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CHARACTERIZATION OF KEVLAR-49 YARN

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ABSTRACT

A study was made to determine the variability in Dupont's 380-denier Kevlar-49 yarn. Both in-spool and spool-to-spool variations in tensile strength, cross-sectional area, and chemical composition were determined for one lot of material.

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SUMMARY

A program is complete that randomly sampled Kevlar-49 yarns for chemical analysis. Two samples from four regions of four spools of the yarn were randomly selected and analyzed for major elements, ash, and trace elements, as sampled in a 10% RH (relative humidity) environment. The resulting empirical chemical formula ($C_{6.93}H_{5.19}O_{1.18}N_{1.00}$) was in good agreement with the theoretical formula of $C_7H_5O_1N_1$, except for slightly high values for hydrogen and oxygen due to some absorbed moisture. The Kevlar-49 yarns contained $1.0 \pm 0.2\%$ ash that consisted of mixed sodium carbonate/sulfate and was a major source of spool-to-spool variability for these chemical analyses. The overall material balance ($C + H + O + N + \text{ash}$) was 99.9+% by weight for all 32 measurements. Spark-source mass spectrographic analysis of the ash was used to indicate the major trace impurities.

INTRODUCTION

Careful control of both the winding process and basic materials is required to assure the consistent behavior of high-performance, filament-wound, composite structures. Variation in such fiber properties as the tensile strength and fiber cross-sectional area can cause noticeable changes in the performance of the finished composite structure. These factors can affect such composite properties as ultimate strength, stiffness, volume fraction fiber, and the composite dimensions. This study, conducted at the Oak Ridge Y-12 Plant,^(a) provides information on the tensile strength, strand cross-sectional area, and chemical composition of Dupont's 380-denier Kevlar-49 yarn. The study also provides information on the spool-to-spool and in-spool variability of these parameters. Data from the study will be useful for the design and fabrication of filament-wound composites as well as providing a data base for long-term aging studies.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the Department of Energy.

CHARACTERIZATION OF THE YARN

EXPERIMENTAL DESIGN

An experiment was designed to evaluate the variability in three areas of interest: (1) ultimate tensile strength, (2) strand cross-sectional area, and (3) chemical composition. Both spool-to-spool and in-spool variability was evaluated. The design was constructed to allow estimations to be made of the associated variabilities in three areas of interest, namely: (1) variability (σ^2) within a localized sampling area of the yarn; (2) variability ($\sigma^2_{A/S}$) within a spool of yarn, and (3) variability (σ^2_S) between spools of yarn.

Two basic goals were established for this study: (1) to determine if there is any real variability between spools (ie, is $\sigma^2_S > 0$?); (2) to determine if there is any real variability within a spool from location to location (ie, is $\sigma^2_{A/S} > 0$?).

Spools were randomly selected, based on the following criteria: Select an S number of spools that contain k areas from which an n number of samples can be taken. The total number of samples taken for testing would then be $Sk n$. Values of S, k, and n were chosen so that if the variability between spools is less than the localized variability ($\sigma^2_S < \sigma^2$), then the between-spool variability would not be considered significantly greater than zero. However, if the variability between spools is greater than the localized variability ($\sigma^2_S \geq \sigma^2$), then it can be detected with a high degree of confidence. Given a 5% level of significance, there is a 95% confidence of detecting values of $\sigma^2_S > 0$ if $\sigma^2_S \geq \sigma^2$.

The final design required the random selection and characterization of four spools of Kevlar-49 taken from a total quantity of 480 spools. Five samples were taken for the tensile-strength test, and five samples were taken for denier measurements at ten random locations in each spool. Two hundred samples of each type were collected and tested. Evaluation of the chemical variability of the yarn was based on a subsample of the denier/tensile strength sample. This subsample consisted of four of the ten areas for each spool and two of the five subregions within each area. The areas making up the subsample were chosen randomly. The material was chosen from a 1135-kg (2500-lb) lot of Dupont's 380-denier Kevlar-49 yarn without finish. The material was shipped on nominal 2.3-kg (5-lb) spools, with 48 spools packaged per shipping carton. The 1135-kg (2500-lb) lot of material was received in ten cartons.

TESTING PROCEDURES

A discussion of the testing procedures used in the experiment follows:

Cross-Sectional Area

The average cross-sectional area of the yarn was measured indirectly by measuring the weight per unit length of the yarn. This value is reported in terms of denier, where the standard definition (the weight in grams of 9000 meters of yarn) is used. A uniform density of 1.45 g/cm^3 was assumed for Kevlar-49.

The length of a sample was measured by winding 50 circuits of yarn directly from the spool onto a 203.18-mm (7.999-in)-diameter mandrel, then the yarn was removed from the mandrel and dried. A drying cycle of 16 hours at 70° C in a vacuum less than 13 Pa (100 μ m) was used. Finally, the dried yarn was weighed to the nearest 0.1 mg, and the denier was calculated as the weight in grams of 9000 meters. Appendix A reports the data that were obtained from this test.

Tensile Strength

Standard 0.46-m (18-in), epoxy-coated strands were fabricated. An epoxy-resin system was used, that was composed of one hundred parts by weight of Dow's DER 332 epoxy resin and 43 parts by weight of Jefferson Chemical Jeffamine T403 hardener. The strands were wound over a metal frame and cured for 16 hours at 85° C (185° F). The strands were then tested in an Instron tensile tester, using standard 25 x 102 mm (1 x 4 in) hard-rubber-faced grips. The tests were conducted according to ASTM D2343, Procedure B. Appendix B reports the data that were obtained from this test.

Chemical Analysis and Gradient-Density Measurements

Chemical analyses were carried out on the Kevlar-49 samples as removed from the spool in a 10% relative humidity (RH) environment (Appendix C). Elemental composites for carbon, nitrogen, and hydrogen were determined, using a Perkin-Elmer CHN analyzer. This analyzer was converted to an oxygen-analysis mode for the oxygen determinations. Oxygen was also determined by neutron activation analysis. In order to screen this material for major organic contamination, infrared analyses of these samples were determined after grinding the Kevlar-49 in liquid nitrogen (-210° C) and compacting 1 mg of this powder in 400 mg of potassium bromide. The samples were converted to ash by heating in air at 250° C or by ignition in a Parr bomb. The ash yield was determined by weighing, and the composition of the ash was qualitatively determined by X-ray diffraction analysis. The ash was then compacted with high-purity silver powder and analyzed for trace-element impurities by spark-source mass spectroscopy (Appendix D). The density of these Kevlar-49 samples was determined by the liquid-gradient-column method (Appendix C).^(b)

Results

One hundred and ninety-five denier samples were collected from the four spools. Fifty samples were removed from each spool with the exception of the third spool. This spool ran out of yarn before the tenth sampling location was reached, allowing only 45 samples to be collected. The data were analyzed, and the results are summarized in Table 1. The average dry denier for all of the samples was 380.97. The actual data are reported in Figure 1.

Results indicate that 94.3% of the variability occurs from spool-to-spool differences. Very little variation (0.2%) in denier was observed between locations within each spool. The local variation was 5.5%. Most of this variability is due to a sinusoidal variation of approximately

(b) Canada D. C. and Laing, W. R.; "Use of a Density Gradient Column to Measure the Density of Microspheres", *Analytical Chemistry*, 39, pp 691 and 692 (1967).

± 5 denier that occurs every 50.7 m (166 ft). This variation was determined by using a non-contact-capacitance-type denier monitor, and a typical reading is given in Figure 2.

One hundred and eighty-five Kevlar epoxy strands were tested for tensile strength. Results of the test

Table 1
RESULTS OF A STATISTICAL ANALYSIS
OF THE DENIER VARIATION IN KEVLAR-49 YARN

Source of Variability ⁽¹⁾	Estimate of Variance (denier)	Percent of Variability	Coefficient of Variation (%)
σ^2_D (total)	48.43	100.0	1.83
σ^2_S (spool to spool)	45.66	94.3	1.77
$\sigma^2_{A/S}$ (in spool)	0.10	0.2	0.08
σ^2 (local)	2.66	5.5	0.43

(1) Mean denier for all samples = 380.97.

Figure 1. DENIER VARIATIONS IN 380-DENIER KEVLAR-49 YARN. (Vertical Bars Indicate the Standard Deviation for Five Points)

are given in Figure 3. Five strands were not made because of reasons stated previously. Two additional sets of strands were rejected because of their very low resin content which resulted in an obvious change in the appearance of the fractured strand. The results of the test are summarized in Table 2. Initial analysis indicates that significant in-spool and local variability in tensile-strength exists in the Kevlar-49 yarn.

Greater scatter was observed in the data than was expected, based on earlier preliminary testing. When the strands were made, 20 to 30 strands were taken at each sampling location. Five strands were then selected from each group and tested. Because of the scatter, a second set of five strands was taken from each group and weighed to determine the average resin content. The average weight percent resin for each group was plotted versus the average tensile strength of each group (Figure 4). A definite trend was observed in which the average

Figure 2. LOCAL DENIER VARIATION AS DETERMINED BY THE CAPACITANCE GAGE.
(Variation = ± 5 Denier; Period = 50.9 Meters)

tensile strength increased as the resin content increased. This phenomenon has not been observed in the composite structures fabricated in the Y-12 Plant. An increase in the tensile strength of composite structures has always occurred with increased fiber contents.

Photomicrographs were made of samples with low and high resin contents (Figures 5 and 6). The strands with low resin contents show poor impregnation with an increased void content. These strands also have a large percentage of fibers on the surface that are weakly connected to the main body of the strand by thin webs of resin. It will be very difficult for these fibers to behave as an integral part of the strand. Both of these factors probably contribute to the decrease in strand strength. Strands, for these reasons, do not appear to accurately predict optimum resin contents for large composite structures.

A second statistical analysis was made on the tensile-strength data in which corrections were made for the effects of variation in the resin content. A straight line was fitted through the data, using least-squares techniques. These results are reported in Table 3. A statistically significant difference in the tensile-strength variability within the spool was observed, but the majority of variability (60.46%) was local variability. If a more appropriate curve was fitted to the data, then the in-spool variability would decrease. Variations in tensile strength were not large; and, when the test specimens were restricted to a resin content in the 39 to 50% range, the average tensile strength for 380-denier Kevlar-49 yarn was in the 3.79-GPa (550-ksi) range.

The major elemental, ash, and density data resulting from the chemical analyses are summarized in Table 4. The material balance, using the averages of all samples reported in Table 4, totaled 99.93% (when applying the CHN-determined oxygen) and 99.90% (when applying the oxygen values from the neutron activation analysis). The simple chemical formulas are in good agreement with the theoretical formula of $C_7H_5O_1N_1$, except for the hydrogen and oxygen values which probably resulted from the moisture content of the yarn ($\sim 1.5\%$).

Figure 3. STRENGTH VARIATION IN 380-DENIER KEVLAR-49 YARN. (Vertical Bars Indicate the Standard Variation for Five Points)

Table 2
STATISTICAL ANALYSIS OF THE STRENGTH VARIATION IN KEVLAR-49 YARN

Source of Variability	Estimate of Variance(1) (Pa x 10 ¹⁵)	Percent of Variability	Coefficient of Variation (%)
σ^2_D (total)	72.35	100.00	7.35
σ^2_S (spool to spool)	2.79	3.86	1.44
$\sigma^2_{A/S}$ (in spool)	48.46	66.98	6.01
σ^2 (local)	21.10	29.16	3.97

(1) Mean tensile strength for all samples = 3.661 GPa (530.9 ksi).

Figure 4. EFFECTS OF POOR IMPREGNATION ON KEVLAR-49 YARN TENSILE STRENGTHS.

Figure 5. A STRAND THAT SHOWS POOR IMPREGNATION. MS-77-0173-7

Figure 6. A STRAND THAT SHOWS GOOD IMPREGNATION. MS-77-0173-3

Table 3
STATISTICAL ANALYSIS OF THE STRENGTH VARIATION IN KEVLAR-49 CORRECTED FOR THE VARIATION IN RESIN CONTENT

Source of Variability(1)	Estimate of Variance (Pa x 10 ¹⁵)	Percent of Variability	Coefficient of Variation (%)
σ^2_D (total)	31.76	100.00	4.87
σ^2_S (spool to spool)	0.88	2.78	0.81
$\sigma^2_{A/S}$ (in spool)	9.77	30.76	2.70
σ^2 (local)	21.10	60.46	3.97

(1) Mean tensile strength for all samples = 3.661 GPa (530.9 ksi).

Table 4
CHEMICAL ANALYSIS OF KEVLAR-49 YARNS

Empirical Chemical Formula	Spool Number	Composition (wt %)(1)						Gradient Density (g/cm ³)(1)
		Nitrogen	Carbon	Hydrogen	Oxygen by CHN	Oxygen by ACT	Ash(2)	
C _{6.91} H _{5.14} O _{1.20} N _{1.00}	1	11.42 (0.03)	67.68 (0.13)	4.23 (0.06)	15.62 (0.32)	14.90 ⁽³⁾ (0.37)	1.16 (0.04)	1.4577 (0.0185)
C _{6.92} H _{5.14} O _{1.21} N _{1.00}	2	11.44 (0.07)	67.86 (0.22)	4.24 (0.03)	15.84 (0.26)	15.02 ⁽³⁾ (0.69)	1.25 (0.03)	1.4468 (0.0137)
C _{6.98} H _{5.25} O _{1.17} N _{1.00}	3	11.33 (0.10)	67.81 (0.29)	4.28 (0.05)	15.19 (0.22)	15.82 ⁽⁴⁾ (0.35)	0.94 (0.01)	1.4361 (0.0627)
C _{6.92} H _{5.23} O _{1.16} N _{1.00}	4	11.44 (0.09)	67.82 (0.41)	4.31 (0.07)	15.18 (0.35)	15.94 ⁽⁴⁾ (0.71)	1.03 (0.04)	1.4011 (0.0603)
C _{6.93} H _{5.19} O _{1.18} N _{1.00}	1 - 4	11.41 (0.09)	67.76 (0.26)	4.26 (0.06)	15.44 (0.40)	15.41 (0.71)	1.06 (0.12)	1.4374 (0.0461)

(1) Standard deviation is given in parentheses.

(2) X-ray diffraction analysis identified this ash as sodium sulfate, sodium carbonate, and mixed sodium sulfate carbonate compounds.

(3) Activation analyzer standardized against a 1% oxygen standard.

(4) Activation analyzer standardized against an 11% oxygen standard.

Table 5 gives the sources of variability for the chemical analyses. The major source of variability was within measurements, with oxygen exhibiting the greatest variability. This oxygen variability probably results from moisture absorption by the Kevlar and the complex composition of the ash (ie, part of the oxygen retained in the ash may be reflected in the oxygen determination). The ash data displayed a significant spool-to-spool variability. The in-spool variability of the gradient-density measurements was greater for Spools 3 and 4 because of a few very low values for gradient-density samples, which resulted in a lowering of the mean value of the gradient density of these rolls.

Table 5
SOURCES OF VARIABILITY FOR THE CHEMICAL ANALYSIS OF KEVLAR-49 YARN

Element	Type of Variation			Total
	Spool to Spool	Area to Area	Pairs of Measurements within an Area	
Nitrogen				
Standard Deviation	0.036	0.050	0.063	0.088
Percent Variability(1)	(16)	(33)	(51)	(100)
Carbon				
Standard Deviation	0.000	0.248	0.160	0.295
Percent Variability(1)	(0)	(71)	(29)	(100)
Hydrogen				
Standard Deviation	0.030	0.034	0.040	0.060
Percent Variability(1)	(24)	(31)	(45)	(100)
Oxygen by CHN				
Standard Deviation	0.298	0.000	0.337	0.450
Percent Variability(1)	(44)	(0)	(56)	(100)
Oxygen by ACT				
Standard Deviation	0.473	0.256	0.517	0.746
Percent Variability(1)	(40)	(12)	(48)	(100)

(1) The percent variability was based on variances, not on standard deviation.

Table 6 gives the major trace in the ash, as determined by spark-source mass spectroscopy. The major elemental components of the ash and its matrix [ie, the elements comprising mixed sodium carbonate/sulfate (Na, O, S, C) and the silver electrode material (AG)] could

not be determined by this method. A detailed variability analysis was not carried out since the precision of spark-source mass spectroscopy analysis is approximately a factor of two. However, spool-to-spool and in-spool variability was generally within this factor-of-two precision range. Notable exceptions were: a high chlorine content in Spool 1, a high iron content for Spool 1 that resulted from a high in-spool variability, a high thorium content in Spool 1, and high zinc and uranium contents in Spool 3.

A typical infrared analysis is given in Figure 7. The infrared spectra were qualitatively similar, but there were very significant differences (approximately a factor of 2) in the magnitude of the absorption of specimens having "identical" preparative histories.

CONCLUSIONS

As a result of this study, the following conclusions can be stated:

Table 6
MAJOR TRACE ELEMENTS IN KEVLAR-49 YARNS AS DETERMINED BY SPARK-SOURCE MASS SPECTROMETRIC ANALYSIS OF THE ASH COMPACTED WITH SILVER POWDER

Element(2)	Spool(1)				
	1	2	3	4	1 - 4
Al	8	10	6	5	7
Ba	0.2	0.3	0.5	0.8	0.5
Ca	7	6	15	10	9
Cl	60(3)	20	20	20	30
Cr	2	3	3	2	2
Fe	40(4)	20	20	10	20
K	30	50	40	30	40
Mg	4	3	5	3	4
Ni	2	1	2	1	2
P	3	4	4	5	4
Si	30	20	30	20	20
Th	4(3)	0.03	0.05	0.02	0.8
U	0.2	0.1	2(3)	0.2	0.8
W	0.08	0.8	0.3	0.7	0.5
Zn	1	2	20(3)	2	8

- (1) These results are reported as parts per million by weight (wppm) rounded to one significant figure.
- (2) Sodium, oxygen, carbon, sulfur, and silver were present in quantities too great to measure by this analysis. Some tantalum (~ 1 wppm) was detected, but was attributed to the electrode clamps in the spectrometer.
- (3) Significantly different from other spools.
- (4) In-spool variability was responsible for this high value relative to the other spools.

Figure 7. A TYPICAL INFRARED ANALYSIS OF KEVLAR-49 YARN.

1. No significant change was observed in the cross-sectional area of an end of 380-denier Kevlar-49 throughout the length of a spool.

2. If the thickness of a filament-wound part or the modulus of a molded part must be precisely controlled, care will have to be exercised in material selection due to a significant spool-to-spool variation in the cross-sectional area of the yarn.
3. The tensile strength of 380-denier Kevlar-49 yarn is in the 3.79-GPa (550-ksi) range when strands with 39 to 50% resin are tested.
4. While a significant in-spool variation in the tensile strength was observed, the overall variability was small ($< 5\%$) and the spool-to-spool variability was very small ($< 1\%$).
5. Variability in the chemical analyses is small, with good agreement with the empirical formula. Major sources of variability appear to result from moisture absorption, ash content, and the measurements themselves.
6. Future analyses should require a thorough drying step, rigorous control of cleanliness in sampling yarn for ashing by the Parr-bomb method and subsequent spark-source mass spectroscopy, and a considerable improvement in infrared analysis if this analysis is to be of significant value.

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APPENDIX A

Data from the Denier Studies

Table A-1 DENIER VALUES FOR SPOOL 1		Table A-2 DENIER VALUES FOR SPOOL 2	
Sample Location (km)	Denier Value	Sample Location (km)	Denier Value
2.47925	390.24	1.927	376.61
2.47925	389.08	1.927	373.48
2.47925	390.4	1.927	375.15
2.47925	388.46	1.927	375.68
2.47925	389.93	1.927	373.03
5.51305	390.24	10.832	375.6
5.51305	389.9	10.832	376.76
5.51305	387.95	10.832	374.02
5.51305	388.06	10.832	377.4
5.51305	389.45	10.832	373
8.54553	390.35	16.089	373.6
8.54553	387.08	16.089	380.42
8.54553	390.07	16.089	373.74
8.54553	389.59	16.089	377.01
8.54553	387.98	16.089	377.12
12.47623	390.12	20.789	378.31
12.47623	387.84	20.789	372.91
12.47623	389.7	20.789	380.22
12.47623	390.69	20.789	378.05
12.47623	387.89	20.789	377.46
19.90387	390.93	30.26	376.53
19.90387	389.64	30.26	375.51
19.90387	387.44	30.26	377.04
19.90387	391.42	30.26	374.08
19.90387	388.49	30.26	377.63
24.32377	392.15	33.569	376.3
24.32377	387.13	33.569	375.26
24.32377	390.15	33.569	377.15
24.32377	390.15	33.569	373.91
24.32377	387.27	33.569	378.73
33.23109	389.08	36.603	372.92
33.23109	390.01	36.603	375.8
33.23109	386.92	36.603	377.38
33.23109	389.28	36.603	374.67
33.23109	390.01	36.603	374.78
39.04425	391.73	39.636	374.81
39.04425	387.33	39.636	375.15
39.04424	391.17	39.636	373.91
39.04424	389.73	39.636	372.75
39.04424	388.12	39.636	374.75
43.46689	390.55	44.05363	379.8
43.46689	392.43	44.05363	372.5
43.46689	387.5	44.05363	377.15
43.46689	392.46	44.05363	373.34
43.46689	389.9	44.05363	373.94
47.05443	393.59		
47.05443	390.18		
47.05443	391.25		
47.05443	393.11		
47.05443	388.52		

Table A-3
DENIER VALUES FOR SPOOL 3

Sample Location (km)	Denier Value
6.35921	382.48
6.35921	383.81
6.35921	379.66
6.35921	380.53
6.35921	382.28
8.83815	380.84
8.83815	382.42
8.83815	381.3
8.83815	381.66
8.83815	381.78
10.49295	383.5
10.49295	382.73
10.49295	382
10.49295	381.44
10.49295	383.55
15.74923	381.01
15.74923	382.59
15.74923	383.64
15.74923	383.64
15.74923	382.73
17.67557	383.35
17.67557	381.27
17.67557	385.67
17.67557	381.07
17.67557	381.66
22.09437	382.68
22.09437	384.65
22.09437	381.24
22.09437	385.47
22.09437	382.71
28.50998	381.66
28.50998	383.44
28.50998	380.79
28.50998	380.99383
28.50998	384.4
32.93015	382.88
32.93015	384.43
32.93015	384.4
32.93015	382.4
32.93015	380.64
36.5188	381.21
36.5188	382.73
36.5188	381.27
36.5188	381.66
36.5188	383.02
40.9376	386.91
40.9376	380.68
40.9376	383.44
40.9376	387.73
40.9376	382.03

Table A-4
DENIER VALUES FOR SPOOL 4

Sample Location (km)	Denier Value
6.218	374.89
6.218	375.74
6.218	374.53
6.218	372.81
6.218	373.96
11.9	374.5
11.9	374.46
11.9	373.57
11.9	375.97
11.9	375.91
15.489	375.51
15.489	375.49
15.489	374.64
15.489	376.78
15.489	376.45
17.968	375.23
17.968	375.99
17.968	376.78
17.968	378
17.968	375.94
19.343	375.32
19.343	377.23
19.343	377.23
19.343	374.47
19.343	378
29.395	375.97
29.395	377.01
29.395	375.8
29.395	375.2
29.395	375.57
32.152	376.19
32.152	374.67
32.152	373.34
32.152	375.32
32.152	376.33
37.966	374.7
37.966	374.13
37.966	375.29
37.966	376.61
37.966	374.41
41.831	374.73
41.831	375.88
41.831	375.82
41.831	373.4
41.831	374.1
46.139	376.11
46.139	377.43
46.139	374.22
46.139	374.75
46.139	376.19

APPENDIX B

Data from the Tensile-Strength Studies

Table B-1

TENSILE STRENGTHS FOR SPOOL 1

Sample Location (km)	Tensile Strength (ksi)
2.47925	538.064
2.47925	553.191
2.47925	540.225
2.47925	551.03
2.47925	522.938
5.51305	566.866
5.51305	538.739
5.51305	504.122
5.51305	577.68
5.51305	573.357
8.54553	560.545
8.54553	534.457
8.54553	580.024
8.54553	571.367
8.54553	543.231
12.47623	510.469
12.47623	525.61
12.47623	547.24
12.47623	564.544
12.47623	536.425
19.90387	518.748
19.90387	503.681
19.90387	486.461
19.90387	477.851
19.90387	507.986
24.32377	529.764
24.32377	553.549
24.32377	575.172
24.32377	490.843
24.32377	521.115
33.23109	560.553
33.23109	558.38
33.23109	530.135
33.23109	512.754
33.23109	543.171
39.04425	507.823
39.04425	497.018
39.04425	514.305
39.04425	514.305
39.04425	522.949
43.46689	551.855
43.46689	521.675
43.46689	545.388
43.46689	560.478
43.46689	532.454
47.05443	527.108
47.05443	486.231
47.05443	550.775
47.05443	544.32
47.05443	574.441

Table B-2

TENSILE STRENGTHS FOR SPOOL 2

Sample Location (km)	Tensile Strength (ksi)
1.927	579.6
1.927	500.9
1.927	539.1
1.927	487.5
1.927	534.6
10.832	560.8
10.832	533.8
10.832	520.4
10.832	549.5
10.832	545.1
16.089	574.9
16.089	563.8
16.089	541.4
16.089	530.2
16.089	574.9
20.789	508.7
20.789	539.9
20.789	519.8
20.789	526.5
20.789	515.4
30.26	550.6
30.26	566.3
30.26	541.7
30.26	573
30.26	530
33.569	572.8
33.569	545.97
33.569	528.1
33.569	514.7
33.569	534.8
36.603	563.8
36.603	570.6
36.603	566.1
36.603	563.8
36.603	575
39.636	512.9
39.636	512.9
39.636	530.9
39.636	535.4
39.636	533.1
44.054	540.6
44.054	549.6
44.054	529.4
44.054	554
44.054	565.3

Table B-3

TENSILE STRENGTHS FOR SPOOL 3

Sample Location (km)	Tensile Strength (ksi)
6.35921	562.392
6.35921	542.543
6.35921	544.749
6.35921	564.598
6.35921	524.9
8.83813	542.735
8.83813	560.038
8.83813	573.622
8.83813	573.622
8.83813	586.86
10.49295	488.47
10.49295	517.074
10.49295	543.478
10.49295	558.88
10.49295	574.283
15.74923	519.161
15.74923	534.559
15.74923	519.161
15.74923	530.16
15.74923	499.362
17.67557	539.125
17.67557	510.518
17.67557	495.115
17.67557	503.917
17.67557	486.313
22.09437	474.382
22.09437	434.859
22.09437	480.98
22.09437	467.803
22.09437	491.962
28.50998	562.033
28.50998	539.993
28.50998	513.544
28.50998	537.788
28.50998	570.849
32.93015	426.514
32.93015	452.897
32.93015	455.095
32.93015	485.874
32.93015	459.492
36.5188	491.525
36.5188	504.749
36.5188	491.525
36.5188	487.117
36.5188	526.791
40.9376	471.202
40.9376	451.477
40.9376	499.683
40.9376	466.819
40.9376	477.777

Table B-4

TENSILE STRENGTHS FOR SPOOL 4

Sample Location (km)	Tensile Strength (ksi)
6.218	562.2
6.218	557.7
6.218	564.5
6.218	544.2
6.218	609.4
11.9	509.8
11.9	532.2
11.9	552.5
11.9	559.2
11.9	561.4
15.489	555.7
15.489	524.3
15.489	508.6
15.489	533.3
15.489	553.4
17.968	545.7
17.968	590.7
17.968	543.5
17.968	556.965
17.968	656.9
19.343	561.4
19.343	561.4
19.343	543.5
19.343	552.4
19.343	570.3
32.152	576.7
32.152	574.5
32.152	570
32.152	567.8
32.152	520.6
37.966	572.4
37.966	558.9
37.966	572.4
37.966	576.9
37.966	574.661
46.139	490.6
46.139	504.1
46.139	497.4
46.139	479.4
46.139	492.9

APPENDIX C

Chemical Analysis and Gradient-Density Measurements on Kevlar-49 Yarn

Table C-1
 CHEMICAL ANALYSES AND GRADIENT DENSITY
 MEASUREMENTS ON KEVLAR-49 YARNS
 (All Values in wt %)

Sample Location	Nitrogen	Carbon	Hydrogen	Oxygen by CHN	Oxygen by ACT	Ash	Gradient Density (g/cm ³)
111	11.41	67.51	4.16	15.88	14.80	1.17	1.4573
112	11.46	67.74	4.22	15.23	14.95		1.4537
121	11.39	67.68	4.34	15.54	15.07	1.11	1.4632
122	11.42	67.65	4.29	15.46	15.66	1.19	1.4197
131	11.40	67.54	4.22	15.14	14.76	1.12	1.4568
132	11.36	67.72	4.19	15.98	14.92		1.4619
141	11.46	67.68	4.19	15.89	14.43	1.21	1.4619
142	11.43	67.92	4.20	15.81	14.58		1.4874
211	11.27	67.98	4.21	16.07	13.74		1.4580
212	11.44	68.06	4.23	15.98	14.68	1.27	1.4240
221	11.44	67.96	4.22	16.04	14.93	1.25	1.4501
222	11.47	68.14	4.28	16.04	15.56	1.21	1.4494
231	11.42	67.52	4.23	15.34	16.08		1.4511
232	11.48	67.62	4.24	15.61	14.76	1.25	1.4275
241	11.48	67.91	4.28	15.85	15.18		1.4529
242	11.50	67.70	4.26	15.78	15.22		1.4616
311	11.30	67.88	4.24	14.96	16.38	0.94	1.5166
312	11.30	67.67	4.26	15.24	16.12	0.91	1.3879
321	11.15	67.32	4.36	15.54	15.77	0.95	
322	11.36	67.55	4.30	15.40	15.87	0.95	1.4631
331	11.39	67.92	4.28	15.18	15.29	0.94	1.3222
332	11.50	68.01	4.32	15.26	15.83	0.94	1.4594
341	11.32	68.22	4.26	14.92	15.41	0.95	1.4486
342	11.35	67.94	4.20	15.02	15.91	0.95	1.4552
411	11.44	67.72	4.28	15.04	16.08	1.05	
412	11.36	67.44	4.38	15.58	15.58	1.01	1.4417
421	11.36	67.44	4.32	15.01	16.49	1.06	1.4403
422	11.38	67.33	4.38	15.70	16.31	0.95	1.3214
431	11.48	68.32	4.38	15.00	16.09	1.05	1.4493
432	11.34	67.91	4.28	15.19	16.34	1.05	1.4279
441	11.53	68.02	4.28	14.60	16.29	1.05	1.3261
442	11.59	68.39	4.19	15.32	14.33	1.05	

APPENDIX D

Spark-Source Mass Spectrographic Analysis of Kevlar-49 Yarn

Table D-1
 SPARK-SOURCE MASS SPECTROGRAPHIC ANALYSIS OF
 KEVLAR-49 SPOOL 1 YARN
 (All Values in wppm)

Element		Sample Number ⁽¹⁾				
Z Value	Symbol	111	121	122	131	141
4	Be	< 0.001	0.003	0.007	0.003	0.07
8	O	Matrix	Matrix	Matrix	Matrix	Matrix
9	F	0.07	0.03	0.1	0.03	0.1
11	Na	Matrix	Matrix	Matrix	Matrix	Matrix
12	Mg	8.0	0.8	6.0	0.8	5.0
13	Al	9.0	3.0	10.0	9.0	9.0
14	Si	40.0	10.0	40.0	6.0	40.0
15	P	2.0	5.0	2.0	2.0	2.0
16	S	Matrix	Matrix	Matrix	Matrix	Matrix
17	Cl	50.0	50.0	100.0	50.0	50.0
19	K	40.0	20.0	50.0	10.0	30.0
20	Ca	9.0	1.0	10.0	7.0	10.0
21	Sc	< 0.009	< 0.004	< 0.01	< 0.004	< 0.01
22	Ti	0.4	0.2	0.5	0.06	0.2
23	V	0.0	0.005	0.01	0.005	0.01
24	Cr	2.0	0.3	2.0	0.7	2.0
25	Mn	0.1	0.06	0.1	0.2	1.0
26	Fe	10.0	3.0	20.0	70.0	70.0
27	Co	0.01	< 0.006	0.01	< 0.006	0.02
28	Ni	2.0	0.9	0.6	0.9	6.0
29	Cu	0.3	0.1	0.1	0.03	1.0
30	Zn	2.0	0.7	0.6	0.8	2.0
31	Ga	< 0.02	< 0.01	< 0.03	< 0.004	< 0.03
32	Ge	< 0.01	< 0.006	< 0.02	< 0.006	< 0.02
33	As	< 0.02	0.007	< 0.02	0.01	0.02
34	Se	< 0.01	≤ 0.02	≤ 0.02	≤ 0.006	< 0.01
35	Br	< 0.3	0.2	0.3	0.2	1.0
37	Rb	< 0.03	0.01	< 0.03	< 0.01	< 0.03
38	Sr	0.2	0.03	≤ 0.2	≤ 0.1	0.2
39	Y	< 0.02	0.009	< 0.02	< 0.009	0.02
40	Zr	0.02	0.009	0.02	0.02	0.02
41	Nb	0.1	0.009	0.01	< 0.009	0.2
42	Mo	0.3	0.06	0.3	0.1	0.3
44	Ru	< 0.02	< 0.01	< 0.02	< 0.01	< 0.02
45	Rh	< 0.007	< 0.003	< 0.008	< 0.003	< 0.008
46	Pd	< 0.03	< 0.01	< 0.03	< 0.01	< 0.03
47	Ag	Matrix	Matrix	Matrix	Matrix	Matrix
48	Cd	< 0.03	< 0.01	< 0.03	< 0.01	< 0.03
49	In	< 0.008	< 0.004	< 0.009	< 0.004	< 0.009
50	Sn	0.2	< 0.01	0.04	< 0.01	0.09
51	Sb	< 0.02	< 0.007	< 0.02	< 0.007	< 0.05
52	Te	< 0.03	< 0.01	< 0.03	< 0.01	< 0.03
53	I	< 0.009	< 0.004	< 0.009	< 0.004	< 0.009
55	Cs	< 0.009	< 0.004	< 0.01	< 0.004	< 0.01
56	Ba	0.4	0.03	0.2	0.2	0.1
57	La	< 0.01	< 0.004	< 0.01	< 0.004	< 0.01

Table D-1 (continued)
 SPARK-SOURCE MASS SPECTROGRAPHIC ANALYSIS OF
 KEVLAR-49 SPOOL 1 YARN
 (All Values in wppm)

Element		Sample Number ⁽¹⁾				
Z Value	Symbol	111	121	122	131	141
58	Ce	< 0.01	< 0.005	< 0.01	< 0.005	< 0.01
59	Pr	< 0.01	< 0.004	< 0.01	< 0.005	< 0.01
60	Nd	< 0.04	< 0.02	< 0.04	< 0.02	< 0.04
62	Sm	< 0.04	< 0.02	< 0.04	< 0.02	< 0.04
63	Eu	< 0.02	< 0.009	< 0.02	< 0.009	< 0.02
64	Gd	< 0.05	< 0.02	< 0.05	< 0.02	< 0.05
65	Tb	< 0.01	< 0.005	< 0.01	< 0.005	< 0.01
66	Dy	< 0.04	< 0.02	< 0.04	< 0.02	< 0.04
67	Ho	< 0.03	< 0.02	< 0.04	< 0.02	< 0.04
68	Er	< 0.04	< 0.02	< 0.04	< 0.02	< 0.04
69	Tm	< 0.01	< 0.005	< 0.01	< 0.005	< 0.01
70	Yb	< 0.04	< 0.02	< 0.04	< 0.02	< 0.04
71	Lu	< 0.01	< 0.006	< 0.01	< 0.006	< 0.01
72	Hf	< 0.05	< 0.02	< 0.05	< 0.02	< 0.05
73	Ta	≤ 1.0	≤ 0.3	≤ 0.1	≤ 0.06	< 0.1
74	W	0.1	0.06	0.1	0.06	0.1
75	Re	< 0.02	< 0.009	< 0.02	< 0.009	< 0.02
76	Os	< 0.03	< 0.02	< 0.03	< 0.02	< 0.03
77	Ir	< 0.02	< 0.01	< 0.02	< 0.01	< 0.02
78	Pt	< 0.04	< 0.02	< 0.04	< 0.02	< 0.04
79	Au	< 0.04	< 0.02	< 0.04	< 0.02	< 0.04
80	Hg	< 0.05	< 0.02	< 0.05	< 0.02	< 0.05
81	Tl	< 0.02	< 0.009	< 0.02	< 0.009	< 0.02
82	Pb	< 0.03	< 0.01	< 0.03	0.1	0.3
83	Bi	< 0.01	< 0.007	< 0.02	< 0.007	< 0.02
90	Th	0.5	2.0	3.0	7.0	6.0
92	U	0.2	0.04	0.09	0.08	0.6

(1) Data obtained by visual estimation of line densities and should be correct within a factor of 2.

Table D-2
 SPARK-SOURCE MASS SPECTROGRAPHIC ANALYSIS OF
 KEVLAR-49 SPOOL 2 YARN
 (All Values in wppm)

Element		Sample Number ⁽¹⁾			
Z Value	Symbol	212	221	222	232
4	Be	0.001	0.001	≤ 0.001	≤ 0.001
8	O	Matrix	Matrix	Matrix	Matrix
9	F	0.04	0.1	0.03	0.04
11	Na	Matrix	Matrix	Matrix	Matrix
12	Mg	0.9	6.0	3.0	1.0
13	Al	5.0	20.0	10.0	5.0
14	Si	10.0	40.0	10.0	10.0
15	P	2.0	6.0	4.0	4.0
16	S	Matrix	Matrix	Matrix	Matrix
17	Cl	20.0	30.0	8.0	9.0
19	K	50.0	50.0	50.0	50.0
20	Ca	5.0	10.0	5.0	5.0
21	Sc	0.005	< 0.01	< 0.005	< 0.005
22	Ti	0.2	0.1	< 0.07	0.07

Table D-2 (continued)
 SPARK-SOURCE MASS SPECTROGRAPHIC ANALYSIS OF
 KEVLAR-49 SPOOL 2 YARN
 (All Values in wppm)

Element		Sample Number(1)			
Z Value	Symbol	212	221	222	232
23	V	0.006	0.04	0.006	0.006
24	Cr	2.0	4.0	2.0	2.0
25	Mn	0.1	0.1	0.2	0.1
26	Fe	20.0	40.0	10.0	20.0
27	Co	0.01	0.02	0.006	< 0.006
28	Ni	0.5	3.0	1.0	1.0
29	Cu	0.2	0.3	0.3	0.3
30	Zn	0.9	2.0	0.4	0.3
31	Ga	0.01	< 0.03	< 0.01	< 0.01
32	Ge	0.007	< 0.01	< 0.007	< 0.007
33	As	0.008	0.02	< 0.003	< 0.003
34	Se	0.02	< 0.01	< 0.006	< 0.006
35	Br	0.6	1.0	0.6	0.6
37	Rb	0.04	0.04	< 0.01	< 0.01
38	Sr	0.1	≤ 0.2	0.2	0.1
39	Y	0.01	< 0.02	< 0.01	< 0.01
40	Zr	0.01	0.06	< 0.006	0.01
41	Nb	0.03	< 0.02	0.1	0.1
42	Mo	0.2	0.4	0.2	0.1
44	Ru	0.01	< 0.02	< 0.01	< 0.01
45	Rh	0.004	< 0.007	< 0.004	< 0.004
46	Pd	0.01	< 0.03	< 0.01	< 0.01
47	Ag	Matrix	Matrix	Matrix	Matrix
48	Cd	0.01	< 0.03	< 0.01	< 0.01
49	In	0.004	< 0.009	< 0.004	< 0.004
50	Sn	0.02	< 0.03	0.1	0.02
51	Sb	0.008	< 0.05	< 0.02	< 0.02
52	Te	0.01	< 0.03	< 0.01	< 0.01
53	I	0.005	< 0.03	< 0.005	< 0.005
55	Cs	0.005	< 0.01	< 0.005	< 0.005
56	Ba	0.1	1.0	0.07	0.04
57	La	0.005	< 0.03	< 0.02	< 0.02
58	Ce	0.006	< 0.01	< 0.006	< 0.006
59	Pr	0.005	< 0.01	< 0.005	< 0.005
60	Nd	0.02	< 0.04	< 0.02	< 0.02
62	Sm	0.02	< 0.04	< 0.02	< 0.02
63	Eu	0.01	< 0.02	< 0.01	< 0.01
64	Gd	0.03	< 0.05	< 0.03	< 0.03
65	Tb	0.006	< 0.01	< 0.006	< 0.006
66	Dy	0.02	< 0.04	< 0.02	< 0.02
67	Ho	0.02	< 0.04	< 0.006	< 0.02
68	Er	0.02	< 0.04	< 0.02	< 0.02
69	Ta	0.006	< 0.01	< 0.006	< 0.006
70	Yb	0.02	< 0.04	< 0.02	< 0.02
71	Lu	0.007	< 0.01	< 0.006	< 0.007
72	Hf	0.02	< 0.05	< 0.02	< 0.02
73	Ta	0.2	≤ 0.4	≤ 0.1	≤ 0.1
74	W	0.1	0.2	2.0	1.0
75	Re	0.01	< 0.02	< 0.01	< 0.01
76	Os	0.02	< 0.03	< 0.02	< 0.02
77	Ir	0.01	< 0.02	< 0.01	< 0.01
78	Pt	0.02	< 0.04	< 0.02	< 0.02
79	Au	0.02	< 0.04	< 0.02	< 0.02
80	Hg	0.03	< 0.05	< 0.02	< 0.03

Table D-2 (continued)

SPARK-SOURCE MASS SPECTROGRAPHIC ANALYSIS OF
KEVLAR-49 SPOOL 2 YARN
(All Values in wppm)

Element		Sample Number ⁽¹⁾			
Z Value	Symbol	212	221	222	232
81	Tl	0.1	< 0.02	< 0.01	< 0.01
82	Pb	0.07	1.0	< 0.01	< 0.02
83	Bi	0.008	< 0.02	< 0.007	< 0.008
90	Th	0.03	0.03	0.01	0.04
92	U	0.03	0.2	0.09	0.09

(1) Data obtained by visual estimation of line densities and should be correct within a factor of 2.

Table D-3
SPARK-SOURCE MASS SPECTROGRAPHIC ANALYSIS OF
KEVLAR-49 SPOOL 3 YARN
(All Values in wppm)

[illegible]

Table D-3 (continued)
 SPARK-SOURCE MASS SPECTROGRAPHIC ANALYSIS OF
 KEVLAR-49 SPOOL 3 YARN
 (All Values in wppm)

Element		Sample Number ⁽¹⁾							
Z Value	Symbol	311	312	321	322	331	332	341	342
48	Cd	< 0.02	0.03	0.03	0.02	0.03	0.04	0.02	0.02
49	In	< 0.007	< 0.006	< 0.003	< 0.003	< 0.007	< 0.003	< 0.003	< 0.003
50	Sn	0.3	0.6	0.04	0.05	0.1	0.1	0.05	0.05
51	Sb	< 0.01	< 0.03	0.02	< 0.02	< 0.04	0.02	< 0.02	0.02
52	Te	< 0.02	< 0.02	< 0.008	< 0.01	< 0.02	< 0.01	< 0.01	< 0.01
53	I	< 0.02	< 0.02	< 0.003	< 0.003	< 0.007	< 0.003	< 0.003	< 0.01
55	Cs	< 0.007	< 0.007	< 0.003	< 0.004	< 0.008	< 0.004	< 0.004	< 0.01
56	Ba	1.0	2.0	0.06	0.3	0.2	0.2	0.3	0.3
57	La	< 0.02	0.04	< 0.009	< 0.01	< 0.02	0.04	0.01	< 0.01
58	Ce	< 0.009	0.03	< 0.003	< 0.004	< 0.009	< 0.004	< 0.004	< 0.004
59	Pr	< 0.008	< 0.02	< 0.009	0.01	< 0.008	0.01	< 0.004	< 0.004
60	Nd	< 0.03	< 0.03	< 0.01	< 0.02	< 0.04	< 0.02	< 0.02	< 0.02
62	Sm	< 0.03	< 0.03	< 0.01	< 0.02	< 0.03	< 0.02	< 0.02	< 0.02
63	Eu	< 0.02	< 0.02	< 0.006	< 0.008	< 0.02	< 0.008	< 0.008	< 0.008
64	Gd	< 0.04	< 0.04	0.02	< 0.02	< 0.04	< 0.02	0.02	< 0.02
65	Tb	< 0.009	< 0.008	< 0.003	< 0.004	< 0.009	< 0.004	< 0.004	< 0.004
66	Dy	< 0.03	< 0.03	< 0.01	< 0.02	< 0.03	< 0.02	< 0.02	< 0.02
67	Ho	< 0.03	< 0.03	< 0.01	< 0.01	< 0.03	< 0.01	< 0.01	< 0.01
68	Er	< 0.03	< 0.03	< 0.01	< 0.01	< 0.03	< 0.01	< 0.01	< 0.01
69	Tm	< 0.009	< 0.009	< 0.004	< 0.005	< 0.01	< 0.005	< 0.005	< 0.005
70	Yb	< 0.03	< 0.03	0.01	< 0.02	< 0.03	< 0.02	< 0.02	< 0.02
71	Lu	< 0.01	< 0.01	< 0.004	< 0.005	< 0.01	< 0.005	< 0.005	< 0.005
72	Hf	< 0.04	< 0.04	< 0.01	< 0.02	< 0.04	< 0.02	< 0.02	< 0.02
73	Ta	≤ 0.3	≤ 0.4	≤ 0.4	≤ 0.5	≤ 2.0	≤ 0.2	≤ 0.2	≤ 0.5
74	W	0.3	1.0	0.07	0.2	0.2	0.2	0.2	0.06
75	Re	< 0.02	< 0.02	< 0.006	< 0.008	< 0.02	< 0.008	< 0.008	< 0.008
76	Os	< 0.03	< 0.03	< 0.01	< 0.01	< 0.03	< 0.01	< 0.01	< 0.01
77	Ir	< 0.02	< 0.02	< 0.007	< 0.008	< 0.02	< 0.008	< 0.008	< 0.009
78	Pt	< 0.03	10.0	< 0.01	< 0.02	< 0.03	< 0.02	< 0.02	< 0.02
79	Au	< 0.03	0.03	< 0.01	< 0.02	< 0.03	< 0.02	< 0.02	< 0.02
80	Hg	< 0.04	< 0.04	< 0.02	< 0.02	< 0.04	< 0.02	< 0.02	< 0.02
81	Tl	< 0.02	< 0.02	< 0.006	< 0.008	< 0.02	< 0.008	< 0.008	< 0.008
82	Pb	< 0.02	< 0.7	0.09	0.03	< 0.02	0.4	0.2	0.06
83	Bi	< 0.01	0.01	< 0.005	< 0.006	< 0.01	< 0.006	< 0.006	< 0.006
90	Th	0.1	< 0.2	< 0.005	0.02	< 0.01	0.03	0.03	0.02
92	U	7.0	4.0	0.08	0.7	2.0	1.0	1.0	1.0

(1) Data obtained by visual estimation of line densities and should be correct within a factor of 2.

Table D-4
 SPARK-SOURCE MASS SPECTROGRAPHIC ANALYSIS OF
 KEVLAR-49 SPOOL 4 YARN
 (All Values in wppm)

Element		Sample Number ⁽¹⁾							
Z Value	Symbol	411	412	421	422	431	432	441	442
4	Be	≤ 0.001	≤ 0.001	0.006	≤ 0.001	0.003	0.009	0.006	≤ 0.001
8	O	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix
9	F	0.06	0.05	0.1	0.05	0.06	0.04	0.1	0.06
11	Na	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix
12	Mg	2.0	3.0	2.0	1.0	5.0	5.0	5.0	1.0
13	Al	3.0	3.0	8.0	1.0	8.0	6.0	8.0	3.0
14	Si	8.0	40.0	40.0	5.0	20.0	10.0	10.0	9.0

Table D-4 (continued)
 SPARK-SOURCE MASS SPECTROGRAPHIC ANALYSIS OF
 KEVLAR-49 SPOOL 4 YARN
 (All Values in wppm)

Element		Sample Number(1)							
Z Value	Symbol	411	412	421	422	431	432	441	442
15	P	2.0	6.0	6.0	1.0	2.0	20.0	3.0	3.0
16	S	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix
17	Cl	5.0	40.0	30.0	10.0	30.0	10.0	30.0	10.0
19	K	20.0	50.0	40.0	20.0	40.0	40.0	10.0	20.0
20	Ca	4.0	10.0	8.0	6.0	10.0	9.0	30.0	6.0
21	Sc	< 0.004	< 0.003	< 0.008	< 0.004	< 0.008	< 0.009	< 0.008	< 0.004
22	Ti	< 0.05	0.04	0.4	0.08	0.4	0.1	0.2	0.06
23	V	0.02	0.01	0.03	0.01	0.03	0.03	0.03	0.02
24	Cr	2.0	0.7	2.0	2.0	4.0	2.0	4.0	2.0
25	Mn	0.2	0.1	0.1	0.2	0.2	0.1	0.3	0.09
26	Fe	9.0	7.0	20.0	20.0	20.0	10.0	20.0	9.0
27	Co	< 0.005	0.004	0.02	< 0.005	0.01	0.01	0.01	< 0.005
28	Ni	0.9	1.0	2.0	0.4	0.8	3.0	0.8	0.4
29	Cu	0.3	0.03	0.9	0.08	0.3	0.3	0.3	0.09
30	Zn	4.0	8.0	0.5	2.0	1.0	0.7	1.0	0.4
31	Ga	< 0.01	< 0.008	< 0.02	< 0.009	< 0.02	< 0.02	1.0	< 0.004
32	Ge	< 0.006	< 0.005	< 0.01	< 0.005	< 0.01	< 0.01	< 0.01	< 0.006
33	As	< 0.007	< 0.005	< 0.01	< 0.006	< 0.01	< 0.02	< 0.01	< 0.007
34	Se	≤ 0.05	≤ 0.04	< 0.01	≤ 0.01	< 0.01	0.03	< 0.01	< 0.005
35	Br	0.2	0.6	0.5	0.2	1.0	0.5	1.0	0.1
37	Rb	0.02	< 0.008	< 0.02	< 0.01	< 0.02	< 0.02	0.02	< 0.01
38	Sr	0.3	0.07	0.2	0.4	≤ 0.2	0.2	0.6	0.09
39	Y	< 0.008	< 0.006	< 0.02	< 0.007	< 0.02	< 0.02	< 0.02	< 0.008
40	Zr	0.03	< 0.004	0.02	0.007	< 0.01	< 0.01	0.04	0.009
41	Nb	< 0.009	< 0.007	0.06	< 0.008	< 0.02	0.09	< 0.02	< 0.009
42	Mo	0.1	0.05	0.2	0.2	0.4	0.3	0.4	0.1
44	Ru	< 0.01	< 0.007	< 0.02	< 0.009	< 0.02	< 0.02	< 0.02	< 0.01
45	Rh	< 0.003	< 0.002	< 0.006	< 0.003	< 0.006	< 0.006	< 0.006	< 0.003
46	Pd	< 0.01	< 0.03	< 0.02	< 0.01	< 0.02	< 0.03	< 0.02	< 0.01
47	Ag	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix	Matrix
48	Cd	< 0.01	< 0.009	< 0.02	< 0.01	< 0.02	< 0.03	< 0.02	< 0.01
49	In	< 0.004	< 0.003	< 0.007	< 0.003	< 0.02	< 0.008	< 0.02	< 0.004
50	Sn	0.06	0.08	0.03	0.1	0.04	0.04	< 0.02	< 0.01
51	Sb	0.03	< 0.02	< 0.04	< 0.006	< 0.01	< 0.04	< 0.01	< 0.007
52	Te	< 0.01	< 0.009	< 0.02	< 0.01	< 0.02	< 0.02	< 0.02	< 0.01
53	I	< 0.004	< 0.009	< 0.02	< 0.01	< 0.02	< 0.02	< 0.02	< 0.004
55	Cs	< 0.004	< 0.009	< 0.008	< 0.004	< 0.008	< 0.008	< 0.008	< 0.004
56	Ba	0.2	0.07	4.0	0.2	0.2	1.0	0.4	0.06
57	La	0.01	< 0.01	< 0.03	< 0.01	< 0.03	< 0.03	< 0.03	< 0.01
58	Ce	< 0.005	< 0.004	< 0.01	< 0.004	< 0.01	< 0.01	< 0.01	< 0.005
59	Pr	< 0.01	< 0.003	< 0.009	< 0.01	< 0.009	< 0.009	< 0.009	< 0.004
60	Nd	< 0.02	< 0.01	< 0.04	< 0.02	< 0.04	< 0.04	< 0.04	< 0.02
62	Sm	< 0.02	< 0.01	< 0.04	< 0.02	< 0.04	< 0.04	< 0.04	< 0.02
63	Eu	< 0.009	< 0.007	< 0.02	< 0.008	< 0.02	< 0.02	< 0.02	< 0.009
64	Gd	< 0.02	< 0.02	< 0.04	< 0.02	< 0.05	< 0.05	< 0.05	< 0.02
65	Tb	< 0.005	< 0.004	< 0.01	< 0.004	< 0.01	< 0.01	< 0.01	< 0.005
66	Dy	< 0.02	< 0.01	< 0.04	< 0.02	< 0.04	< 0.04	< 0.04	< 0.02
67	Ho	< 0.005	< 0.004	< 0.01	< 0.01	< 0.03	< 0.01	< 0.03	< 0.02
68	Er	< 0.02	< 0.01	< 0.03	< 0.01	< 0.03	< 0.03	< 0.03	< 0.02
69	Tm	< 0.005	< 0.004	< 0.01	< 0.005	< 0.01	< 0.01	< 0.01	< 0.005
70	Yb	< 0.02	< 0.01	< 0.03	< 0.02	< 0.03	< 0.03	< 0.03	< 0.02
71	Lu	< 0.005	< 0.004	< 0.01	< 0.005	< 0.01	< 0.01	< 0.01	< 0.006
72	Hf	< 0.02	< 0.02	< 0.04	< 0.02	< 0.04	< 0.04	< 0.04	< 0.02
73	Ta	≤ 0.08	≤ 0.1	≤ 0.3	≤ 0.2	≤ 0.3	≤ 0.3	≤ 1.0	≤ 0.09

Table D-4 (continued)
 SPARK-SOURCE MASS SPECTROGRAPHIC ANALYSIS OF
 KEVLAR-49 SPOOL 4 YARN
 (All Values in wppm)

Element		Sample Number ⁽¹⁾							
Z Value	Symbol	411	412	421	422	431	432	441	442
74	W	0.2	0.1	1.0	0.3	0.6	1.0	2.0	0.6
75	Re	< 0.009	< 0.007	< 0.02	< 0.008	< 0.02	< 0.02	< 0.02	< 0.009
76	Os	< 0.01	< 0.01	< 0.03	< 0.01	< 0.03	< 0.03	< 0.03	< 0.01
77	Ir	< 0.01	< 0.007	< 0.02	< 0.008	< 0.02	< 0.02	< 0.02	< 0.01
78	Pt	< 0.02	< 0.01	< 0.04	< 0.02	< 0.04	< 0.04	< 0.04	< 0.02
79	Au	< 0.02	< 0.01	< 0.04	< 0.02	< 0.04	< 0.04	< 0.04	< 0.02
80	Hg	< 0.02	< 0.02	< 0.04	< 0.02	< 0.04	< 0.04	< 0.04	< 0.02
81	Tl	< 0.009	< 0.007	< 0.02	< 0.008	< 0.02	< 0.02	< 0.02	< 0.009
82	Pb	0.2	< 0.009	< 0.02	0.05	< 0.03	< 0.03	< 0.03	0.06
83	Bi	< 0.006	< 0.005	< 0.01	< 0.006	< 0.01	< 0.01	< 0.01	< 0.006
90	Th	0.02	< 0.005	0.05	< 0.006	< 0.01	0.05	< 0.02	0.02
92	U	0.7	0.3	0.05	0.1	0.05	0.08	0.2	0.04

(1) Data obtained by visual estimation of line densities and should be correct within a factor of 2.

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