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Stress-Rupture Life of Kevlar/Epoxy Spherical Pressure Vessels

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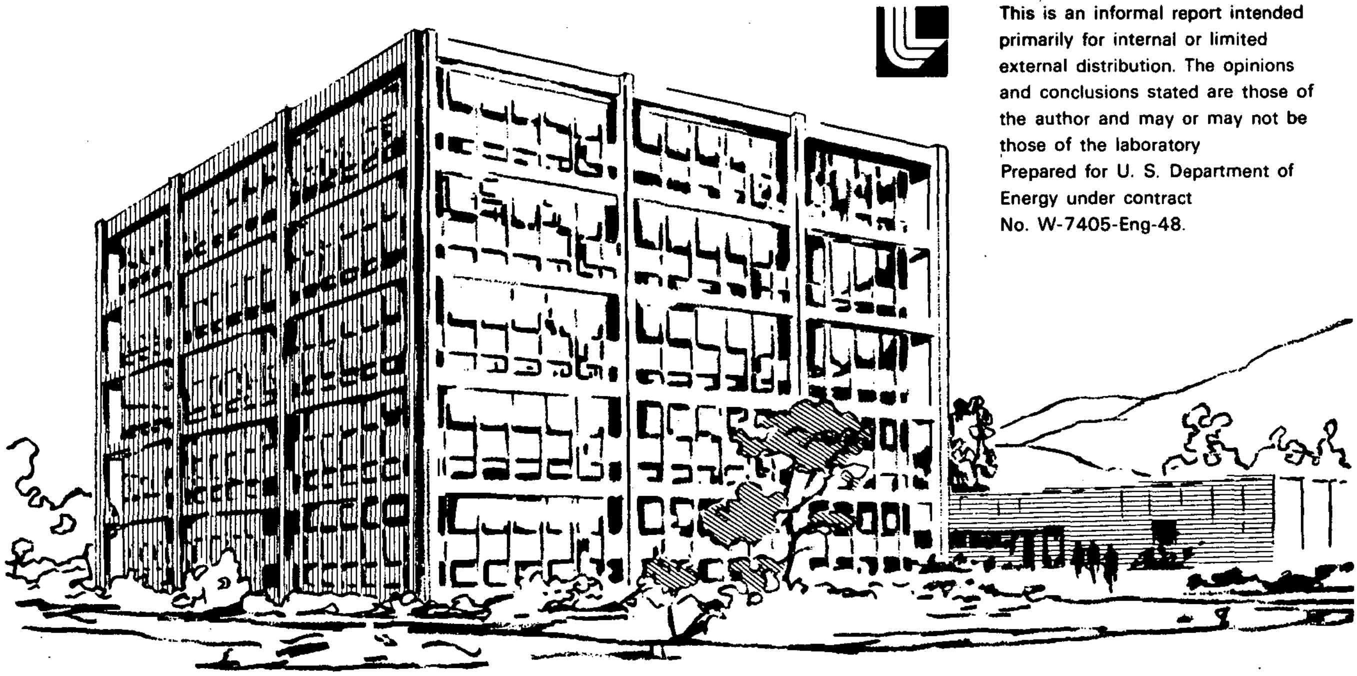

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SPHERICAL PRESSURE VESSELS

ABSTRACT

We are conducting a study to determine the life of Kevlar/epoxy spherical pressure vessels subjected to a constant, sustained pressure until vessel failure, i.e., stress-rupture. This study has two objectives: to generate baseline data on the stress-rupture life of Kevlar/epoxy pressure vessel and to apply statistical reliability theory to vessel and strand data to define vessel life statistics and reliability at given pressure (stress) levels. This report, the second of three, is a compilation of the current pressure vessel data to-date and all strand stress-rupture data generated at Lawrence Livermore Laboratory on several composite materials.

INTRODUCTION

Approximately 250 vessels are used in our study of the life of Kevlar/epoxy pressure vessels subjected to a constant, sustained pressure until vessel failure (commonly known as static fatigue or stress-rupture). This investigation, addressing a recognized need to develop statistical methods and baseline data for predicting vessel life and design reliability, has two objectives:

- To generate baseline data on stress-rupture life of Kevlar/epoxy pressure vessels.

- To apply statistical reliability theory to vessel and strand data to define vessel life statistics and relability at given levels of pressure (stress).

The progress and results of this study are being presented in three reports; additional reports will be written presenting the most recent information. In the first report, we described vessel design, fabrication, and static burst performance as well as the stress-rupture test plan and the test facility.

This second report is a compilation of all strand stress-rupture data (time-to-failure) generated at LLL (including Kevlar/epoxy, S-glass/epoxy, and graphite/epoxy) and the current vessel data to date.[1-18] Although strand failure distributions have been published previously, the raw data have not. The data are ranked according to the specimen time to failure, T_f (in hours), and are suitable for statistical treatment by other researchers.

A list of the fiber composite stress-rupture studies conducted at LLL is given in Table 1. In Appendix A, we have reproduced Ref. 9, stress-rupture data for S-glass epoxy strands; the data for this composite also is updated to June 1978. In Appendix B, stress-rupture data on graphite/epoxy strands is tabulated. In Appendix C, we have reproduced Ref. 15, stress-rupture data for Kevlar 49/epoxy strands at elevated temperatures, is reproduced from Ref. 16. Finally, in Appendix E, we present all our available data on the stress-rupture of Kevlar 49/epoxy, spherical pressure vessels.

Table 1. LLL stress-rupture test programs for fiber composites.

Program	Material system	Start date	Stress levels[a]	Temperature °C	Status	References
Past (discontinued)						
Graphite/epoxy strands[b]	Thornel 50-S	1/69 4/70	90,80	21	Discontinued, incomplete data	3,4
Graphite/epoxy strands[b]	Thornel 500	10/73	90	21	Discontinued, incomplete data	5
Beryllium wire/epoxy strands	Beryllium wire	1/69	90.4, 85.1, 80.4, 75.1	21	Completed data set	b
Ongoing						
S-glass/epoxy strands[b]	Single-end Six-end	4/70 10/70	83.5, 81.4, 81.3, 75.6, 74.6, 70.1, 65, 57.9, 50, 40, 33	21	Continuing levels 57.9, 50, 40, 33	7, 8, 9[c]
Kevlar 49/epoxy strands[b]	380 denier	10/71	90, 87, 84, 80, 70, 60, 50	21, 100, 110, 120	Continuing levels 60, 50	10-16[c]
Kevlar 49/epoxy pressure vessels[b]	Spherical with thin aluminum liner	6/77	86, 80, 74, 68,50	28	Continuing levels 74,68,50	This report
New[d] (underway)						
Kevlar 49/epoxy strands	DER 332/T-403 resin	5/78	86, 80, 74, 68, 50, 40	21	Continuing all levels	-

[a]Percent of mean static ultimate strength.
[b]Life data presented in this report.
[c]Reproduced in this report.
[d]New programs planned at LLL but not yet underway include an expanded graphite/epoxy strand study with Thornel 500 fiber and an E-glass/epoxy strand study. Additional studies of Kevlar 49 pressure vessels also are planned.

BRIEF STATISTICAL TREATMENT

The initial goal of our statistical study was to examine the Kevlar 49/epoxy and S-glass/epoxy strand data for the basic information on composite failure rates at each stress level (Refs. 17, 18). For the Kevlar strands, it was demonstrated graphically that the distribution shape (as well as the scale) depends on the accelerated test condition (stress level). At the 90% stress level, the sample data exhibit a very slightly decreasing failure rate (DFR); at 80%, slightly increasing failure rate (IFR). At 70% and 60%, the data becomes successively higher IFR. Highly IFR data indicate a strong wear-out characteristic. The exponential distribution (random failure) is a reasonable fit to the 90% and 80% data sets. The Weibull distribution models the 60% data very well and is acceptable for the 70% data. We have used Bayesian inference theory to estimate the maximum likelihood and confidence contours of the likelihood function of the shape and scale parameters. This will be discussed in detail in Part 3 of this report.

By contrast, the glass/epoxy strand life data exhibit generally either DFR or CFR (constant failure rate) characteristics (i.e., either not representative of a wear-out process or involving specimen or test random influences). The data are not well modeled by the usual parametric models.

ACKNOWLEDGMENTS

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Appendix A.

Stress-Rupture of S-Glass/Epoxy Strands: Time-to-Break Data

The data presented here are reprinted from Ref. 9. Data for the S-glass composite at low stress levels (57.9, 50, 40, and 33%) have been updated to June 1978.

Material System	Stress Levels,[a] %
Single-end S-glass yarn in Dow DER 332/Union Carbide ERL 4206/ Celanese Epi-Cure 855 (70/30/40)	83.5, 75.6, 65, 57.9 50, 40, 33
Single-end S-glass yarn in Dow DER 332/Jefferson Jeffamine T-403 (100/36)	81.3, 74.6 70.1
Six-end S-glass roving in Dow DER 332/Jefferson Jeffamine T-403 (100/36)	81.4

[a]Percent of mean average fiber stress at strand failure in static test.

STRESS RUPTURE OF S-GLASS/EPOXY MULTIFILAMENT STRANDS: TIME-TO-BREAK DATA

Abstract

We present time-to-break data for S-glass/epoxy strands loaded at stresses from 188 to 478 ksi (i.e., from 33 to 83.8 percent of the average short-term breaking strength).

Introduction

The stress-rupture behavior of filamentary composites is of great concern in many long-term applications. In our stress-rupture program, statistically acceptable numbers of simple epoxy-bonded strands are loaded at a specified fraction of their average short-term breaking strength and the time to break is determined. We have reported our methods for specimen preparation[1-3] and testing,[1,2] and have discussed the stress-rupture data for S-glass/epoxy strands loaded at 83.8, 74.5, and 65.2% of the average short-term breaking strength. Additional publications in preparation will discuss the stress-rupture of S-glass/epoxy strands at other load levels. The program continues with additional tests on S-glass and on graphite and organic fibers.

The mathematical treatment of these data has been discussed by Chiao and Moore[2] and by Robinson and Chiao.[4] In order that other interested persons may perform their own analyses of these data, we are publishing the available time-to-break data for S-glass/epoxy strands.

Specimens

The S-glass, epoxy resin, and specimen preparation fall into three categories as follows (note — CV is coefficient of variation, N is number of specimens):

<u>Specimen Type 1</u>

Glass:	Single-end S-glass yarn, SCG-150 1/0 1.0Z-HTS 901, 204 filaments. Spool I. One single-end yarn per specimen.
Resin:	Dow DER 332*/Union Carbide ERL 4206*/Celanese Epi-Cure 855* (70/30/40 parts by weight), 40% in acetone solution.

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

Cure: Evaporate acetone, cure 1 hr at 350°F.

Specimen preparation method: Batch process.[1, 2]

Short-term breaking strength: 572 ksi, CV = 3.6%, N = 57.

Specimen Type 2

Glass: Single-end S-glass yarn, SCG-150 1/0 1.0Z-HTS 901, 204 filaments. Spool II. One single-end yarn per specimen.

Resin: Dow DER 332*/Jefferson Chemical Jeffamine T-403* (100/36 parts by weight).

Cure: Overnight at room temperature plus 24 hr at 170°F.

Specimen preparation method: Resin application at 160°F using simple winding machine.[3]

Short-term breaking strength: 562 ksi, CV = 2.5%, N = 50.

Specimen Type 3

Glass: Six-end S-glass roving, HTS-901 finish.

Resin, cure, and specimen preparation method: Same as Specimen Type 2.

Short-term breaking strength: 544 ksi, CV = 3.2%, N = 50.

Time-to-Break Data

Tables 1 to 11 give the time-to-break data that are currently available, taken at stresses from 478 ksi down to 188 ksi (i.e., from 83.8% down to 33% of the average short-term breaking strength).

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

Table 1. Specimen Type 1 (single-end) loaded at 478 ksi; 201 specimens.

Rank	Time to break (hr)	Rank	Time to break (hr)	Rank	Time to break (hr)	Rank	Time to break (hr)
1	0.01	52	0.13	102	0.28	152	0.65
2	0.01	53	0.13	103	0.29	153	0.66
3	0.01	54	0.13	104	0.30	154	0.69
4	0.01	55	0.13	105	0.30	155	0.69
5	0.02	56	0.13	106	0.30	156	0.70
6	0.02	57	0.13	107	0.32	157	0.71
7	0.02	58	0.14	108	0.32	158	0.73
8	0.02	59	0.14	109	0.32	159	0.74
9	0.02	60	0.14	110	0.32	160	0.74
10	0.03	61	0.14	111	0.33	161	0.75
11	0.03	62	0.14	112	0.33	162	0.77
12	0.03	63	0.14	113	0.34	163	0.79
13	0.03	64	0.15	114	0.35	164	0.83
14	0.03	65	0.15	115	0.35	165	0.85
15	0.04	66	0.15	116	0.35	166	0.85
16	0.04	67	0.15	117	0.37	167	0.87
17	0.04	68	0.15	118	0.38	168	0.87
18	0.05	69	0.16	119	0.38	169	0.89
19	0.05	70	0.16	120	0.38	170	0.90
20	0.05	71	0.16	121	0.40	171	0.91
21	0.05	72	0.17	122	0.40	172	0.92
22	0.05	73	0.17	123	0.40	173	0.92
23	0.05	74	0.17	124	0.40	174	0.96
24	0.05	75	0.17	125	0.43	175	0.96
25	0.06	76	0.18	126	0.44	176	0.97
26	0.06	77	0.18	127	0.44	177	0.97
27	0.06	78	0.19	128	0.45	178	0.97
28	0.06	79	0.19	129	0.45	179	1.03
29	0.07	80	0.19	130	0.46	180	1.04
30	0.07	81	0.19	131	0.47	181	1.04
31	0.07	82	0.20	132	0.47	182	1.07
32	0.07	83	0.20	133	0.48	183	1.15
33	0.08	84	0.21	134	0.49	184	1.16
34	0.08	85	0.22	135	0.49	185	1.20
35	0.08	86	0.22	136	0.50	186	1.25
36	0.08	87	0.22	137	0.51	187	1.32
37	0.08	88	0.22	138	0.52	188	1.42
38	0.08	89	0.22	139	0.53	189	1.46
39	0.08	90	0.22	140	0.53	190	1.56
40	0.08	91	0.23	141	0.53	191	1.61
41	0.09	92	0.23	142	0.54	192	1.63
42	0.09	93	0.23	143	0.54	193	1.67
43	0.09	94	0.24	144	0.55	194	1.79
44	0.10	95	0.24	145	0.57	195	2.33
45	0.10	96	0.24	146	0.58	196	2.57
46	0.10	97	0.25	147	0.58	197	3.21
47	0.11	98	0.25	148	0.58	198	3.38
48	0.11	99	0.26	149	0.60	199	4.47
49	0.11	100	0.27	150	0.61	200	5.38
50	0.11	101	0.28	151	0.62	201	8.55
51	0.12						

Average = 0.54
Std. dev. = 0.89
Coeff. var. = 1.66
Median = 0.28

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Table 2. Specimen Type 2 (single-end) loaded at 457 ksi; 100 specimens.

Rank	Time to break (hr)	Rank	Time to break (hr)	Rank	Time to break (hr)
1	0.07	35	0.48	68	1.18
2	0.10	36	0.49	69	1.26
3	0.10	37	0.50	70	1.44
4	0.12	38	0.54	71	1.55
5	0.12	39	0.54	72	1.55
6	0.12	40	0.54	73	1.64
7	0.13	41	0.54	74	1.72
8	0.16	42	0.60	75	1.76
9	0.16	43	0.61	76	1.81
10	0.16	44	0.66	77	2.12
11	0.17	45	0.67	78	2.16
12	0.21	46	0.68	79	2.20
13	0.21	47	0.70	80	2.21
14	0.21	48	0.74	81	2.40
15	0.25	49	0.75	82	2.49
16	0.27	50	0.75	83	2.59
17	0.28	51	0.76	84	2.79
18	0.28	52	0.77	85	2.79
19	0.29	53	0.77	86	2.83
20	0.29	54	0.80	87	2.99
21	0.30	55	0.83	88	3.00
22	0.31	56	0.87	89	3.08
23	0.32	57	0.88	90	3.20
24	0.32	58	0.92	91	3.32
25	0.34	59	0.95	92	3.32
26	0.36	60	0.95	93	3.70
27	0.38	61	0.99	94	4.17
28	0.39	62	1.01	95	5.04
29	0.39	63	1.04	96	5.55
30	0.40	64	1.05	97	6.68
31	0.40	65	1.09	98	7.28
32	0.41	66	1.12	99	9.20
33	0.46	67	1.15	100	10.19
34	0.47				

Average = 1.44
Std. dev. = 1.83
Coeff. var. = 1.27
Median = 0.76

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Table 3. Specimen Type 3 (6-end) loaded at 443 ksi; 200 specimens.

Rank	Time to break (hr)	Rank	Time to break (hr)	Rank	Time to break (hr)	Rank	Time to break (hr)
1	0.08	51	5.04	101	11.24	151	20.94
2	0.14	52	5.05	102	11.24	152	21.15
3	0.28	53	5.23	103	11.36	153	21.28
4	0.52	54	5.50	104	11.47	154	21.39
5	0.61	55	5.57	105	11.91	155	21.48
6	0.77	56	5.62	106	12.13	156	21.84
7	0.86	57	5.64	107	12.19	157	22.21
8	0.87	58	5.66	108	12.28	158	22.53
9	0.88	59	5.69	109	12.68	159	22.67
10	0.90	60	5.72	110	13.12	160	23.11
11	1.07	61	5.80	111	13.24	161	23.67
12	1.10	62	5.98	112	13.30	162	23.67
13	1.18	63	6.20	113	13.32	163	23.90
14	1.31	64	6.45	114	13.33	164	24.23
15	1.33	65	6.50	115	13.38	165	24.50
16	1.43	66	6.57	116	13.41	166	24.74
17	1.47	67	6.59	117	13.45	167	25.27
18	1.49	68	6.62	118	13.52	168	25.28
19	1.50	69	6.69	119	13.56	169	26.59
20	1.70	70	6.95	120	13.57	170	26.72
21	1.72	71	7.07	121	14.10	171	26.78
22	1.74	72	7.28	122	14.12	172	27.25
23	1.87	73	7.35	123	14.30	173	27.45
24	2.31	74	7.49	124	14.58	174	27.57
25	2.33	75	7.58	125	14.84	175	28.29
26	2.33	76	7.61	126	15.39	176	28.38
27	2.76	77	7.70	127	15.41	177	30.43
28	2.80	78	7.75	128	15.63	178	31.18
29	2.87	79	7.81	129	16.36	179	31.36
30	2.90	80	7.86	130	16.43	180	31.48
31	2.98	81	7.89	131	16.50	181	33.36
32	3.05	82	7.97	132	16.65	182	34.45
33	3.35	83	8.01	133	16.76	183	34.60
34	3.44	84	8.02	134	17.07	184	36.24
35	3.46	85	8.03	135	17.39	185	36.24
36	3.62	86	8.22	136	17.90	186	37.25
37	3.88	87	8.47	137	18.08	187	37.32
38	3.90	88	8.71	138	18.80	188	38.62
39	3.94	89	9.11	139	18.82	189	39.09
40	3.98	90	9.21	140	18.85	190	39.18
41	4.01	91	9.31	141	19.04	191	42.76
42	4.19	92	9.70	142	19.26	192	43.97
43	4.35	93	9.85	143	19.43	193	43.99
44	4.54	94	9.92	144	19.45	194	49.30
45	4.60	95	10.40	145	19.57	195	52.67
46	4.62	96	10.40	146	19.59	196	53.97
47	4.79	97	10.60	147	19.81	197	55.07
48	4.90	98	10.65	148	19.90	198	60.96
49	4.97	99	11.10	149	20.04	199	62.02
50	4.97	100	11.11	150	20.52	200	73.92

Average = 14.73
Std. dev. = 13.33
Coeff. var. = 0.90
Median = 11.18

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Table 4. Specimen Type 2 (single-end) loaded at 425 ksi; 201 specimens.

Rank	Time to break (hr)	Rank	Time to break (hr)	Rank	Time to break (hr)	Rank	Time to break (hr)
1	0.20	52	2.39	102	6.60	152	14.71
2	0.39	53	2.58	103	6.61	153	14.78
3	0.40	54	2.80	104	6.66	154	14.80
4	0.50	55	2.86	105	7.18	155	15.10
5	0.60	56	2.90	106	7.30	156	15.10
6	0.60	57	2.96	107	7.40	157	15.85
7	0.60	58	3.00	108	7.40	158	16.32
8	0.70	59	3.00	109	7.49	159	16.38
9	0.70	60	3.10	110	7.70	160	16.56
10	0.70	61	3.10	111	7.93	161	17.20
11	0.75	62	3.20	112	8.00	162	18.08
12	0.85	63	3.40	113	8.14	163	18.58
13	0.89	64	3.55	114	8.18	164	18.69
14	0.90	65	3.59	115	8.18	165	18.98
15	0.92	66	3.65	116	8.20	166	19.50
16	0.93	67	3.70	117	8.29	167	20.20
17	1.00	68	3.79	118	8.33	168	20.70
18	1.00	69	3.86	119	8.50	169	20.90
19	1.00	70	3.86	120	8.66	170	21.70
20	1.06	71	4.02	121	8.75	171	22.20
21	1.19	72	4.04	122	9.13	172	22.80
22	1.20	73	4.30	123	9.19	173	23.50
23	1.20	74	4.42	124	9.20	174	23.70
24	1.22	75	4.58	125	9.50	175	24.60
25	1.27	76	4.76	126	9.76	176	25.76
26	1.28	77	4.80	127	9.90	177	25.93
27	1.28	78	4.91	128	9.96	178	26.78
28	1.30	79	4.96	129	10.10	179	27.81
29	1.30	80	5.00	130	10.40	180	28.80
30	1.30	81	5.10	131	10.58	181	29.63
31	1.30	82	5.20	132	10.83	182	29.80
32	1.30	83	5.20	133	11.10	183	31.99
33	1.35	84	5.33	134	11.20	184	32.27
34	1.38	85	5.40	135	11.22	185	34.00
35	1.40	86	5.50	136	11.29	186	34.60
36	1.40	87	5.56	137	11.60	187	35.28
37	1.40	88	5.66	138	11.70	188	36.00
38	1.45	89	5.71	139	12.10	189	37.80
39	1.47	90	5.80	140	12.15	190	40.00
40	1.60	91	5.81	141	12.30	191	41.06
41	1.60	92	6.00	142	12.65	192	42.10
42	1.60	93	6.10	143	12.75	193	50.30
43	1.70	94	6.10	144	12.90	194	53.50
44	1.80	95	6.20	145	13.10	195	55.00
45	1.80	96	6.22	146	13.40	196	55.72
46	2.08	97	6.33	147	13.40	197	72.00
47	2.21	98	6.40	148	13.54	198	82.30
48	2.30	99	6.47	149	13.63	199	92.70
49	2.30	100	6.50	150	13.72	200	99.30
50	2.35	101	6.50	151	13.90	201	115.70
51	2.37						

Average = 12.35
Std. dev. = 17.14
Coeff. var. = 1.39
Median = 6.50

Table 5. Specimen Type 2 (single-end) loaded at 419 ksi; 101 specimens.

Rank	Time to break (hr)	Rank	Time to break (hr)	Rank	Time to break (hr)
1	0.23	35	5.48	69	17.13
2	0.34	36	5.80	70	17.51
3	0.44	37	5.90	71	17.87
4	0.70	38	6.02	72	18.00
5	0.80	39	6.20	73	19.00
6	1.00	40	6.30	74	19.26
7	1.35	41	6.50	75	19.37
8	1.40	42	6.70	76	19.70
9	1.60	43	6.90	77	21.90
10	1.70	44	7.10	78	23.90
11	1.80	45	7.39	79	25.04
12	1.80	46	7.39	80	26.80
13	1.83	47	7.76	81	29.02
14	1.89	48	7.78	82	29.60
15	1.95	49	8.50	83	31.80
16	2.00	50	8.55	84	33.90
17	2.00	51	9.22	85	35.54
18	2.10	52	9.40	86	37.21
19	2.30	53	9.41	87	37.30
20	2.50	54	9.67	88	39.39
21	2.50	55	9.70	89	39.50
22	2.60	56	9.87	90	40.19
23	2.80	57	10.40	91	40.32
24	2.91	58	10.40	92	42.45
25	3.36	59	10.94	93	42.85
26	3.51	60	12.67	94	43.40
27	3.70	61	12.70	95	44.20
28	3.86	62	14.57	96	49.30
29	4.32	63	14.60	97	49.70
30	4.50	64	14.86	98	50.96
31	4.60	65	14.97	99	70.69
32	4.80	66	15.41	100	78.65
33	5.20	67	16.50	101	109.44
34	5.41	68	16.80		

Average = 16.21
Std. dev. = 18.69
Coeff. dev. = 1.15
Median = 9.22

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Table 6. Specimen Type 2 (single-end) loaded at 394 ksi; 99 specimens.

Rank	Time to break (hr)	Rank	Time to break (hr)	Rank	Time to break (hr)
1	1.50	34	22.85	67	59.49
2	3.43	35	23.00	68	61.50
3	3.49	36	23.40	69	63.00
4	5.10	37	23.78	70	66.87
5	5.70	38	24.30	71	68.50
6	6.04	39	24.90	72	70.94
7	6.70	40	25.50	73	73.30
8	7.60	41	26.00	74	75.80
9	7.90	42	26.18	75	76.20
10	8.30	43	26.60	76	79.10
11	8.52	44	27.70	77	82.40
12	9.67	45	28.30	78	83.09
13	11.34	46	28.30	79	88.30
14	11.46	47	28.40	80	88.60
15	11.70	48	28.60	81	98.80
16	12.30	49	30.90	82	100.11
17	12.85	50	31.00	83	104.70
18	14.99	51	31.10	84	105.70
19	15.70	52	32.77	85	108.90
20	16.00	53	33.90	86	115.00
21	17.20	54	34.60	87	118.09
22	17.30	55	34.90	88	121.65
23	17.64	56	35.10	89	131.00
24	18.00	57	38.30	90	131.20
25	18.40	58	39.40	91	160.25
26	18.50	59	47.20	92	184.70
27	20.20	60	51.54	93	185.10
28	20.56	61	54.20	94	186.55
29	20.82	62	54.80	95	195.70
30	21.10	63	56.30	96	242.94
31	21.88	64	56.90	97	246.40
32	22.09	65	58.60	98	249.40
33	22.72	66	58.80	99	784.56

Average = 62.75
Std. dev. = 92.36
Coeff. var. = 1.47
Median = 31.00

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Table 7. Specimen Type 1 (single-end) loaded at 372 ksi; 101 specimens.

Rank	Time to break (hr)	Rank	Time to break (hr)	Rank	Time to break (hr)
1	8.56	35	413.70	69	1011.55
2	20.45	36	419.73	70	1029.78
3	35.27	37	426.85	71	1063.54
4	39.78	38	443.54	72	1226.94
5	45.31	39	443.72	73	1297.48
6	69.20	40	451.89	74	1308.14
7	87.05	41	475.01	75	1334.54
8	110.49	42	499.65	76	1336.00
9	115.71	43	504.93	77	1361.00
10	123.33	44	507.24	78	1379.39
11	127.14	45	513.18	79	1381.28
12	135.62	46	533.76	80	1391.84
13	136.38	47	537.88	81	1403.21
14	144.82	48	563.57	82	1434.38
15	149.76	49	570.18	83	1467.39
16	183.62	50	596.65	84	1550.00
17	190.68	51	643.07	85	1600.21
18	196.63	52	655.04	86	1630.74
19	202.51	53	690.04	87	1648.10
20	206.10	54	707.38	88	1742.00
21	209.87	55	729.26	89	1786.25
22	218.23	56	730.37	90	1889.00
23	222.24	57	770.84	91	1894.02
24	231.07	58	823.23	92	2152.81
25	237.87	59	830.89	93	2262.09
26	238.09	60	842.39	94	2395.92
27	240.74	61	855.17	95	2673.58
28	274.67	62	865.13	96	3321.70
29	305.41	63	866.83	97	3357.32
30	318.04	64	891.61	98	3996.04
31	341.02	65	900.14	99	4033.22
32	368.45	66	945.28	100	4194.86
33	374.87	67	948.14	101	5014.00
34	391.64	68	1004.63		

Average = 945.25
Std. dev. = 982.50
Coeff. var. = 1.04
Median = 643.07

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1. T. T. Chiao and R. L. Moore, J. Composite Materials 4, 118 (1970).
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3. T. T. Chiao and R. L. Moore, Strength of S-Glass Fiber, Lawrence Livermore Laboratory, Rept. UCRL-73564 Preprint (1971), prepared for SAMPE quarterly.
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PLL

Page 10 of Ref. 9 has not been reproduced. Tables A1 and A2 give updated data for the 57.9% and 50% stress levels. For the 50 specimens loaded at 228 ksi (40%) on 4/7/70, one specimen failed at 39 720 h; as of June 1978, 49 specimens were hanging intact (Laboratory notebook Vol. II, pages 9, 10). For the 50 specimens loaded at 188 ksi (33%) on 4/3/70, one was discarded early as unsuitable, and one specimen failed at 64 056 h. As on June 1978, 48 specimens were hanging intact (Laboratory notebook Vol. II, pages 12-14).

Table A1. Specimen Type 1 (single-end) loaded at 331 ksi (57.9% stress level) on 10/1/70: 100 specimens, of which 50 were removed after 7 200 h for strength retention tests. As of June 1978, seven specimens remain after more than 67 000 h (see Laboratory notebook Vol. II, page 21).

Rank	T_f, h	Rank	T_f, h
1	746	23	21,294[a]
2	914	24	21,863[a]
3	2,653	25	22,385
4	3,135	26	23,886
5	4,211	27	24,479
6	4,561	28	24,484[a]
7	5,286	29	24,560[b]
8	5,990	30	24,632[b]
9	6,400	31	24,749[a]
10	6,835	32	24,868
11	6,906	33	25,000[b]
12	6,950	34	25,480[b]
13	7,173	35	25,583
14	7,503	36	27,010
15	8,617	37	27,504
16	9,208	38	31,584
17	9,795	39	36,144[a]
18	14,781[b]	40	40,872[a]
19	17,299	41	52,224
20	18,283	42	54,000
21	20,829[a]	43	57,600
22	20,993[b]		

[a]Specimen slipped at clamp.

[b]Specimen failed at clamp.

Table A2. Specimen Type 1 (single-end) loaded at 286 ksi (50% stress level) on 4/3/70: 100 specimens. As of June 1978, 57 specimens remain after more than 71 400 h, five are unrecorded (see Laboratory notebook Vol. II, pages 6-8).

Rank	T_f, h	Rank	T_f, h
1	2 241	20	27 579
2	3 806	21	27 644
3	4 771	22	28 000[a]
4	7 081	23	28 566[b]
5	7 694	24	31 320
6	9 326	25	31 320
7	9 392	26	31 510
8	9 998	27	31 510
9	10 600[b]	28	38 952
10	10 882[a]	29	40 104[b]
11	13 420[a]	30	41 544
12	17 254	31	45 625
13	19 337	32	48 180
14	23 210[b]	33	48 792
15	24 111	34	50 784
16	24 507[a]	35	52 728
17	25 000[a]	36	55 128
18	25 237[a]	37	65 040[b]
19	25 805[b]	38	66 480

[a]Specimen slipped at clamp.

[b]Specimen failed at clamp.

APPENDIX B.

STRESS-RUPTURE OF GRAPHITE/EPOXY STRANDS: TIME-TO-BREAK DATA

Stress-rupture data on two graphite composites are current as of June 1978 (see Tables B1-B4).

Material system	Stress Levels[a] %
Thornel 50-S in Dow DER 332/Union Carbide ERL-4206/ Celanese Epi-Cure 855 (70/30/40)	90, 80
Thornel 500 in Dow DER 332/Jefferson Jeffamine T-403 (100/36)	90

[a]Percent of mean average fiber stress at strand failure in static test.

Table B1. Thornel 50-S composite strands loaded at 1.33 GPa (90% stress level); see Refs. 3, 4, and Laboratory notebook Vol. I, page 26 (1/9/69).

Rank	T_f, h	Rank	T_f, h
1	0.01	21	1 834.00[a]
2	0.02	22	2 752.30[b]
3	0.02	23	3 204.00
4	0.05	24	3 396.50
5	0.23	25	4 860.20
6	2.83	26	5 416.30
7	5.07	27	5 882.30
8	6.65	28	8 685.10
9	7.47	29	12 953.00
10	7.68	30	18 473.00
11	21.35	31	19 384.70
12	25.46	32	19 835.00[c]
13	100.92	33	23 836.00[a]
14	108.33	34	23 935.00[a]
15	231.56	35	25 522.00[c]
16	266.83	36	26 261.00[c]
17	498.63	37	26 359.00[c]
18	1 528.50	38	26 388.00[c]
19	1 731.90	39	27 980.00[a]
20	1 757.00		

[a]Specimen slipped at clamp.

[b]Specimen failed at clamp.

[c]Terminated without failure.

Table B2. Thornel 50-S composite strands loaded at 1.33 GPa (90% stress lever); see Refs. 3, 4, and Laboratory notebook Vol. II, pages 11, 12 (4/1/70). Sixteen specimens were removed after 18 000 h and used for strength retention tests.

Rank	T_f, h	Rank	T_f, h
1	0.7	22	1 573.1
2	2.5	23	1 612.4
3	8.5	24	1 846.8
4	14.5	25	1 849.5
5	31.3	26	2 040.5
6	36.4	27	2 566.3
7	53.8	28	2 692.9
8	62.7	29	3 001.3
9	123.1	30	3 424.0
10	164.0	31	3 439.0
11	182.3	32	5 160.7
12	194.9	33	5 735.2
13	241.0	34	6 787.0
14	264.8	35	9 300.0[a]
15	426.2	36	9 300.0
16	457.4	37	10 276.2
17	582.2	38	12 719.6
18	766.1	39	12 720.0
19	1 138.9	40	12 572.0[a]
20	1 307.2	41	16 404.0[a]
21	1 508.2	42	18 000.0+[a]

[a]Specimen slipped at clamp.

Table B3. Thornel 50-S composite strands loaded at 1.18 GPa (80% stress level); see Ref. 3 and data from Fig. 46, Ref. 4. Thirty-one specimens did not fail after 13 000 to 19 000 h; these specimens were tested for strength retention.

Rank	T_f, h
1	163
2	543
3	3 980
4	7 250

Table B4. Thornel 500 composite strands loaded at 3.21 GPa (90% stress level); see Ref. 5. Strand specimens were put on test during the period from October 1973 to February 1975; the test was discontinued June 1977. Six specimens were removed intact after more than 14 000 h.

Rank	T_f, h	Rank	T_f, f
1	0.03	26	13.12
2	0.09	27	14.41
3	0.10	28	22.73
4	0.21	29	39.41
5	0.45	30	39.79
6	0.62	31	62.54
7	0.90	32	78.51
8	1.17	33	83.73
9	1.49	34	100.33
10	1.99	35	119.04
11	2.32	36	132.79
12	2.38	37	257.53
13	4.03	38	331.86
14	4.58	39	386.66
15	4.62	40	448.64
16	5.00	41	661.49
17	5.43	42	704.59
18	6.34	43	731.54
19	8.14	44	1 098.00
20	8.64	45	2 784.00
21	9.74	46	5 376.00
22	11.11	47	5 712.00
23	12.00	48	5 976.00
24	12.42	49	7 560.00
25	12.89	50	13 870.00
		51	14 232.00

APPENDIX C.

Stress-Rupture of Kevlar 49/Epoxy Strands: Time-To-Break Data

The data presented here are reprinted from Ref. 15; data have been updated to June 1978.

Material system	Stress Levels %
Kevlar 49 (380 denier, single-end in Union Carbide ERL 2258/ZZL 0820) (100/30)	90, 87, 84, 80, 70, 60, 50

[a]Percent of mean average fiber stress at strand failure in static test.

STRESS-RUPTURE DATA FOR KEVLAR 49/EPOXY STRANDS

ABSTRACT

Raw data obtained from a study of the stress-rupture behavior of filament-wound organic fiber/epoxy strand specimens is tabulated. See ASTM Special Technical Publication No. 546, "Stress-Rupture Behavior of Strands of an Organic Fiber/Epoxy Matrix," by T. T. Chiao, J. E. Wells, R. L. Moore, and M. A. Hamstad (1974), for a detailed discussion of the study.

EXPLANATION

In this report, we present the raw data obtained from over five years of study of the stress-rupture behavior of Kevlar 49/epoxy strands. The ASTM Special Technical Publication No. 546, "Stress-Rupture Behavior of Strands of an Organic Fiber/Epoxy Matrix," by T. T. Chiao, J. E. Wells, R. L. Moore, and M. A. Hamstad (1974, p. 209), details the experiment.

Because we have received numerous requests for the raw data and because we have collected more data since the ASTM article was published, we are tabulating the raw data obtained from October 1972 to February 1978. Our study of the stress-rupture behavior of these strands is continuing.

SPECIMENS

The specimens tested were strands, filament-wound from single-end (380 denier, 267 to 280 filaments) preproduction Kevlar 49 fiber. The fiber was without finish; there was a twist of one turn per inch; the fiber specific gravity was 1.45. The epoxy matrix used was Union Carbide ERL 2258/ZZL 0820 in a weight ratio of 100/30. The system was cured for 3 h at 90°C plus 2 h at 163°C. The fiber volume of the strand population was determined by weighing seven randomly selected groups of five strands each; the average fiber content was 71.5 vol%. These data are shown in Table 1.

The average breaking load of a sample (sample size = 53) randomly selected from the strand population was 10,011 g (standard deviation = 544 g). This corresponds to a fiber failure stress (i.e., grams load at failure divided by a cross-sectional area of 4.364×10^{-5} in.^{2} of bare fiber strand) of 505,000 psi. Table 2 presents the data.

TEST CONDITIONS

In 1971, the strands were carefully loaded at the following load levels. The specimens were kept in a controlled environment; the temperature was held between 22 and 28^{o}C and the relative humidity was maintained between 24 and 37%.

Percent of ultimate tensile strength	Load level, g	Number of strands hung
90	9010	101
87	8710	100
84	8409	103
80	8009	99
70	7008	50
60	6007	50
50	5006	50

RESULTS

As of February 1978, all of the specimens at the 90, 87, 84, 80, and 70% load levels had failed. Only 38 of the 50 specimens hung at the 60% level had failed and only 2 of the 50 specimens at the 50% level had failed. These data are given in Tables 3 through 9. Where fewer data than the number of strands hung are listed, the deleted specimens were deemed unsutiable (e.g., because of equipment failure).

Table 1. Fiber content data (vol%) for the epoxy-coated strand population. (Bare fiber weight in g/100 in. = 0.1044, 0.1030, 0.1037, 0.1047, and 0.1032 for an average of 0.1038 g/100 in. which equals 0.0199 g/19.2 in.)

Weight of 19.2-in. specimen, g	Average weight of 5 samples, g	Weight of resin alone, g	Weight % resin	Volume % resin
0.0267 0.0270 0.0263 0.0272 0.0267	0.0263	0.0263 - 0.0199 = 0.0064	24.3	72.0
0.0267 0.0270 0.0263 0.0272 0.0267	0.0268	0.0268 - 0.0199 = 0.0069	25.7	70.6
0.0276 0.0270 0.0264 0.0267 0.0260	0.0267	0.0267 - 0.0199 = 0.0068	25.4	70.8
0.0263 0.0267 0.0265 0.0275 0.0271	0.0268[a]	0.0268 - 0.0200 = 0.0068	25.6	70.9
0.0266 0.0268 0.0262 0.0262 0.0260	0.0264	0.0264 - 0.0199 = 0.0065	24.6	71.7
0.0266 0.0260 0.0270 0.0264 0.0264	0.0265	0.0265 - 0.0200 = 0.0065	24.5	71.9
0.0257 0.0260 0.0271 0.0261 0.0262	0.0262	0.0262 - 0.0199 = 0.0063	24.0	72.4

[a]Average specimen length = 19.3 in.

Table 2. Breaking load of individual Kevlar/epoxy strands.

Specimen No.	Load, lb.	Specimen No.	Load, lb.
1	22.0	28	22.2
2	22.0	29	22.7
3	22.0	30	22.7
4	21.6	31	22.5
5	21.6	32	22.2
6	22.0	33	22.5
7	22.0	34	22.0
8	20.9	35	20.5
9	22.5	36	22.5
10	22.7	37	21.1
11	22.9	38	22.2
12	22.0	39	21.4
13	22.5	40	22.5
14	22.5	41	21.4
15	21.6	42	21.6
16	21.8	43	22.0
17	22.0	44	21.4
18	22.0	45	21.4
19	21.8	46	22.7
20	22.9	47	21.6
21	21.8	48	21.6
22	23.1	49	22.7
23	22.9	50	21.8
24	22.0	51	22.0
25	22.2	52	22.2
26	22.5	53	22.0
27	21.4		

Table 3. Ordered list for 90% load level (9010 g).

Rank	T_f[a]	Rank	T_f	Rank	T_f	Rank	T_f
1	0.01	26	0.24	51	0.80	76	1.45
2	0.01	27	0.24	52	0.80	77	1.50
3	0.02	28	0.29	53	0.83	78	1.51
4	0.02	29	0.34	54	0.85	79	1.52
5	0.02	30	0.35	55	0.90	80	1.53
6	0.03	31	0.36	56	0.92	81	1.54
7	0.03	32	0.38	57	0.95	82	1.54
8	0.04	33	0.40	58	0.99	83	1.55
9	0.05	34	0.42	59	1.00	84	1.58
10	0.06	35	0.43	60	1.01	85	1.60
11	0.07	36	0.52	61	1.02	86	1.63
12	0.07	37	0.54	62	1.03	87	1.64
13	0.08	38	0.56	63	1.05	88	1.80
14	0.09	39	0.60	64	1.10	89	1.80
15	0.09	40	0.60	65	1.10	90	1.81
16	0.10	41	0.63	66	1.11	91	2.02
17	0.10	42	0.65	67	1.15	92	2.05
18	0.11	43	0.67	68	1.18	93	2.14
19	0.11	44	0.68	69	1.20	94	2.17
20	0.12	45	0.72	70	1.29	95	2.33
21	0.13	46	0.72	71	1.31	96	3.03
22	0.18	47	0.72	72	1.33	97	3.03
23	0.19	48	0.73	73	1.34	98	3.34
24	0.20	49	0.79	74	1.40	99	4.20
25	0.23	50	0.79	75	1.43	100	4.69
						101	7.89

[a]Time to failure in hours.

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Table 4. Ordered list for 87% load level (8710 g).

Rank	T_f [a]	Rank	T_f	Rank	T_f	Rank	T_f
1	0.03	26	1.35	51	2.80	76	5.92
2	0.04	27	1.35	52	2.89	77	6.19
3	0.07	28	1.36	53	2.91	78	6.33
4	0.08	29	1.39	54	2.91	79	6.59
5	0.08	30	1.40	55	3.10	80	6.62
6	0.09	31	1.48	56	3.11	81	6.94
7	0.15	32	1.55	57	3.42	82	7.16
8	0.15	33	1.56	58	3.47	83	7.29
9	0.20	34	1.57	59	3.50	84	7.36
10	0.28	35	1.59	60	3.64	85	7.38
11	0.28	36	1.80	61	3.67	86	7.42
12	0.30	37	1.85	62	3.68	87	8.09
13	0.38	38	1.86	63	3.75	88	8.88
14	0.41	39	1.92	64	4.39	89	9.05
15	0.50	40	2.00	65	4.50	90	9.25
16	0.51	41	2.08	66	4.53	91	9.26
17	0.57	42	2.27	67	4.53	92	9.47
18	0.70	43	2.38	68	4.65	93	10.50
19	0.72	44	2.46	69	4.65	94	10.57
20	0.82	45	2.49	70	4.69	95	11.25
21	0.84	46	2.61	71	4.70	96	13.49
22	1.05	47	2.61	72	4.75	97	13.78
23	1.13	48	2.62	73	4.84	98	16.15
24	1.19	49	2.74	74	5.01	99	16.59
25	1.32	50	2.79	75	5.71	100	18.16

[a] Time to failure in hours.

Table 5. Ordered list for 84% load level (8409 g).

Rank	T_f[a]	Rank	T_f	Rank	T_f	Rank	T_f
1	0.25	27	7.32	53	12.94	79	34.51
2	0.31	28	7.45	54	16.42	80	34.74
3	0.44	29	7.92	55	16.47	81	35.63
4	0.45	30	7.99	56	17.68	82	36.84
5	0.57	31	8.22	57	17.79	83	36.97
6	0.65	32	8.35	58	18.45	84	39.17
7	0.73	33	8.38	59	18.95	85	41.54
8	0.89	34	8.39	60	19.07	86	42.32
9	1.06	35	8.45	61	19.40	87	42.53
10	1.22	36	8.53	62	19.62	88	43.61
11	1.37	37	8.55	63	19.86	89	48.54
12	1.83	38	8.64	64	20.76	90	49.02
13	1.96	39	8.68	65	21.38	91	55.20
14	2.15	40	8.92	66	23.03	92	55.99
15	2.40	41	8.93	67	23.10	93	61.37
16	2.51	42	9.45	68	23.83	94	63.17
17	2.77	43	9.57	69	24.46	95	66.48
18	4.05	44	9.80	70	24.81	96	67.06
19	4.07	45	9.83	71	25.15	97	74.01
20	4.34	46	10.60	72	25.18	98	74.61
21	4.98	47	10.82	73	26.96	99	76.46
22	5.86	48	10.83	74	27.53	100	84.26
23	5.90	49	11.03	75	27.86	101	89.87
24	6.18	50	11.12	76	29.89	102	97.37
25	6.30	51	11.13	77	32.55	103	119.09
26	7.14	52	12.52	78	33.95		

[a]Time to failure in hours.

Table 6. Ordered list for 80% load level (8009 g).

Rank	T_f [a]	Rank	T_f	Rank	T_f	Rank	T_f
1	1.8	26	84.2	51	152.2	76	285.9
2	3.1	27	87.1	52	152.8	77	292.6
3	4.2	28	87.3	53	157.7	78	295.1
4	6.0	29	93.2	54	160.0	79	301.1
5	7.5	30	103.4	55	163.6	80	304.3
6	8.2	31	104.6	56	166.9	81	316.8
7	8.5	32	105.5	57	170.5	82	329.8
8	10.3	33	108.8	58	174.9	83	334.1
9	10.6	34	112.6	59	177.7	84	346.2
10	24.2	35	116.8	60	179.2	85	351.2
11	29.6	36	118.0	61	183.6	86	353.3
12	31.7	37	122.0	62	183.8	87	369.3
13	41.9	38	123.5	63	194.3	88	372.3
14	44.1	39	124.4	64	195.1	89	381.3
15	49.5	40	125.4	65	195.3	90	393.5
16	50.1	41	129.5	66	202.6	91	451.3
17	59.7	42	130.4	67	220.2	92	461.5
18	61.7	43	131.6	68	221.3	93	574.2
19	64.4	44	132.8	69	227.2	94	653.3
20	69.7	45	133.8	70	251.0	95	663.0
21	70.0	46	137.0	71	266.5	96	669.8
22	77.8	47	140.2	72	267.9	97	739.7
23	80.5	48	140.9	73	269.2	98	759.6
24	82.3	49	148.5	74	270.4	99	894.7
25	83.5	50	149.2	75	272.5	100	974.9

[a] Time to failure in hours.

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Table 7. Ordered list for 70% load level (7008 g).

Rank	T_f[a]	Rank	T_f
1	1,051	26	9,106
2	1,337	27	9,711
3	1,389	28	9,806
4	1,921	29	10,205
5	1,942	30	10,396
6	2,322	31	10,861
7	3,629	32	11,026
8	4,006	33	11,214
9	4,012	34	11,362
10	4,063	35	11,604
11	4,921	36	11,608
12	5,445	37	11,745
13	5,620	38	11,762
14	5,817	39	11,895
15	5,905	40	12,044
16	5,956	41	13,520
17	6,068	42	13,670
18	6,121	43	14,110
19	6,473	44	14,496
20	7,501	45	15,395
21	7,886	46	16,179
22	8,108	47	17,092
23	8,546	48	17,568
24	8,666	49	17,568
25	8,831		

[a]Time to failure in hours.

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Table 8. Ordered list for 60% load level (6007 g).

Rank	T_f [a]	Rank	T_f
1	13,872	26	39,144
2	18,024	27	39,480
	18,948	28	39,648
4	21,960	29	39,648
5	22,608	30	41,520
6	25,100	31	41,610
7	25,536	32	41,620
8	27,216	33	42,384
9	27,744	34	42,720
10	27,840	35	44,616
11	28,512	36	49,080
12	28,676	37	49,416
13	29,784	38	51,168
14	29,784	34	42,720
15	31,188	35	44,616
16	31,644	36	49,080
17	32,760	37	49,416
18	33,480	38	51,168
19	35,880		
20	36,024		
21	36,240		
22	36,480		
23	36,648		
24	38,640		
25	38,976		

[a] Time to failure in hours.

Total No. of Specimens: 50
38 Failed
3 Removed
9 Remaining on test

START DATE

11/4/71 For 7 of the Remaining Specimens

6/27/72 For 2 of the remaining specimens

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Table 9. Ordered list for 50% load level (5006 g).

Rank	T_f[a]
1	30,960
2	32,040

[a]Time to failure in hours.

Total No. of Specimens: 50

2 Failed

2 Removed

46 Remaining on test

Start Date: 11/4/71

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APPENDIX D.

STRESS-RUPTURE OF KEVLAR 49/EPOXY STRANDS AT ELEVATED TEMPERATURES: TIME-TO-BREAK DATA

The data presented here are reprinted from Ref. 16 and are current to June 1978.

Material system	Temperature, °C	Stress level,[a] %
Kevlar 49 (380 denier, single-end) in	100	85.5, 80.4, 73.2, 67.2
Union Carbide ERL2258/ ZZl 0820 (100/29)	110	85.5, 80.4, 73.2, 67.2, 56.4
	120	85.5, 80.4, 73.2, 67.2

[a]Percent of mean average fiber stress at strand failure in static test.

STRESS-RUPTURE DATA FOR KEVLAR 49/EPOXY STRANDS AT ELEVATED TEMPERATURES

ABSTRACT

Raw data obtained from two studies of the stress-rupture behavior of filament wound, organic fiber/epoxy strand specimens is tabulated. The major portion of the data is discussed in "Experimental Verification of an Accelerated Test for Predicting the Lifetime of Organic Fiber Composites," by C. C. Chiao, R. J. Sherry, and N. W. Hetherington, *J. Composite Mat. 11,* 79 (1977), and a small portion of the data in "Stress-Rupture Life and Strength Retention of an Aramid Fiber/Epoxy Composite Under Accelerating Conditions," by Lynn Penn and R. J. Sherry, in *Proc. Failure Modes and Processing of Composites IV,* sponsored by the Composite Material Committees of the Metallurgical Society of AIME and of the American Society of Metals, Chicago, Illinois, October 24-27, 1977.

EXPLANATION

In this report, we present the raw data obtained from accelerated stress-rupture studies of Kevlar 49/epoxy strand specimens. The experimental details are presented in Refs. 1 and 2. We tabulated these data because we have received numerous requests for the information and because additional data has been collected since Refs. 1 and 2 were published. The stress-rupture data taken on the same composite at room temperature is reported in Ref. 3.

SPECIMENS

The reinforcing fiber was poly(p-phenylene terephthalamide), known commercially as Kevlar 49 from DuPont. The single-end, 380-denier fiber contained approximately 267 filaments. It was dried in a vacuum oven for 24 h at 50°C and 1 Pa and then stored in a light-tight desiccator. The epoxy was an amine-cured bisphenol A, Union Carbide ERL 2258/ZZL 0820 (100/29 parts by weight).

The fiber was vacuum-impregnated with the epoxy and filament wound onto a rack with a 1600-strand capacity. The composite specimens were then cured on the rack for 3 h at 100°C plus 2 h at 170°C. After curing, the strands were cut off the rack and divided into groups of approximately 200 each. Each group was characterized by randomly selecting 10 strands and determining the average volumetric fiber content. We chose four groups of strands for testing as reported in Ref. 1 and one group for testing as in Ref. 2. Table 1 lists the fiber volume content and tensile strength of these specimen groups.

The average fiber cross-sectional area of the strand was calculated to be 2.98×10^{-8} m^2 from the fiber specific gravity of 1.45 and the mean fiber weight of 0.0432 g/m (determined from 10 lengths of bare fiber each 2.5 m long). We used this cross-sectional area as a constant to convert all fiber tensile loads to tensile stresses.

To prepare the specimens for the stress-rupture tests, a high-temperature-curable epoxy resin was used to bond the end tabs to the composite strands. The specimen gage length between the tabs was 225 mm. After curing the adhesive with specimens in place (3 h at 150°C), we determined the ultimate tensile strength of each group by testing 20 specimens on a universal tensile test machine.

TEST APPARATUS

Eight temperature-controlled chambers with associated loading and timing components were used in these tests. Each chamber was insulated with a 50-mm-thick asbestos sheet, and each contained a frame for holding the specimen, a 1000-W electric heater, an air-circulating fan, and temperature sensors. A proportional temperature controller with a platinum sensing element held the chamber temperature constant to within 0.6°C of the desired value and the fan maintained a uniform chamber temperature to within 0.5°C. (The specimen was shielded from the air current generated by the fan.) An eight-point recorder monitored one type-J thermocouple junction in each chamber to provide the temperature readout.

We loaded the specimen and measured the duration of the test from outside the chamber. Rigid rods passing through the chamber floor connected the bottom specimen mount to a crossbar located below the chamber. Lead weights attached to the crossbar provided the load: the loading mechanism was a hand-operated scissors jack. A timer switch was mounted on a plate underneath the lead weight. Thus when loading the specimen, the timer was not activated until the specimen held the weight off the switch. When the specimen failed, the lead weight fell onto the switch, turning off the timer. Five-digit timers, readable to 0.01 min and driven by synchronous motors using 60-Hz power, were used to measure the short-term tests. All times were recorded in minutes and then converted to hours.

RESULTS

The times to failure, T_f (in hours), under various load and temperature conditions are reported in the tables below (Tables 2 and II to 14 and XIII). Also included are "clamp break" data: these are the failures that occured within 1.27 cm from the end tab or clamp and are not included in the reported data from which we draw conclusions. Data obtained from specimens at 85.5% load (Tables 2, II, 3, III, 4, and IV) are provided here because they were not included in Refs. 1 or 2. For comparison, the room-temperature stress-rupture data are tabulated in Ref. 3.

REFERENCES

1. C. C. Chiao, R. J. Sherry, and N. W. Hetherington, "Experimental Verification of an Accelerated Test for Predicting the Lifetime of Organic Fiber Composites," *J. Composite Mat. 11,* 79 (1977).
2. Lynn Penn and R. J. Sherry, "Stress-Rupture Life and Strength Retention of an Aramid Fiber/Epoxy Composite Under Accelerating Conditions," in *Proc. Failure Modes and Processing of Composites IV,* sponsored by the Composite Material Committees of the Metallurgical Society of AIME and of the American Society of Metals, Chicago, Illinois, October 24-27, 1977.
3. Lynn Penn, *Stress-Rupture Data for Kevlar 49/Epoxy Strands,* Lawrence Livermore Laboratory, Rept. UCID-17738 (1978).

Table 1. Fiber volume content and fiber tensile strength of four groups of cured composite strand specimens (the ± values represent 95% confidence limits).

Specimen group	Fiber content, vol%	Fiber tensile strength, MPa
1	69.2 ± 1.4	3374 ± 128
2	67.1 ± 2.0	3325 ± 229
3	67.7 ± 2.4	3374 ± 218
4	67.1 ± 0.8	3374 ± 94
5	64.0 ± 1.0	3450 ± 225

[a]Groups 1-4 are the subject of Ref. 1, and group 5 is the subject of Ref. 2.

Table 2. Ordered list for 85.5% load-level at 100°C.

Rank	T_f, h	Rank	T_f, h
1	0.0015	21	0.1612
2	0.0407	22	0.1613
3	0.0437	23	0.1662
4	0.0463	24	0.1912
5	0.0480	25	0.1932
6	0.0526	26	0.1950
7	0.0532	27	0.1963
8	0.0545	28	0.2032
9	0.0587	29	0.2080
10	0.0697[a]	30	0.2262[a]
11	0.0718	31	0.2432
12	0.0770	32	0.2478
13	0.0837	33	0.2537
14	0.0977[a]	34	0.2873[a]
15	0.1087		
16	0.1223		
17	0.1233		
18	0.1362		
19	0.1517		
20	0.1567		

[a]Not reported in Ref. 1 to restrict reported sample size to 30.

Table II. Ordered list for 85.5% load-level clamp breaks at 100°C.

Rank	T_f, h
1	0.0890
2	0.1063
3	0.1119
4	0.1347
5	0.1432
6	0.1463
7	0.1500
8	0.1750
9	0.1876
10	0.2249
11	0.2497
12	0.2917
13	0.3762

Table 3. Ordered list for 85.5% load level at 110°C.

Rank	T_f, h	Rank	T_f, h
1	0.0248	21	0.1113
2	0.0323	22	0.1240
3	0.0530	23	0.1330
4	0.0573	24	0.1347
5	0.0580	25	0.1395
6	0.0593	26	0.1448
7	0.0593	27	0.1663
8	0.0595	28	0.1727
9	0.0605	29	0.1762
10	0.0713	30	0.1783
11	0.0728		
12	0.0770		
13	0.0775		
14	0.0830		
15	0.0885		
16	0.0900		
17	0.0910		
18	0.0928		
19	0.0933		
20	0.0963		

Table III. Ordered list for 85.5% load-level clamp breaks at 110°C.

Rank	T_f, h
1	0.0015
2	0.0148
3	0.0263
4	0.0301
5	0.0461
6	0.0618
7	0.0740
8	0.1410
9	0.1516
10	0.1783

Table 4. Ordered list for 85.5% load level at 120°C.

Rank	T_f, h	Rank	T_f, h
1	0.0068[a]	21	0.0262[a]
2	0.0072	22	0.0290
3	0.0080	23	0.0308
4	0.0118	24	0.0342
5	0.0122	25	0.0350
6	0.0132	26	0.0383[a]
7	0.0150	27	0.0403
8	0.0152	28	0.0425
9	0.0162[a]	29	0.0478[a]
10	0.0162	30	0.0485
11	0.0175	31	0.0547
12	0.0177	32	0.0665
13	0.0182	33	0.0700[a]
14	0.0185[a]	34	0.0747
15	0.0217[a]	35	0.0752[a]
16	0.0233	36	0.0763
17	0.0235	37	0.0815
18	0.0242	38	0.0830
19	0.0245	39	0.1247
20	0.0247		

[a]Not reported in Ref. 1 to restrict reported sample size to 30.

Table IV. Ordered list for 85.5% load-level clamp breaks at 120°C.

Rank	T_f, h
1	0.0095
2	0.0130
3	0.0152
4	0.0190
5	0.0233
6	0.0317
7	0.0332
8	0.0333
9	0.0413

Table 5. Ordered list for 80.41% load level at 100°C.

Rank	T_f, h	Rank	T_f, h
1	0.0013	21	0.7042
2	0.0875	22	0.7808
3	0.1880	23	0.8052
4	0.1982	24	0.8473[a]
5	0.2533	25	0.8567
6	0.2697	26	0.8743
7	0.2697[a]	27	0.9833
8	0.2782	28	0.9907[a]
9	0.2783	29	1.007
10	0.2882	30	1.103
11	0.2983	31	1.137
12	0.3183	32	1.138
13	0.3697	33	1.175
14	0.4415	34	1.320
15	0.4620	35	2.069
16	0.4625[a]		
17	0.5312[a]		
18	0.5550		
19	0.5837		
20	0.5972		

[a]Not reported in Ref. 1 to restrict reported sample size to 30.

Table V. Ordered list for 80.41% load-level clamp breaks at 100°C.

Rank	T_f, h
1	0.0392
2	0.0815
3	0.1233
4	0.1342
5	0.1787
6	0.1833
7	0.2997
8	0.3087
9	0.5535
10	0.5550
11	0.6042
12	0.6465
13	0.7013
14	0.8732
15	1.272
16	1.480
17	1.832
18	2.070
19	2.164

Table 6. Ordered list for 80.41% load level at 110°C.

Rank	T_f, h	Rank	T_f, h
1	0.0095	21	0.2735
2	0.0113	22	0.2947
3	0.0217	23	0.2957
4	0.0797	24	0.3068
5	0.0985	25	0.3087
6	0.0995	26	0.3492[a]
7	0.1682	27	0.3673[a]
8	0.1707	28	0.3753
9	0.1880[a]	29	0.3802
10	0.1915	30	0.3858
11	0.1958	31	0.4433
12	0.2083	32	0.4745
13	0.2170	33	0.5115
14	0.2195	34	0.5685[a]
15	0.2345		
16	0.2437		
17	0.2487		
18	0.2635		
19	0.2650		
20	0.2658		

[a]Not reported in Ref. 1 to restrict reported sample size to 30.

Table VI. Ordered list for 80.41% load-level clamp breaks at 110°C.

Rank	T_f, h	Rank	T_f, h	Rank	T_f, h
1	0.0602	21	0.2235	41	0.4268
2	0.0855	22	0.2313	42	0.4478
3	0.1063	23	0.2463	43	0.5010
4	0.1232	24	0.2478	44	0.5518
5	0.1272	25	0.2513		
6	0.1315	26	0.2630		
7	0.1347	27	0.2762		
8	0.1423	28	0.2828		
9	0.1432	29	0.2928		
10	0.1453	30	0.3008		
11	0.1497	31	0.3193		
12	0.1603	32	0.3252		
13	0.1665	33	0.3267		
14	0.1780	34	0.3278		
15	0.1825	35	0.3577		
16	0.1848	36	0.3633		
17	0.1865	37	0.3663		
18	0.2013	38	0.3758		
19	0.2032	39	0.3942		
20	0.2217	40	0.3977		

Table 7a. Ordered list for 80.41% load-level at 120^{o}C.

Rank	T_f, h	Rank	T_f, h
1	0.0102	21	0.1633
2	0.0650	22	0.1707
3	0.0749	23	0.1897
4	0.0752	24	0.2133
5	0.0800	25	0.2162
6	0.0879	26	0.2567
7	0.0997	27	0.2578
8	0.1078	28	0.2798
9	0.1082	29	0.3443
10	0.1113	30	0.3967
11	0.1213		
12	0.1222		
13	0.1248		
14	0.1280		
15	0.1337		
16	0.1419		
17	0.1440		
18	0.1452		
19	0.1472		
20	0.1548		

Table VIIa. Ordered list for 80.41% load-level clamp breaks at 120°C.

Rank	T_f, h
1	0.0200
2	0.0200
3	0.0612
4	0.0738
5	0.0862
6	0.0970
7	0.1170
8	0.1607
9	0.1607
10	0.1695
11	0.1747
12	0.2597
13	0.2730
14	0.3493
15	0.3493
16	0.3607

Table 7b. Ordered list for 80.41% load-level rerun[a] at 120°C.

Rank	T_f, h	Rank	T_f, h
1	0.0777	21	0.2035
2	0.0777	22	0.2124
3	0.0804	23	0.2299
4	0.0846	24	0.2542
5	0.0852	25	0.2578
6	0.0961	26	0.2588
7	0.0990	27	0.2773
8	0.1277	28	0.2801
9	0.1291	29	0.3445
10	0.1297	30	0.3555
11	0.1342	31	0.3889
12	0.1380		
13	0.1538		
14	0.1569		
15	0.1639		
16	0.1685		
17	0.1738		
18	0.1828		
19	0.1947		
20	0.1952		

[a]Rerun not included in Ref. 1.

Table VIIb. Ordered list for 80.41% load-level rerun clamp breaks at 120°C.

Rank	T_f, h
1	0.0097
2	0.0195
3	0.0728
4	0.0920
5	0.1140
6	0.1628

Table 8a. Ordered list for 73.21% load-level at 100°C.

Rank	T_f, h	Rank	T_f, h
1	0.2833	21	5.9757
2	0.4378	22	6.0955
3	1.2750	23	6.6546
4	1.2900	24	6.6752
5	1.4228	25	6.7150
6	1.4651	26	6.8616
7	1.5178	27	8.0610
8	1.7276	28	8.4076
9	2.7045	29	9.0733
10	2.7721	30	11.2280
11	3.0147	31	14.7858
12	3.4085	32	19.8447
13	3.6768	33	23.0297
14	3.7078		
15	4.0253		
16	4.3113		
17	4.4788		
18	4.6260		
19	4.9577		
20	5.2326		

Table VIIIa. Ordered list for 73.21% load-level clamp breaks at 100°C.

Rank	T_f, h	Rank	T_f, h	Rank	T_f, h
1	0.0017	21	2.9480	41	8.4940
2	0.1050	22	2.9503	42	9.4785
3	0.1516	23	3.0525	43	10.2180
4	0.1367	24	3.1625	44	17.2493
5	0.3013	25	3.3065		
6	0.3882	26	3.3260		
7	0.3902	27	3.4562		
8	0.4083	28	3.7095		
9	0.5113	29	3.7997		
10	0.5863	30	4.0242		
11	1.1243	31	4.2678		
12	1.4882	32	4.4470		
13	1.6163	33	4.5420		
14	1.7042	34	6.0613		
15	1.7267	35	6.1063		
16	1.8098	36	6.8033		
17	1.8292	37	6.8560		
18	2.0078	38	7.2442		
19	2.2367	39	7.5138		
20	2.8795	40	8.3400		

Table 8b. Ordered list for 73.21% load-level rerun[a] at 100°C.

Rank	T_f, h	Rank	T_f, h
1	1.0261	21	5.7962
2	1.1418	22	6.1056
3	1.7031	23	6.3561
4	1.7893	24	8.5293
5	1.8215	25	8.8097
6	1.9235	26	9.0847
7	2.0853	27	10.4767
8	2.2469	28	10.9102
9	3.3243	29	11.2593
10	3.5120	30	11.7333
11	3.5596	31	12.5322
12	3.8522	32	13.9708
13	3.9305	33	14.5115
14	3.9472	34	19.4522
15	3.9859		
16	4.1200		
17	4.2385		
18	4.2975		
19	5.1482		
20	5.7364		

[a]Rerun not included in Ref. 1.

Table VIIIb. Ordered list for 73.21% load-level rerun clamp breaks at 100°C.

Rank	T_f, h
1	0.3236
2	1.0596
3	1.0717
4	1.2007
5	1.2891
6	1.6714
7	2.0575
8	2.2927
9	2.8507
10	3.5098
11	3.9057
12	4.6307
13	4.6457
14	9.2010
15	9.5388
16	11.9886
17	12.8487

Table 9. Ordered list for 73.21% load-level at 110°C.

Rank	T_f, h	Rank	T_f, h
1	0.0886	21	2.4951
2	0.5650	22	2.9911
3	0.6748	23	3.0256
4	0.8851	24	3.2678
5	0.9113	25	3.4846
6	0.9120	26	3.7455
7	0.9836	27	3.9143
8	1.2570	28	4.8073
9	1.2985	29	5.4435
10	1.3211	30	5.5295
11	1.3503	31	9.0960[a]
12	1.4880		
13	1.5733		
14	1.7263		
15	1.8375		
16	1.8503		
17	2.2100		
18	2.2878		
19	2.3203		
20	2.3513		

[a]Not reported in Ref. 1 to restrict reported sample size to 30.

Table IX. Ordered list for 73.21% load-level clamp breaks at 110°C.

Rank	T_f, h	Rank	T_f, h	Rank	T_f, h
1	0.0251	21	1.3551	41	2.5260
2	0.0891	22	1.4595	42	3.4045
3	0.2501	23	1.5728	43	3.7433
4	0.3113	24	1.7083	44	5.4005
5	0.3451	25	1.7460	45	6.5541
6	0.4763	26	1.7630		
7	0.5671	27	1.7746		
8	0.6566	28	1.8275		
9	0.6751	29	1.8808		
10	0.6753	30	1.8878		
11	0.7696	31	1.8881		
12	0.8375	32	1.9316		
13	0.8391	33	1.9558		
14	0.8425	34	2.0048		
15	0.8645	35	2.0408		
16	1.0483	36	2.0903		
17	1.0596	37	2.1093		
18	1.0773	38	2.1330		
19	1.1733	39	2.2460		
20	1.2766	40	2.3470		

Table 10. Ordered list for 73.21% load-level at 120°C.

Rank	T_f, h	Rank	T_f, h
1	0.4217	21	1.5947
2	0.4375	22	1.6887
3	0.5748	23	1.8027
4	0.6323	24	2.2075
5	0.6600	25	2.3642
6	0.7923	26	2.4338
7	0.8143	27	2.6652
8	0.8268	28	3.1533
9	0.9142	29	3.3112
10	0.9362	30	3.7097
11	0.9562		
12	0.9990		
13	1.1547		
14	1.2247		
15	1.2278		
16	1.3070		
17	1.4352		
18	1.4980		
19	1.5045		
20	1.5180		

Table X. Ordered list for 73.21% load-level clamp breaks at 120°C.

Rank	T_f, h	Rank	T_f, h	Rank	T_f, h
1	0.1427	21	0.8585	41	1.6583
2	0.1782	22	0.9097	42	1.6828
3	0.2633	23	0.9566	43	1.8480
4	0.2967	24	0.9876	44	1.9000
5	0.3900	25	0.9920	45	2.1300
6	0.4278	26	1.0075	46	2.1980
7	0.4318	27	1.1120	47	2.2110
8	0.4390	28	1.2043	48	2.8480
9	0.4542	29	1.2063	49	2.9662
10	0.5313	30	1.2092	50	4.2721
11	0.5330	31	1.2411		
12	0.5353	32	1.2800		
13	0.5397	33	1.3091		
14	0.5538	34	1.3345		
15	0.5942	35	1.3732		
16	0.6197	36	1.3913		
17	0.6520	37	1.4313		
18	0.6762	38	1.4415		
19	0.7008	39	1.4430		
20	0.8112	40	1.5045		

Table 11. Ordered list for 67.19% load-level at 100°C.

Rank	T_f, h	Rank	T_f, h
1	4.5145	21[a]	168.6850
2	11.3375		
3	21.0517		
4	26.1750		
5	26.9767		
6	27.8417		
7	27.9033		
8	28.5850		
9	29.7867		
10	35.0933		
11	36.9050		
12	41.1783		
13	42.0117		
14	46.0433		
15	47.1717		
16	52.2283		
17	60.6517		
18	65.9333		
19	74.5300		
20	103.5917		

[a]There were only 21 samples in this test condition; see Ref. 1.

Table XI. Ordered list for 67.19% load-level clamp breaks at 100°C.

Rank	T_f, h	Rank	T_f, h
1	7.4662	21	43.9867
2	12.9017	22	47.6983
3	14.5092	23	48.6550
4	18.2700	24	49.3833
5	18.2867	25	51.9239
6	18.4283	26	54.1567
7	18.9767	27	57.8333
8	19.6067	28	59.4983
9	24.5867	29	65.8350
10	25.2250	30	70.9167
11	25.4050	31	74.7133
12	26.1517	32	87.0617
13	27.2833	33	102.2000
14	33.2800	34	105.4233
15	35.3183	35	109.3800
16	36.7000	36	138.4283
17	39.6950	37	156.8033
18	41.4117		
19	41.6983		
20	41.9100		

Table 12. Ordered list for 67.19% load-level at 110°C.

Rank	T_f, h	Rank	T_f, h
1	3.4347	21	26.4000
2	5.0883	22	28.1317
3	8.5342	23	28.5900
4	9.8350	24	28.6517
5	9.9262	25	30.6183
6	10.6818	26	30.9917
7	11.4787	27	31.4000
8	11.6778	28	39.2433
9	12.9188	29	40.8633
10	14.3510	30	60.1983[a]
11	14.8937	31	63.6067
12	15.0912		
13	16.6075		
14	17.5983		
15	19.2267		
16	19.5367		
17	19.7300		
18	22.5367		
19	22.8000		
20	24.4950		

[a]Not reported in Ref. 1 to restrict reported sample size to 30.

Table XII. Ordered list for 67.19% load-level clamp breaks at 110°C.

Rank	T_f, h	Rank	T_f, h
1	5.2947	21	35.0900
2	5.8670	22	37.8417
3	7.1213	23	45.1067
4	8.6980		
5	8.7880		
6	9.2728		
7	9.6667		
8	10.0907		
9	10.9848		
10	11.1485		
11	11.4930		
12	12.6927		
13	13.4178		
14	15.1522		
15	18.0317		
16	19.4867		
17	21.5833		
18	27.0783		
19	30.5233		
20	30.5433		

Table 13. Ordered list for 67.19% load-level at 120°C.

Rank	T_f, h	Rank	T_f, h
1	1.8945	21	7.3313
2	3.1152	22	7.7587[a]
3	3.1335[a]	23	8.0393
4	3.2647	24	8.0693[a]
5	3.8520	25	8.7558
6	4.2488[a]	26	9.2563
7	4.3017	27	9.5418
8	4.3942	28	9.6902
9	4.6416	29	9.9316
10	5.5310	30	10.0180
11	5.6333	31	10.4188
12	5.7006	32	10.7250[a]
13	5.8730	33	10.9411
14	5.8737	34	11.7962[a]
15	5.9378	35	13.5307[a]
16	6.1960[a]	36	14.5067
17	6.4513	37	15.3013
18	6.8320[a]	38	16.2742[a]
19	7.2595	39	18.2682
20	7.3183	40	19.2033

[a]Not reported in Ref. 1 to restrict reported sample size to 30.

Table XIII. Ordered list for 67.19% load-level clamp breaks at 120°C.

Rank	T_f, h	Rank	T_f, h
1	0.7367	21	6.2217
2	1.1627	22	6.2630
3	1.9340	23	6.3163
4	2.3180	24	6.9447
5	2.6483	25	8.1928
6	2.9918	26	8.4166
7	2.8573	27	8.8398
8	3.0797	28	9.2497
9	3.4873	29	9.6472
10	3.5380	30	10.4028
11	3.6335	31	12.0750
12	3.6541	32	12.6933
13	3.7645	33	13.8105
14	3.8196		
15	3.9653		
16	4.7070		
17	4.8885		
18	5.1746		
19	5.4962		
20	5.5588		

Table 14. Ordered list for 56.40% load-level at 110°C.[b]

Rank	T_f, h	Rank	T_f, h	Rank	T_f, h
1	58[a]	21	186[a]	41	336
2	66[a]	22	192	42	337
3	66[a]	23	196[a]	43	338
4	72	24	198	44	338
5	74[a]	25	209[a]	45	357
6	96	26	216	46	360
7	102[a]	27	232	47	360
8	110[a]	28	236	48	360
9	120	29	237	49	360
10	120	30	240	50	376
11	120	31	240	51	384
12	132	32	252	52	402
13	135[a]	33	257	53	408
14	143[a]	34	266	54	418
15	144[a]	35	275[a]	55	432
16	164[a]	36	278	56	462
17	168	37	285[a]	57	463[a]
18	168	38	292	58	482
19	168	39	327	59	523[a]
20	172	40	336		

[a]Data collected after Ref. 2 was published.

[b]No clamp break data available.

APPENDIX E.

STESS-RUPTURE OF KEVLAR 49/EPOXY SPHERICAL PRESSURE VESSELS: TIME-TO-BURST DATA

The data presented in Tables E1-E4 were obtained from LLL studies of composite pressure vessel lifetimes (see UCID-17755,Part 1). Kevlar 491 epoxy spherical pressure vessels were held under constant load (pressure) until failure (burst). As of June 1978, no vessels at the 50% pressure level had failed (test start date, 6/14/77), one vessel (No. 169) was withheld. Vessels were withheld from these test if...

Material system	Vessel geometry	Pressure levels,[a] %
Kevlar 49 (380 denier) in Dow DER 332/Jeferson Jeff-amine T-403 (100/44.7)	114-mm-diameter spherical pressure with a 1.1-mm-composite wall thickness: wound in a delta axisym metric pattern over a thin aluminum liner	86, 80, 74, 68, and 50

[a]Percent of mean average static burst pressure.

Table E1. Kevlar 49/epoxy pressure vessels loaded at 86% pressure level. Five vessels were withheld, Nos. 137, 189, 222, 233, and 238; vessel No. 233 was used for holographic studies.

Rank	Vessel No.	T_f, h	Rank	Vessel No.	T_f, h
1	65	2.2	20	51	55.4
2	197	4.0	21	208	61.2
3	210	4.0	22	138	87.5
4	205	4.6	23	245	98.2
5	202	6.1	24	83	101.0
6	176	6.7	25	36	111.4
7	209	7.9	26	166	144.0
8	140	8.3	27	31	158.7
9	66	8.5	28	147	243.9
10	42	9.1	29	124	254.1
11	49	10.2	30	13	444.4
12	87	12.5	31	244	590.1
13	135	13.3	32	241	638.2
14	220	14.0	33	17	755.2
15	94	14.6	34	21	952.2
16	170	15.0	35	23	1 108.2
17	90	18.7	36	122	1 148.5
18	46	22.1	37	109	1 569.3
19	217	45.9	38	105	1 750.6
			39	120	1 802.1

Table E2. Kevlar 49/epoxy pressure vessels loaded to 80% pressure level. Five vessels were withheld, Nos. 4, 7, 84, 168, and 239.

Rank	Vessel No.	T_f, h
1	80	19.1
2	75	24.3
3	79	69.8
4	60	71.2
5	77	136.0
6	55	199.1
7	57	403.7
8	44	432.2
9	15	453.4
10	74	514.1
11	191	514.2
12	183	541.6
13	69	544.9
14	237	554.2
15	29	664.5
16	61	694.1
17	110	876.7
18	12	930.4
19	185	1 254.9
20	118	1 275.6
21	119	1 536.8
22	26	1 755.5
23	247	2 046.2
24	108	6 177.5

Table E3. Kevlar 49/epoxy pressure vessels loaded at 74% pressure level on 11/14/77. As of June 1978, 13 vessels were remaining on test. These vessels were pressurized previously to 74% load (3 700 psi) with acoustic emission monitoring.

Rank	Vessel No.	T_f, h
1	174	225.2
2	200	503.6
3	93	1 087.7
4	39	1 134.3
5	50	1 824.3
6	45	1 920.1
7	56	2 383.0
8	243	2 442.5
9	112	2 974.6
10	35	3 708.9
11	231	4 908.0

Table E4. Kevlar 49/epoxy pressure vessels loaded to 68% pressure level on 6/27/77. As of June 1978, 18 vessels were remaining on test. Four vessels were withheld, Nos. 22, 52, 98, and 136.

Rank	Vessel No.	T_f, h
1	204	4 000
2	218	5 230
3	163	7 320

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