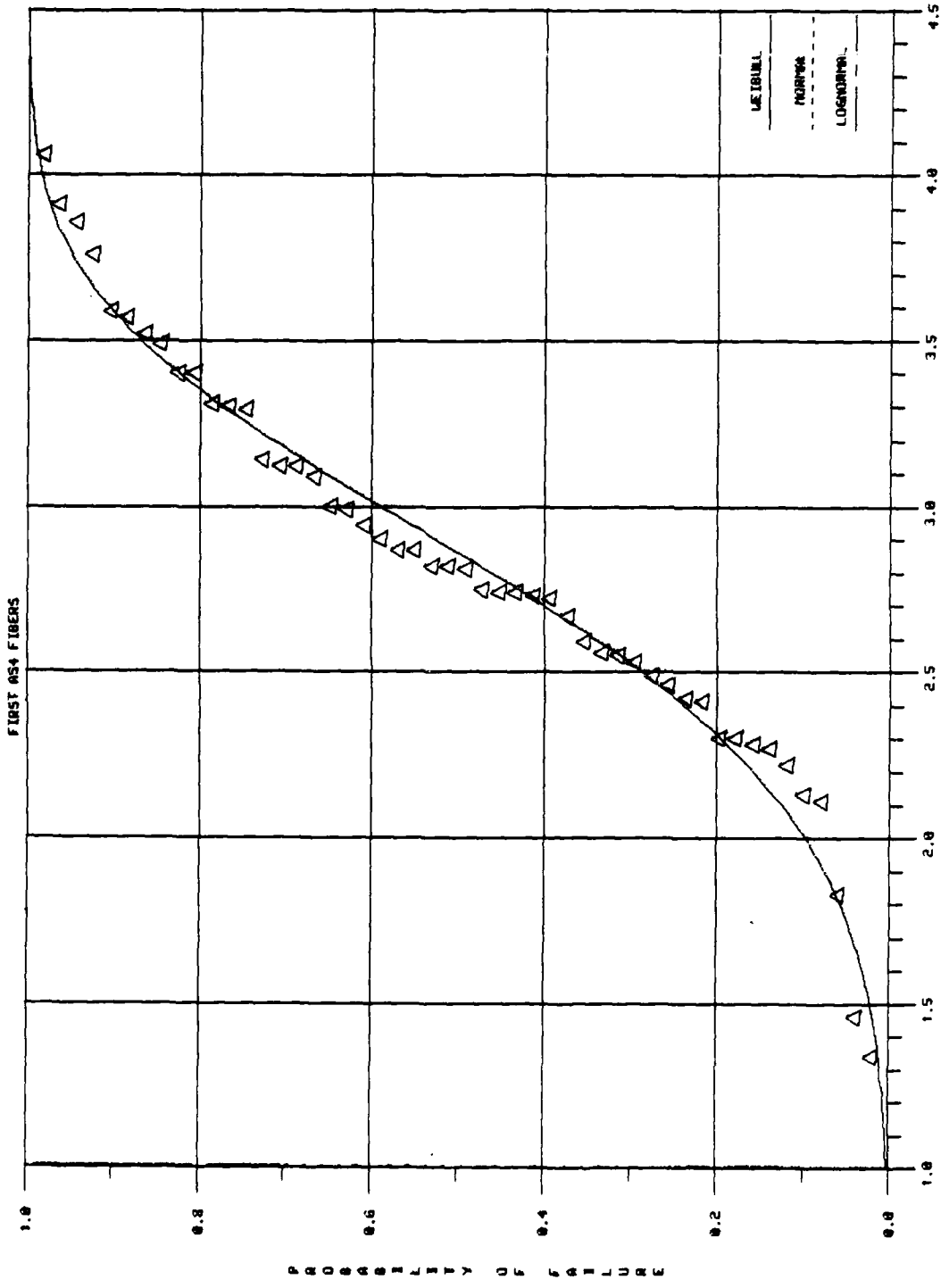

FIRST AS4 FIBERS
PROBABILITY OF FAILURE
FAILURE STRESS (GPA)
WEIBULL
NORMAL
LOGNORMAL
0.0
0.2
0.4
0.6
0.8
1.0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

Figure 5c.

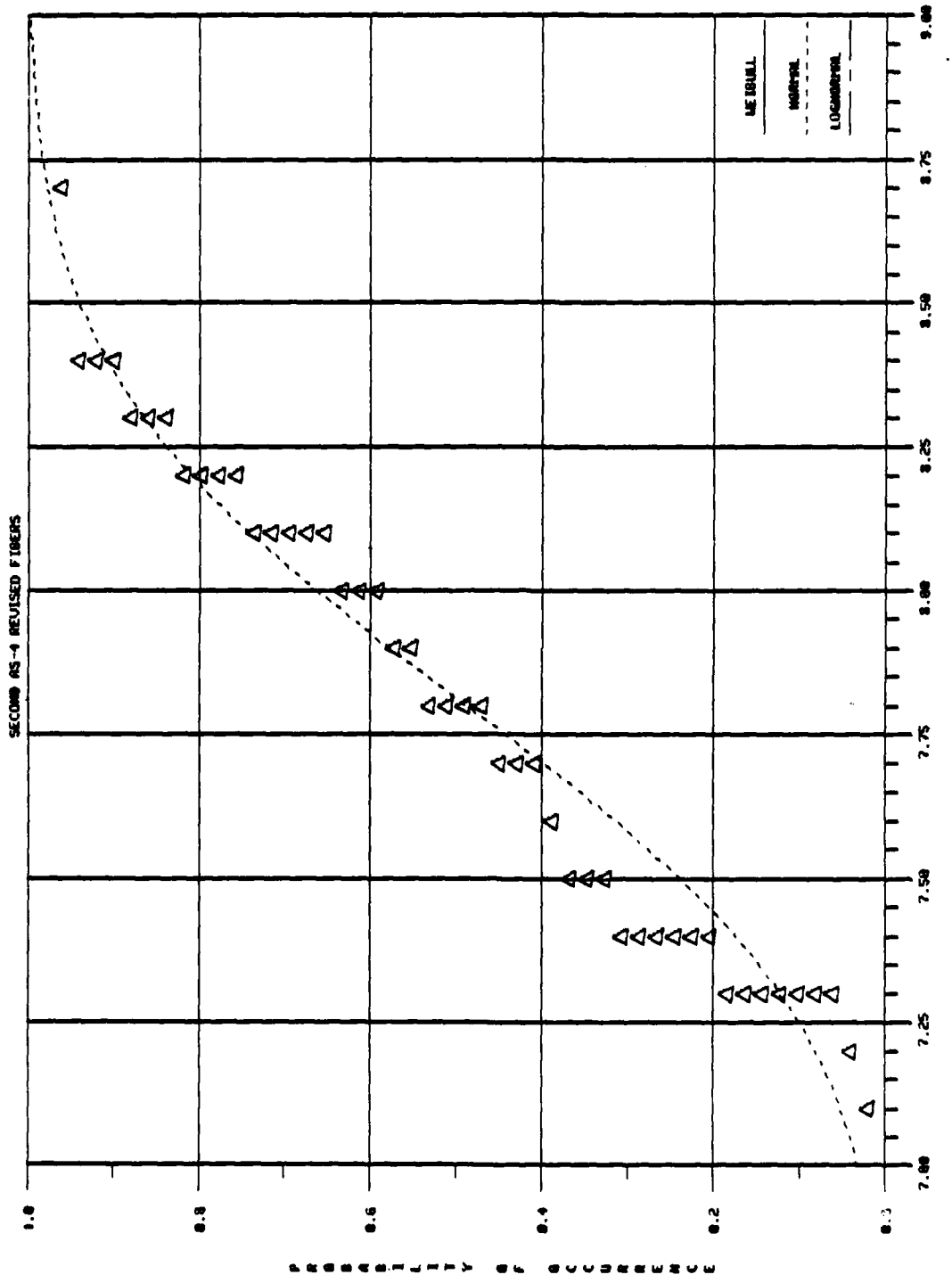

SECOND AS-4 REVISED FIBERS
WEIBULL
NORMAL
LOGNORMAL
DIAMETER (MICRONS)

Figure 5d.

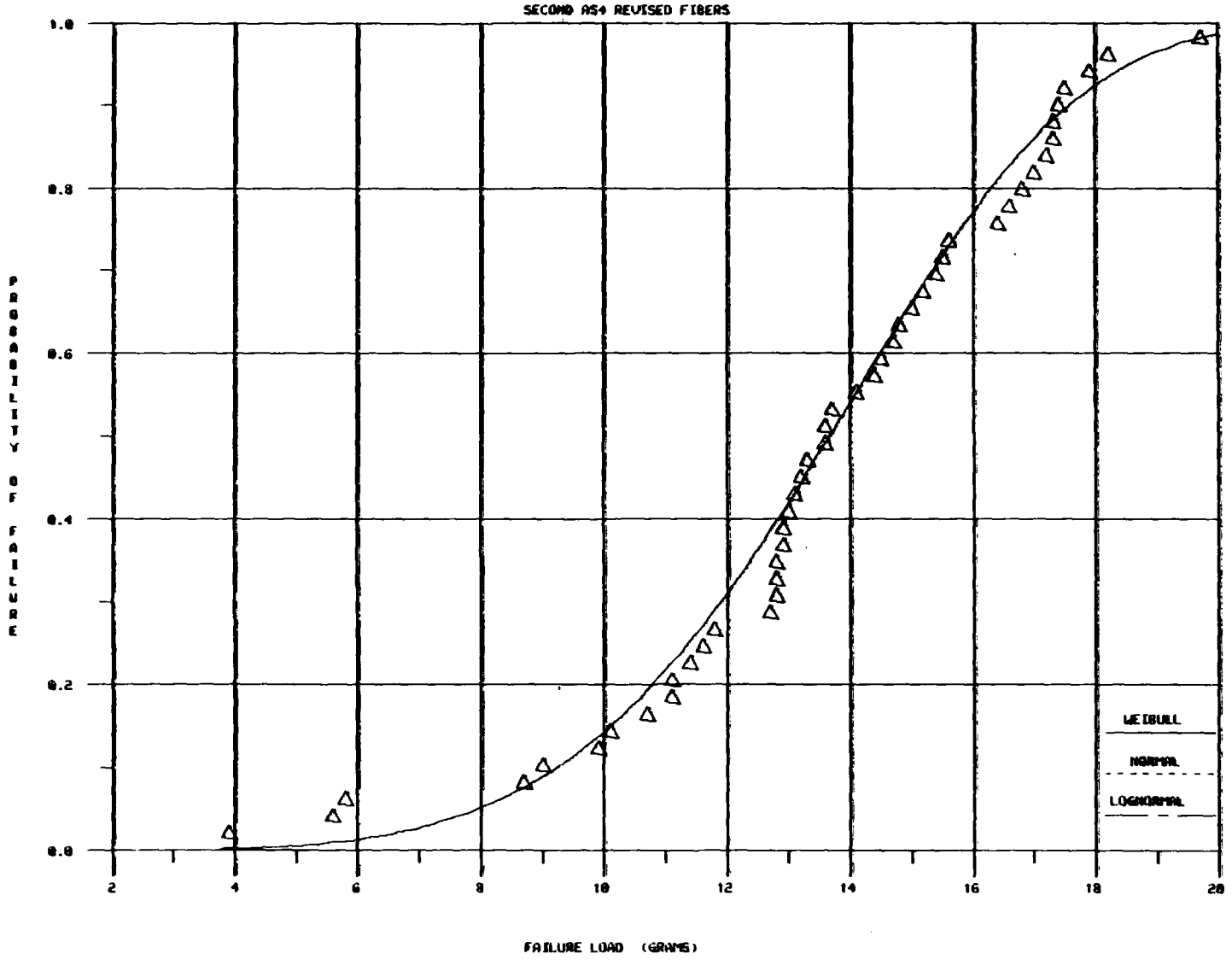

SECOND AS4 REVISED FIBERS
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8
10
12
14
16
18
20
FAILURE LOAD (GRAMS)
WEIBULL
NORMAL
LOGNORMAL

Figure 5e.

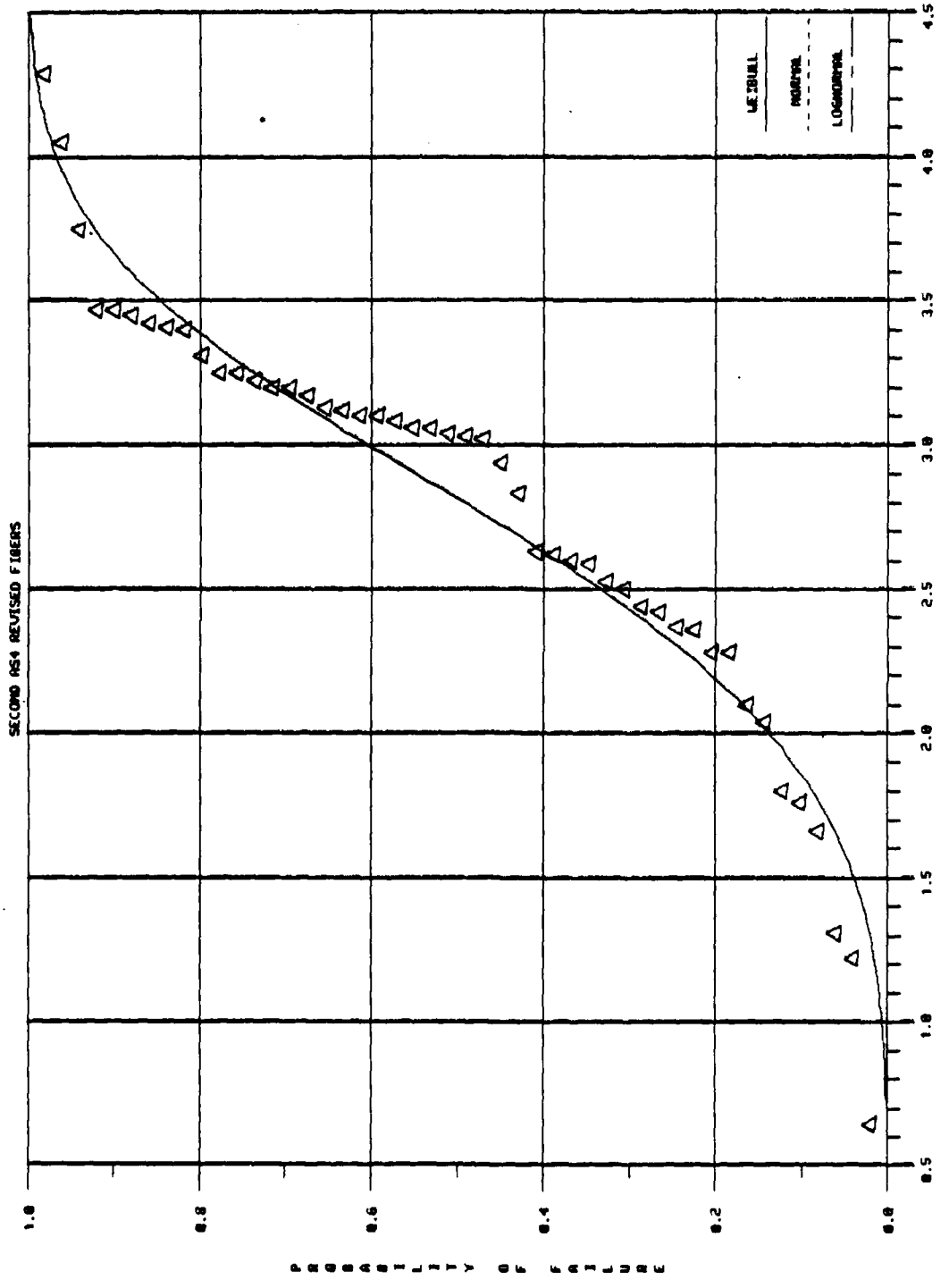
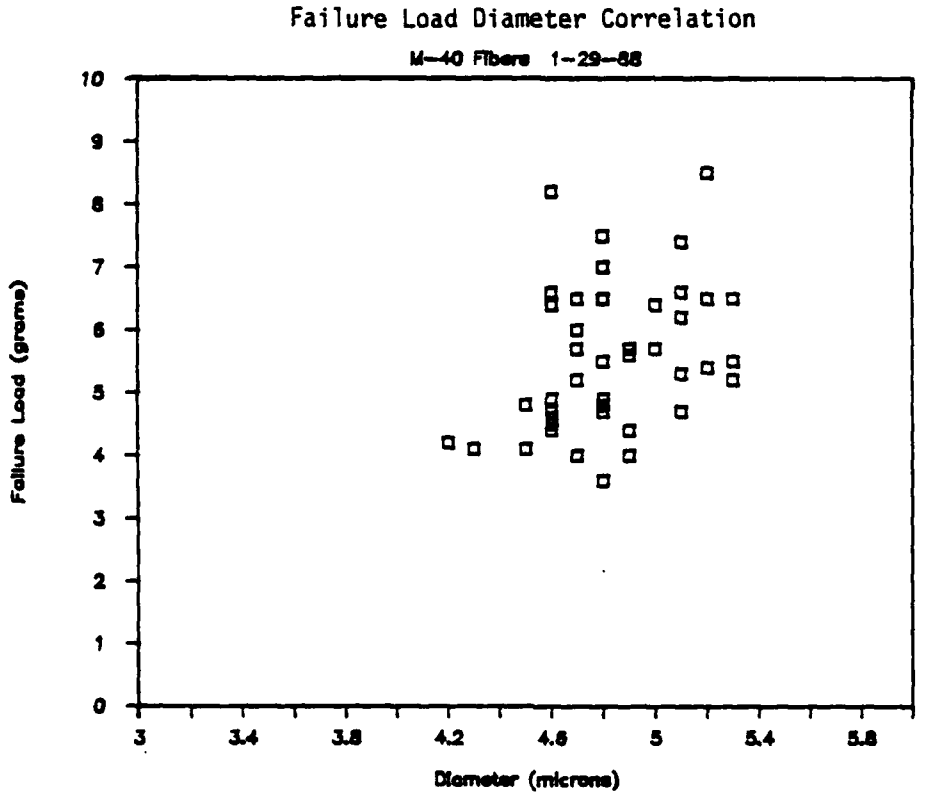

SECOND AS4 REVISED FIBERS
WEIBULL
NORMAL
LOGNORMAL
PROBABILITY OF FAILURE
FAILURE STRESS (GPA)
0.0
0.2
0.4
0.6
0.8
1.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

Figure 5f.


Failure Load Diameter Correlation
M-40 Fibers 1-29-88
Failure Load (grams)
10
9
8
7
6
5
4
3
2
1
0
3
3.4
3.8
4.2
4.6
5
5.4
5.8
Diameter (microns)

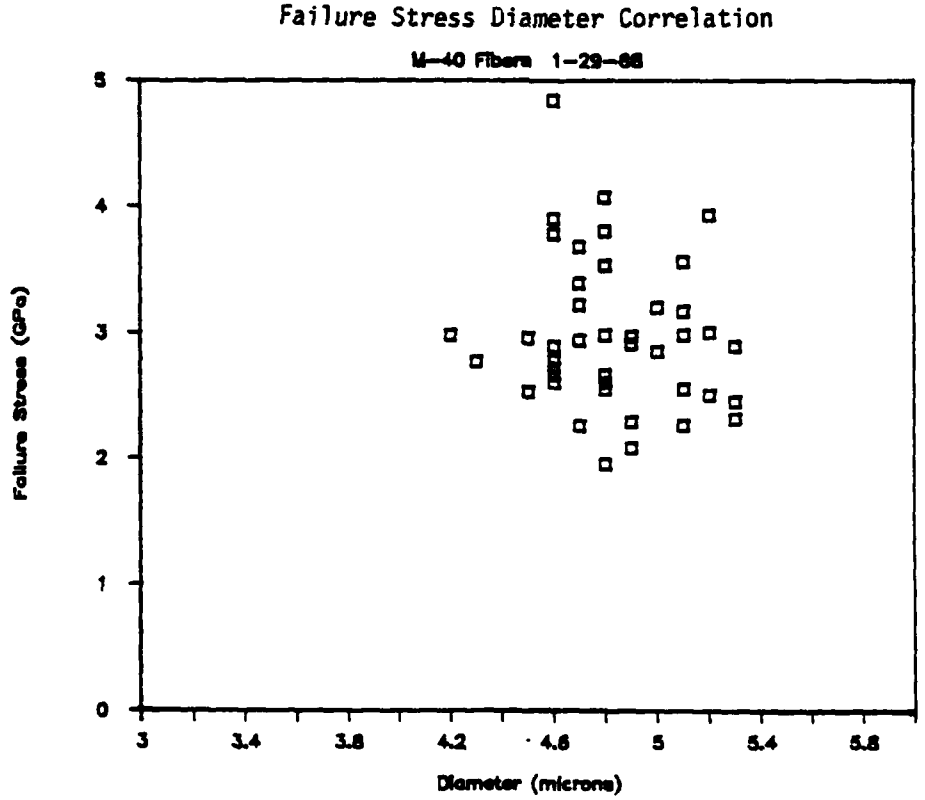

Failure Stress Diameter Correlation
M-40 Fibers 1-29-88
Failure Stress (GPa)
5
4
3
2
1
0
3
3.4
3.8
4.2
4.6
5
5.4
5.8
Diameter (microns)

Figure 6.

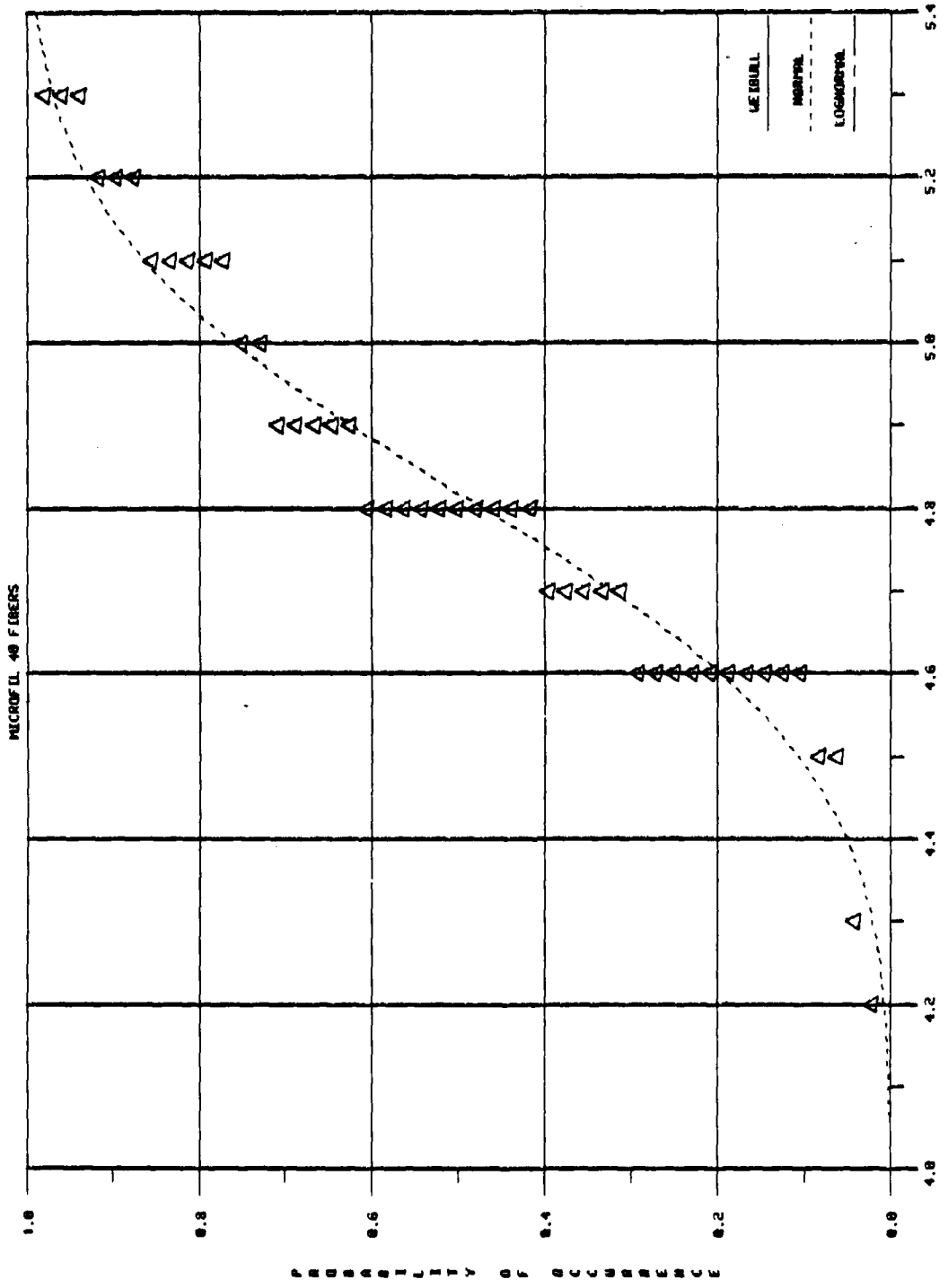

MICROFIL 48 FIBERS
WEIBULL
NORMAL
LOGNORMAL
DIAMETER (MICRONS)
1.0
0.8
0.6
0.4
0.2
0.0
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4

Figure 7a.

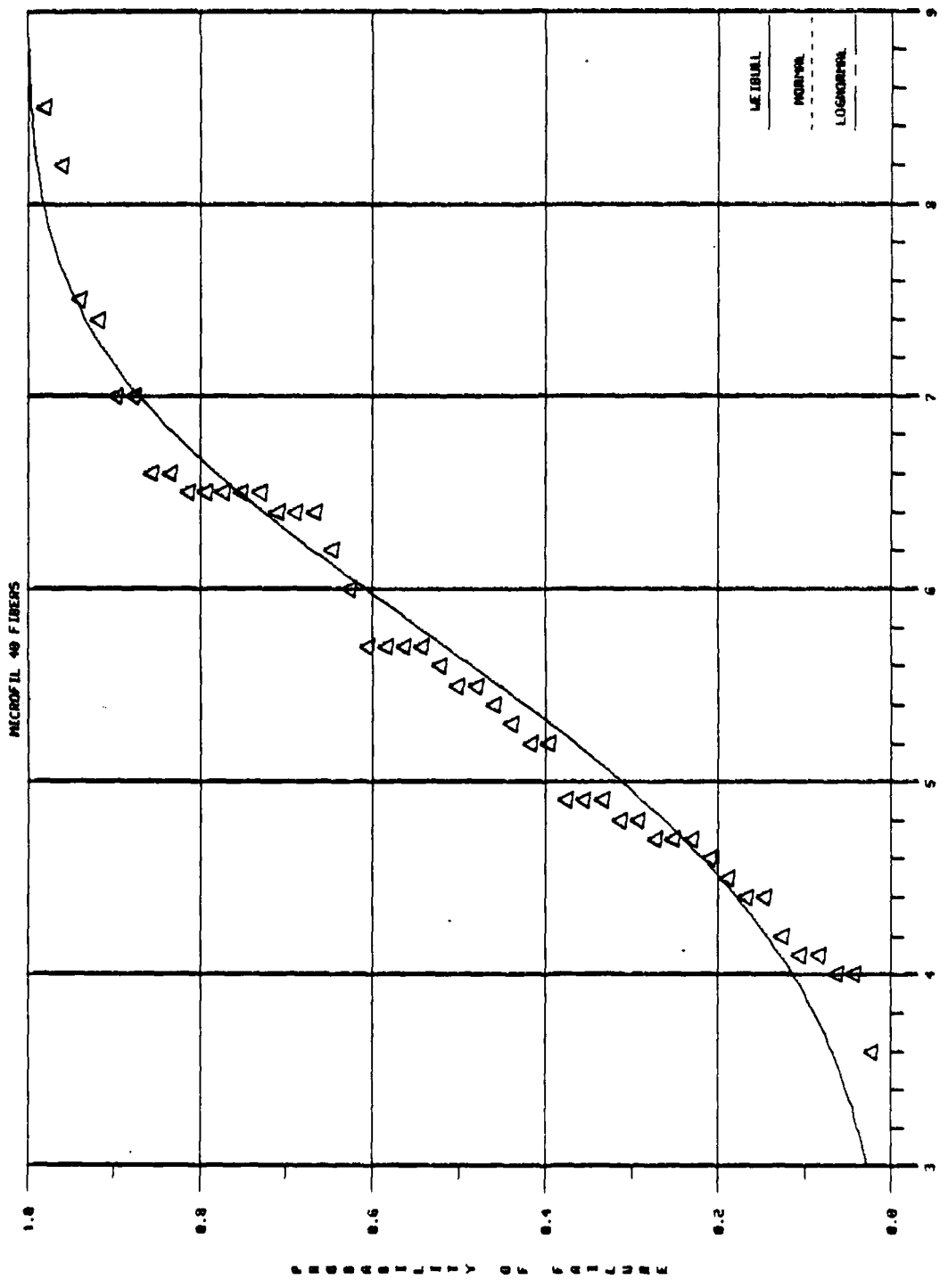

MICROFIL 49 FIBERS
WEIBULL
NORMAL
LOGNORMAL
FAILURE LOAD (GRAMS)
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
3
4
5
6
7
8
9

Figure 7b.

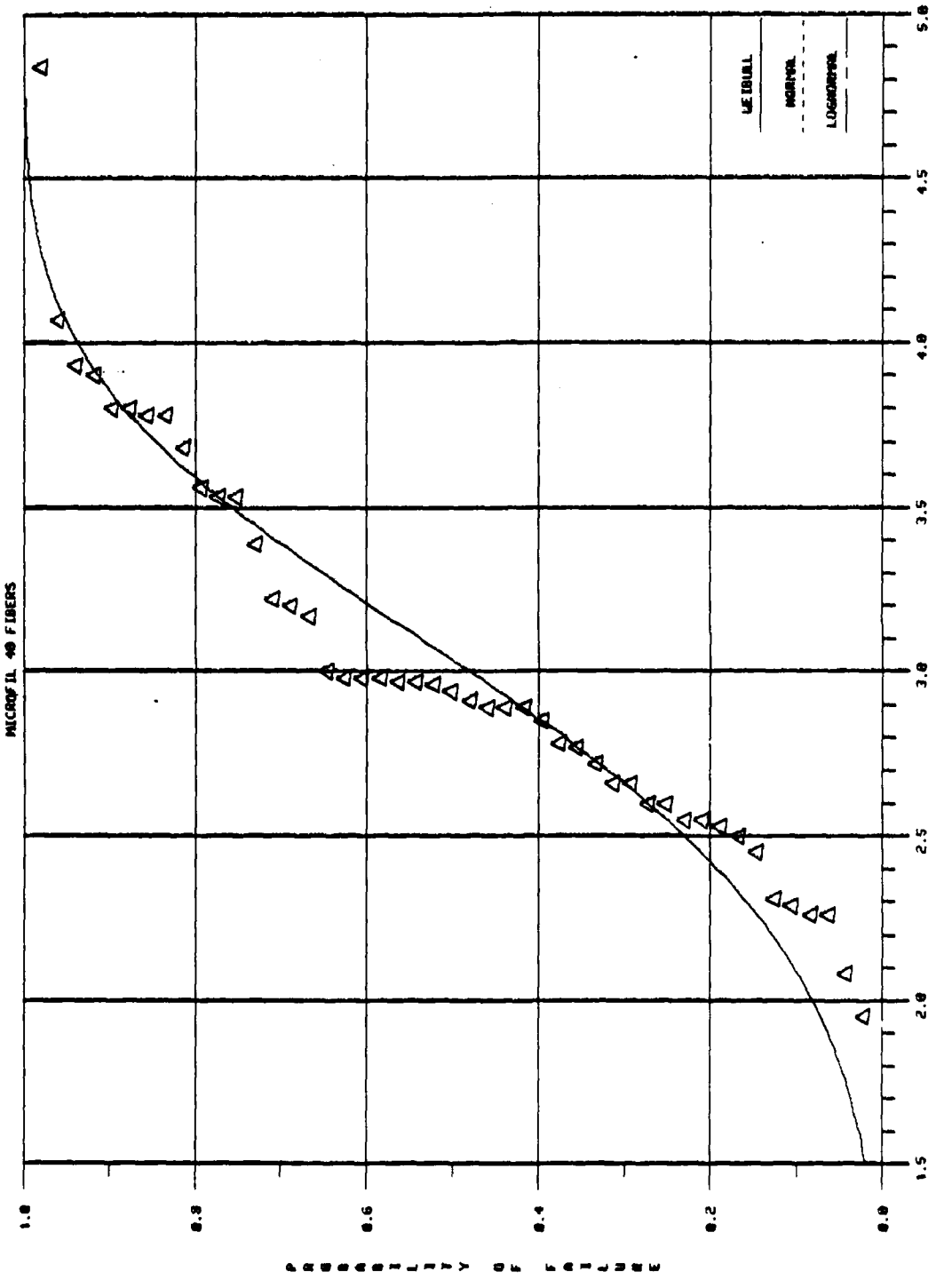
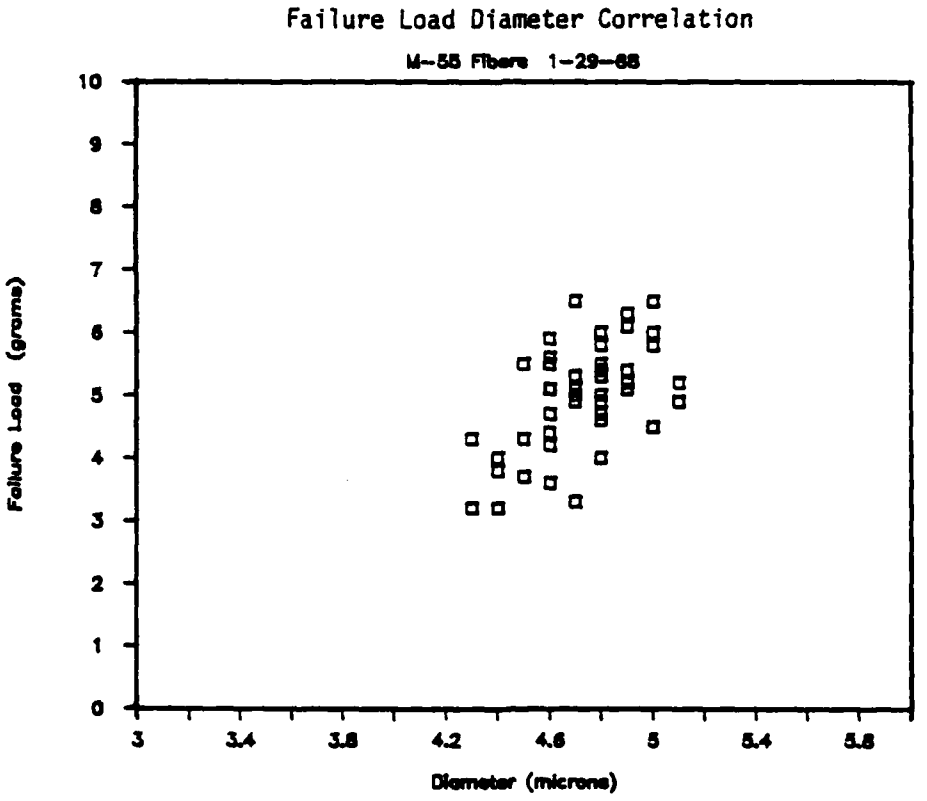

MICROFIL 49 FIBERS
WEIBULL
NORMAL
LOGNORMAL
1.0
0.8
0.6
0.4
0.2
0.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
FAILURE STRESS (GPA)

Figure 7c.


Failure Load Diameter Correlation
M-55 Fibers 1-29-88
Failure Load (grams)
10
9
8
7
6
5
4
3
2
1
0
3
3.4
3.8
4.2
4.6
5
5.4
5.8
Diameter (microns)

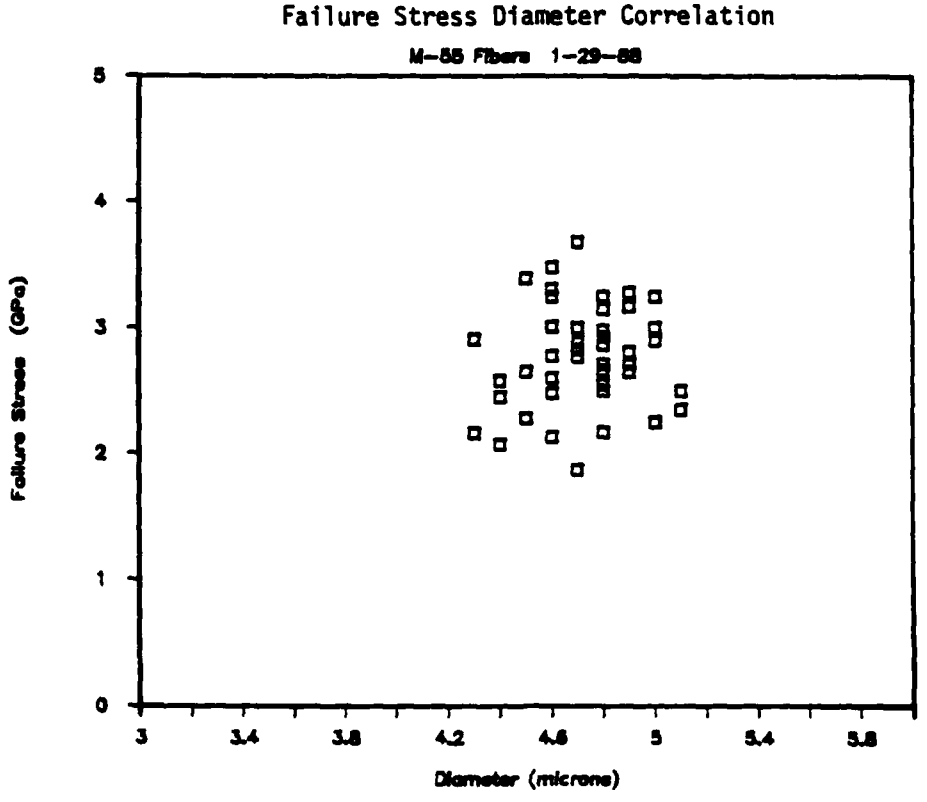

Failure Stress Diameter Correlation
M-55 Fibers 1-29-88
Failure Stress (GPa)
5
4
3
2
1
0
3
3.4
3.8
4.2
4.6
5
5.4
5.8
Diameter (microns)

Figure 8.

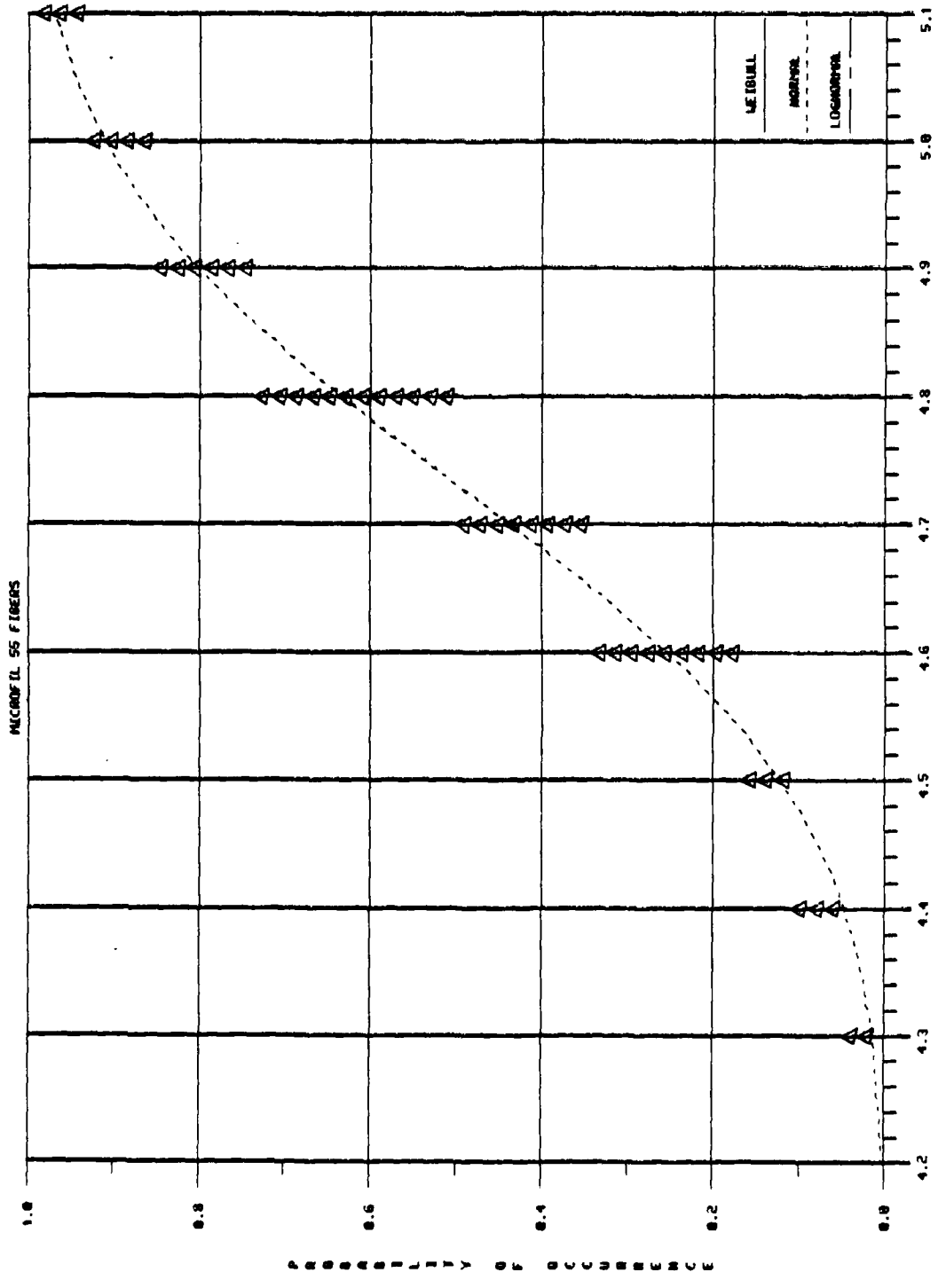

MICROFIL 55 FIBERS
PROBABILITY OF OCCURRENCE
DIAMETER (MICRONS)
WEIBULL
NORMAL
LOGNORMAL
1.0
0.8
0.6
0.4
0.2
0.0
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5.0
5.1

Figure 9a.

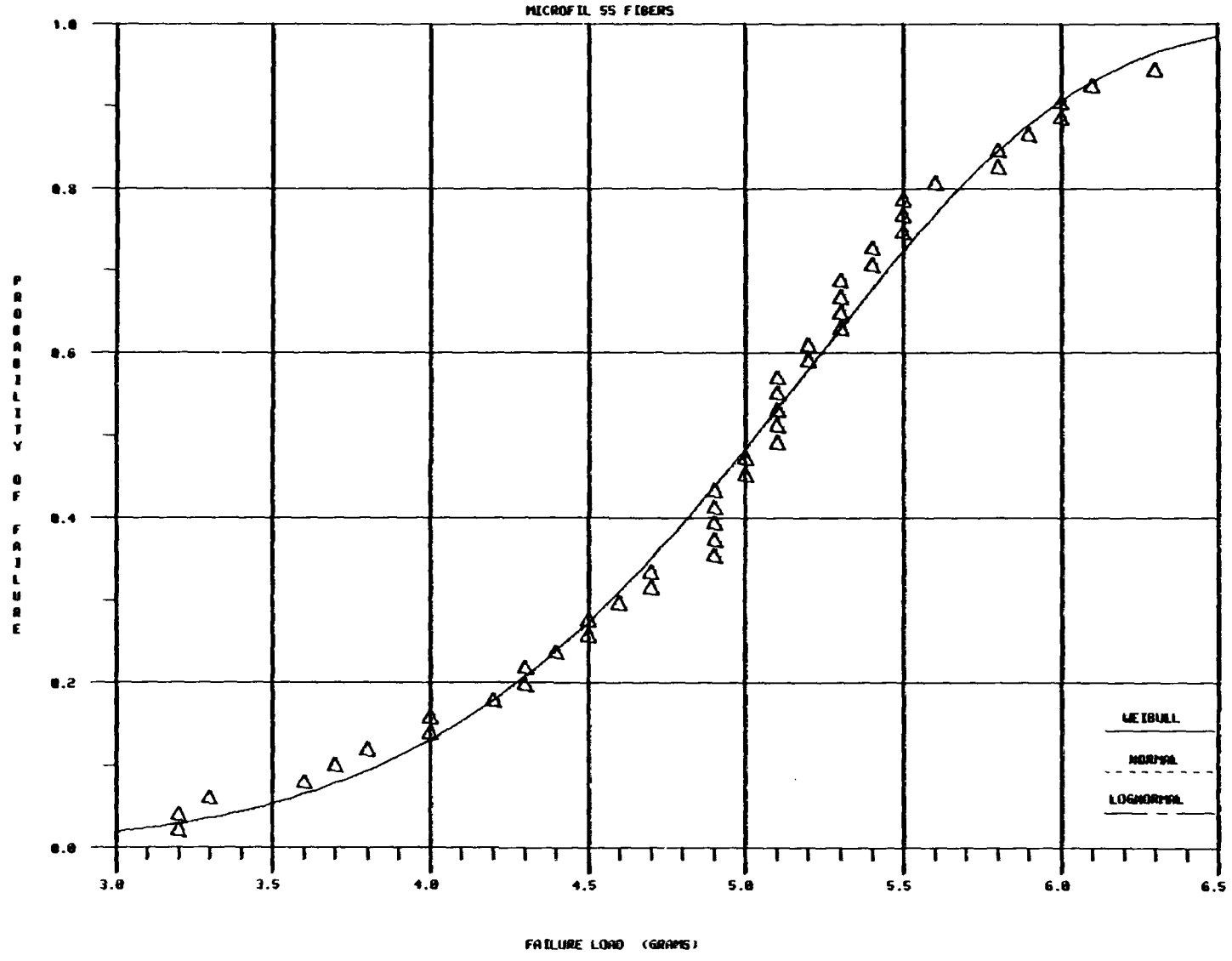

MICROFIL 55 FIBERS
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
FAILURE LOAD (GRAMS)
WEIBULL
NORMAL
LOGNORMAL

Figure 9b.

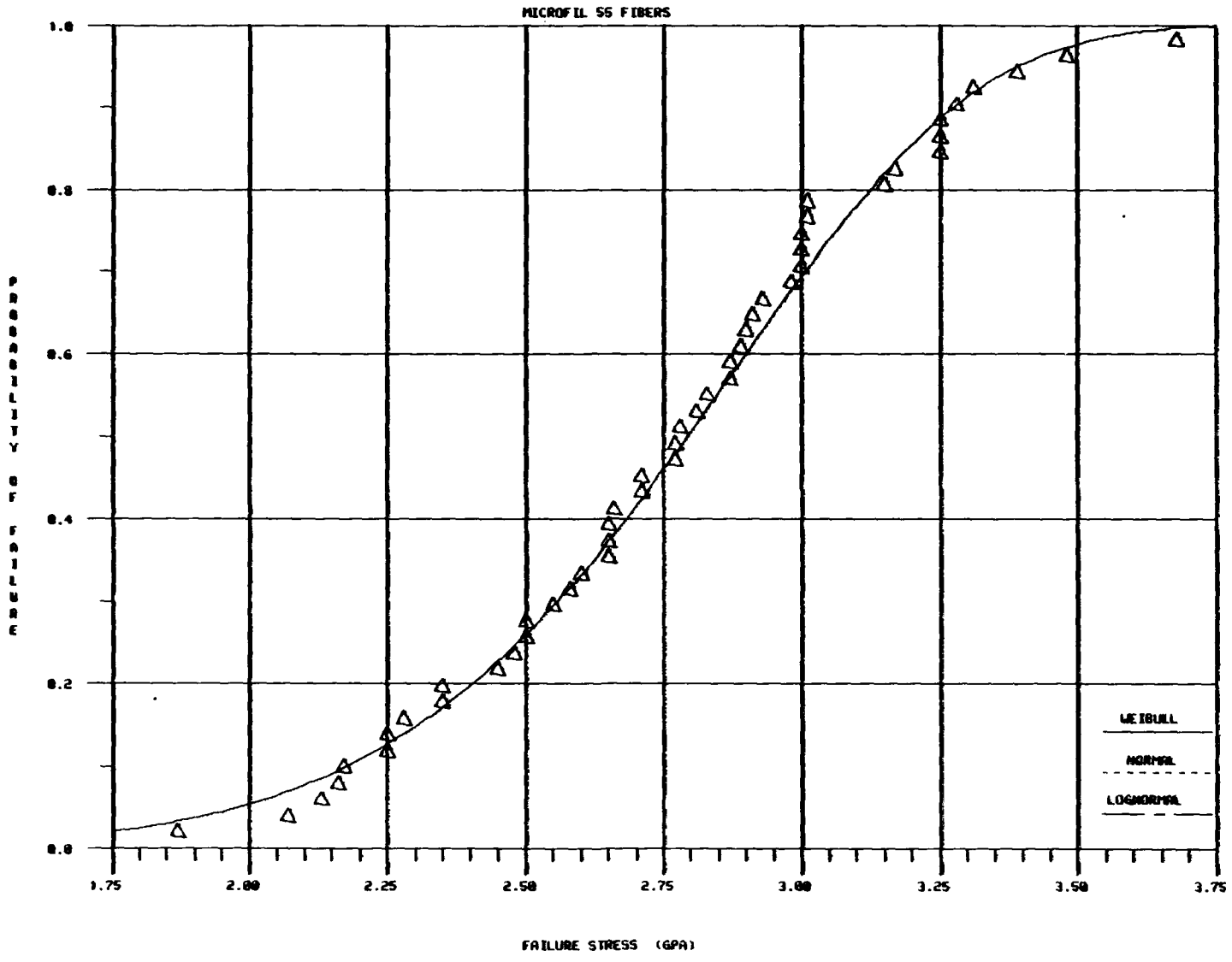
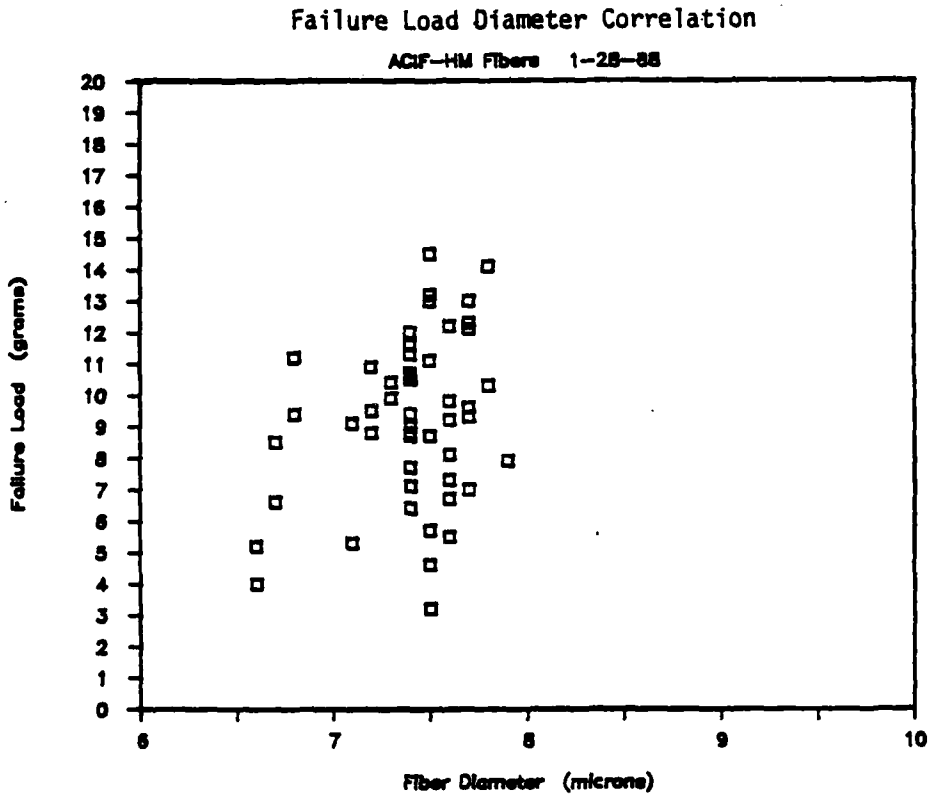

MICROFIL SS FIBERS
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
FAILURE STRESS (GPA)
WEIBULL
NORMAL
LOGNORMAL

Figure 9c.


Failure Load Diameter Correlation
ACIF-HM Fibers 1-28-88
Failure Load (grams)
Fiber Diameter (microns)

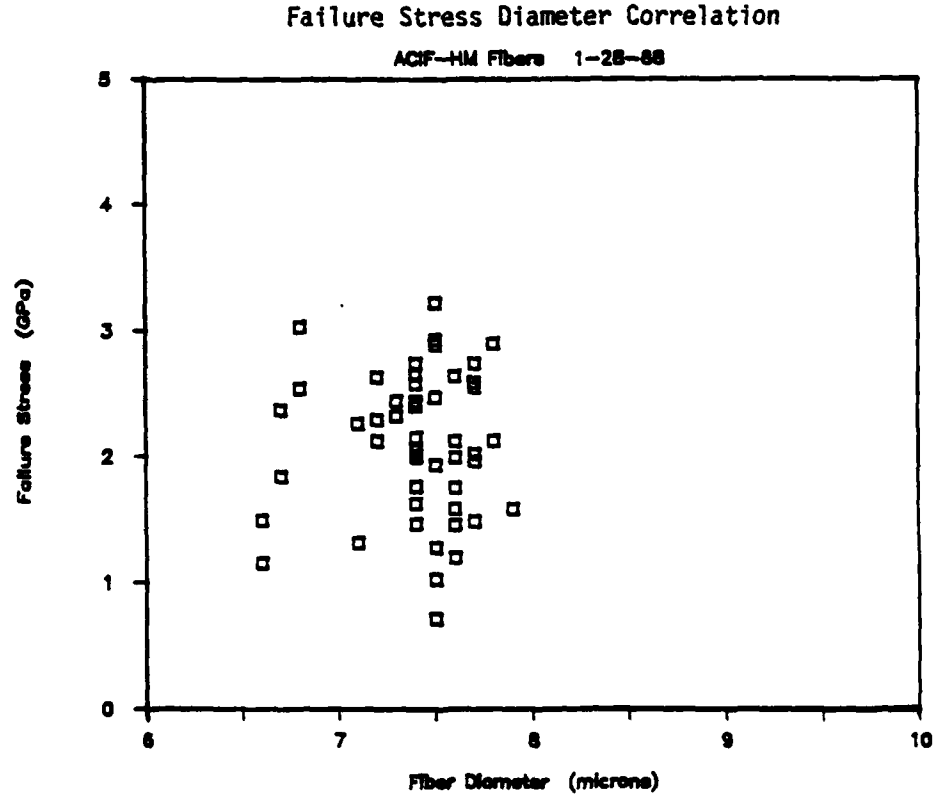

Failure Stress Diameter Correlation
ACIF-HM Fibers 1-28-88
Failure Stress (GPa)
Fiber Diameter (microns)

Figure 10.

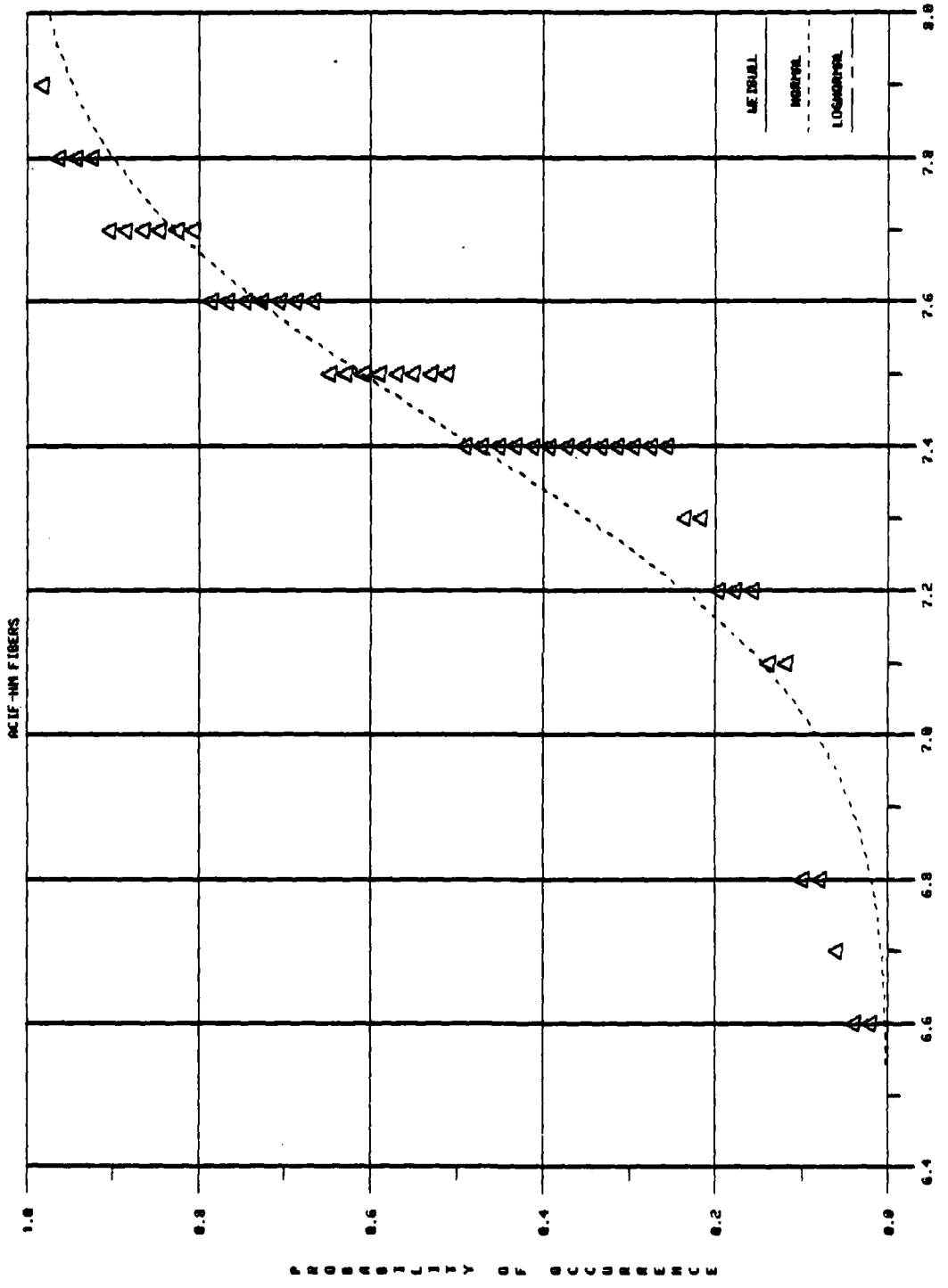

ACIE-NM FIBERS
PROBABILITY OF OCCURRENCE
DIAMETER (MICRONS)
WEIBULL
NORMAL
LOGNORMAL
1.0
0.8
0.6
0.4
0.2
0.0
6.4
6.6
6.8
7.0
7.2
7.4
7.6
7.8
8.0

Figure 11a.

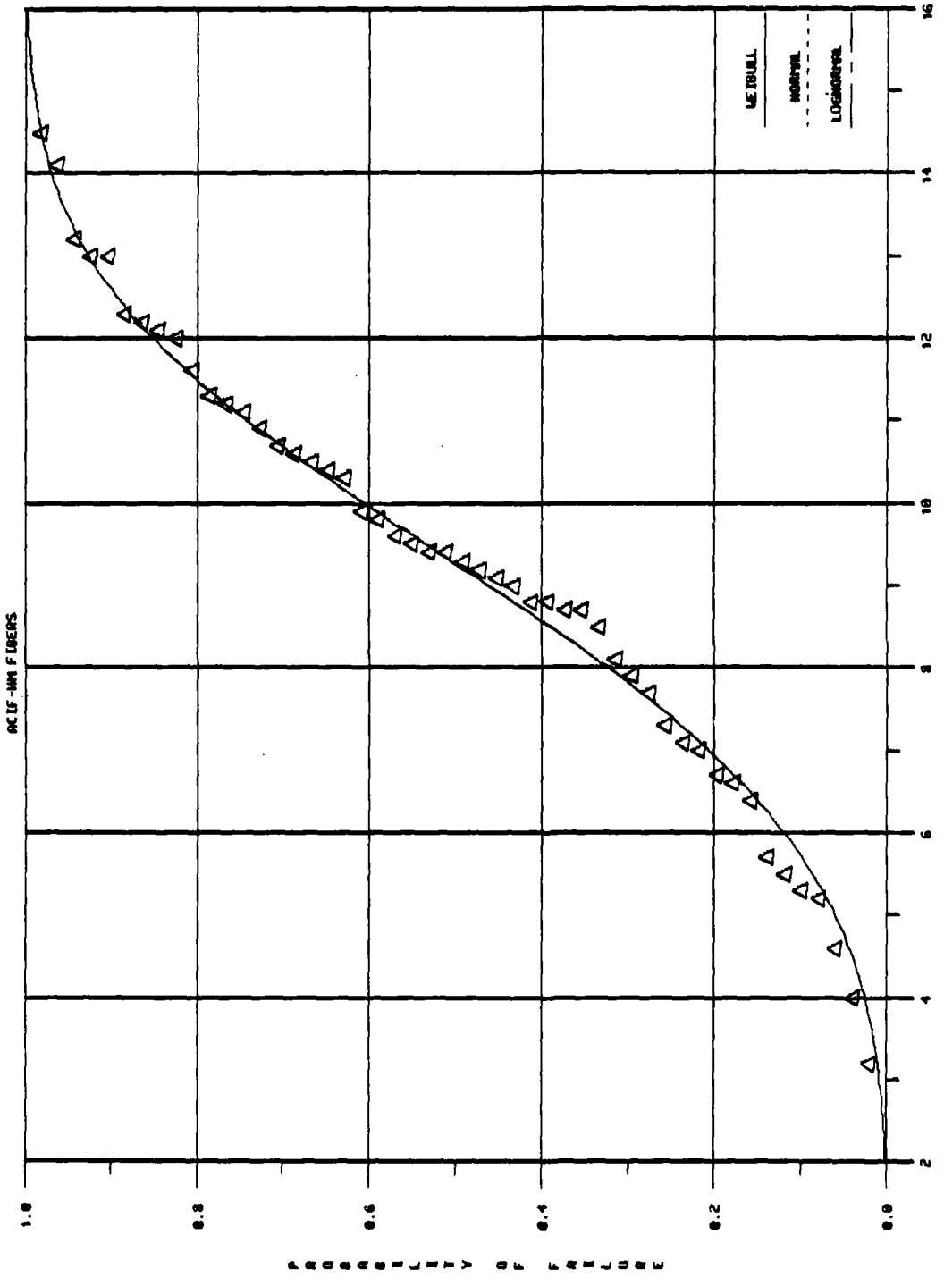

ACIF-MM FIBERS
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8
10
12
14
16
FAILURE LOAD (GRAMS)
WEIBULL
NORMAL
LOGNORMAL

Figure 11b.

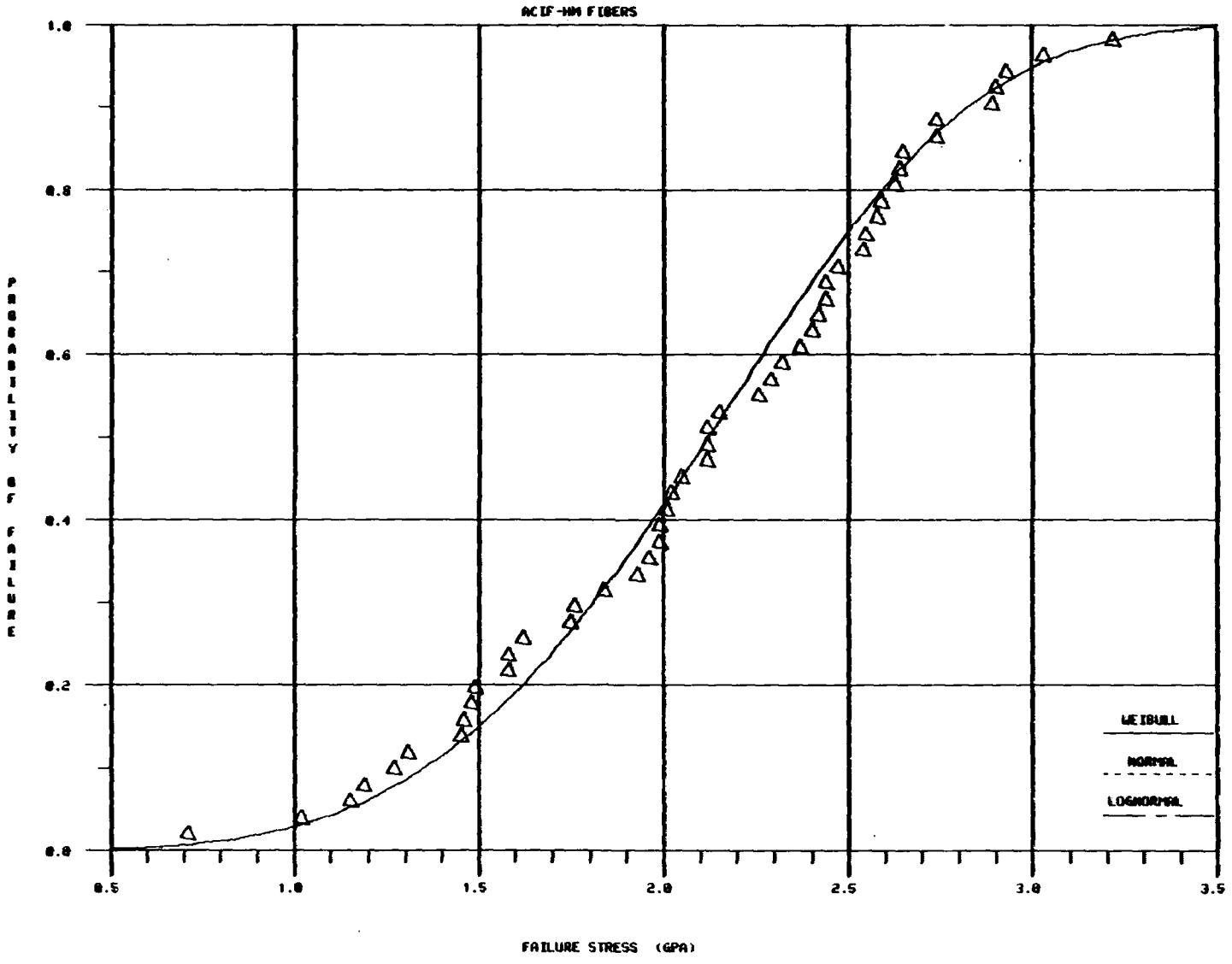
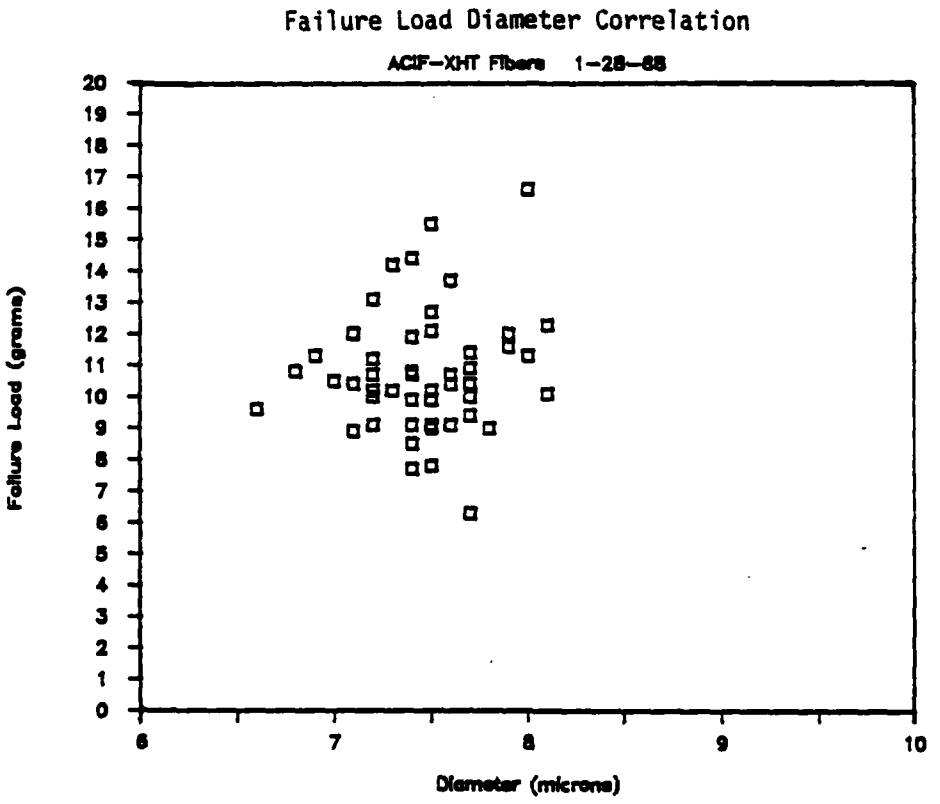

ACIF-HM FIBERS
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
FAILURE STRESS (GPA)
WEIBULL
NORMAL
LOGNORMAL

Figure 11c.


Failure Load Diameter Correlation
ACIF-XHT Fibers 1-28-88
Failure Load (grams)
Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
6
7
8
9
10

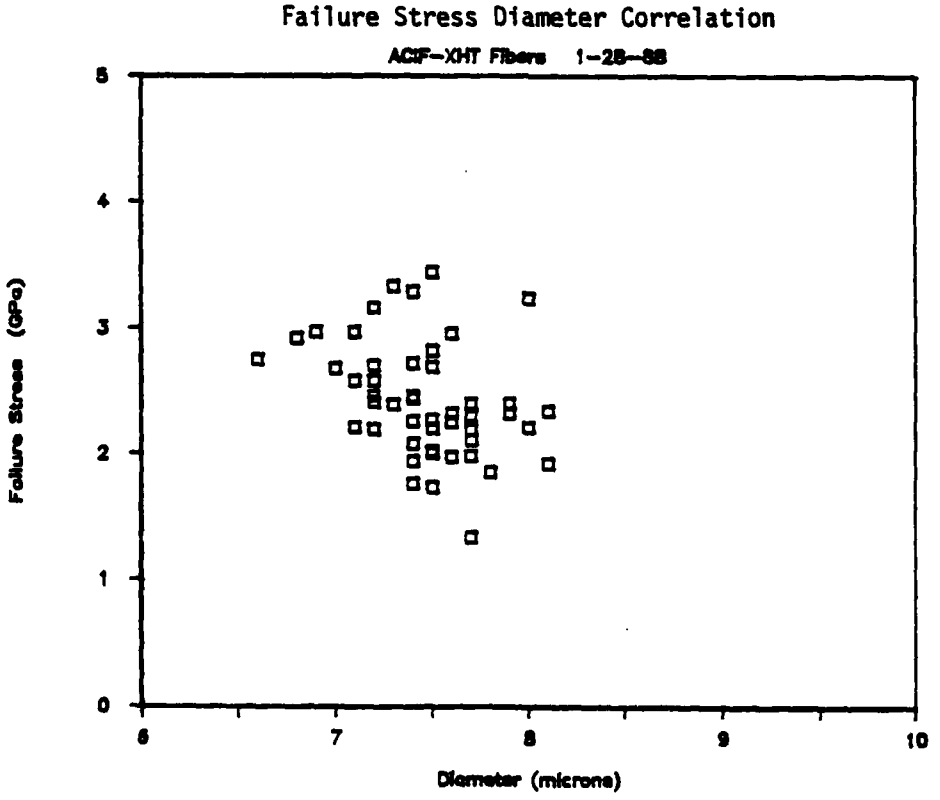

Failure Stress Diameter Correlation
ACIF-XHT Fibers 1-28-88
Failure Stress (GPa)
Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10

Figure 12.

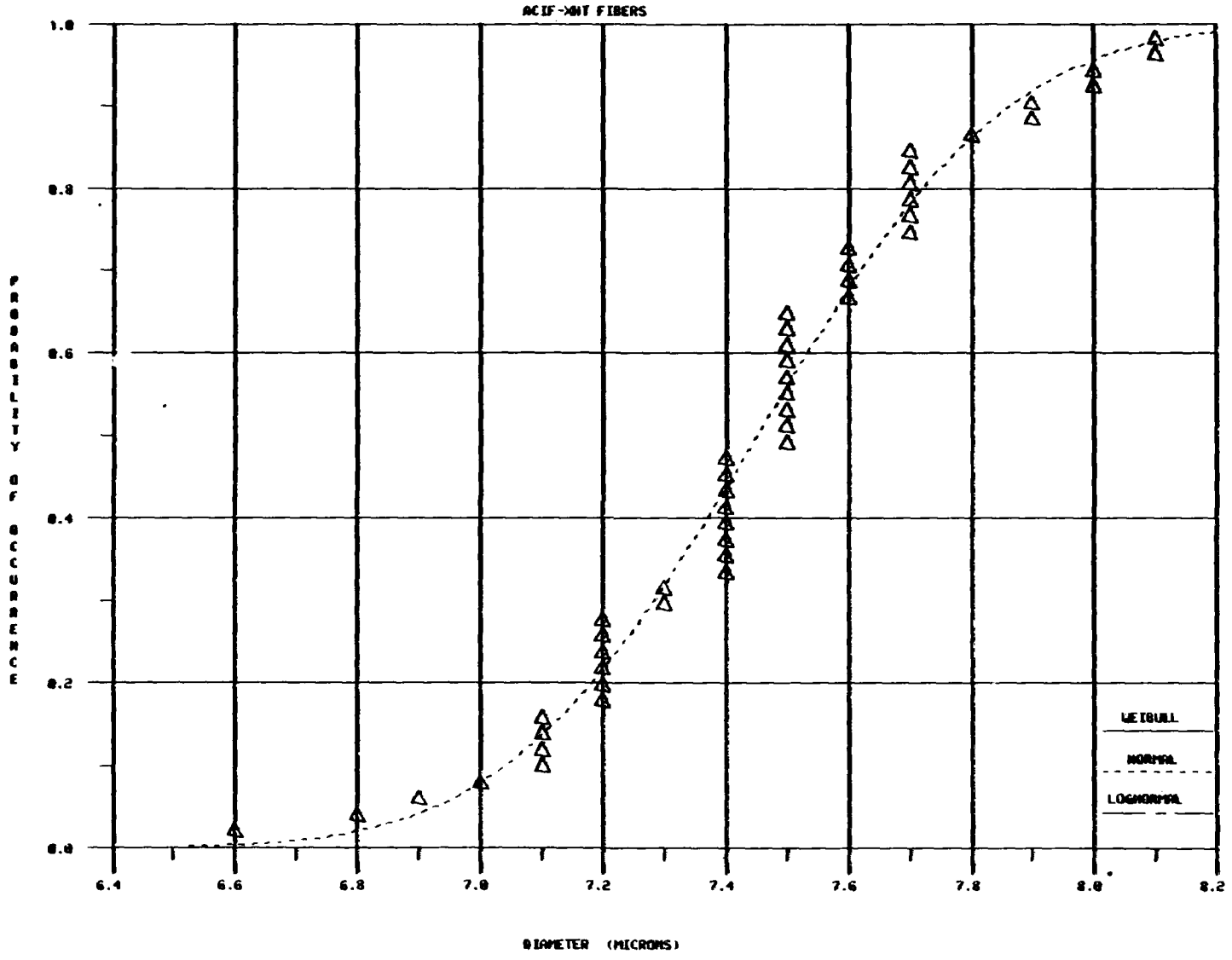

ACIF->INT FIBERS
1.0
0.8
0.6
0.4
0.2
0.0
PROBABILITY OF OCCURRENCE
6.4
6.6
6.8
7.0
7.2
7.4
7.6
7.8
8.0
8.2
DIAMETER (MICRONS)
WEIBULL
NORMAL
LOGNORMAL

Figure 13a.

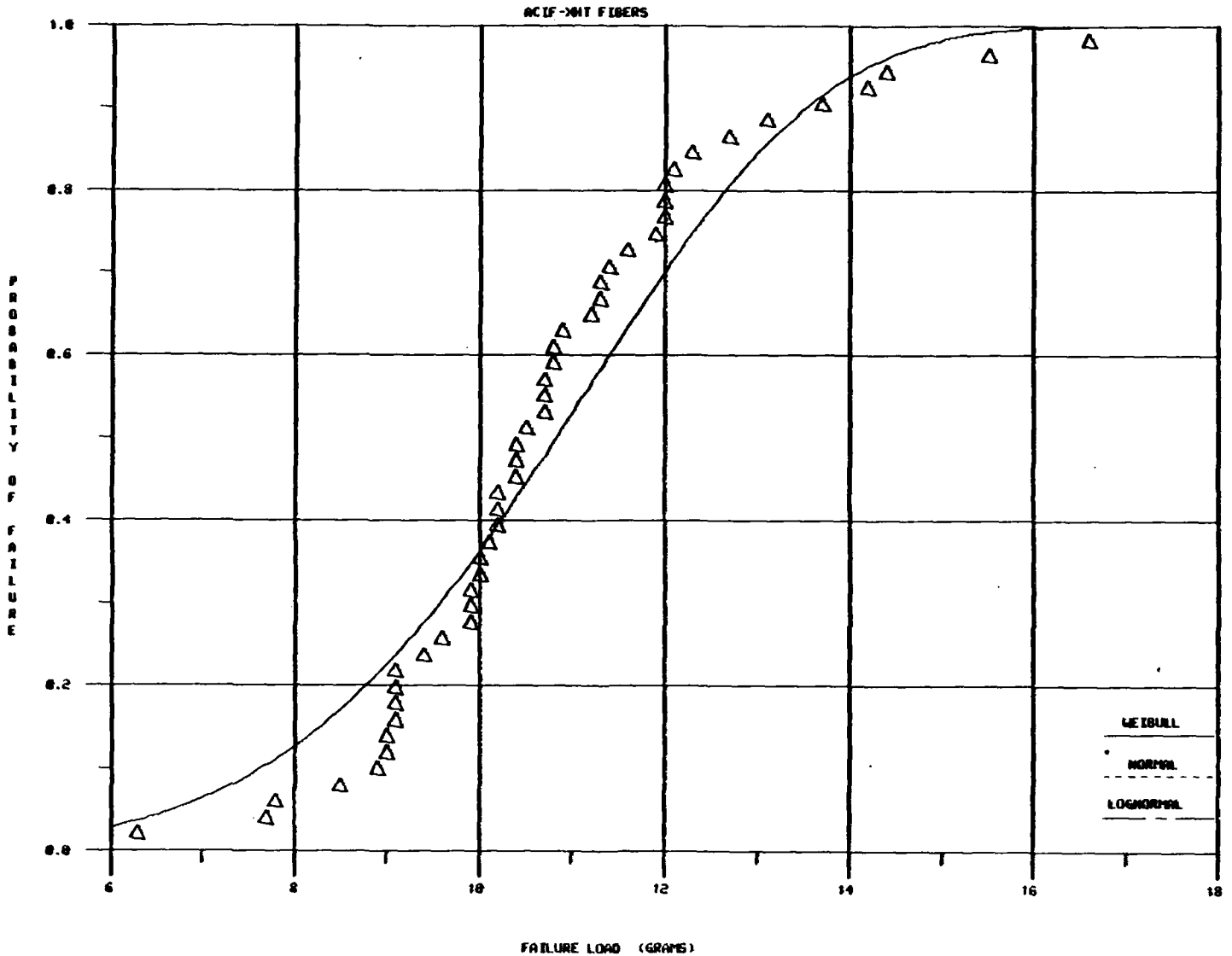

ACID-HNT FIBERS
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
6
8
10
12
14
16
18
FAILURE LOAD (GRAMS)
WEIBULL
NORMAL
LOGNORMAL

Figure 13b.

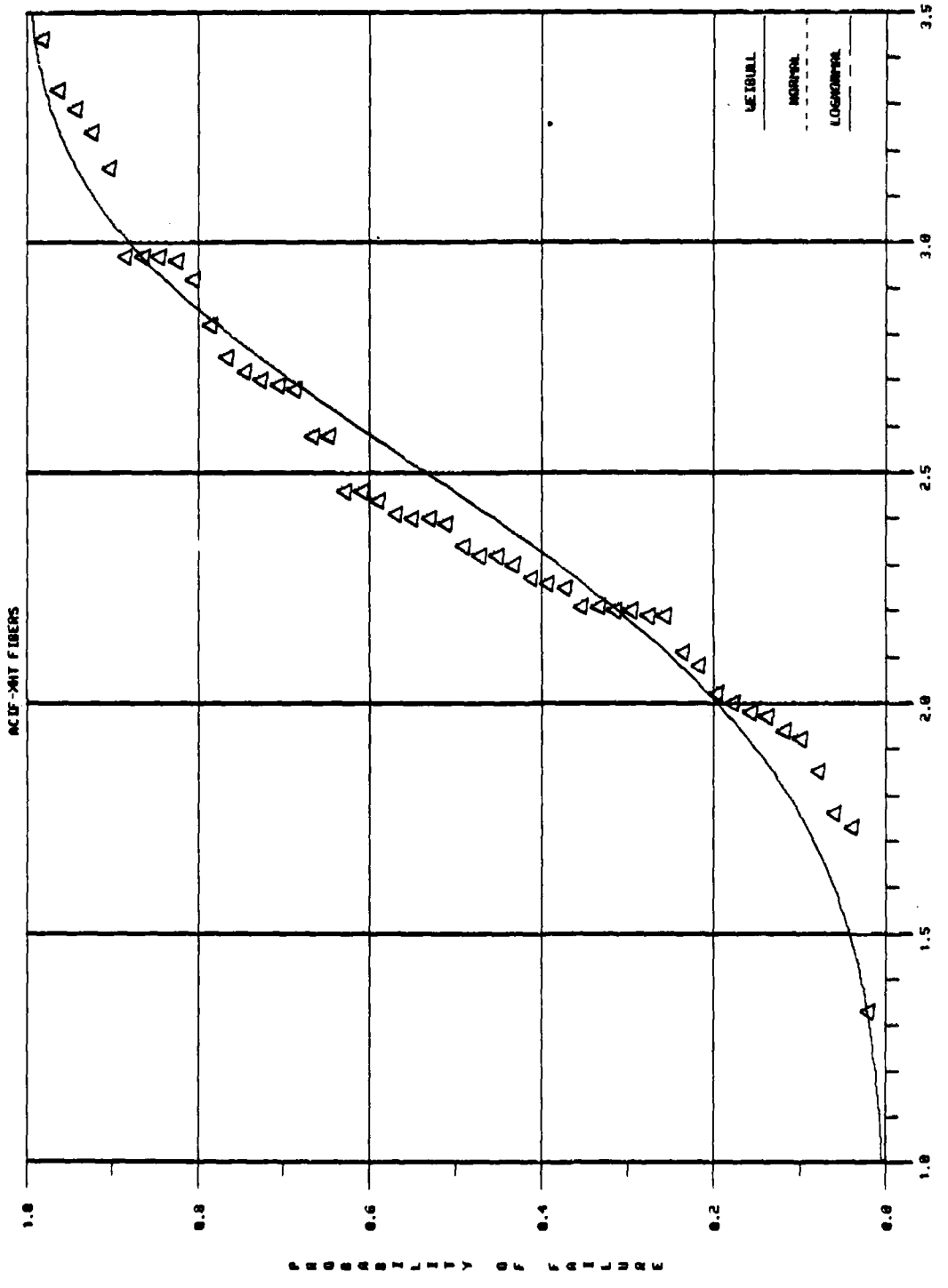
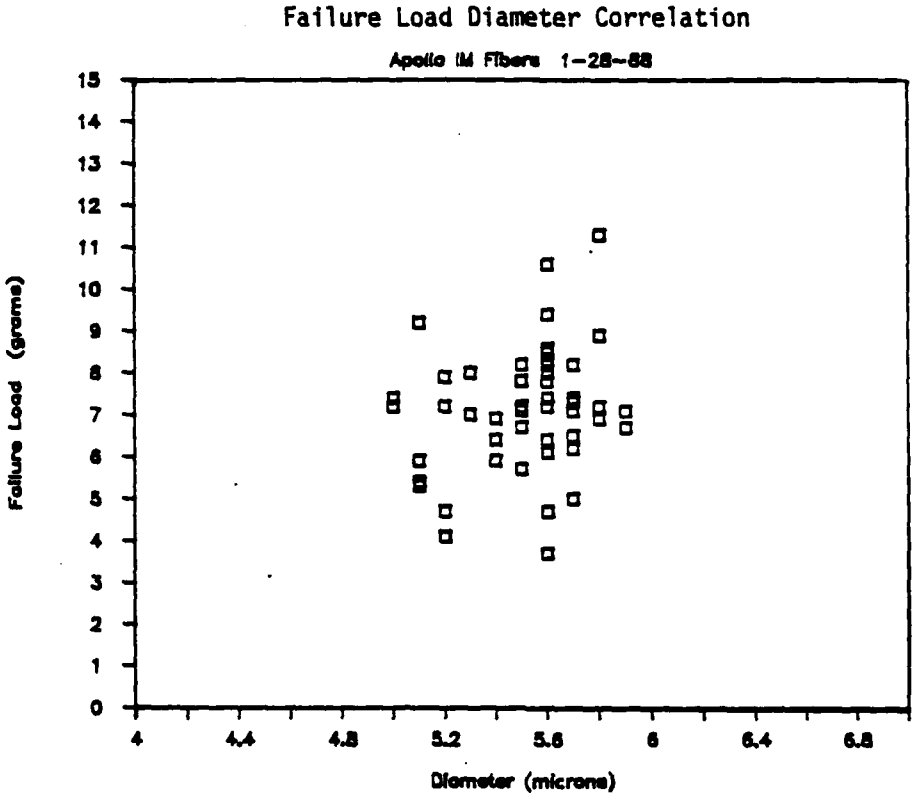

ACID-WAT FIBERS
PROBABILITY OF FAILURE
FAILURE STRESS (GPA)
WEIBULL
NORMAL
LOGNORMAL
0.0
0.2
0.4
0.6
0.8
1.0
1.5
2.0
2.5
3.0
3.5

Figure 13c.


Failure Load Diameter Correlation
Apollo IM Fibers 1-28-88
Failure Load (grams)
Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
4
4.4
4.8
5.2
5.6
6
6.4
6.8

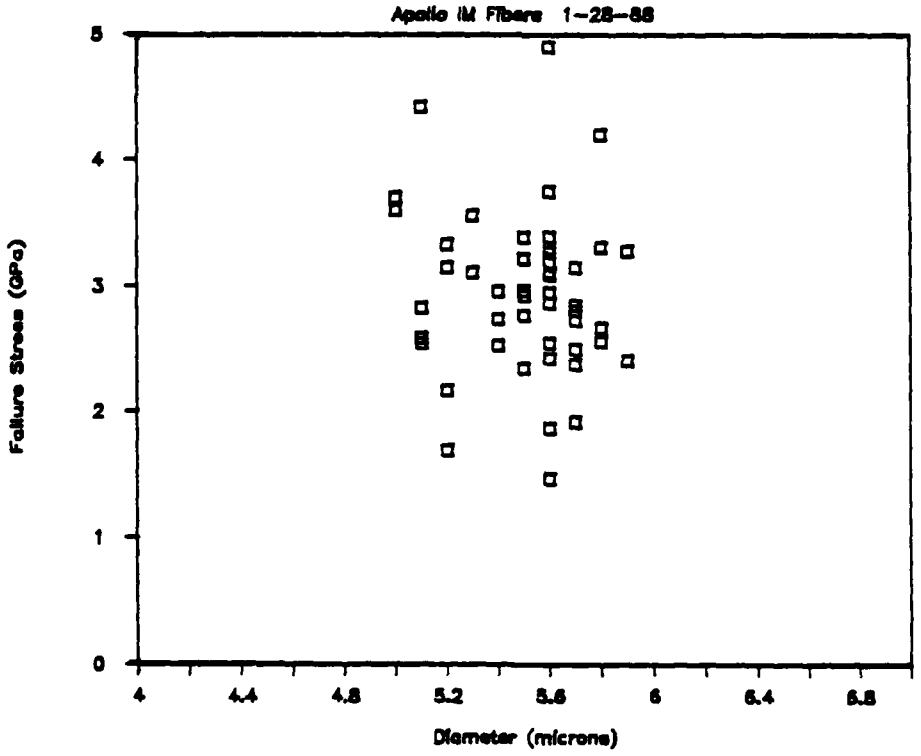

Failure Stress Diameter Correlation
Apollo IM Fibers 1-28-88
Failure Stress (GPa)
Diameter (microns)
0
1
2
3
4
5
4
4.4
4.8
5.2
5.6
6
6.4
6.8

Figure 14.

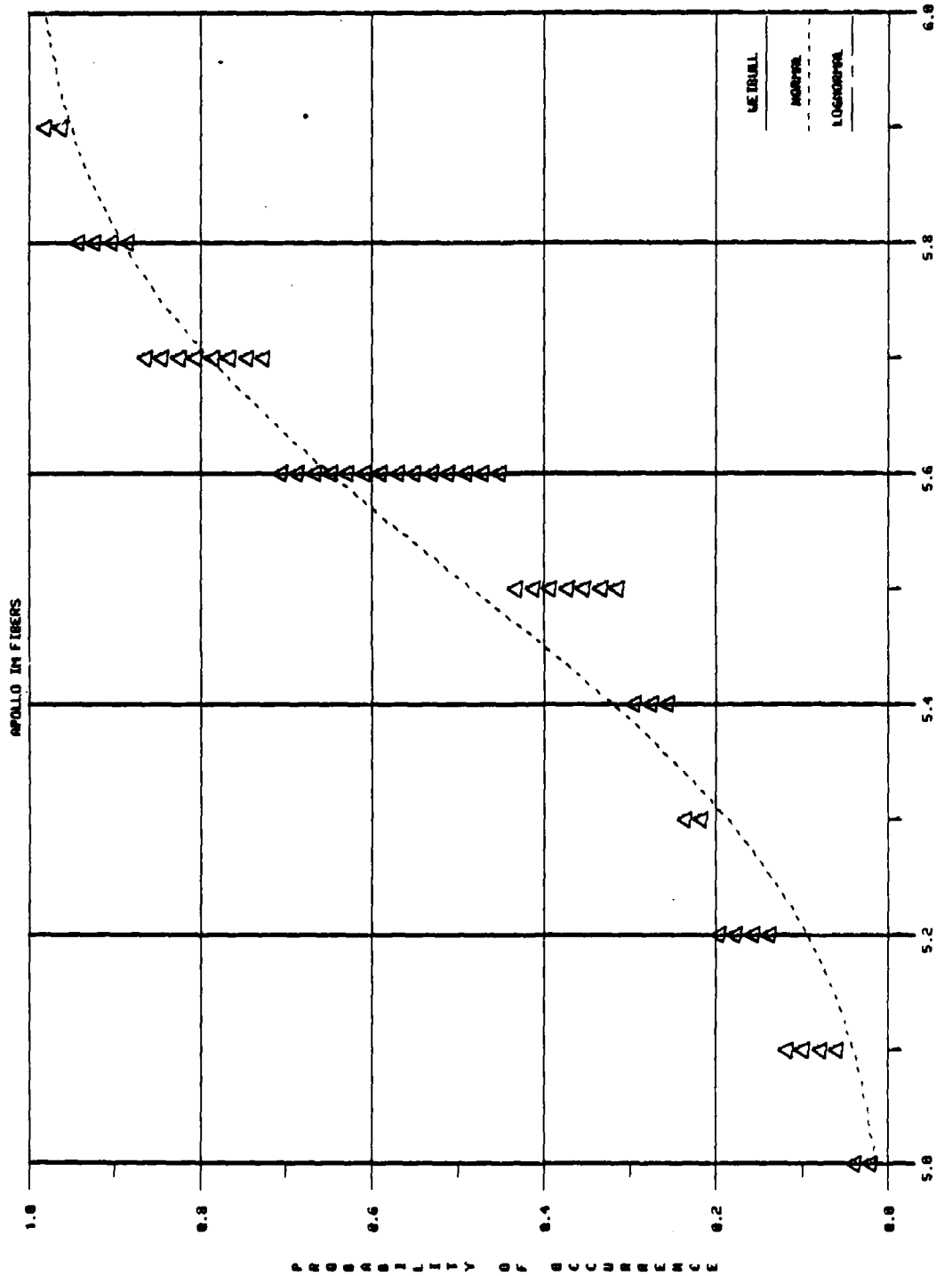

APOLLO IM FIBERS
WEIBULL
NORMAL
LOGNORMAL
PROBABILITY OF OCCURRENCE
DIAMETER (MICRONS)
1.0
0.8
0.6
0.4
0.2
0.0
5.0
5.2
5.4
5.6
5.8
6.0

Figure 15a.

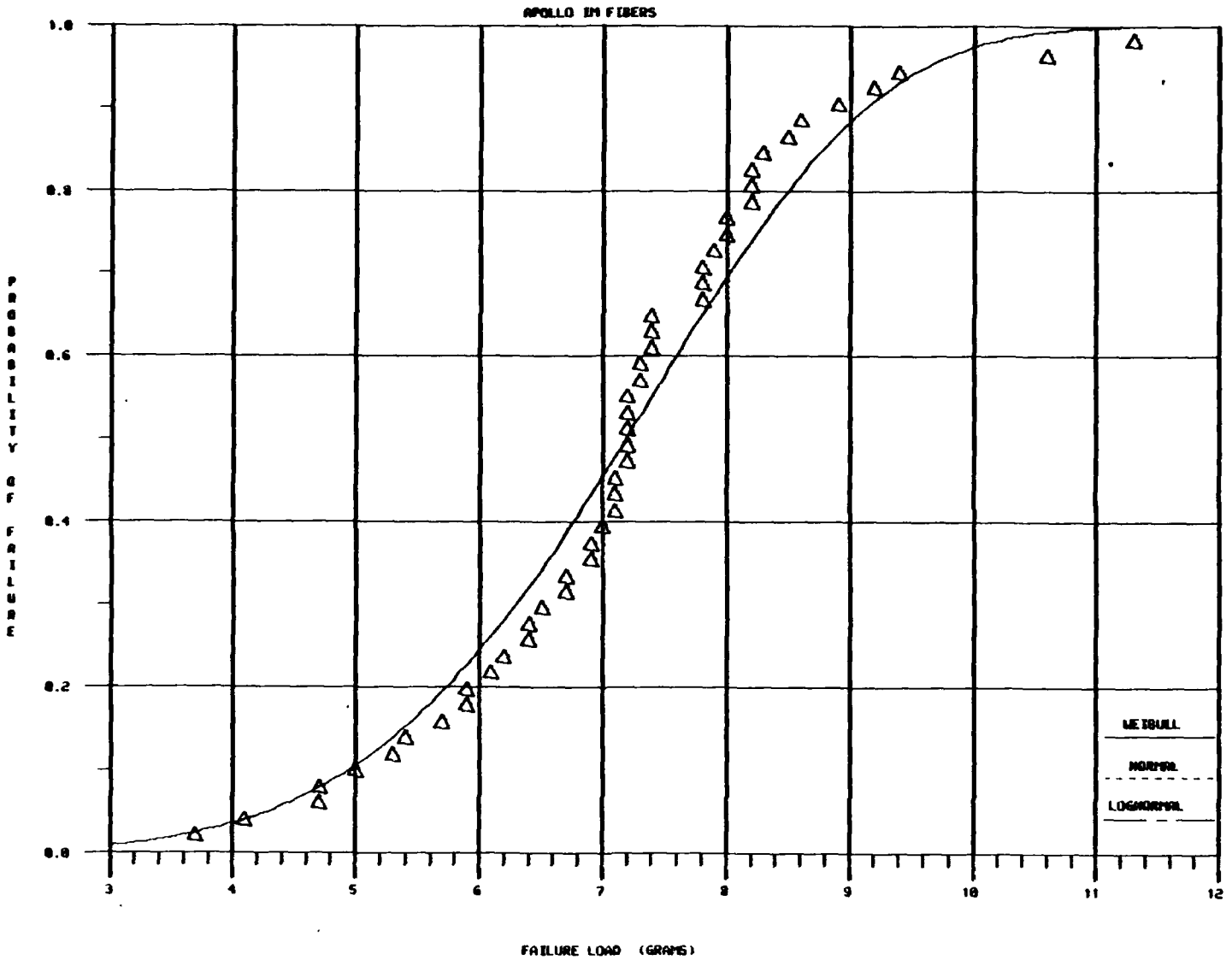

APOLLO IM FIBERS
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
3
4
5
6
7
8
9
10
11
12
FAILURE LOAD (GRAMS)
WEIBULL
NORMAL
LOGNORMAL

Figure 15b.

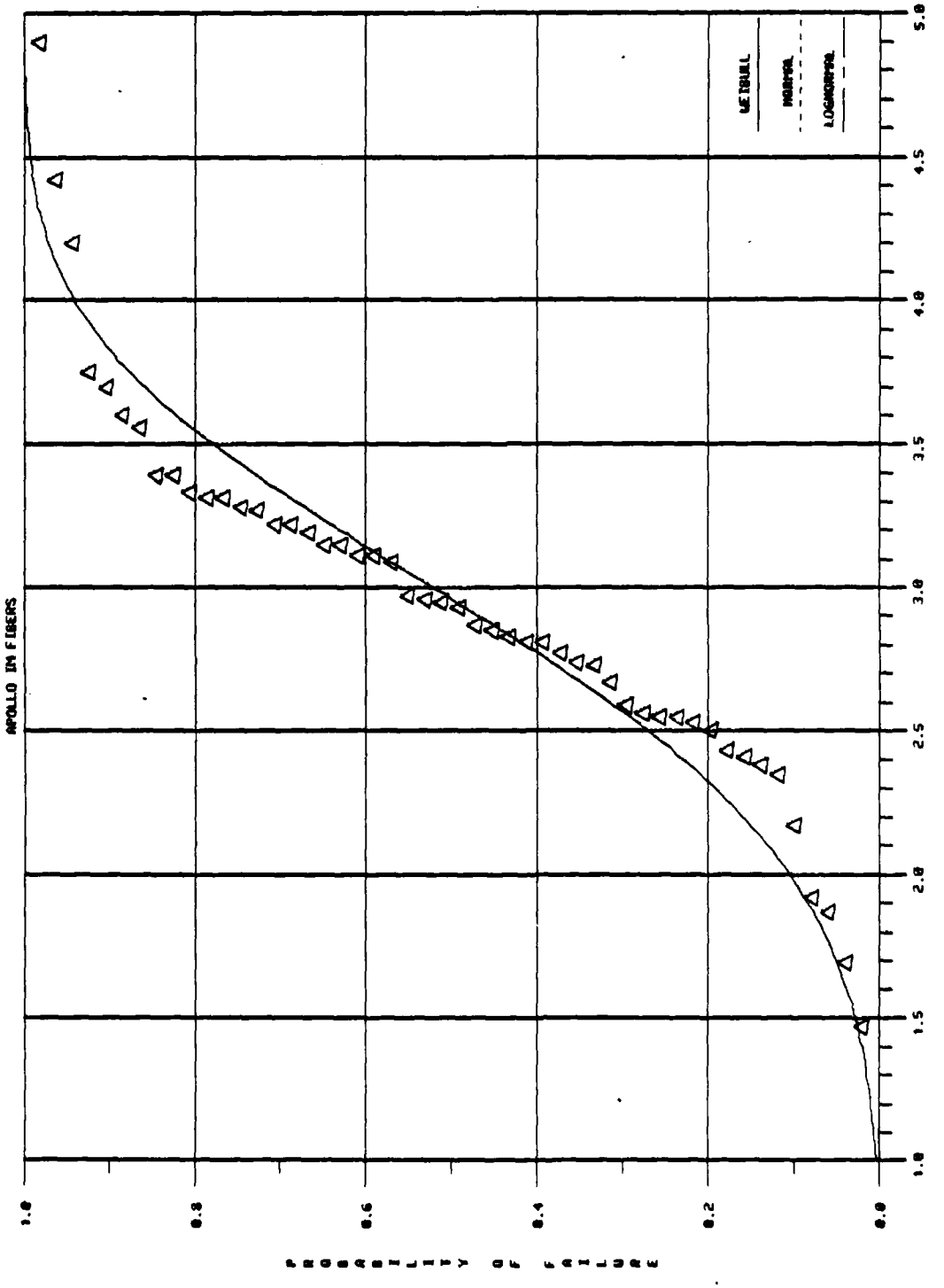
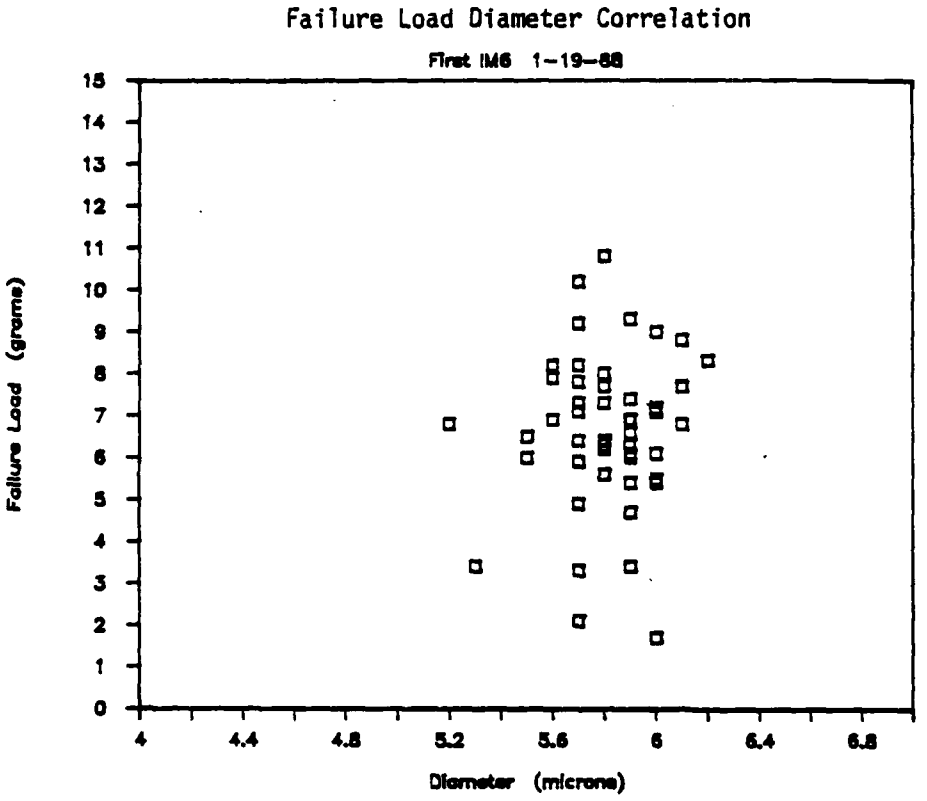

APOLLO IM FIBERS
WEIBULL
NORMAL
LOGNORMAL
1.0
0.8
0.6
0.4
0.2
0.0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
FAILURE STRESS (GPA)

Figure 15c.


Failure Load Diameter Correlation
First IM6 1-19-88
Failure Load (grams)
Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
4
4.4
4.8
5.2
5.6
6
6.4
6.8

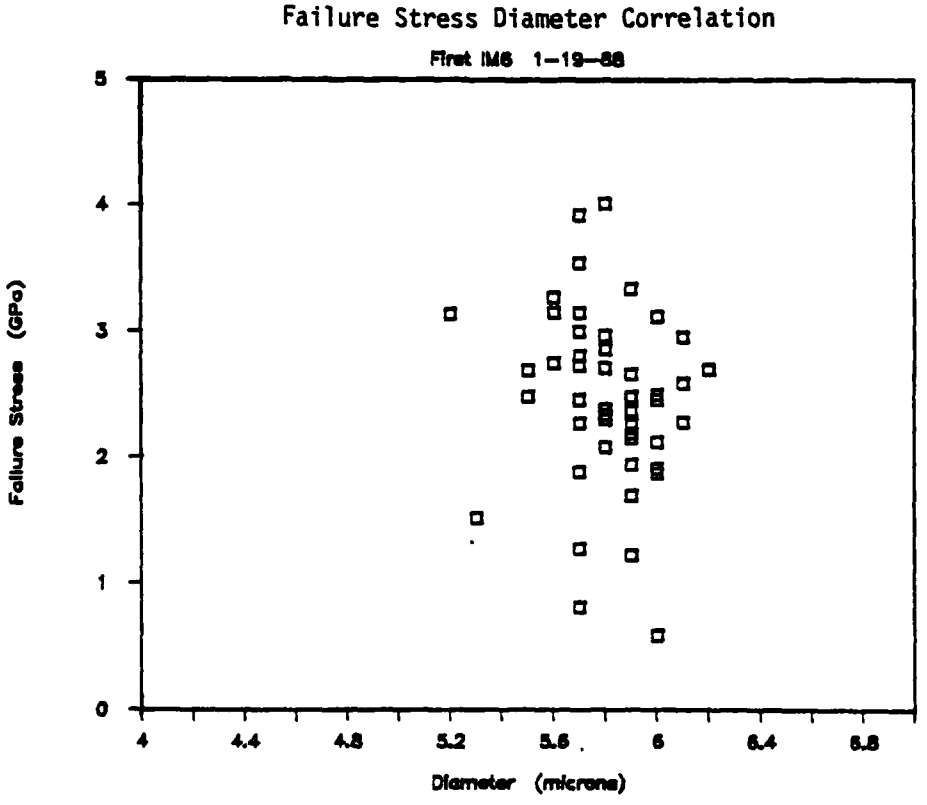
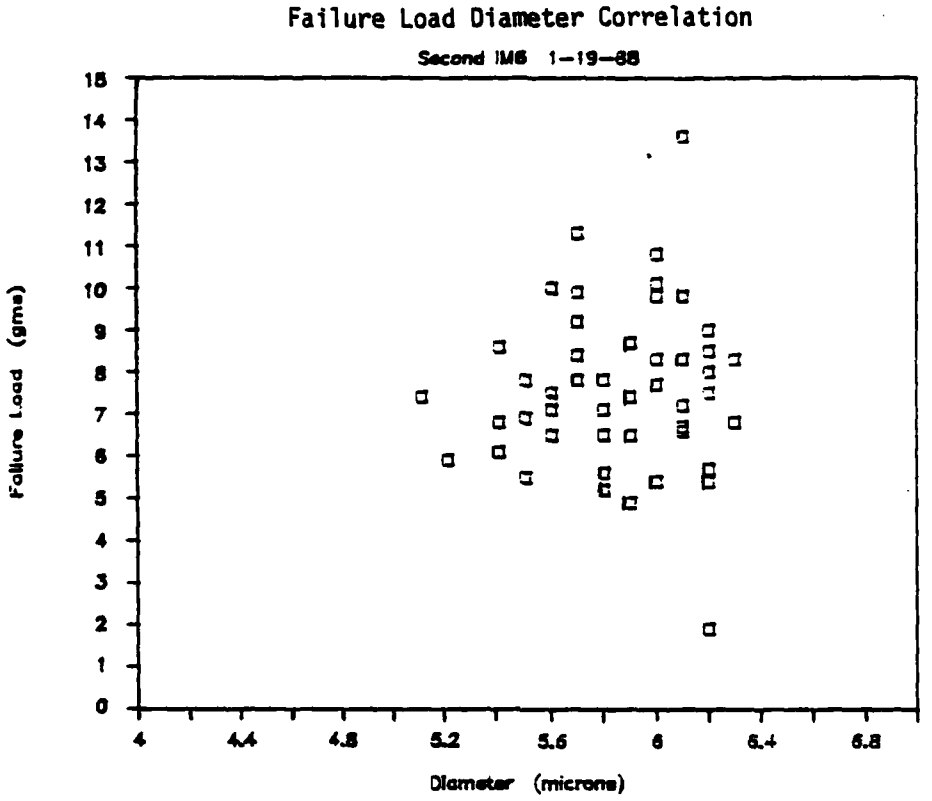

Failure Stress Diameter Correlation
First IM6 1-19-88
Failure Stress (GPa)
Diameter (microns)
0
1
2
3
4
5
4
4.4
4.8
5.2
5.6
6
6.4
6.8

Figure 16a.


Failure Load Diameter Correlation
Second IM6 1-19-88
Failure Load (gms)
Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
4
4.4
4.8
5.2
5.6
6
6.4
6.8

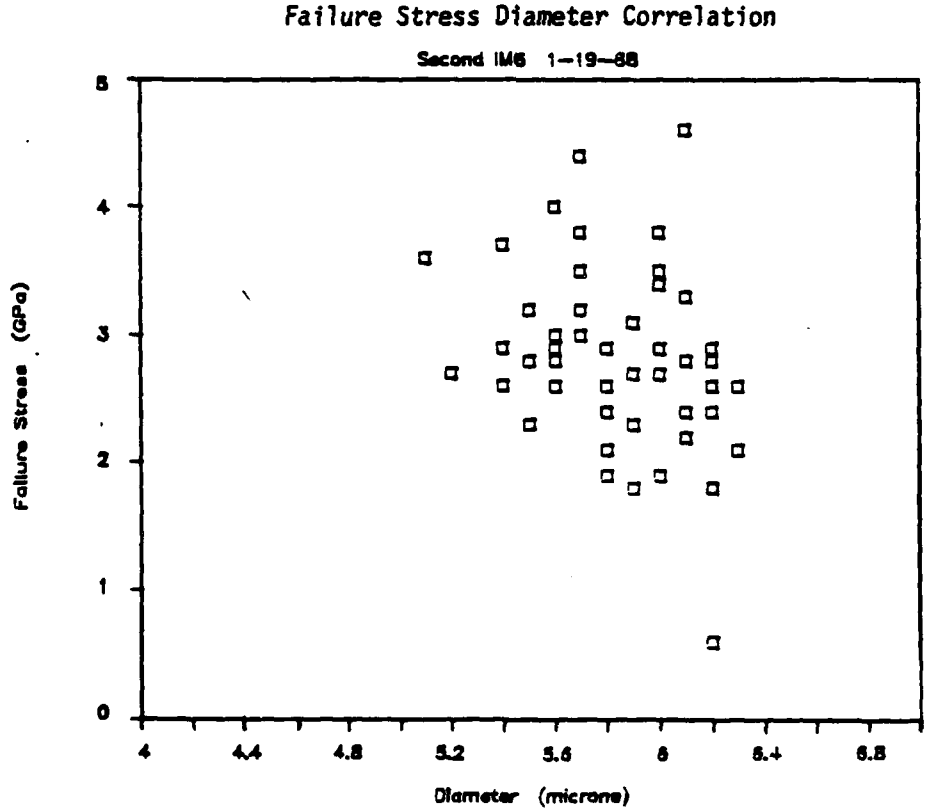
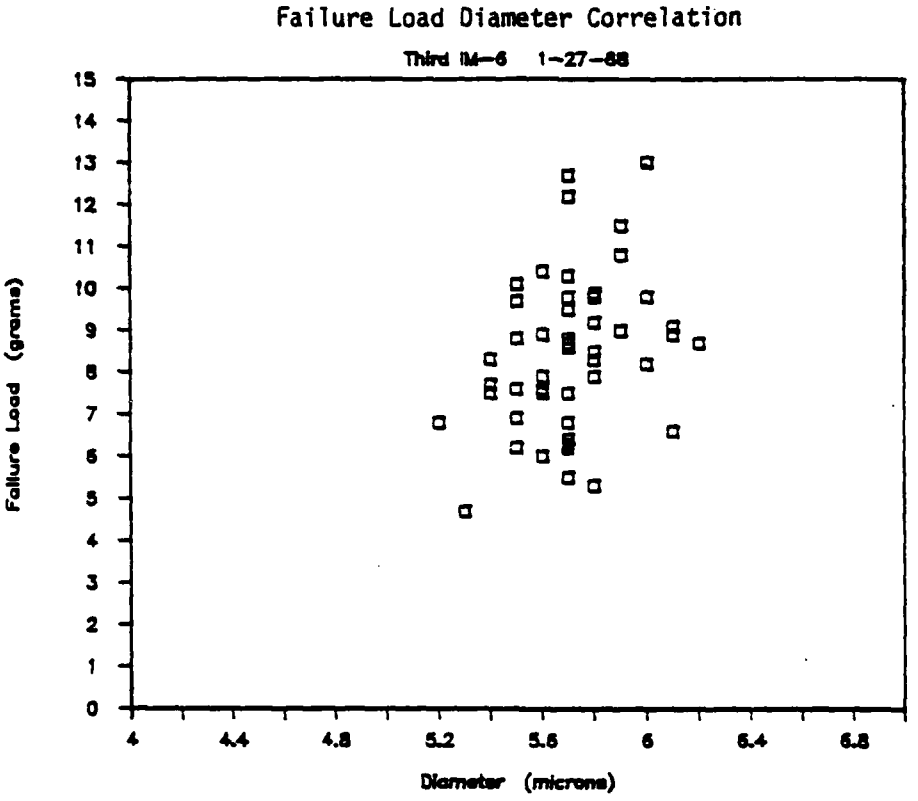

Failure Stress Diameter Correlation
Second IM6 1-19-88
Failure Stress (GPa)
Diameter (microns)
0
1
2
3
4
5
4
4.4
4.8
5.2
5.6
6
6.4
6.8

Figure 16b.


Failure Load Diameter Correlation
Third IM-6 1-27-88
Failure Load (grams)
Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
4
4.4
4.8
5.2
5.6
6
6.4
6.8

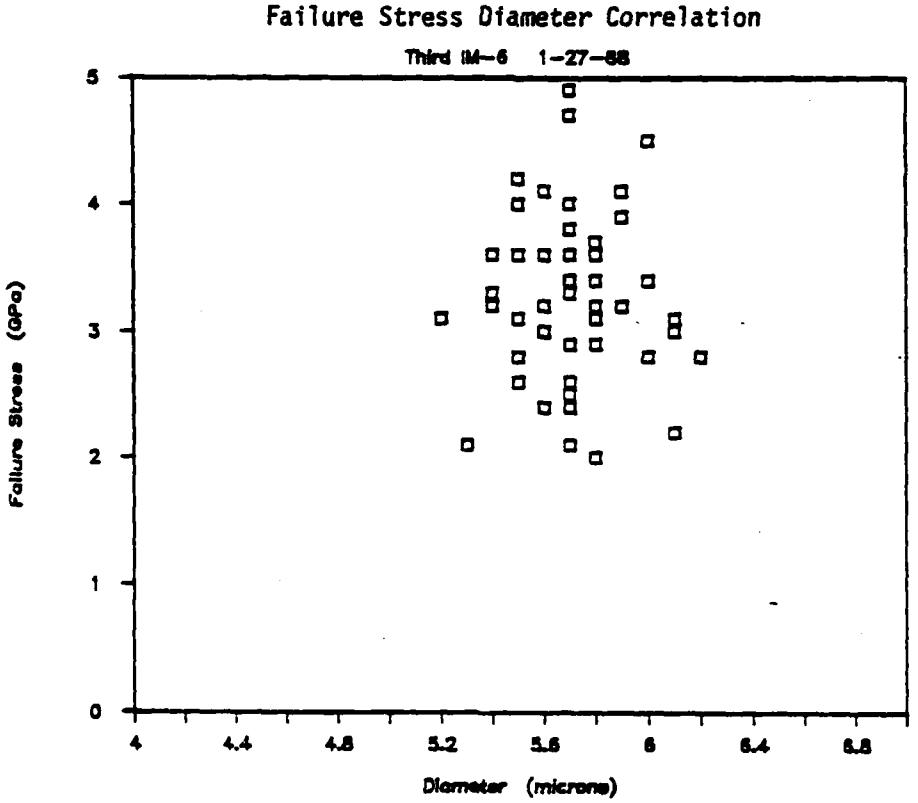

Failure Stress Diameter Correlation
Third IM-6 1-27-88
Failure Stress (GPa)
Diameter (microns)
0
1
2
3
4
5
4
4.4
4.8
5.2
5.6
6
6.4
6.8

Figure 16c.

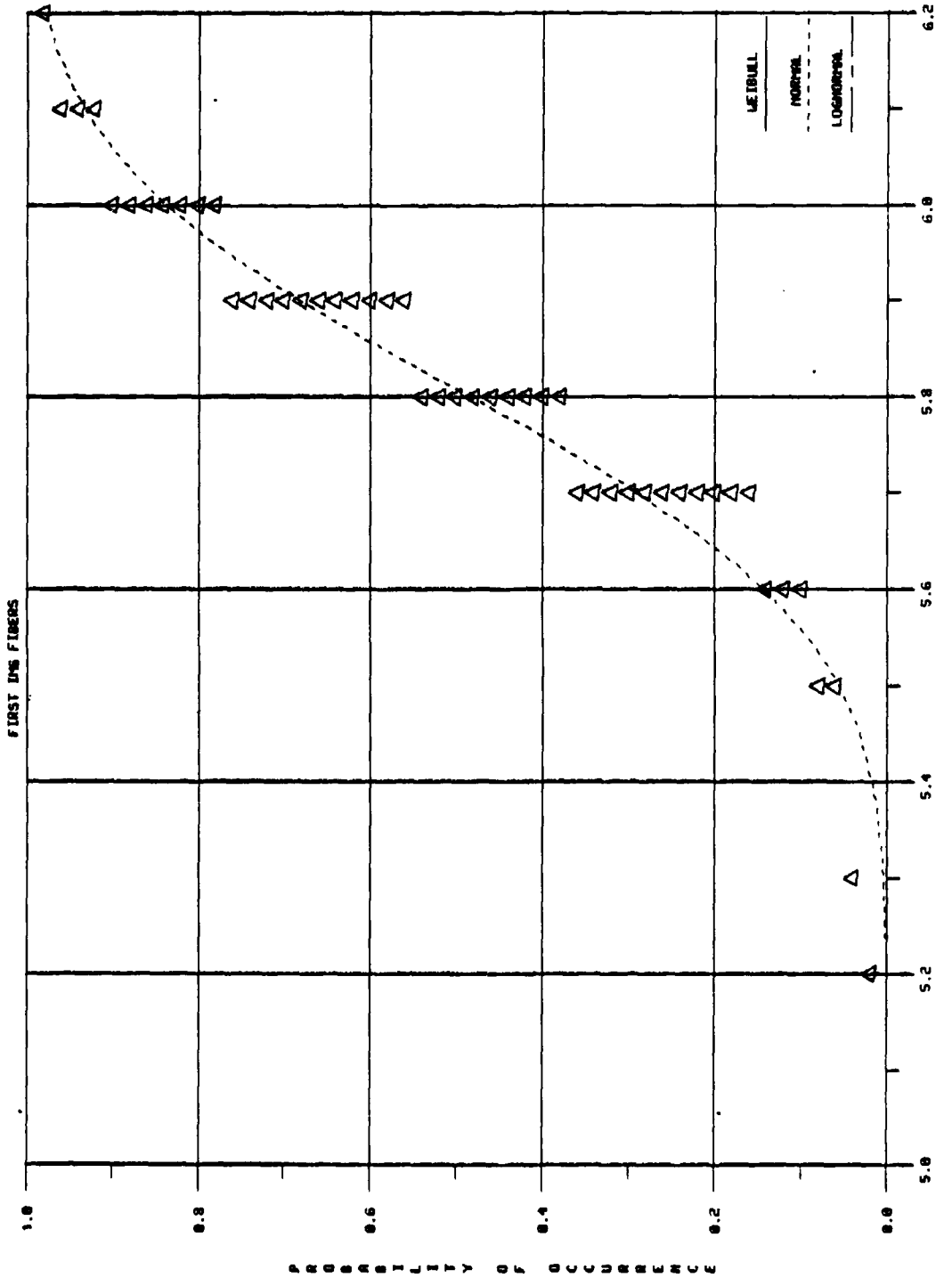

FIRST DNS FIBERS
PROBABILITY OF OCCURRENCE
1.0
0.8
0.6
0.4
0.2
0.0
5.0
5.2
5.4
5.6
5.8
6.0
6.2
DIAMETER (MICRONS)
WEIBULL
NORMAL
LOGNORMAL

Figure 17a.

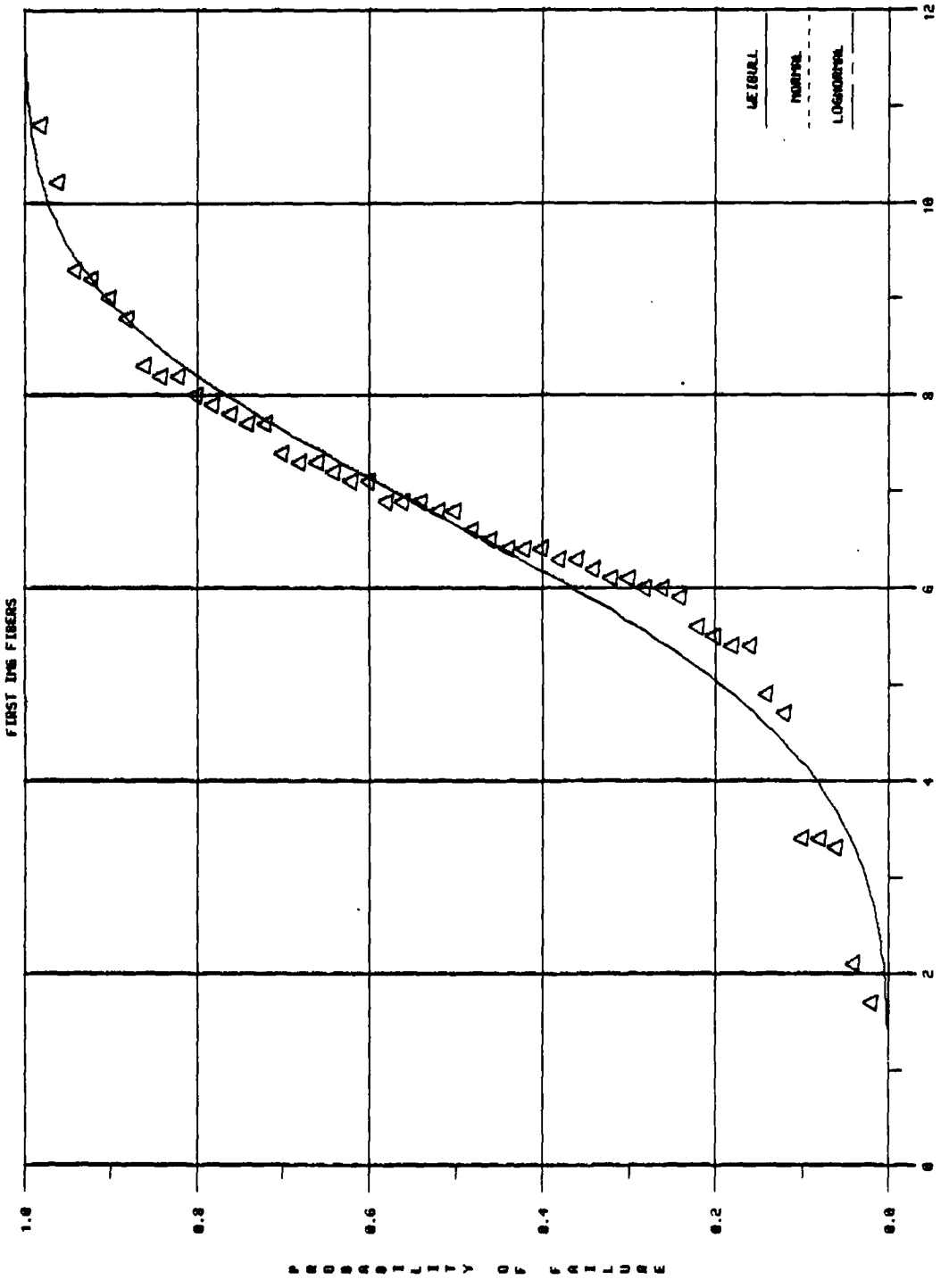

FIRST ING FIBERS
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
FAILURE LOAD (GRAMS)
WEIBULL
NORMAL
LOGNORMAL

Figure 17b.

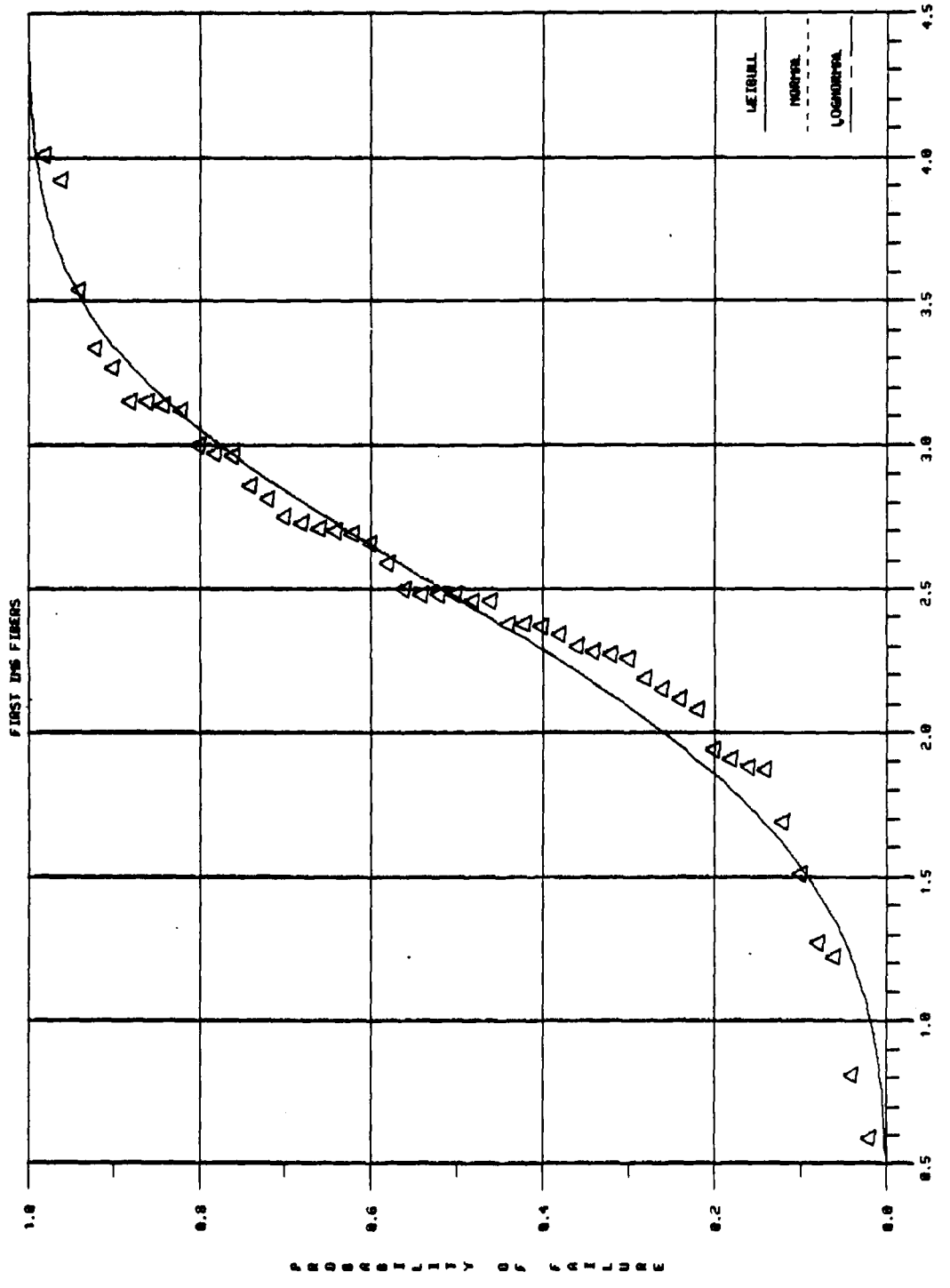

FIRST UNS FIBERS
PROBABILITY OF FAILURE
FAILURE STRESS (GPA)
WEIBULL
NORMAL
LOGNORMAL
0.0
0.2
0.4
0.6
0.8
1.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

Figure 17c.

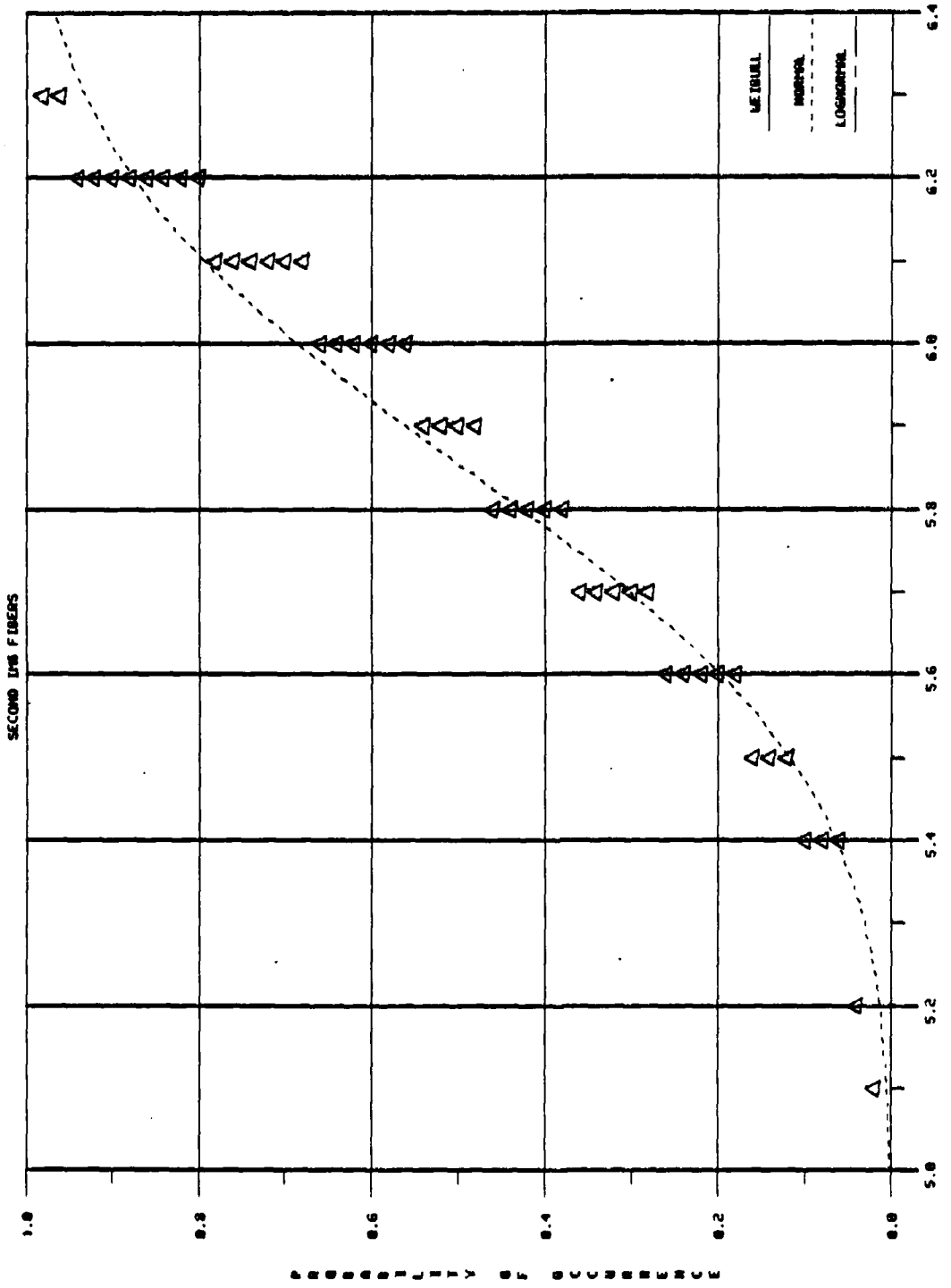

SECOND LMS FIBERS
1.0
0.8
0.6
0.4
0.2
0.0
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
DIAMETER (MICRONS)

Figure 17d.

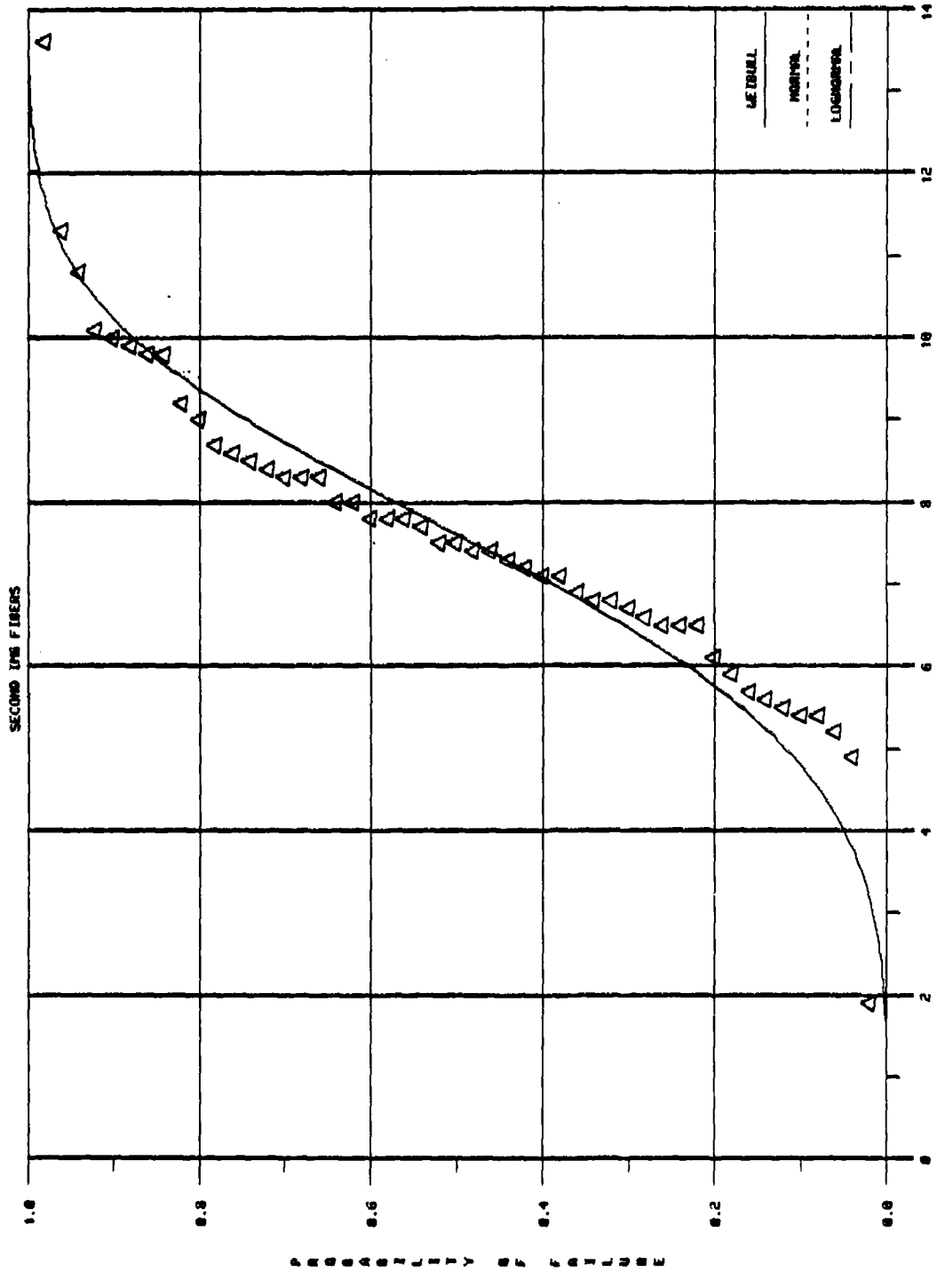

SECOND UNS FIBERS
FAILURE LOAD (GRAMS)
WEIBULL
NORMAL
LOGNORMAL
0
2
4
6
8
10
12
14
0.0
0.2
0.4
0.6
0.8
1.0

Figure 17e.

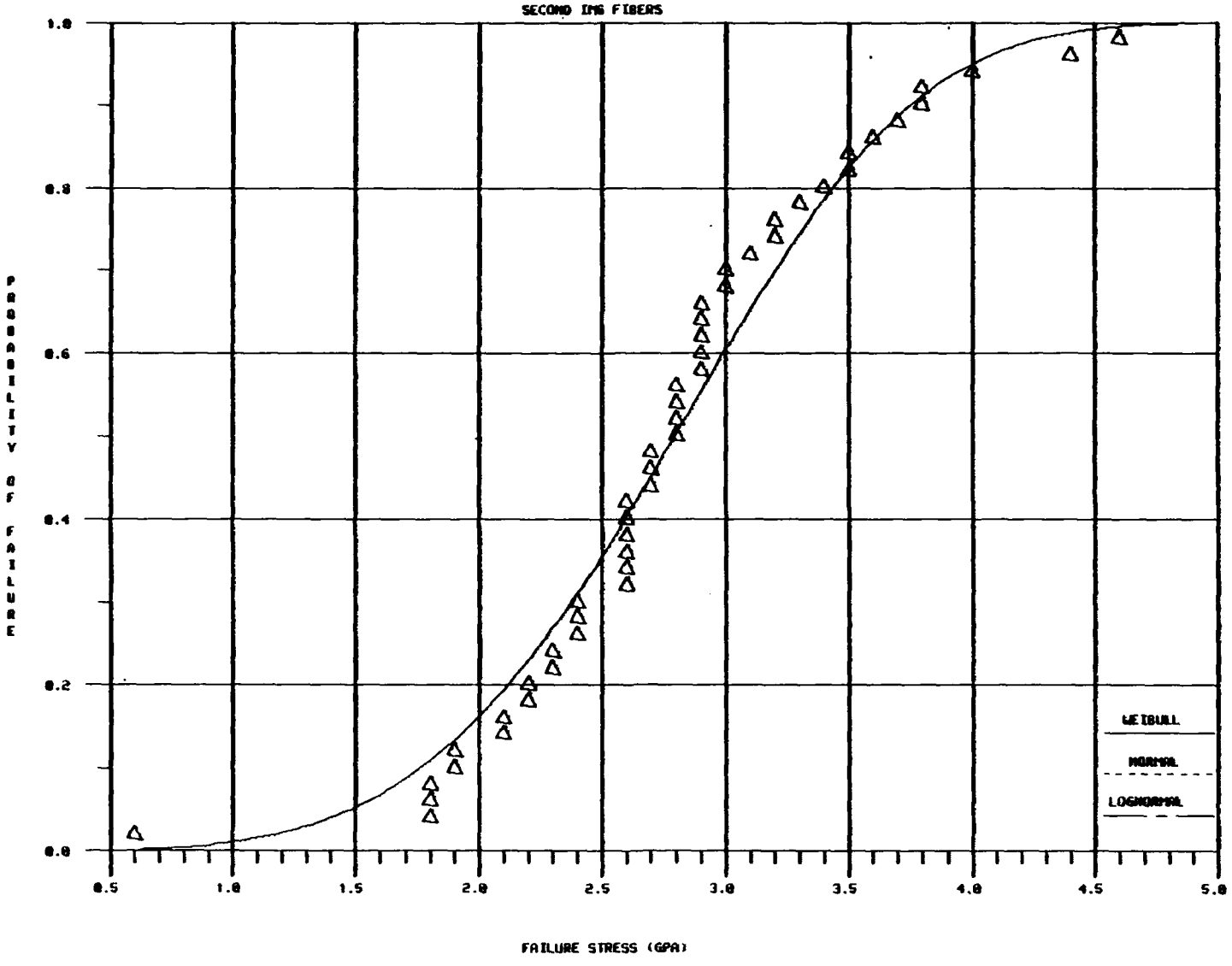

SECOND IM6 FIBERS
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
FAILURE STRESS (GPA)
WEIBULL
NORMAL
LOGNORMAL

Figure 17f.

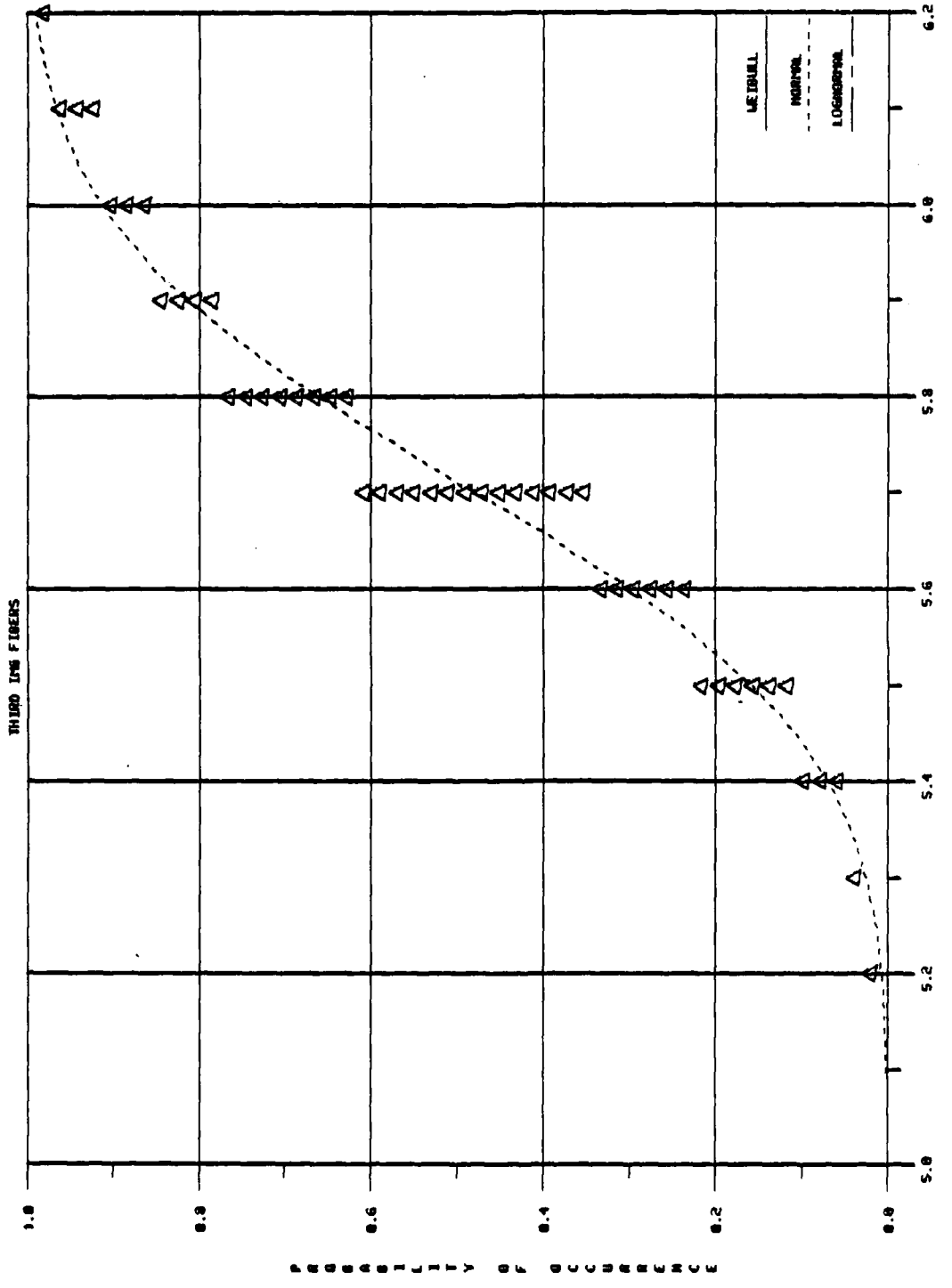

THIRD IMS FIBERS
PROBABILITY OF OCCURRENCE
1.0
0.8
0.6
0.4
0.2
0.0
5.0
5.2
5.4
5.6
5.8
6.0
6.2
DIAMETER (MICRONS)
WEIBULL
NORMAL
LOGNORMAL

Figure 17g.

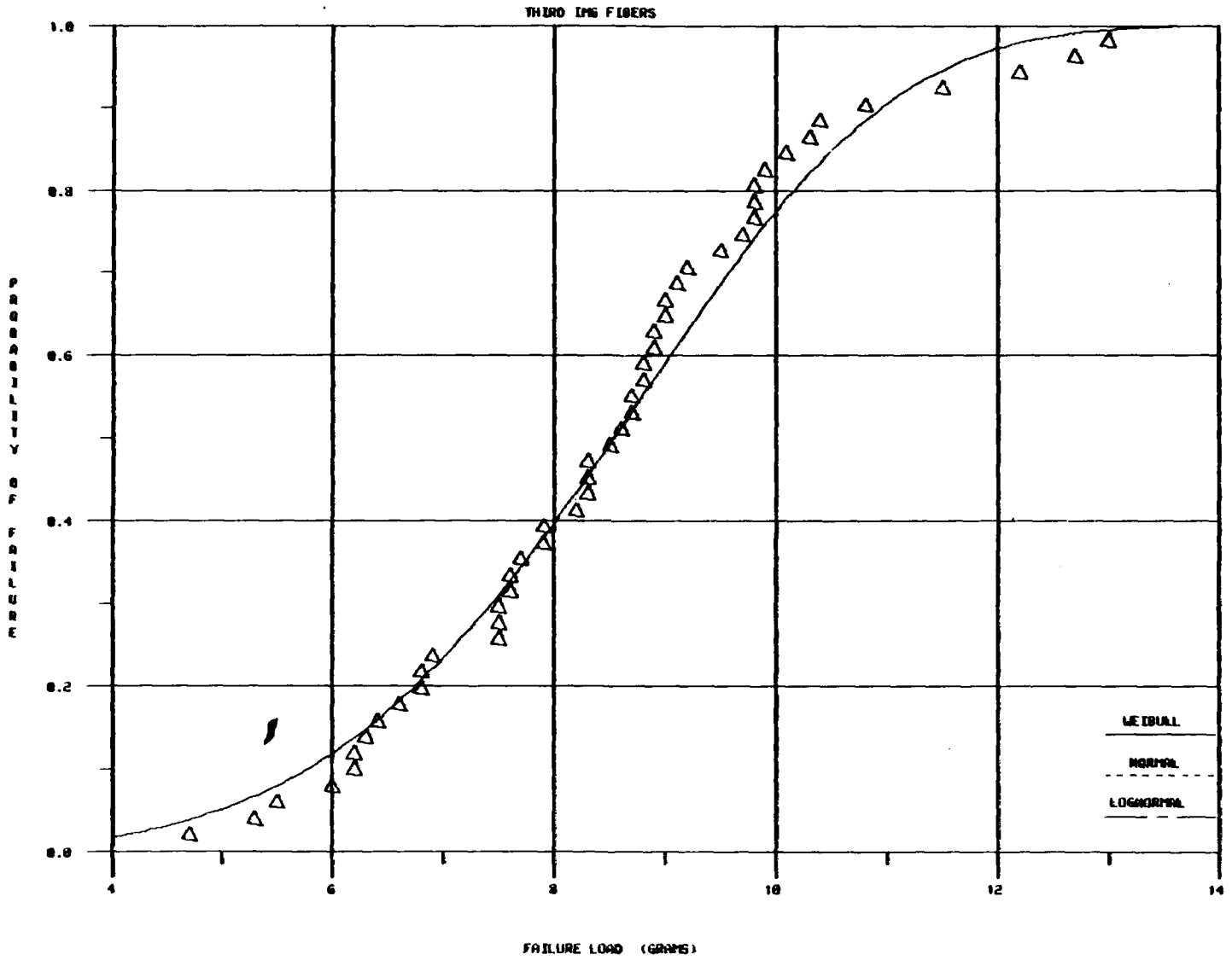

THIRD IMG FIBERS
1.0
0.8
0.6
0.4
0.2
0.0
PROBABILITY OF FAILURE
4
6
8
10
12
14
FAILURE LOAD (GRAMS)
WEIBULL
NORMAL
LOGNORMAL

Figure 17h.

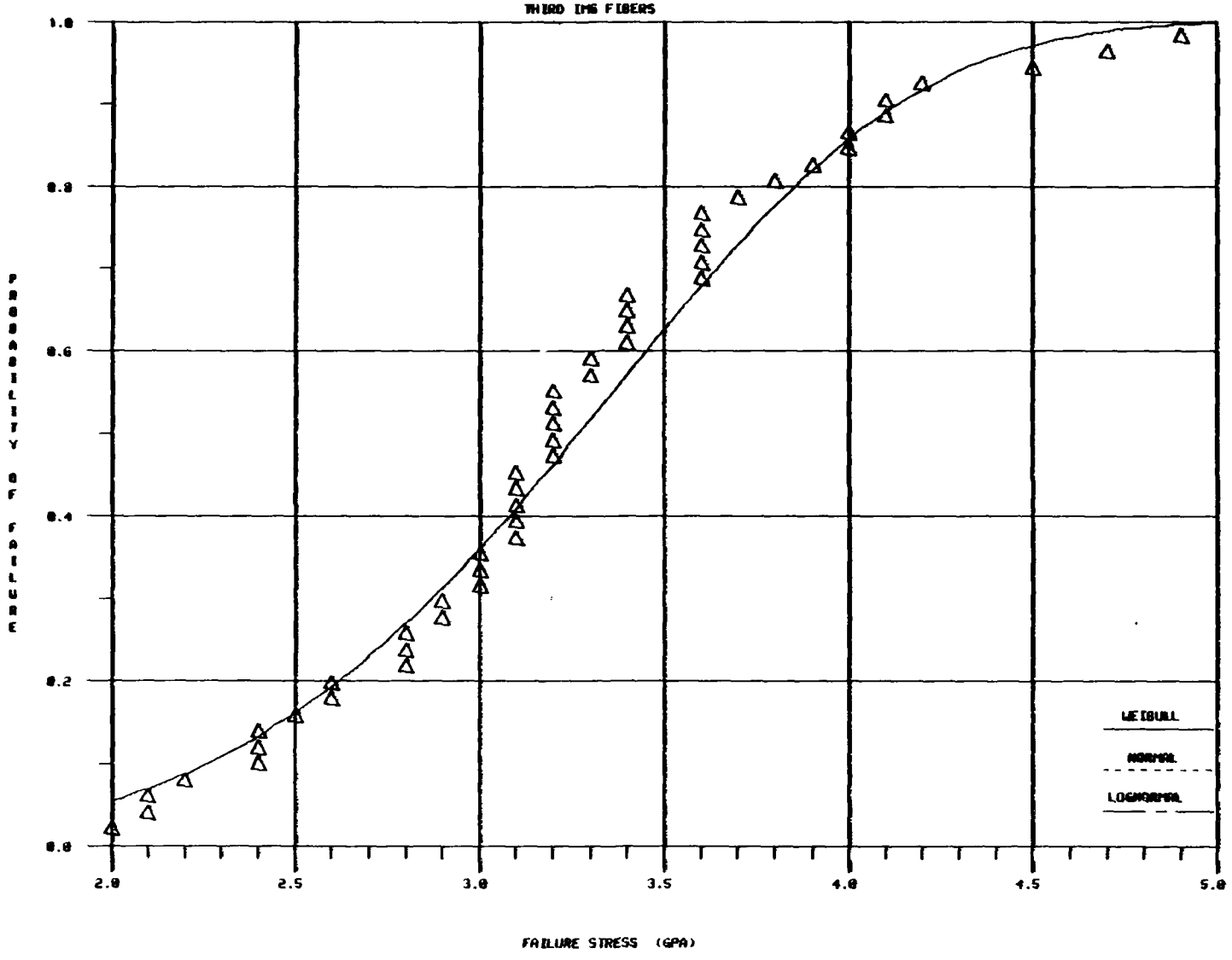
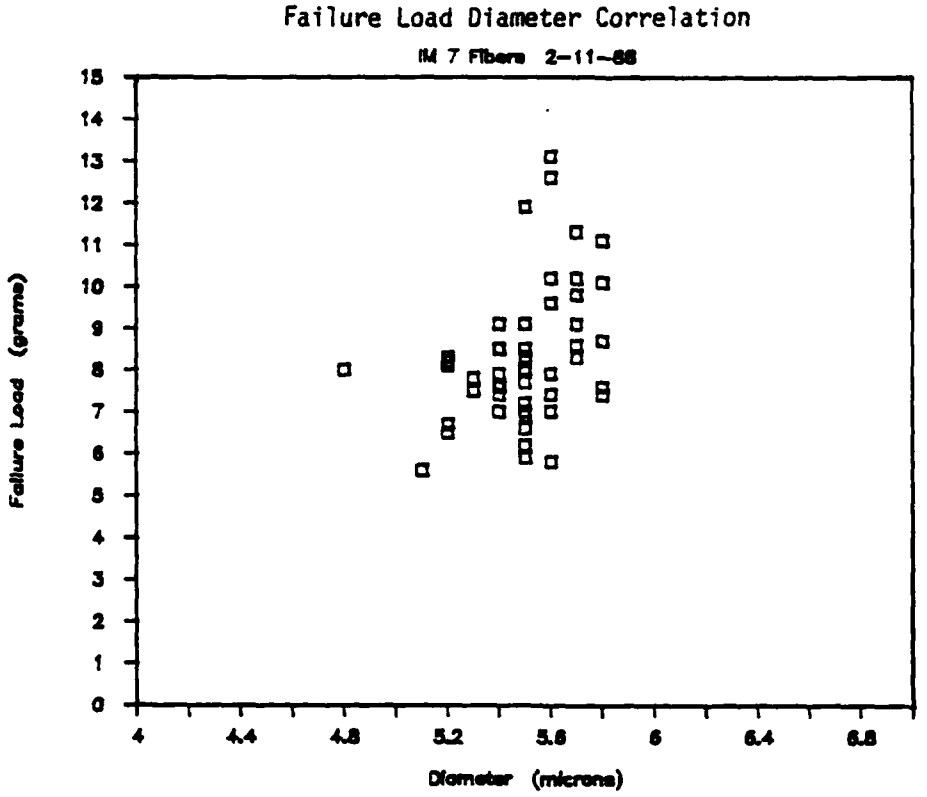

THIRD IMG FIBERS
PROBABILITY OF FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
2.0
2.5
3.0
3.5
4.0
4.5
5.0
FAILURE STRESS (GPA)
WEIBULL
NORMAL
LOGNORMAL

Figure 171.


Failure Load Diameter Correlation
IM 7 Fibers 2-11-88
Failure Load (grams)
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
4
4.4
4.8
5.2
5.6
6
6.4
6.8
Diameter (microns)

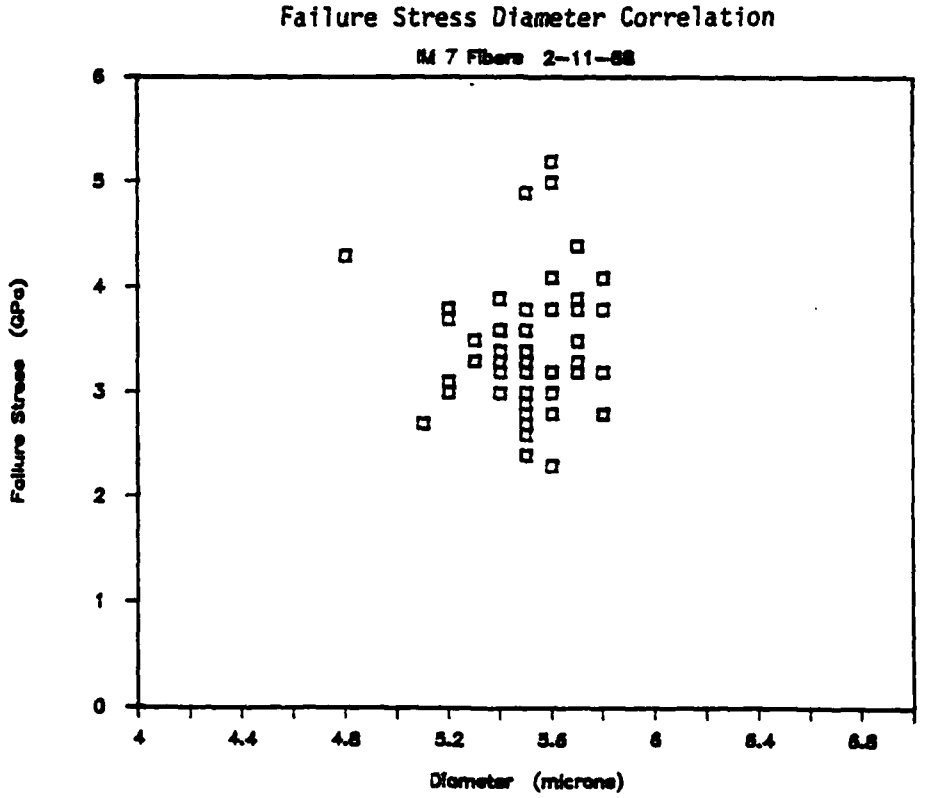

Failure Stress Diameter Correlation
IM 7 Fibers 2-11-88
Failure Stress (GPa)
6
5
4
3
2
1
0
4
4.4
4.8
5.2
5.6
6
6.4
6.8
Diameter (microns)

Figure 18.

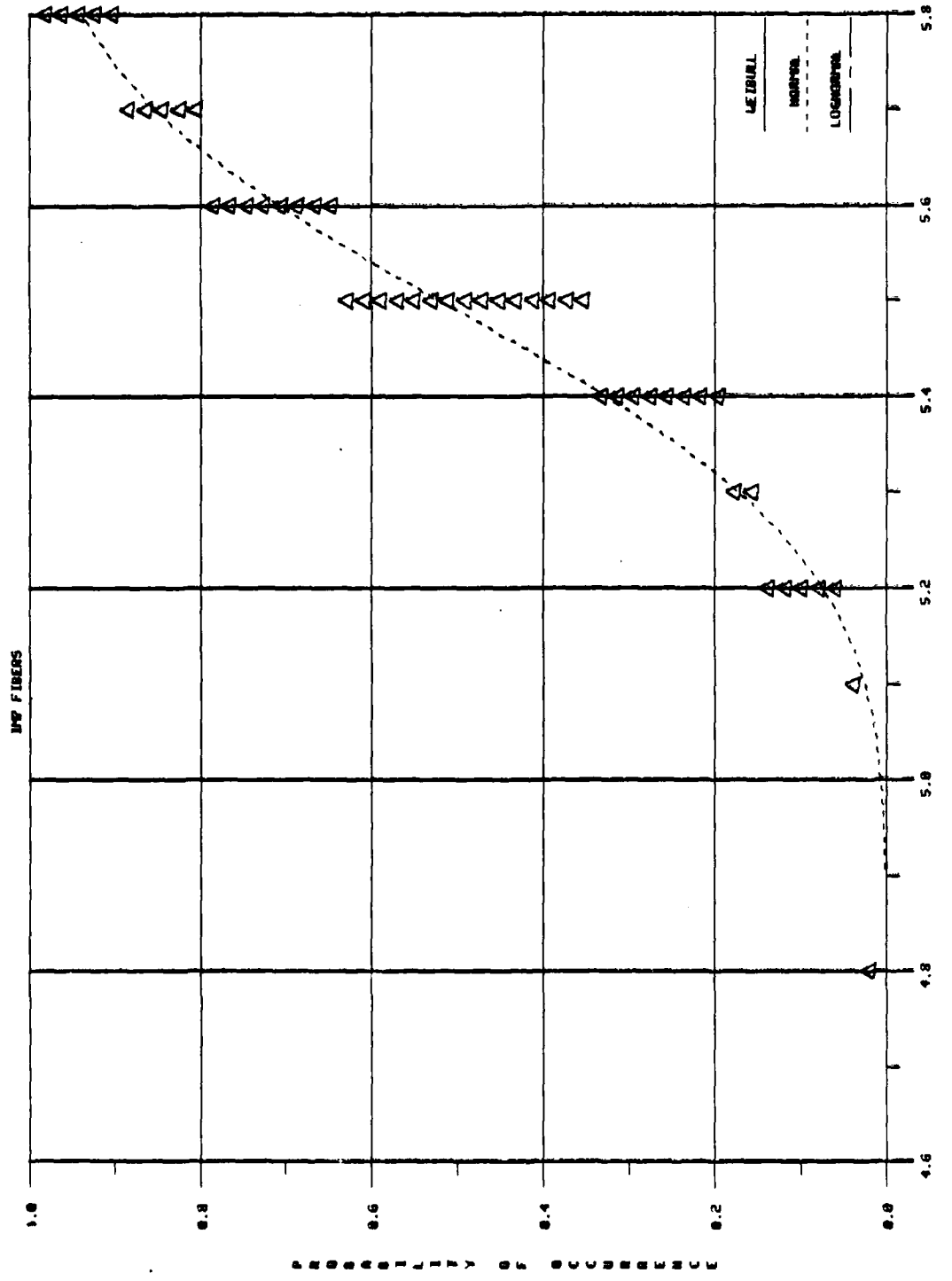



Figure 19a.

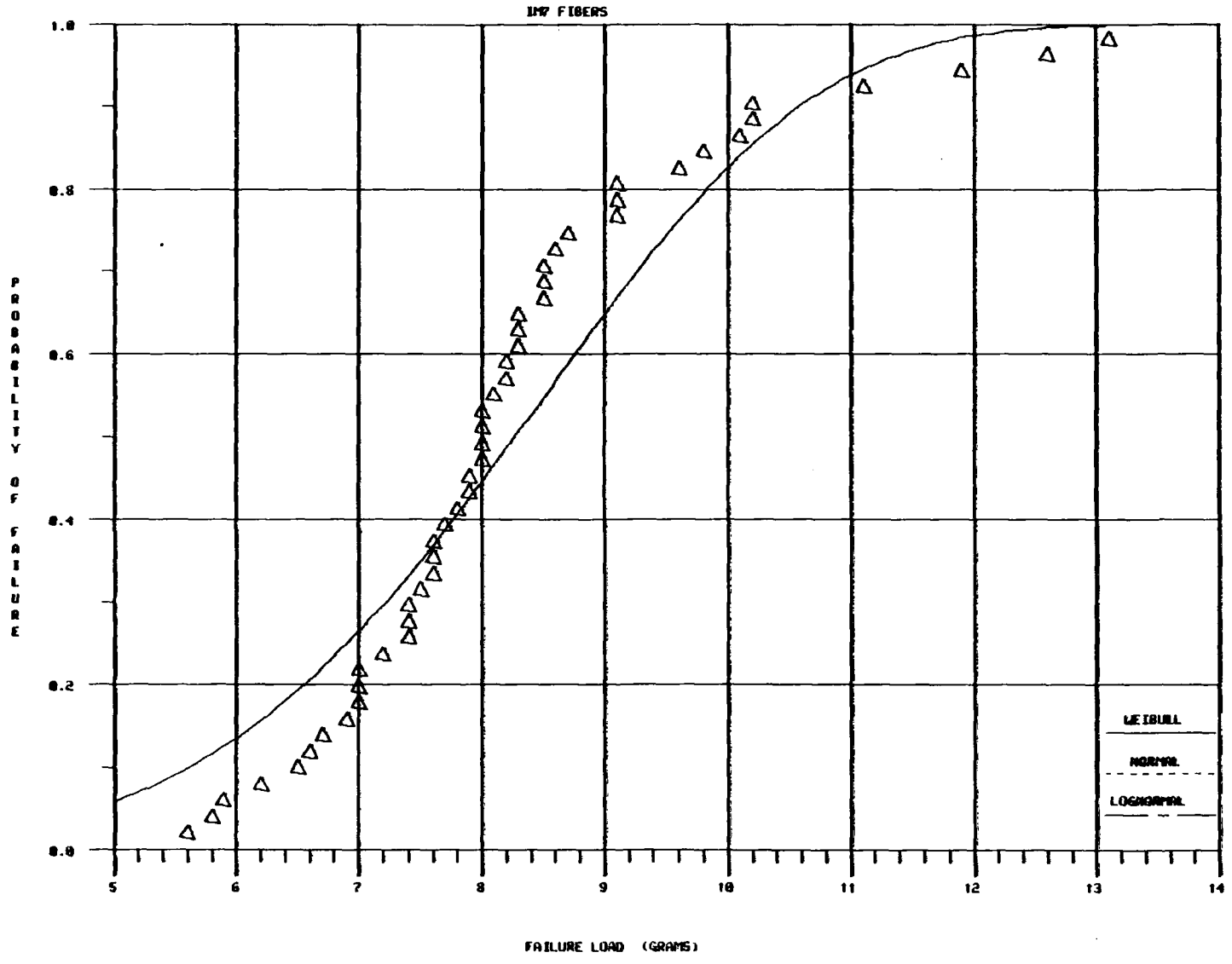

IM7 FIBERS
1.0
0.8
0.6
0.4
0.2
0.0
PROBABILITY OF FAILURE
5
6
7
8
9
10
11
12
13
14
FAILURE LOAD (GRAMS)
WEIBULL
NORMAL
LOGNORMAL

Figure 19b.

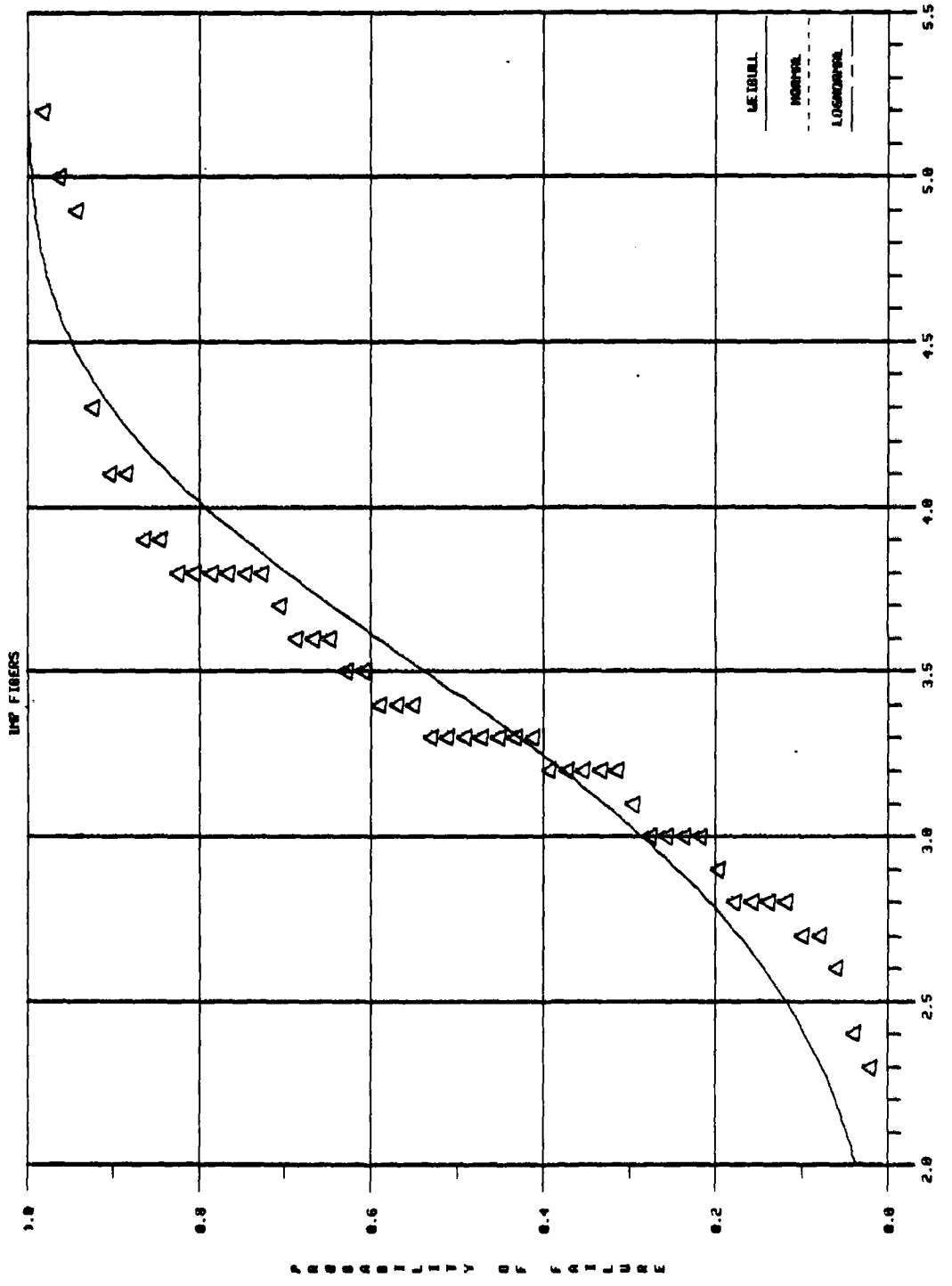
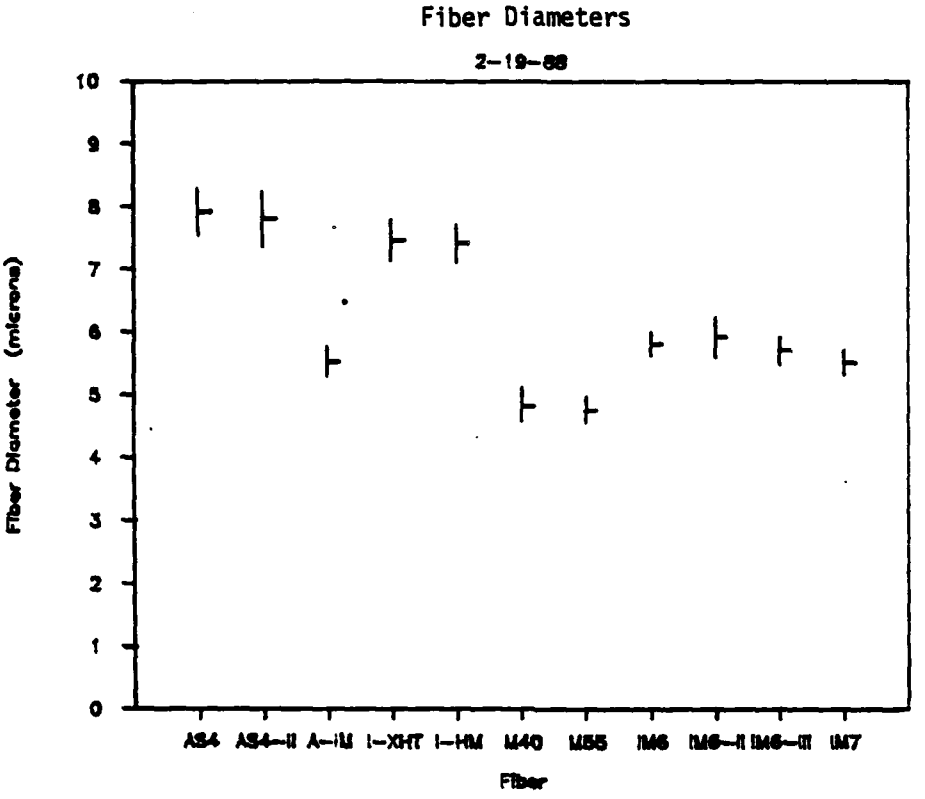

UNF FIBERS
PROBABILITY OF FAILURE
FAILURE STRESS (GPA)
WEIBULL
NORMAL
LOGNORMAL
0.0
0.2
0.4
0.6
0.8
1.0
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5

Figure 19c.


Fiber Diameters
2-19-88
Fiber Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10
AS4
AS4-II
A-IM
I-XHT
I-HM
M40
M55
IM6
IM6-II
IM6-III
IM7
Fiber

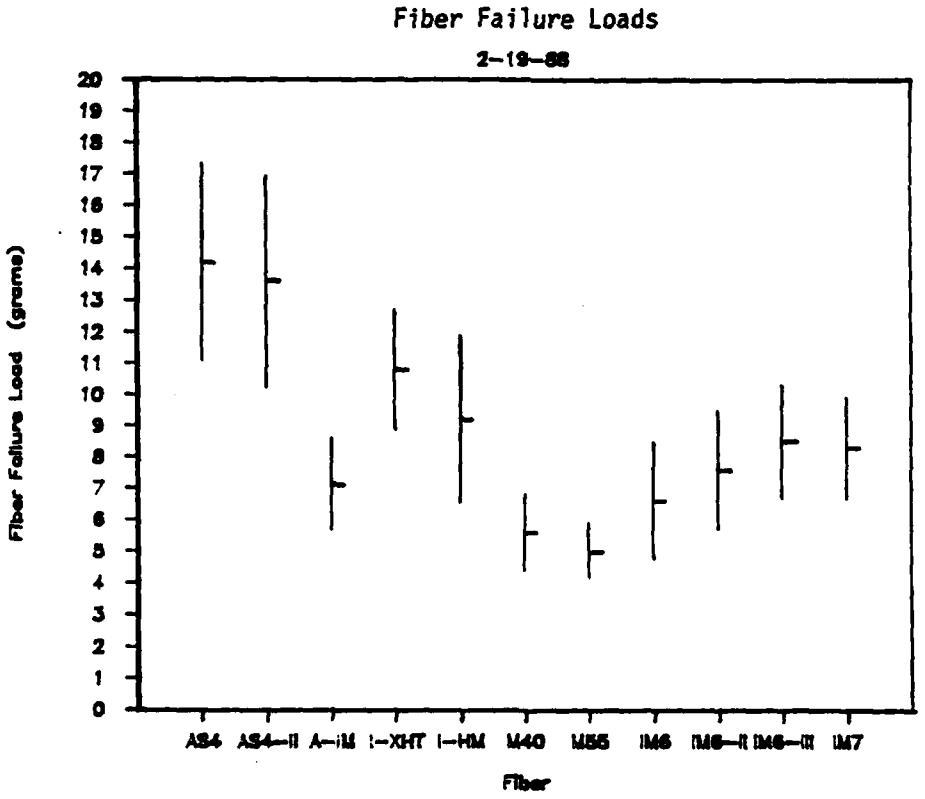

Fiber Failure Loads
2-19-88
Fiber Failure Load (grams)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
AS4
AS4-II
A-IM
I-XHT
I-HM
M40
M55
IM6
IM6-II
IM6-III
IM7
Fiber

Figure 20.

## APPENDIX A. NOTES ON CALCULATING THE FIBER DIAMETER

The fiber acts as a slit in the laser beam creating a diffraction pattern whose dimensions vary with the fiber diameter. Jenkins and White give the separation between successive minima of the diffraction patterns as:

$$d = f \lambda/b$$

where f is the focal length of a lens placed close to the slit, $\lambda$ is the wavelength of the light, and b is the width of the slit.

For the fiber tester, this means that the detector separation is related to the fiber diameter by:

$$D/2 = f \lambda/b$$

where f is the distance from the fiber to the detector, $\lambda$ is 0.6328 microns, and b is the fiber diameter.

For convenience, this has been converted to have D in mm, f in inches and b in microns. The relationship then becomes:

$$b = 50.8 \times 0.6328 \, f/D$$

A program to make the calculation has been written in True Basic for the Lisa. It is called FIBEREDUCE.

D is found by adding the R value to R1 and R2. R is the zero distance for the digital caliper and should be recorded at the beginning of each test. R1 and R2 are read from the plots of resistance versus distance for the left hand and right hand detectors:

$$D = R + R1 + R2$$

The official laboratory record of each data set should include:

a. The complete identification of the spool from which the fibers were taken.

b. A description of the f-d distance, pinhole position, detectors used, and load cell calibration.

c. A description of the fiber mounting details.

d. The data on each fiber:
   - test number
   - fiber number
   - R value
   - R1 value measured on a detector plot
   - R2 value measured on the other detector plot
   - D value
   - b value
   - failure load in grams
   - S - failure stress in grams

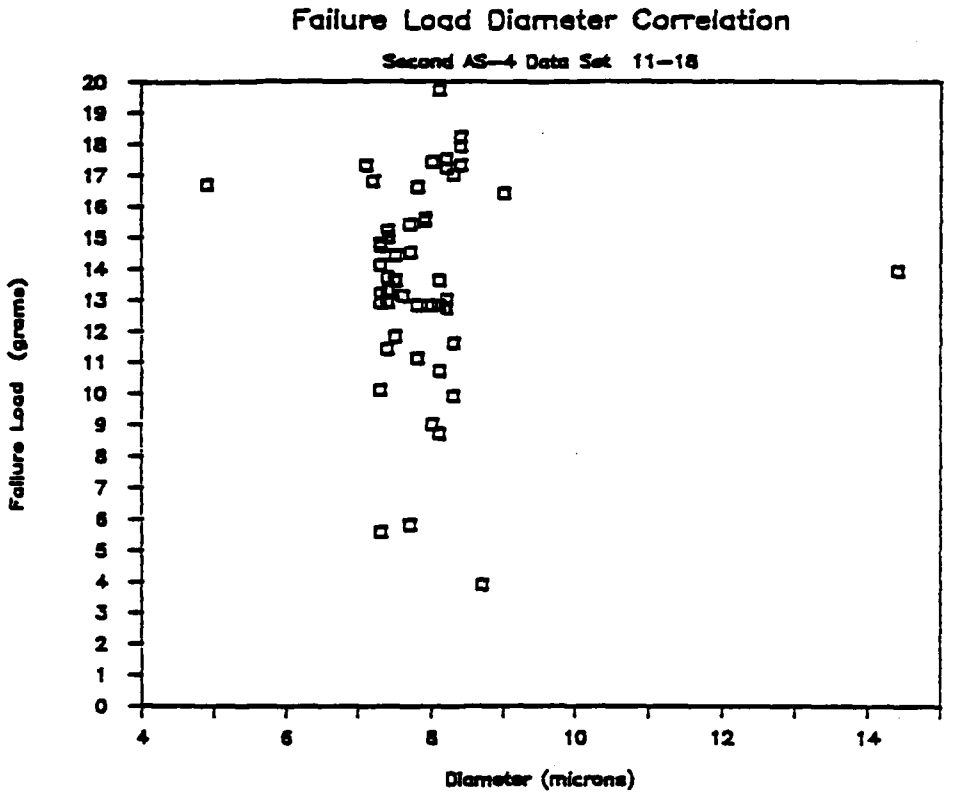
e. Values of mean and standard deviation calculated with the Symphony and/or the MARS code.

f. Value of shape parameter for the Weibull distribution from the MARS code plot.

## APPENDIX B. EXAMINATION OF THE DATA FOR THE SECOND AS-4 FIBER SET

The fibers for the second AS-4 data set were taken from the same tow segment as those for the first AS-4 data set. One of the objectives of the study was the demonstration that a data set consisting of 50 fibers is large enough to characterize a given fiber type. This would be true if the statistics from both data sets agreed. After 50 fibers had been measured, the diameter correlation plots shown in Figure B-1 were made. It was obvious from these plots that two fibers had diameters differing greatly from the remainder of the sample. It was concluded that these fibers were outlying values and as such not representative of the population. They were removed from the sample and the statistics for the sample recalculated. The new correlation plots appear in Figures 4a and 4b. The agreement between the first and second data sets now is within the bounds for accepting them as identical (see Table 2).

The sample was processed with the MARS code in both the original and revised form. The revised MARS plots are Figures 5d, 5e, and 5f. The Weibull parameters from these fit the pattern shown by the other data sets measured.


Failure Load Diameter Correlation
Second AS-4 Data Set 11-16
Failure Load (grams)
Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
4
6
8
10
12
14

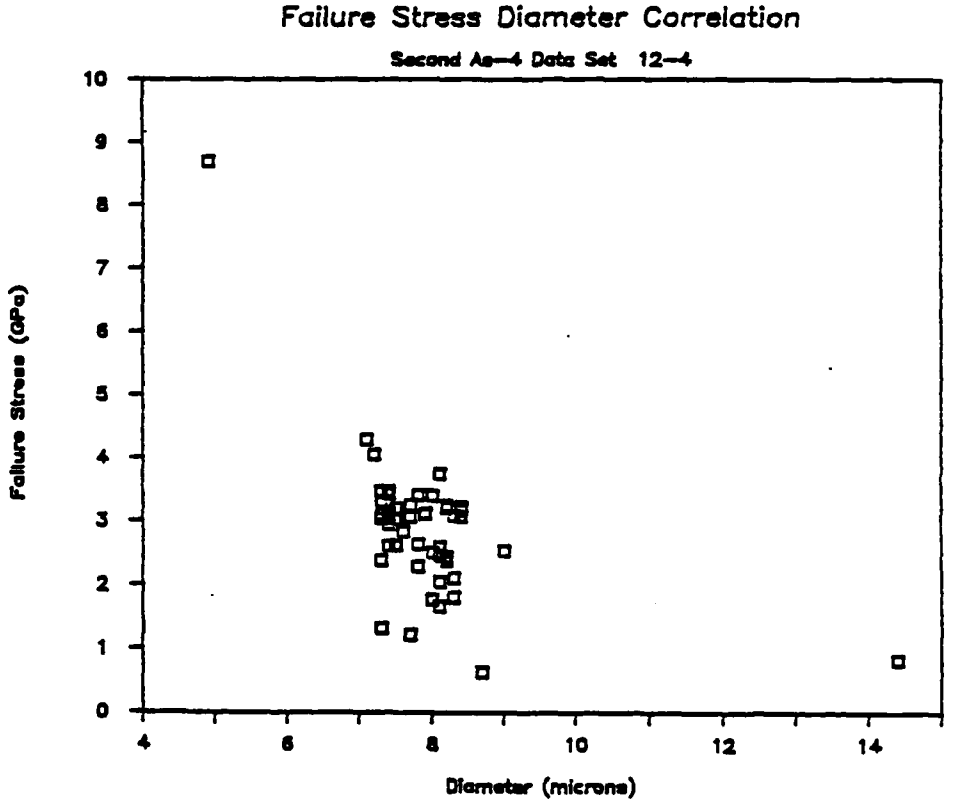

Failure Stress Diameter Correlation
Second As-4 Data Set 12-4
Failure Stress (GPa)
Diameter (microns)
0
1
2
3
4
5
6
7
8
9
10
4
6
8
10
12
14

Figure B-1.

# APPENDIX C. FIBER DATA

AS-4 Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 8 | 11.7 | 2.28 |
| 8.4 | 12 | 2.13 |
| 8.2 | 19.2 | 3.57 |
| 7.7 | 12.1 | 2.55 |
| 8.1 | 21.3 | 4.06 |
| 8.3 | 10.1 | 1.83 |
| 8 | 14.4 | 2.81 |
| 8 | 7.5 | 1.46 |
| 8 | 17.4 | 3.4 |
| 7.4 | 12 | 2.74 |
| 8.1 | 12.1 | 2.3 |
| 8.4 | 18.7 | 3.31 |
| 8.3 | 15 | 2.72 |
| 8.3 | 14.7 | 2.67 |
| 8.1 | 17.3 | 3.3 |
| 8.3 | 13.3 | 2.41 |
| 7.8 | 6.5 | 1.34 |
| 8.1 | 16.2 | 3.09 |
| 8.1 | 18.5 | 3.52 |
| 7.7 | 13.4 | 2.82 |
| 7.7 | 13.6 | 2.87 |
| 8.3 | 17.2 | 3.12 |
| 7.8 | 11.2 | 2.3 |
| 7.8 | 18.3 | 3.76 |
| 7.9 | 12.1 | 2.42 |
| 7.6 | 13.8 | 2.99 |
| 8 | 16 | 3.12 |
| 8.4 | 19.7 | 3.49 |
| 8 | 20 | 3.91 |
| 8 | 11.6 | 2.27 |
| 7.8 | 18.8 | 3.86 |
| 7.1 | 12.1 | 3 |
| 8 | 14 | 2.73 |
| 7.6 | 12.7 | 2.75 |
| 8.7 | 15.7 | 2.59 |
| 7.9 | 14.1 | 2.82 |
| 7.8 | 10.8 | 2.22 |
| 7.2 | 14.1 | 3.4 |
| 7.4 | 14.4 | 3.29 |
| 8.5 | 14.8 | 2.56 |
| 8.2 | 13.6 | 2.53 |
| 7.6 | 13.6 | 2.94 |
| 8 | 12.6 | 2.46 |
| 7.4 | 12 | 2.74 |
| 8.1 | 15.2 | 2.9 |
| 7.3 | 15.3 | 3.59 |
| 8 | 10.8 | 2.11 |
| 8 | 14.7 | 2.87 |
| 7.4 | 10.9 | 2.49 |
| 7.3 | 13.4 | 3.14 |
| Average | | |
| 7.922 | 14.21 | 2.831 |
| Standard Deviation | | |
| 0.356 | 3.084 | 0.583 |

Second AS-4 Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 7.7 | 15.4 | 3.25 |
| 7.8 | 11.1 | 2.28 |
| 8.1 | 10.7 | 2.04 |
| 7.7 | 14.5 | 3.06 |
| 7.4 | 15.2 | 3.47 |
| 8.1 | 19.7 | 3.75 |
| 7.9 | 15.5 | 3.1 |
| 8.2 | 17.5 | 3.25 |
| 8.2 | 13 | 2.42 |
| 7.3 | 5.6 | 1.31 |
| 7.4 | 13.7 | 3.13 |
| 8 | 17.4 | 3.4 |
| 7.3 | 12.9 | 3.03 |
| 7.7 | 5.8 | 1.22 |
| 7.4 | 13.3 | 3.04 |
| 7.3 | 10.1 | 2.37 |
| 8.3 | 17 | 3.08 |
| 7.3 | 14.7 | 3.45 |
| 8.3 | 9.9 | 1.8 |
| 7.6 | 13.1 | 2.83 |
| 8.3 | 11.6 | 2.1 |
| 8.2 | 12.7 | 2.36 |
| 7.8 | 16.6 | 3.41 |
| 7.8 | 12.8 | 2.63 |
| 7.3 | 13.2 | 3.1 |
| 4.9 | 16.7 | 8.69 |
| 8.7 | 3.9 | 0.64 |
| 8.4 | 18.2 | 3.22 |
| 9 | 16.4 | 2.53 |
| 7.4 | 15 | 3.42 |
| 7.9 | 15.6 | 3.12 |
| 8.4 | 17.3 | 3.06 |
| 7.5 | 14.4 | 3.2 |
| 7.4 | 12.9 | 2.94 |
| 8.1 | 12.8 | 2.44 |
| 7.1 | 17.3 | 4.29 |
| 7.3 | 14.8 | 3.47 |
| 7.5 | 13.6 | 3.02 |
| 7.5 | 11.8 | 2.62 |
| 7.2 | 16.8 | 4.05 |
| 7.4 | 11.4 | 2.6 |
| 8.4 | 17.9 | 3.17 |
| 7.8 | 11.1 | 2.28 |
| 8 | 9 | 1.76 |
| 8.2 | 17.2 | 3.2 |
| 7.3 | 14.1 | 3.31 |
| 8.1 | 13.6 | 2.59 |
| 14.4 | 13.9 | 0.84 |
| 8.1 | 8.7 | 1.66 |
| 8 | 12.8 | 2.5 |
| Average | | |
| 7.888 | 13.604 | 2.87 |
| Standard Deviation | | |
| 1.103 | 3.294 | 1.121 |

Revised AS-4 II Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 7.7 | 15.4 | 3.25 |
| 7.8 | 11.1 | 2.28 |
| 8.1 | 10.7 | 2.04 |
| 7.7 | 14.5 | 3.06 |
| 7.4 | 15.2 | 3.47 |
| 8.1 | 19.7 | 3.75 |
| 7.9 | 15.5 | 3.1 |
| 8.2 | 17.5 | 3.25 |
| 8.2 | 13 | 2.42 |
| 7.3 | 5.6 | 1.31 |
| 7.4 | 13.7 | 3.13 |
| 8 | 17.4 | 3.4 |
| 7.3 | 12.9 | 3.03 |
| 7.7 | 5.8 | 1.22 |
| 7.4 | 13.3 | 3.04 |
| 7.3 | 10.1 | 2.37 |
| 8.3 | 17 | 3.08 |
| 7.3 | 14.7 | 3.45 |
| 8.3 | 9.9 | 1.8 |
| 7.6 | 13.1 | 2.83 |
| 8.3 | 11.6 | 2.1 |
| 8.2 | 12.7 | 2.36 |
| 7.8 | 16.6 | 3.41 |
| 7.8 | 12.8 | 2.63 |
| 7.3 | 13.2 | 3.1 |
| 8.7 | 3.9 | 0.64 |
| 8.4 | 18.2 | 3.22 |
| 9 | 16.4 | 2.53 |
| 7.4 | 15 | 3.42 |
| 7.9 | 15.6 | 3.12 |
| 8.4 | 17.3 | 3.06 |
| 7.5 | 14.4 | 3.2 |
| 7.4 | 12.9 | 2.94 |
| 8.1 | 12.8 | 2.44 |
| 7.1 | 17.3 | 4.29 |
| 7.3 | 14.8 | 3.47 |
| 7.5 | 13.6 | 3.02 |
| 7.5 | 11.8 | 2.62 |
| 7.2 | 16.8 | 4.05 |
| 7.4 | 11.4 | 2.6 |
| 8.4 | 17.9 | 3.17 |
| 7.8 | 11.1 | 2.28 |
| 8 | 9 | 1.76 |
| 8.2 | 17.2 | 3.2 |
| 7.3 | 14.1 | 3.31 |
| 8.1 | 13.6 | 2.59 |
| 8.1 | 8.7 | 1.66 |
| 8 | 12.8 | 2.5 |
| Average | | |
| 7.814583 | 13.53333 | 2.791041 |
| Standard Deviation | | |
| 0.437792 | 3.331061 | 0.714919 |

Apollo IM Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 5 | 7.4 | 3.7 |
| 5.4 | 6.4 | 2.74 |
| 5.7 | 7.1 | 2.73 |
| 5.7 | 6.5 | 2.5 |
| 5 | 7.2 | 3.6 |
| 5.3 | 7 | 3.11 |
| 5.6 | 8.2 | 3.27 |
| 5.6 | 7.2 | 2.87 |
| 5.6 | 3.7 | 1.47 |
| 5.6 | 7.8 | 3.11 |
| 5.1 | 9.2 | 4.42 |
| 5.9 | 6.7 | 2.41 |
| 5.6 | 8 | 3.19 |
| 5.5 | 7.8 | 3.22 |
| 5.2 | 4.1 | 1.69 |
| 5.9 | 7.1 | 3.28 |
| 5.6 | 8.6 | 3.09 |
| 5.6 | 4.7 | 1.87 |
| 5.2 | 7.9 | 3.15 |
| 5.6 | 10.6 | 4.9 |
| 5.6 | 9.4 | 3.75 |
| 5.6 | 6.1 | 2.43 |
| 5.6 | 7.4 | 2.95 |
| 5.5 | 7.2 | 2.97 |
| 5.6 | 8.5 | 3.39 |
| 5.4 | 6.9 | 2.96 |
| 5.4 | 5.9 | 2.53 |
| 5.8 | 7.2 | 2.67 |
| 5.5 | 7.1 | 2.93 |
| 5.5 | 7.8 | 3.22 |
| 5.5 | 8.2 | 3.39 |
| 5.7 | 7.3 | 2.81 |
| 5.8 | 11.3 | 4.2 |
| 5.2 | 7.2 | 3.33 |
| 5.6 | 6.4 | 2.55 |
| 5.8 | 8.9 | 3.31 |
| 5.6 | 8.3 | 3.31 |
| 5.7 | 7.4 | 2.85 |
| 5.8 | 6.9 | 2.56 |
| 5.3 | 8 | 3.56 |
| 5.7 | 8.2 | 3.15 |
| 5.5 | 5.7 | 2.35 |
| 5.1 | 5.3 | 2.55 |
| 5.1 | 5.4 | 2.59 |
| 5.7 | 6.2 | 2.38 |
| 5.7 | 7.3 | 2.81 |
| 5.5 | 6.7 | 2.77 |
| 5.2 | 4.7 | 2.17 |
| 5.1 | 5.9 | 2.83 |
| 5.7 | 5 | 1.92 |
| Average | | |
| 5.51 | 7.14 | 2.9502 |
| Standard Deviation | | |
| 0.234 | 1.464 | 0.632 |

Microfil 40 Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 4.9 | 5.6 | 2.91 |
| 4.8 | 6.5 | 3.53 |
| 4.6 | 4.9 | 2.89 |
| 4.6 | 4.6 | 2.72 |
| 4.6 | 4.5 | 2.66 |
| 4.6 | 6.4 | 3.78 |
| 4.5 | 4.1 | 2.53 |
| 4.9 | 5.7 | 2.97 |
| 4.6 | 8.2 | 4.84 |
| 4.8 | 7 | 3.8 |
| 4.7 | 4 | 2.26 |
| 4.8 | 5.5 | 2.98 |
| 4.6 | 4.7 | 2.78 |
| 4.8 | 4.8 | 2.6 |
| 5 | 6.4 | 3.2 |
| 4.6 | 6.4 | 3.78 |
| 4.8 | 4.7 | 2.55 |
| 5 | 5.7 | 2.85 |
| 5.3 | 5.2 | 2.31 |
| 5.1 | 6.2 | 2.98 |
| 5.2 | 8.5 | 3.93 |
| 5.3 | 6.5 | 2.89 |
| 4.9 | 5.7 | 2.97 |
| 5.1 | 6.6 | 3.17 |
| 5.1 | 5.3 | 2.55 |
| 4.5 | 4.8 | 2.96 |
| 4.7 | 6 | 3.39 |
| 4.7 | 6.5 | 3.68 |
| 5.1 | 7.4 | 3.56 |
| 4.6 | 4.4 | 2.6 |
| 4.9 | 4 | 2.08 |
| 5.2 | 6.5 | 3 |
| 4.2 | 4.2 | 2.98 |
| 4.8 | 6.5 | 3.53 |
| 5.2 | 5.4 | 2.5 |
| 4.6 | 6.6 | 3.9 |
| 4.8 | 4.9 | 2.66 |
| 4.7 | 5.2 | 2.94 |
| 4.9 | 4.4 | 2.29 |
| 4.8 | 3.6 | 1.95 |
| 4.8 | 7 | 3.8 |
| 5.1 | 4.7 | 2.26 |
| 5.3 | 5.5 | 2.45 |
| 4.3 | 4.1 | 2.77 |
| 4.7 | 5.7 | 3.22 |
| 4.6 | 4.9 | 2.89 |
| 4.8 | 7.5 | 4.07 |
| Average | | |
| 4.819148 | 5.606382 | 3.019361 |
| Standard Deviation | | |
| 0.254021 | 1.137261 | 0.588913 |

Microfil 55 Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 5 | 6 | 3 |
| 5 | 4.5 | 2.25 |
| 4.9 | 5.1 | 2.65 |
| 4.6 | 5.1 | 3.01 |
| 4.9 | 5.2 | 2.71 |
| 4.8 | 5.3 | 2.87 |
| 4.7 | 6.5 | 3.68 |
| 4.4 | 4 | 2.58 |
| 4.8 | 5.5 | 2.98 |
| 4.5 | 3.7 | 2.28 |
| 4.3 | 3.2 | 2.16 |
| 4.7 | 4.9 | 2.77 |
| 4.5 | 5.5 | 3.39 |
| 4.7 | 5 | 2.83 |
| 4.8 | 4.7 | 2.55 |
| 4.4 | 3.2 | 2.07 |
| 4.8 | 5.3 | 2.87 |
| 4.6 | 5.6 | 3.31 |
| 4.8 | 4.6 | 2.5 |
| 4.9 | 5.1 | 2.65 |
| 4.8 | 4 | 2.17 |
| 4.6 | 4.7 | 2.78 |
| 4.3 | 4.3 | 2.91 |
| 4.8 | 4.9 | 2.66 |
| 4.4 | 3.8 | 2.45 |
| 4.6 | 5.5 | 3.25 |
| 4.7 | 5.1 | 2.89 |
| 4.7 | 3.3 | 1.87 |
| 4.7 | 5.3 | 3 |
| 4.7 | 5.3 | 3 |
| 4.6 | 4.2 | 2.48 |
| 4.9 | 6.1 | 3.17 |
| 4.6 | 5.9 | 3.48 |
| 4.7 | 4.9 | 2.77 |
| 4.8 | 6 | 3.25 |
| 4.8 | 5 | 2.71 |
| 4.6 | 3.6 | 2.13 |
| 4.6 | 5.1 | 3.01 |
| 4.5 | 4.3 | 2.65 |
| 4.6 | 4.4 | 2.6 |
| 5.1 | 4.9 | 2.35 |
| 5 | 6.5 | 3.25 |
| 4.9 | 5.4 | 2.81 |
| 5 | 4.5 | 2.25 |
| 4.8 | 5.8 | 3.15 |
| 5.1 | 5.2 | 2.5 |
| 4.8 | 5.4 | 2.93 |
| 5 | 5.8 | 2.9 |
| 4.9 | 6.3 | 3.28 |
| 5.1 | 4.9 | 2.35 |
| Average | | |
| 4.736 | 4.968 | 2.7622 |
| Standard Deviation | | |
| 0.201 | 0.809 | 0.394 |

ACIFHM Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 7.7 | 7 | 1.48 |
| 7.1 | 5.3 | 1.31 |
| 7.5 | 4.6 | 1.02 |
| 7.4 | 7.7 | 1.76 |
| 7.2 | 8.8 | 2.12 |
| 7.5 | 5.7 | 1.27 |
| 7.1 | 9.1 | 2.26 |
| 7.5 | 8.7 | 1.93 |
| 6.8 | 11.2 | 3.03 |
| 6.7 | 6.6 | 1.84 |
| 6.6 | 4 | 1.15 |
| 6.8 | 9.4 | 2.54 |
| 7.5 | 13 | 2.89 |
| 7.4 | 7.1 | 1.62 |
| 7.4 | 9.4 | 2.15 |
| 7.4 | 9 | 2.05 |
| 7.7 | 9.6 | 2.02 |
| 7.4 | 11.3 | 2.58 |
| 6.6 | 5.2 | 1.49 |
| 7.6 | 5.5 | 1.19 |
| 7.7 | 9.3 | 1.96 |
| 7.6 | 12.2 | 2.64 |
| 7.6 | 9.2 | 1.99 |
| 7.2 | 10.9 | 2.63 |
| 7.4 | 10.7 | 2.44 |
| 7.6 | 7.3 | 1.58 |
| 7.4 | 8.8 | 2.01 |
| 7.4 | 12 | 2.74 |
| 7.4 | 10.5 | 2.4 |
| 7.5 | 3.2 | 0.71 |
| 7.6 | 6.7 | 1.45 |
| 7.4 | 11.6 | 2.65 |
| 7.9 | 7.9 | 1.58 |
| 7.4 | 10.6 | 2.42 |
| 7.7 | 13 | 2.74 |
| 7.7 | 12.1 | 2.55 |
| 7.4 | 6.4 | 1.46 |
| 7.7 | 12.3 | 2.59 |
| 7.8 | 14.1 | 2.9 |
| 7.8 | 10.3 | 2.12 |
| 7.3 | 10.4 | 2.44 |
| 7.6 | 8.1 | 1.75 |
| 7.6 | 9.8 | 2.12 |
| 7.3 | 9.9 | 2.32 |
| 7.4 | 8.7 | 1.99 |
| 7.5 | 11.1 | 2.47 |
| 7.5 | 13.2 | 2.93 |
| 7.2 | 9.5 | 2.29 |
| 7.5 | 14.5 | 3.22 |
| 6.7 | 8.5 | 2.37 |
| Average | | |
| 7.394 | 9.22 | 2.1032 |
| Standard Deviation | | |
| 0.309 | 2.622 | 0.571 |

ACIF-XHT Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 7.7 | 10 | 2.11 |
| 6.9 | 11.3 | 2.97 |
| 6.6 | 9.6 | 2.75 |
| 7.4 | 9.1 | 2.08 |
| 7.8 | 9 | 1.85 |
| 7 | 10.5 | 2.68 |
| 7.4 | 14.4 | 3.29 |
| 7.1 | 12 | 2.97 |
| 7.9 | 11.6 | 2.32 |
| 7.5 | 9.9 | 2.2 |
| 7.5 | 12.7 | 2.82 |
| 7.2 | 9.1 | 2.19 |
| 7.5 | 7.8 | 1.73 |
| 7.5 | 15.5 | 3.44 |
| 7.5 | 10.2 | 2.27 |
| 7.5 | 9.9 | 2.2 |
| 7.3 | 10.2 | 2.39 |
| 7.5 | 9 | 2 |
| 7.4 | 8.5 | 1.94 |
| 7.4 | 9.9 | 2.26 |
| 7.4 | 10.8 | 2.46 |
| 7.6 | 9.1 | 1.97 |
| 7.3 | 14.2 | 3.33 |
| 7.2 | 10.7 | 2.58 |
| 7.7 | 9.4 | 1.98 |
| 6.8 | 10.8 | 2.92 |
| 7.2 | 10.2 | 2.46 |
| 7.6 | 10.4 | 2.25 |
| 7.5 | 9.1 | 2.02 |
| 7.2 | 13.1 | 3.16 |
| 7.6 | 10.7 | 2.32 |
| 7.7 | 6.3 | 1.33 |
| 7.1 | 12 | 2.97 |
| 7.1 | 10.4 | 2.58 |
| 7.4 | 7.7 | 1.76 |
| 7.1 | 8.9 | 2.21 |
| 7.5 | 12.1 | 2.69 |
| 8 | 16.6 | 3.24 |
| 7.7 | 11.4 | 2.4 |
| 7.7 | 10.9 | 2.3 |
| 7.7 | 10.4 | 2.19 |
| 8.1 | 10.1 | 1.92 |
| 7.9 | 12 | 2.4 |
| 8 | 11.3 | 2.21 |
| 7.4 | 10.7 | 2.44 |
| 8.1 | 12.3 | 2.34 |
| 7.4 | 11.9 | 2.72 |
| 7.2 | 11.2 | 2.7 |
| 7.2 | 10 | 2.41 |
| 7.6 | 13.7 | 2.96 |
| Average | | |
| 7.452 | 10.772 | 2.4336 |
| Standard Deviation | | |
| 0.318 | 1.917 | 0.451 |

IM-6 Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 5.9 | 6.3 | 2.26 |
| 6.2 | 8.3 | 2.7 |
| 6 | 9 | 3.12 |
| 5.8 | 8 | 2.97 |
| 5.9 | 4.7 | 1.69 |
| 5.7 | 5.9 | 2.27 |
| 5.9 | 9.3 | 3.34 |
| 6.1 | 6.8 | 2.28 |
| 5.7 | 7.1 | 2.73 |
| 5.8 | 10.8 | 4.01 |
| 5.9 | 7.4 | 2.66 |
| 6 | 1.7 | 0.59 |
| 5.6 | 7.9 | 3.15 |
| 5.7 | 4.9 | 1.88 |
| 5.7 | 6.4 | 2.46 |
| 6.1 | 8.8 | 2.96 |
| 5.7 | 10.2 | 3.92 |
| 5.8 | 6.2 | 2.3 |
| 5.8 | 6.3 | 2.34 |
| 5.9 | 6 | 2.15 |
| 5.9 | 6.1 | 2.19 |
| 5.9 | 6.6 | 2.37 |
| 5.2 | 6.8 | 3.14 |
| 5.7 | 9.2 | 3.54 |
| 6 | 6.1 | 2.12 |
| 5.8 | 6.4 | 2.38 |
| 6 | 7.2 | 2.5 |
| 5.9 | 5.4 | 1.94 |
| 5.7 | 2.1 | 0.81 |
| 5.9 | 6.9 | 2.48 |
| 6.1 | 7.7 | 2.59 |
| 5.8 | 6.4 | 2.38 |
| 5.8 | 7.3 | 2.71 |
| 5.9 | 6.9 | 2.48 |
| 5.8 | 5.6 | 2.08 |
| 5.9 | 3.4 | 1.22 |
| 5.8 | 7.7 | 2.86 |
| 5.6 | 6.9 | 2.75 |
| 5.7 | 8.2 | 3.15 |
| 5.3 | 3.4 | 1.51 |
| 6 | 5.5 | 1.91 |
| 5.7 | 7.3 | 2.81 |
| 5.7 | 7.8 | 3 |
| 6 | 5.4 | 1.87 |
| 5.5 | 6 | 2.48 |
| 5.7 | 3.3 | 1.27 |
| 6 | 7.1 | 2.46 |
| 5.5 | 6.5 | 2.69 |
| 5.6 | 8.2 | 3.27 |
| Average | | |
| 5.808163 | 6.640816 | 2.464081 |
| Standard Deviation | | |
| 0.193608 | 1.823421 | 0.684799 |

Second IM6 Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 5.9 | 8.7 | 3.1 |
| 5.5 | 7.8 | 3.2 |
| 5.9 | 7.4 | 2.7 |
| 6 | 9.8 | 3.4 |
| 6.1 | 7.2 | 2.4 |
| 6 | 8.3 | 2.9 |
| 5.9 | 4.9 | 1.8 |
| 5.6 | 10 | 4 |
| 5.6 | 7.3 | 2.9 |
| 5.6 | 7.1 | 2.8 |
| 5.8 | 6.5 | 2.4 |
| 6.3 | 8.3 | 2.6 |
| 5.8 | 5.6 | 2.1 |
| 6.2 | 8 | 2.6 |
| 6.2 | 7.5 | 2.4 |
| 6 | 5.4 | 1.9 |
| 5.7 | 8.4 | 3.2 |
| 6.2 | 8 | 2.6 |
| 5.7 | 11.3 | 4.4 |
| 5.8 | 7.8 | 2.9 |
| 5.7 | 7.8 | 3 |
| 5.7 | 9.9 | 3.8 |
| 5.7 | 9.2 | 3.5 |
| 5.4 | 6.1 | 2.6 |
| 6 | 7.7 | 2.7 |
| 6.2 | 5.7 | 1.8 |
| 5.6 | 7.5 | 3 |
| 6.1 | 6.7 | 2.2 |
| 5.4 | 8.6 | 3.7 |
| 6.1 | 8.3 | 2.8 |
| 5.2 | 5.9 | 2.7 |
| 6.1 | 6.6 | 2.2 |
| 5.9 | 6.5 | 2.3 |
| 6 | 10.8 | 3.8 |
| 6 | 10.1 | 3.5 |
| 6.2 | 1.9 | 0.6 |
| 5.6 | 6.5 | 2.6 |
| 5.5 | 6.9 | 2.8 |
| 6.1 | 9.8 | 3.3 |
| 6.3 | 6.8 | 2.1 |
| 6.2 | 5.4 | 1.8 |
| 6.1 | 13.6 | 4.6 |
| 5.1 | 7.4 | 3.6 |
| 5.8 | 7.1 | 2.6 |
| 6.2 | 8.5 | 2.8 |
| 6.2 | 9 | 2.9 |
| 5.8 | 5.2 | 1.9 |
| 5.5 | 5.5 | 2.3 |
| 5.4 | 6.8 | 2.9 |
| Average | | |
| 5.855102 | 7.614285 | 2.789795 |
| Standard Deviation | | |
| 0.296277 | 1.902951 | 0.717491 |

Third IM-6 Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 5.9 | 9 | 3.2 |
| 5.8 | 9.8 | 3.6 |
| 5.8 | 7.9 | 2.9 |
| 5.7 | 7.5 | 2.9 |
| 5.7 | 5.5 | 2.1 |
| 5.5 | 9.7 | 4 |
| 5.5 | 8.8 | 3.6 |
| 5.5 | 6.2 | 2.6 |
| 5.3 | 4.7 | 2.1 |
| 5.9 | 9 | 3.2 |
| 6 | 9.8 | 3.4 |
| 5.4 | 7.7 | 3.3 |
| 5.7 | 6.3 | 2.4 |
| 5.9 | 11.5 | 4.1 |
| 6 | 13 | 4.5 |
| 6 | 8.2 | 2.8 |
| 5.7 | 6.4 | 2.5 |
| 5.7 | 9.8 | 3.8 |
| 5.9 | 10.8 | 3.9 |
| 6.2 | 8.7 | 2.8 |
| 5.4 | 8.3 | 3.6 |
| 5.6 | 6 | 2.4 |
| 6.1 | 6.6 | 2.2 |
| 5.7 | 6.2 | 2.4 |
| 5.8 | 9.9 | 3.7 |
| 5.7 | 8.7 | 3.4 |
| 5.7 | 12.2 | 4.7 |
| 5.7 | 6.8 | 2.6 |
| 5.6 | 7.6 | 3 |
| 6.1 | 9.1 | 3.1 |
| 5.8 | 8.5 | 3.2 |
| 5.4 | 7.5 | 3.2 |
| 6.1 | 8.9 | 3 |
| 5.6 | 8.9 | 3.6 |
| 5.6 | 7.5 | 3 |
| 5.6 | 7.9 | 3.2 |
| 5.8 | 9.2 | 3.4 |
| 5.8 | 5.3 | 2 |
| 5.2 | 6.8 | 3.1 |
| 5.7 | 8.6 | 3.3 |
| 5.5 | 10.1 | 4.2 |
| 5.6 | 10.4 | 4.1 |
| 5.7 | 8.8 | 3.4 |
| 5.7 | 10.3 | 4 |
| 5.8 | 8.3 | 3.1 |
| 5.7 | 12.7 | 4.9 |
| 5.7 | 9.5 | 3.6 |
| 5.5 | 6.9 | 2.8 |
| 5.5 | 7.6 | 3.1 |
| 5.8 | 8.3 | 3.1 |
| Average | | |
| 5.712 | 8.474 | 3.242 |
| Standard Deviation | | |
| 0.210 | 1.814 | 0.656 |

IM-7 Fiber Data Set

| Diameter (microns) | Load (grams) | Stress (GPa) |
|---|---|---|
| 5.6 | 9.6 | 3.8 |
| 5.5 | 7 | 2.9 |
| 5.7 | 9.1 | 3.5 |
| 5.5 | 8.3 | 3.4 |
| 5.6 | 7.4 | 3 |
| 5.5 | 11.9 | 4.9 |
| 5.4 | 7.4 | 3.2 |
| 5.4 | 7.9 | 3.4 |
| 5.1 | 5.6 | 2.7 |
| 5.7 | 8.6 | 3.3 |
| 5.8 | 7.4 | 2.8 |
| 5.5 | 6.2 | 2.6 |
| 5.6 | 5.8 | 2.3 |
| 5.5 | 8 | 3.3 |
| 5.3 | 7.8 | 3.5 |
| 5.7 | 8.3 | 3.2 |
| 5.6 | 13.1 | 5.2 |
| 5.5 | 7.7 | 3.2 |
| 5.8 | 7.6 | 2.8 |
| 5.4 | 7.6 | 3.3 |
| 5.7 | 10.2 | 3.9 |
| 5.5 | 7.2 | 3 |
| 5.4 | 7.6 | 3.3 |
| 5.2 | 8.3 | 3.8 |
| 5.8 | 8.7 | 3.2 |
| 5.2 | 8.1 | 3.7 |
| 5.8 | 10.1 | 3.8 |
| 5.2 | 6.7 | 3.1 |
| 5.4 | 7 | 3 |
| 5.4 | 8.5 | 3.6 |
| 5.5 | 6.9 | 2.8 |
| 5.5 | 8.5 | 3.6 |
| 5.5 | 9.1 | 3.8 |
| 5.7 | 9.8 | 3.8 |
| 5.2 | 6.5 | 3 |
| 5.2 | 8.2 | 3.8 |
| 5.4 | 9.1 | 3.9 |
| 5.8 | 11.1 | 4.1 |
| 5.6 | 7 | 2.8 |
| 5.5 | 8 | 3.3 |
| 5.3 | 7.5 | 3.3 |
| 5.6 | 12.6 | 5 |
| 5.5 | 8 | 3.3 |
| 5.5 | 6.6 | 2.7 |
| 4.8 | 8 | 4.3 |
| 5.6 | 10.2 | 4.1 |
| 5.4 | 8.5 | 3.6 |
| 5.5 | 5.9 | 2.4 |
| 5.5 | 8.2 | 3.4 |
| 5.6 | 7.9 | 3.2 |
| 5.7 | 11.3 | 4.4 |
| **Average** | | |
| 5.494117 | 8.305882 | 3.437254 |
| **Standard Deviation** | | |
| 0.199 | 1.624 | 0.610 |

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| | SPARTA, Inc., 1055 Wall Street, Suite 200, P.O. Box 1354, La Jolla, CA 92038 |
| 1 | ATTN: J. Glatz |
| 1 | G. Wonacott |
| | SPARTA, Inc., 3440 Carson Street, Suite 300, Torrance, CA 90503 |
| 1 | ATTN: I. Osofsky |
| | SPARTA, Inc., 1104B Camino Del Mar, Del Mar, CA 92014 |
| 1 | ATTN: D. Weisinger |
| | Southwest Research Institute, 8500 Culebra Road, San Antonio, TX 78206 |
| 1 | ATTN: A. Wenzel |
| | Stone Engineering Company, 805 Madison Street, Suite 2C, Huntsville, AL 35801 |
| 1 | ATTN: W. Stone |
| | Teledyne Brown Engineering, Research Park, 300 Sparkman Drive, Huntsville, AL 35807 |
| 1 | ATTN: C. Patty |
| | Director, U.S. Army Materials Technology Laboratory, Watertown, MA 02172-0001 |
| 1 | ATTN: SLCMT-TML |
| 2 | Authors |

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
EXAMINATION OF THE TENSILE STRENGTH OF GRAPHITE FIBERS - Elizabeth C. Goeke and Shun-Chin Chou

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Key Words

Tensile strength
Composite materials
Carbon fibers

The Single Fiber Graphite Tester was developed to measure the failure load and fiber diameter of graphite fibers. Data have been taken on a number of commercially available fibers with the tester. These data have been examined in order to understand the dispersion in these properties and the correlation between them.

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