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Lightweight Ballistic Protection of Flight-Critical Components on Commercial Aircraft

Part 3: Zylon Yarn Tests

July 2005

Final Report

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16. Abstract

The Boeing Company collaborated with the University of California (UC) at Berkeley and SRI International to investigate lightweight ballistic protection of commercial aircraft from engine fragments. Boeing's role in this task was to perform material property tests on Zylon® fabric after exposure to selected environments that are likely to be encountered in a commercial airplane environment. This report (Part 3) describes the work performed and the results obtained by Boeing. Separate parts of this report describe the UC Berkley and SRI International results.

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LIST OF ACRONYMS

AS	As spun
ASU	Arizona State University
CFR	Code of Federal Regulations
NBS	National Bureau of Standards
PBO	Poly-benzobisoxazole (Zylon®)
RH	Relative humidity
RT	Room temperature
SRI	SRI International
UV	Ultraviolet

EXECUTIVE SUMMARY

Uncontained turbine engine failures remain a major cause of commercial aircraft incidents and has led to catastrophic aircraft accidents. To mitigate the effect of uncontained engine debris on critical aircraft components, the Federal Aviation Administration (FAA), under the Aircraft Catastrophic Failure Prevention Program, sponsored research to develop lightweight barrier systems for aircraft and to develop the computational capability to design these barriers.

The goal of this research project, carried out under the auspices of the FAA Airworthiness Assurance Center of Excellence, was to use the technical strengths and experience of The Boeing Company, SRI International, and the University of California, Berkeley, to develop rotor burst fragment shielding and finite element modeling methodology. Since the development of an experimental set of data to support the calibration of the finite element models was essential, various experimental methods were used to measure material and structural response of the fabrics.

Each member of the team developed a report describing the details and findings of their research task. The comprehensive report "Lightweight Ballistic Protection of Flight Critical Components on Commercial Aircraft," is comprised of the following three parts.

- Part 1: "Small-Scale Testing and Computational Analysis" by the University of California, Berkeley.
- Part 2: "Large-Scale Ballistic Impact Tests and Computational Simulations" by SRI International.
- Part 3: "Zylon Yarn Tests" by The Boeing Company.

To evaluate the efficacy and practicality of Zylon® fabrics for fragment barriers on commercial transport aircraft, Boeing performed tensile tests on Zylon yarn that was extracted from a number of woven fabrics. Yarn strengths at ambient temperatures without exposures were determined for four different samples of fabric. For the baseline, Zylon fabric and a Kevlar® fabric tensile, tests were performed after a number of exposures in environments that are typically experienced in commercial aircraft. This report presents the development of the tensile test configuration and the test results.

A process was developed for extracting yarns from the Zylon fabric and mounting them on a test frame without appreciably altering the individual fiber lengths relative to one another in the yarn bundle. Stress-strain curves were initially produced with two methods (using test machine head travel and with an extensometer) to determine if the simpler head-travel measurement could be used to calculate the yarn strain. The report discusses the successful results.

Since Kevlar is used extensively and successfully in commercial aircraft, it was selected as a baseline comparison material for the 35 by 35 plain weave Zylon in the environmental tests. The main reason for the Kevlar comparison was as a potential guide in assessing the results of the tests.

1. INTRODUCTION AND BACKGROUND.

1.1 PURPOSE.

The overall purpose of this effort was to determine the efficacy and the practicality of using Zylon® fabric for fragment barriers on commercial transport aircraft. The Boeing Company effort was to independently evaluate Zylon material properties, determine the effect of typical aircraft environments on Zylon fibers, and identify nonballistic material properties that would preclude the use of Zylon in an aircraft environment.

1.2 BACKGROUND AND RELATED INFORMATION.

SRI International (hereafter referred to as SRI) did a considerable amount of characterization of Zylon fabrics and yarns as described in reference 1. They have generated an understanding of yarn and fabric characterization that provided a significant foundation for this study. An extensometer mount that SRI described in reference 1 served as the guide to the extensometer mount system used in this study.

The supplier of Zylon yarns, Toyobo Co., Ltd., has supplied technical information on Zylon fiber and yarn [2]. Zylon is their trade name for PBO (poly-benzobisoxazole). This study reproduced some of the data provided in references 1 and 2 and also provided data on the effects of some aircraft-specific environments.

2. TESTING OF ZYLON MATERIAL PROPERTIES.

This section discusses the mechanical testing of Zylon yarns. The focus will be on the fabric and yarn characteristics that need to be controlled to get a strength value that is representative of the constituents of the fabric—the yarns. Items specifically discussed are the development of process methods for extracting the yarns, their preparation for testing, introduction of tensile load, and a discussion of the yarn's stress-strain behavior and its measurement.

The testing for the effects of fabric exposure were based on extracted yarns. The selected aircraft exposure environments are discussed in section 3.1 and the results in section 4.

Testing of fabric strengths is relatively complex with numerous variables, the foremost being the difficulties of applying load uniformly into a fabric sample. The main reasons are differences in slack within the fabric, the ability to grip all the yarns uniformly, and the effects of the cross-direction yarns in the fabric. Because of these difficulties, tensile testing of individual yarns that were extracted from fabric was selected as the means of evaluating effects of aircraft environments on Zylon material.

2.1 DEVELOPMENT OF TENSILE TEST FOR ZYLON YARNS.

2.1.1 Basic Fabric Considerations.

Zylon fabrics for ballistic applications have the same basic characteristics of all fabrics made from yarns. Fabrics are characterized by terms such as areal density, size of the individual fibers, twist of the fibers within the yarn, the numbers of yarns per unit length, the weave description, and the effects of the weaving process and condition on the yarns in the fabric.

As yarns are woven into fabrics, some of the yarns can develop a permanent deformation because of the stresses during and after the weaving process, and can also suffer mechanical damage from the weaving process. Evaluation of Zylon properties (tensile strength being the most important for ballistic applications) needed to include the degradation of yarn properties due to the weaving process. Therefore, tensile testing of Zylon yarns extracted from fabric was selected as the evaluation method to accurately determine the Zylon properties that are representative of the fabric.

Figure 2-1, from SRI, shows the warp and the fill fibers individually and also as the fabric (the warp direction is the lengthwise direction of the woven fabric). SRI found that the warp fibers usually have the most crimp and that the degree of crimp can affect the tensile strength of the yarn, and hence, the fabric in the direction parallel to those yarns. Crimp was the fractional change in elongation when straightened after removal from the fabric.

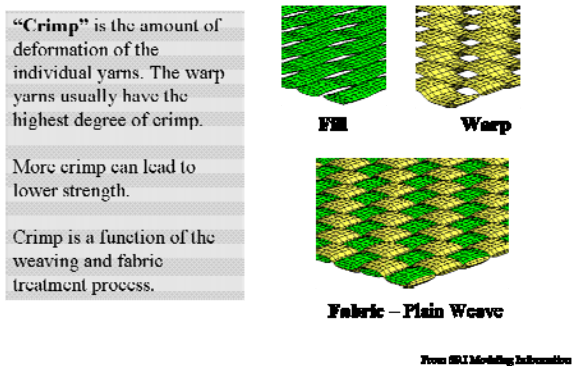

FIGURE 2-1. BASICS OF FABRIC WEAVE—CRIMP

2.1.2 Summary of Fabrics Used in This Project.

The shaded columns in table 2-1 provide the four fabrics (provided by SRI) that were used in this study. The Baseline Zylon was the main fabric that was examined and from which the most yarns were extracted. The Heavy Zylon, the 30 x 30 Zylon, and the Light Kevlar® are the other fabrics from which yarns were extracted and tested. The Light Kevlar was used as the Kevlar baseline in this study and had the full suite of exposure conditions. The other two fabrics (the 30 x 30 Zylon and the Heavy Zylon) were used only for the basic room temperature tensile tests. The baseline Kevlar shown in table 2-1 (Kevlar 49) was not tested in this study.

TABLE 2-1. WOVEN FABRICS USED IN THIS STUDY

Material		Poly-benzobisoxazole			P-Aramid	
Trade Name		Zylon-AS			Kevlar-29	Kevlar-KM2
Designation for this Program		Baseline Zylon	Heavy Zylon	30 x 30 Zylon	Baseline Kevlar	Light Kevlar
Supplier	Unit of Measure	Lincoln Fabrics		Toyobo Corp.	Lincoln Fabrics	
Volume Density (from manufacturer)	(g/cm^3)	1.54	1.54	1.54	1.44	1.44
Yarn Denier—As Ordered	(g/9 km)	500	1500	500	1420	600
Yarn Denier—Measured	(g/9 km)	500	1488	506	1490	595
Yarn dTex—As Ordered	(g/10 km)	556	1667	556		667
Yarn Linear Density—Measured	(mg/cm)	0.556	1.654	0.562	1.656	0.661
Yarn Cross-Sectional Area†	($cm^2 \times 10^{-4}$)	3.61	10.74	3.65	11.50	4.59
	($in.^2 \times 10^{-5}$)	5.59	16.64	5.66	17.82	7.11
Yarn Count	(yarns/in.)	35 x 35	17 x 17	30 x 30	17 x 17	29 x 29
Fabric Ply Thickness (approximately)	(in.)	0.008	0.011	0.006	0.011	0.008
	(mm)	0.21	0.28	0.15	0.28	0.02
Fabric Areal Density—Measured	(g/cm^2)	0.0158	0.0223	0.0130	0.0228	0.0155
	(lb/ft^2)	0.0323	0.0457	0.0266	0.0466	0.0317
	(oz/yd^2)	4.65	6.58	3.83	6.71	4.56
Degree of Crimp*—warp yarns	(%)	3.1	2.2	0.6	1.1	1.2
Fill yarns	(%)	0.6	0.9	0.6	0.8	1.2

† Calculated by dividing measured linear density by volume density.
*Fractional change elongation when straightened after removal from fabric.
Note: The woven fabrics used in this study are shown in the shaded columns.

Table is courtesy of D. Erlich of SRI International – Reference 3

2.1.3 Yarn Extraction From Fabric.

A fundamental guiding requirement for extracted yarns was that they must be representative of the fabric. The yarns must, therefore, retain:

- Twist (nominally zero)
- Individual fiber lengths within yarn
- All fibers in yarn

Yarns for fabrics used for ballistic applications usually have zero twist in the yarns. Unfortunately, the individual fiber within a zero twist yarn readily separates when the yarn is extracted, unless precautions are taken. A number of methods were explored, including applying tape to the fiber ends; but the best method was to apply a fast-drying resin (acrylic nail polish) to both yarn-ends before extraction of the yarn from the fabric. This critical step was accomplished by first cutting a section of fabric of the proper length, removing a number of cross yarns from the fabric ends, and then teasing a few yarn-ends to the side so that they were separated, but not moved far. These ends were then thoroughly coated and infiltrated with the fast-drying acrylic nail polish and allowed to dry. When both coated yarn-ends were dry, the yarn was removed with care to not damage any fibers within the yarn. The process is also described in table 2-2.

TABLE 2-2. YARN EXTRACTION PROCESSES

Process Description	Issue
Mechanically separate yarn	Difficult to ensure retention of individual fiber length
Tape on ends	Better than mechanical, but still difficult to ensure length coherence
Fast-drying resin on ends	Excellent ensurance of individual fiber length coherence
Final Process • Mechanical to slightly separate yarn • Resin to bind ALL individual fibers at ends of yarn in fabric • Tape to ensure accurate twist retention	

2.1.4 Yarn Mounting for Tensile Test Specimen.

The extracted yarn, with the acrylic on both ends, was placed onto a paper frame as the beginning step of the mounting process. Figure 2-2 shows the concept of the yarn mount. The frame (a paper card stock) was in the form of a picture frame with the open window being the gage length of the yarn for tensile testing. The overall length was 6 inches for a 4-inch gage length, and the width (not critical) was approximately 2.5 inches. The yarn was taped at the very ends in the vertical center of the frame, and epoxy resin was spread over and into the yarn from the ends and to the gage area. Once the epoxy was cured, it created (with the yarn) a composite that allowed (1) uniform load introduction, (2) minimal chance for fiber slippage within the yarn, and (3) minimal fiber damage from the test machine grips.

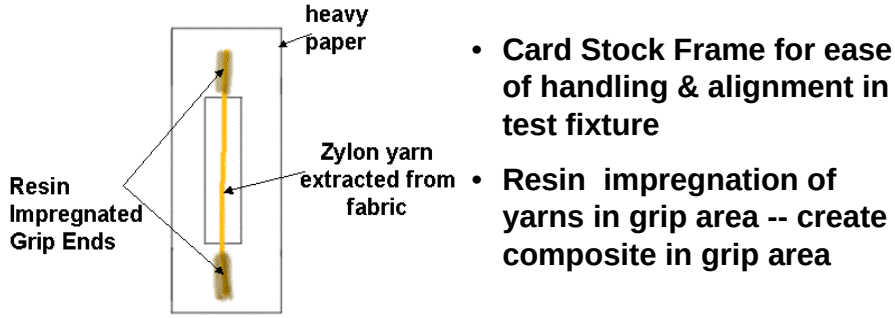

FIGURE 2-2. MOUNTING CONCEPT FOR ZYLON YARNS

2.1.5 Tensile Test Specimen Gripping.

Tensile tests were performed on a SATEC Systems, Inc., Model 50DU screw-driven universal testing machine. The grips were slightly serrated and hydraulically actuated. The layers of the mount were separated and protected from the steels grips with 100-grit emery cloth, as shown in figure 2-3.

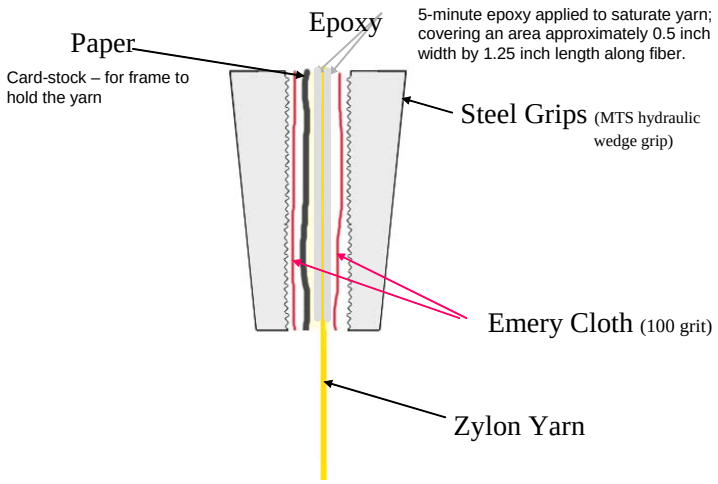

FIGURE 2-3. SCHEMATIC OF TENSILE GRIP ELEMENTS FOR ZYLON YARN MOUNTS

2.1.6 Comparison of Head-Travel Versus Extensometer for Yarn Strain.

Before beginning the matrix tensile tests, virgin Zylon AS® (AS refers to as spun) yarns were mounted and tested to evaluate the process and to develop an easy method for noncontact strain measurement in the yarn. Head-travel was the simplest method available and was the desired method to use for the matrix testing. However, the method had to be first validated by comparing with strain data using an extensometer (delicately attached to the yarn). In addition, the stress-strain data were also compared to the Toyobo data.

The Toyobo data for Zylon fibers (and for carbon and aramid) are reproduced from reference 2 in figure 2-4. The curve of interest is for Zylon AS.

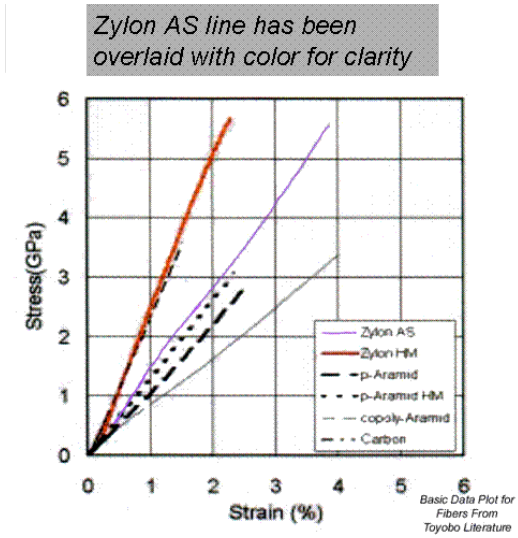

FIGURE 2-4. TOYOBO TENSILE TEST STRESS-STRAIN PLOTS FOR ZYLON FIBERS AND OTHERS

The comparison for head-travel and extensometer-derived strain is shown in figure 2-5 for two separate test specimens (the strain for head-travel was calculated by the total displacement divided by the gage length, which was 4.0 inches). The comparison is also shown for strain data from one specimen during the same run in figure 2-6. The conclusion is that strain measurements using the extensometer and head-travel displacement are equivalent, validating the use of head-travel measurement in the study.

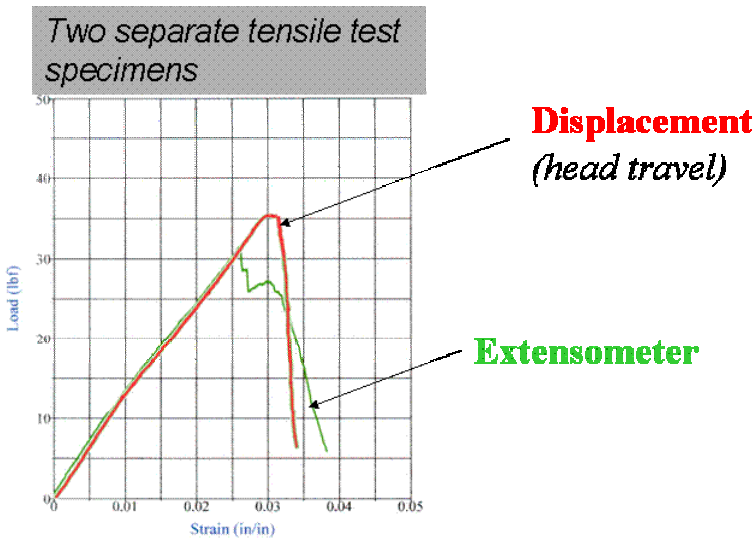

FIGURE 2-5. COMPARISON OF HEAD-TRAVEL TO EXTENSOMETER DATA FOR STRAIN

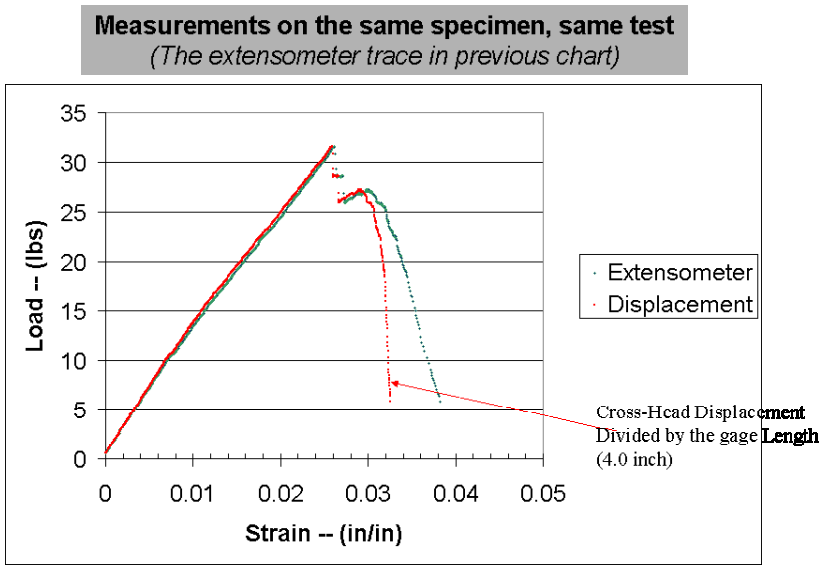

FIGURE 2-6. COMPARISON OF HEAD-TRAVEL TO EXTENSOMETER FOR STRAIN MEASUREMENT ON ONE SPECIMEN

As further evidence for the validity of the Boeing data on stress-strain, figure 2-7 displays the Toyobo data plot for fibers with the overlaid plots for both head-travel and extensometer data for yarns of Zylon-AS. The plots demonstrate the correspondence of the Boeing results for this study on yarns with the Toyobo data on individual fibers.

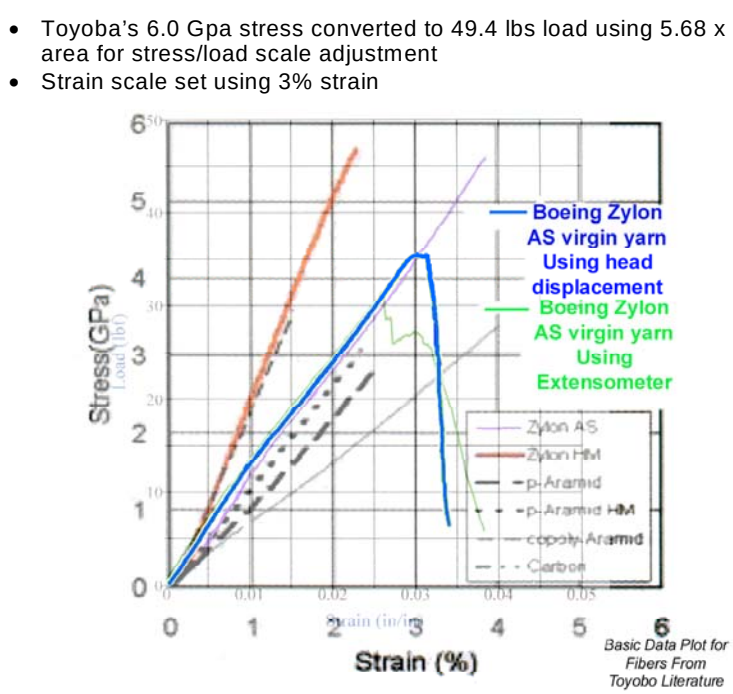

FIGURE 2-7. COMPARISON OF BOEING YARN DATA TO TOYOBO FIBER DATA (Overlaid plots of stress-strain)

3. TEST MATRIX SELECTION.

The following sections describe the environments that were selected for the test matrix and the specific values that were chosen based on requirements for a combination of engine area and cabin areas.

The test matrix is discussed in section 3.2.

3.1 SELECTION OF EXPOSURE ENVIRONMENTS.

The selection of the environments in which to test Zylon yarns was based on Boeing requirements for general commercial aircraft in a combination of two areas that are areas of potential application of Zylon for fragment containment: (1) the engine area and (2) the cabin area. Flammability, smoke, and toxicity are based on interior requirements, and the other environment requirements are based on general aircraft materials requirements.

In general, the exposures were accomplished by exposing Zylon fabric and then extracting yarns prior to tensile testing. The exception was for the majority of the temperature exposures, they were first mounted as individual yarns and then exposed to the proper condition.

3.1.1 Baseline Tensile Strength and Temperature.

Ambient laboratory temperature of 70ºF was the room temperature (RT) value for baseline testing. The other temperatures selected for the matrix were -40º, 160º, and 220ºF because they provided a common range of temperatures in a commercial transport aircraft environment. Exposures for testing at a specific temperature were for 5 to 10 minutes. Near the end of the study, additional exposures were made to yarns at temperatures of 160º and 220ºF for 30 minutes, and these were tested at RT to determine if any thermal effects at those temperatures were irreversible.

3.1.2 Humidity.

Humidity exposure was selected to be at a level of 100% relative humidity (RH) and at temperatures of 120º and 160ºF based on commercial aircraft requirements. These temperatures were also chosen because they bracket the temperature range where Zylon was believed to suffer a moisture and humidity threshold. The exposure times were 2, 7, and 28 days. The exposed fabric was protected, but allowed to dry in the laboratory environment and tested within 2 days.

3.1.3 Light.

Zylon is very light sensitive, apparently even to indoor lighting. However, lack of standard conditions for such indoor exposure precluded using indoor lighting as the environment for the test matrix. It was felt that indoor conditions, if applicable, would be eliminated by covering Zylon articles (or they would be protected as an assembly). Covering was the method used for protecting Zylon in the laboratory during specimen preparation.

Selection of the testing environment for light exposure was predicated on an available, dry test chamber that would be an accelerated test for ultraviolet (UV) exposure, and be a worst-case example.

The facility for the UV exposure was an Atlas Ci 4000 Weather-O-Meter. Its UV source was a xenon lamp that was filtered for a 340-nm wavelength. The energy flux at 340 nm is approximately 0.55 W/m^2. It was programmable for continuous operation to 28 days. Other exposure times at 7 and 14 days were also used.

The total UV energy to simulate an earthbound application lifetime would be on the order of 500 kJ, and this translates to an exposure of around 2 weeks in the Weather-O-Meter.

One of the issues with Zylon and light exposure may be a combination of moisture and UV exposure, as they are for most organic materials. Although the chamber used for UV exposure was dry, it was limited to the ambient humidity in the laboratory, which is around 40% to 50% RH. The chamber is warm (approximately 126ºF) when running.

3.1.4 Fluids and Solvents.

Exposure to a number of fluids and solvents is very likely in an aircraft environment. The fluids selection was based on Boeing requirements for structural organic matrix composites. The fluids are listed in table 3-1. The requirements call for the specimens to be immersed in the fluid for 14 days at room temperature. Immersion in the phosphate-ester-based hydraulic fluid (Skydrol), a particularly aggressive fluid to many organic materials, was also tested at 160ºF for 48 hours.

In the Boeing requirements, the evaluation metric is weight gain of laminates after a 14-day exposure (and in some instances a scratch test with specified hardness tools). However, for this study, tensile testing of yarns was the chosen measurement. It was felt that exposure of bare yarns submerged in the fluids provided a realistic and severe condition.

TABLE 3-1. SELECTED FLUIDS AND SOLVENT FOR ZYLON EXPOSURE

Fluid	Specification
Methyl ethyl ketone	ASTM D740
Jet A fuel	ASTM D1655
Deicing fluid	AMS 1424 Type 1
Hydraulic fluid, fire-resistant	BMS 3-11, Type IV, Class 1

3.1.5 Flammability and Smoke and Toxicity Testing.

The flammability test was performed according to Title 14 Code of Federal Regulations (CFR) Part 25, Appendix F, Part I for both methods F1 and F2. The test specimen was a 12- by 3-inch strip of fabric that was hung vertically in the long direction. A flame source burner was applied to the lower end and held for 60 seconds for method F1 and 12 seconds for method F2. The test required three specimens, and the characteristics to be noted were (1) time to extinguish, (2)

burned length, and (3) dripping extinguish time. The requirements were 15 seconds for extinguish time, 6 inches for burn length, and 3 seconds for drip extinguish time.

Smoke density was performed in a Boeing National Bureau of Standards (NBS) Smoke Density Chamber with three samples heated in a radiant heat flux of 2.5 W/cm^2 in a flaming mode. Smoke density, as specific optical density, was measured for 5 minutes. Toxicity was monitored by ion chromatography analysis for eight toxic gaseous compounds.

3.2 TEST MATRIX.

The test matrix is shown in tables 3-2 and 3-3 for the Baseline Zylon and the Light Kevlar reference. Originally, the plan had included gage lengths other than 4 inches (2 and 8 inches), but the effort that was to go into these was replaced by testing on other Zylon fabrics later in the study (Heavy Zylon and 30 x 30 Zylon).

TABLE 3-2. ZYLON YARN TEST MATRIX
(Lincoln Fabrics 35 x 35 Plain Weave Fabric)

Exposure Condition			Gage Length (inch)	No. Specimens		Denier and dTex	Tensile		
				Warp	Fill		Ultimate	Elongation	Stress/ Strain
As Received	RT-dry		8	20	20	x	x	x	x
			4	20	20	x	x	x	x
			2	20	20	x	x	x	x
Temperature	-40°F dry		4	10	10		x	x	x
	160°F		4	10	10		x	x	x
	220°F		4	10	10		x	x	x
Humidity	100% RH-120°F	2 days	4	5			x	x	x
		7 days	4	5			x	x	x
		4 weeks	4	5			x	x	x
	100% RH-160°F	2 days	4	5			x	x	x
		7 days	4	5			x	x	x
		4 weeks	4	5			x	x	x
Light	Xenon Lamp	1 week	4	5			x	x	x
		2 weeks	4	5			x	x	x
		4 weeks	4	5			x	x	x
Jet Fuel	75°F, 14 days		4	3			x	x	x
MEK	75°F, 14 days		4	3			x	x	x
Deicing fluid	75°F, 14 days		4	3			x	x	x
Skydrol	75°F, 14 days		4	3			x	x	x
	160°F-48 hrs		4	3			x	x	x
Flammability	14 CFR Part 25 Appendix F, method F1		N/A	3					
Vertical Test 12 sec ignition (3 x 12 inches)									

TABLE 3-3. KEVLAR YARN TEST MATRIX
(Lincoln Fabrics 29 x 29 Light Kevlar)

Exposure Condition			Gage Length	No. Specimens		Denier and dTex	Tensile		
				Warp	Fill		Ultimate	Elongation	Stress/ Strain
As Received	75°F, dry		4	5			x	x	x
Temperature	-40°F dry		4	5			x	x	x
	160°F		4	5			x	x	x
	220°F		4	5			x	x	x
Humidity	100% RH-120°F	2 days	4	5			x	x	x
		7 days	4	5			x	x	x
		4 weeks	4	5			x	x	x
	100% RH-160°F	2 days	4	5			x	x	x
		7 days	4	5			x	x	x
		4 weeks	4	5			x	x	x
Light	Xenon Lamp	1 week	4	5			x	x	x
		2 weeks	4	5			x	x	x
		4 weeks	4	5			x	x	x
Jet Fuel	75°F, 14 days		4	3			x	x	x
MEK	75°F, 14 days		4	3			x	x	x
Deicing fluid	75°F, 14 days		4	3			x	x	x
Skydrol	75°F-48 hrs		4	3			x	x	x
	160°F-48 hrs		4	3			x	x	x
Flammability	14 CFR Part 25 Appendix F, method F1			3					
Vertical Test 12 sec ignition (3 x 12 inches)									

4. YARN TEST RESULTS.

This section presents the results of the property testing (described in section 3) performed in this study. The results are presented as both tables and figures of data plots in this subsection. The test matrix conducted is shown in tables 3-2 and 3-3.

All of the test results for tensile strength and modulus are given as cN/dtex (centi-Newtons/dtex), which is a standard textile industry measure. This has the benefit of normalizing the values based on yarn weight. To relate these strengths to stress on the individual fibers within the yarn, one must use the area of total cross-sectional area of a 500-denier yarn, which is approximately 3.66×10^{-4} cm^2 (5.7×10^{-5} in^2), as listed in table 9 of reference 1.

For a 556 dTex (500-denier) yarn, a 38 cN/dtex strength corresponds to individual fiber stresses of 5.80 GPa (840 ksi), or a total load on the yarn of approximately 47.7 pounds.

4.1 BASELINE YARN AND YARN EXPOSED TO TEMPERATURE.

Table 4-1 lists the test result summary for the room temperature tests and also for the thermally exposed yarns from all of the fabrics included in this study. The thermally exposed yarns included yarns that were tested at the temperature of exposure after a brief exposure at that temperature and yarns that were tested at RT after exposure for 30 minutes at temperature. Included in table 4-1 are the number of specimens for each value and the calculated standard deviation.

TABLE 4-1. SUMMARY TENSILE STRENGTH DATA FOR EXTRACTED YARNS
(Temperature exposure with statistics)

	Precondition	Test Condition Dry	Warp Ultimate (cN/dTex)	Warp Modulus (cN/dTex)	Fill Ultimate (cN/dTex)	Fill Modulus (cN/dTex)
Virgin Yarn		70°F	30 n = 20; SDev = 1.7	1075 n = 20; SDev = 37	--	--
Extracted Yarn Zylon Baseline		at -40°F	23.3 n = 8; SDev = 2	1010 n = 8; SDev = 50	29.4 n = 10; SDev = 6	1131 n = 10; SDev = 33
		at RT	20 n = 10; SDev = 2.1	912 n = 20; SDev = 32	27 n = 20; SDev = 1.7	993 n = 20; SDev = 20
		at 160°F	16.1 n = 10; SDev = 1.4	733 n = 10; SDev = 56	19.9 n = 10; SDev = 3	886 n = 10; SDev = 38
		at 220°F	12.2 n = 9; SDev = 1.6	--	--	--
	30 min at 160°F	at RT	21 n = 1	976 n = 1	26.2 n = 5; SDev = 3.0	1011 n = 5; SDev = 1.3
	30 min at 220°F	at RT	20 n = 2	992 n = 2	25.9 n = 5; SDev = 2.7	1059 n = 5; SDev = 31
Extracted Yarn Light Kevlar		at -40°F	17.5 n = 5; SDev = 0.9	627 n = 5; SDev = 43	--	--
		at RT	17.4 n = 20; SDev = 1.4	586 n = 20; SDev = 31	16.8 n = 20; SDev = 1.5	568 n = 20; SDev = 27
		at 160°F	14.2 n = 5; SDev = 2.2	518 n = 5; SDev = 54	--	--
	30 min at 160°F	at RT	14.7 n = 5; SDev = 2.3	563 n = 5; SDev = 64	--	--
	30 min at 220°F	at RT	15.6 n = 5; SDev = 1.6	552 n = 5; SDev = 38	--	--
Extracted Yarn Heavy Zylon		at RT	21.8 n = 20; SDev = 2.0	898 n = 20; SDev = 37	20.7 n = 20; SDev = 2.6	933 n = 20; SDev = 38
Extracted Yarn 30 x 30 Zylon		at RT	21.5 n = 20; SDev = 1.8	969 n = 20; SDev = 36	25.4 n = 20; SDev = 3.2	975 n = 20; SDev = 44

4.1.1 Room Temperature Yarn Results.

A comparison of strengths for both warp and fill yarns, tested at RT, is provided in figure 4-1a. The modulus comparison is shown in figure 4-1b.

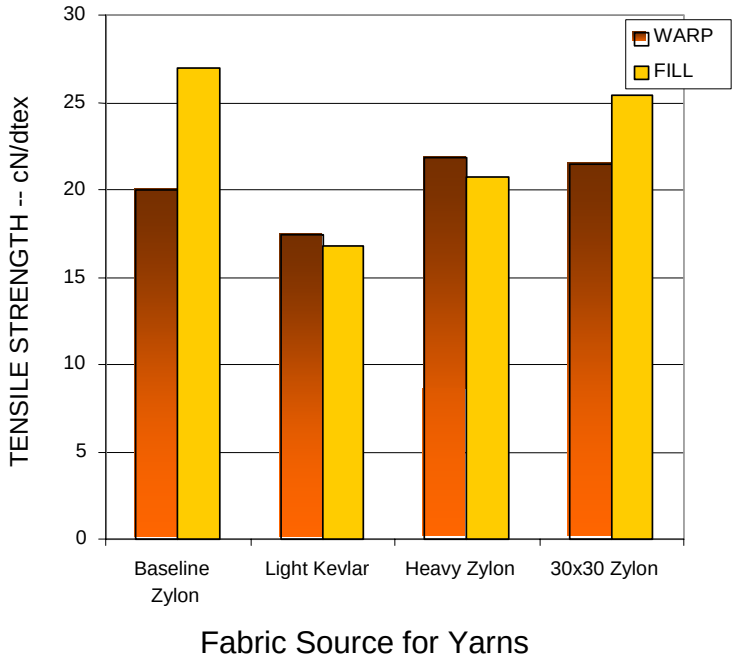

FIGURE 4-1a. WARP AND FILL COMPARISON OF YARN TENSILE STRENGTH AT RT

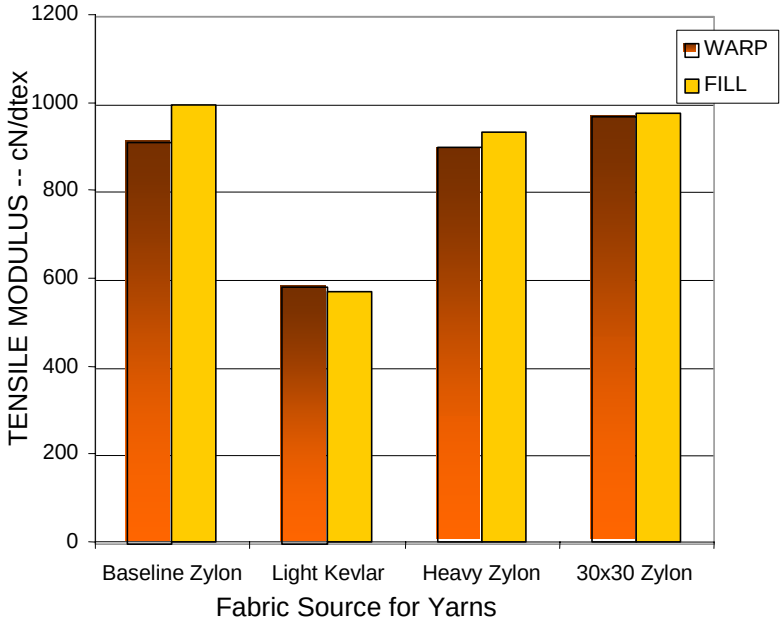

FIGURE 4-1b. WARP AND FILL COMPARISON OF YARN TENSILE MODULUS AT RT

4.1.2 Thermally Exposed Yarn Results.

The summary data for thermally exposed yarns are given in tables 4-2 and 4-3. The graphical presentation is shown in figure 4-2 for tensile strength and figure 4-3 for tensile modulus. There appears to be a sharp drop in the strengths of the yarns tested at temperatures of 160º and 220ºF. However, when yarns were exposed at those temperatures for 30 minutes and tested at RT, the residual strength—and modulus—was essentially the same as for the unexposed yarn. The reasons for this were most likely artifacts of the test setup. The resin used to reinforce the grip areas probably softened at the higher temperatures and allowed localized slippage of fibers within the yarn. The yarns mounted and tested after thermal exposure were not subject to this resin degradation. Tensile behavior in a hot environment is an area that needs resolution because operation at temperatures of 160º to 220ºF is likely. High-temperature-capable polymers would be an option that should be reinvestigated in the future. (Note: In December 2003, Zylon yarn was retested at elevated temperatures as part of a follow-on Federal Aviation Administration project. The results are shown in section 4.6.)

TABLE 4-2. SUMMARY DATA OF THERMALLY EXPOSURED YARNS—TEST AT TEMPERATURE

	Temperature (°F)	Warp Strength (cN/dtex)	Warp Modulus (cN/dtex)	Fill Strength (cN/dtex)	Fill Modulus (cN/dtex)	Virgin Strength (cN/dtex)	Virgin Modulus (cN/dtex)
Baseline Zylon	-40	22.3	1010	29.4	1131		
Baseline Zylon	70	20	912	27	993	30	1088
Baseline Zylon	160	16.1	733	19.9	886		
Baseline Zylon	220	12.2					
Light Kevlar	-40	17.5	627				
Light Kevlar	70	17.4	586	16.8	568		
Light Kevlar	160	14.2	518				
Light Kevlar	220						
Heavy Zylon	RT	21.8	898	20.7	933		
30 x 30 Zylon	RT	21.5	969	25.4	975		

Tested at temperature after 5- to 10-minute exposure.

TABLE 4-3. SUMMARY DATA OF THERMALLY EXPOSED YARNS—TEST AT RT AFTER EXPOSURE

	Temperature (°F)	Warp Strength (cN/dtex)	Warp Modulus (cN/dtex)	Fill Strength (cN/dtex)	Fill Modulus (cN/dtex)
Baseline Zylon	160	21	976	26.2	1011
Baseline Zylon	220	20	992	25.9	1059
Light Kevlar	160	14.7	563		
Light Kevlar	220	15.6	552		

Tested at RT after 30-minute exposure at temperature.

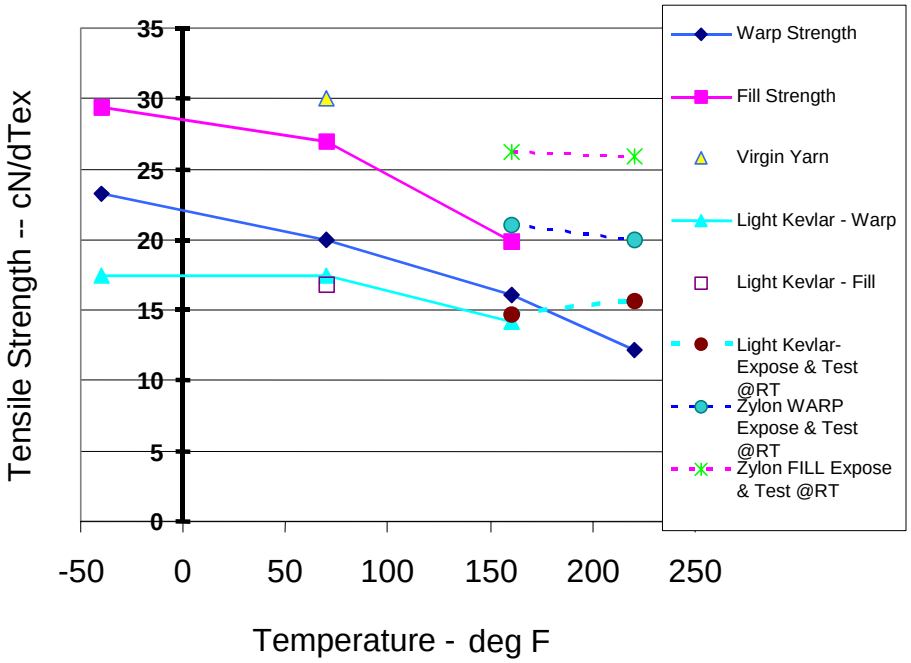

FIGURE 4-2. YARN TENSILE STRENGTH AS A FUNCTION OF TEMPERATURE

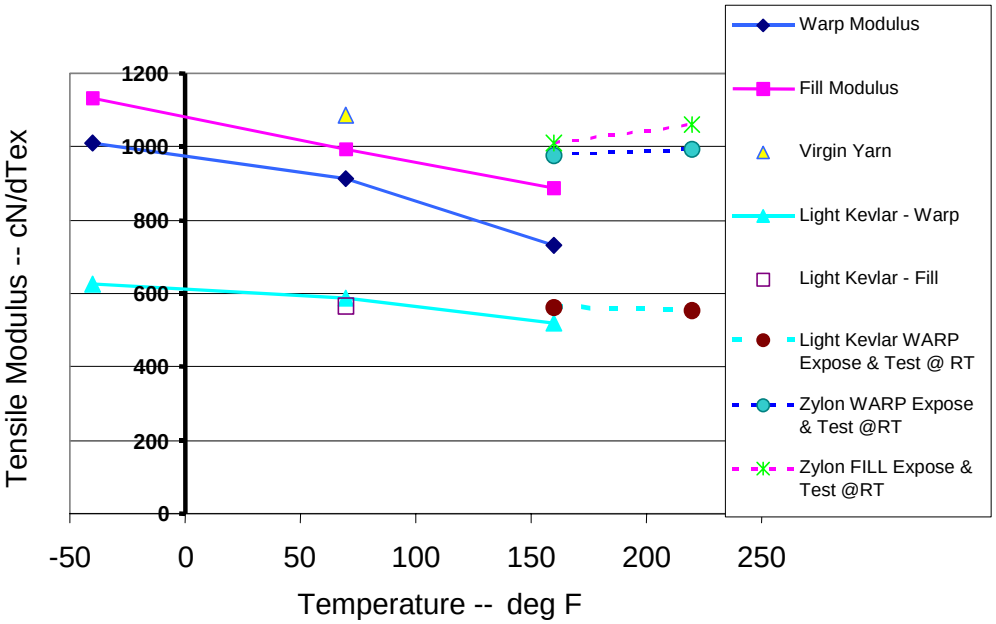

FIGURE 4-3. YARN TENSILE MODULUS AS A FUNCTION OF TEMPERATURE

A better comparison of the relative behavior of different yarns is the plot of normalized (normalized to the RT value of yarns from each fabric) tensile strengths in figure 4-4. The normalized tensile modulus plot is presented in figure 4-5. Individual data points for Toyobo data for Zylon AS and p-aramid are also shown for reference.

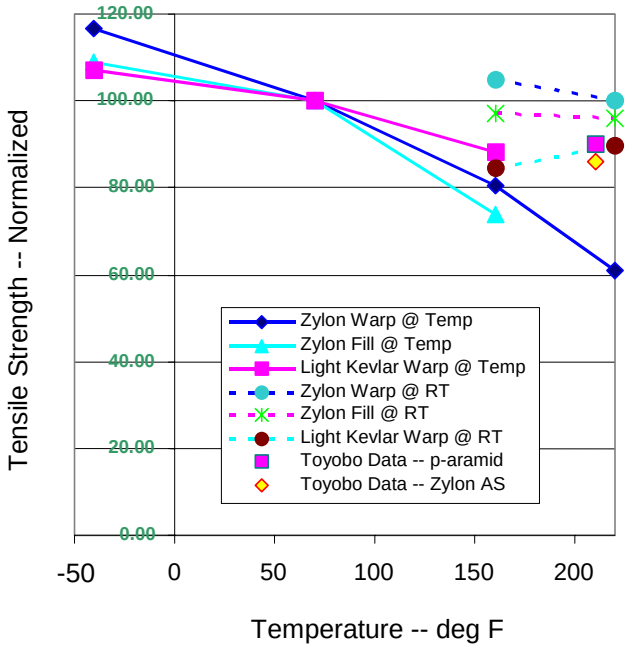

FIGURE 4-4. NORMALIZED YARN TENSILE STRENGTH AS A FUNCTION OF TEMPERATURE

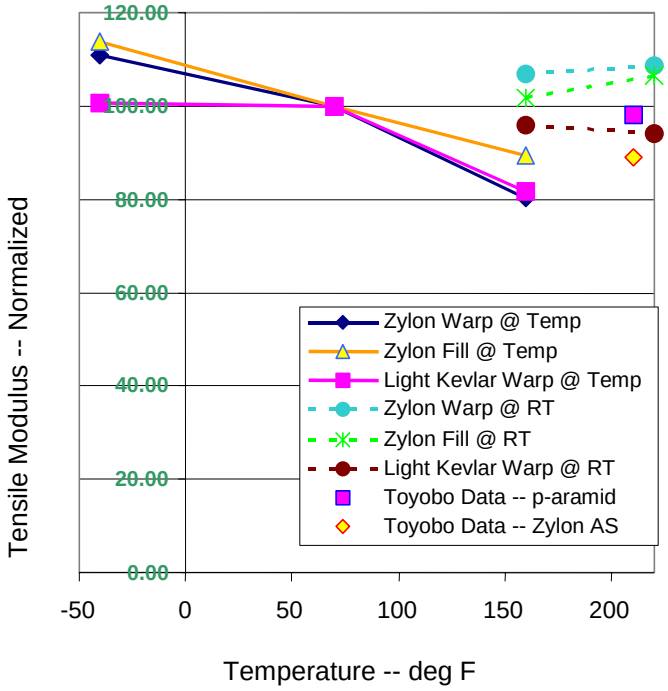

FIGURE 4-5. NORMALIZED YARN TENSILE MODULUS AS A FUNCTION OF TEMPERATURE

4.2 EXPOSURE TO LIGHT.

The data for UV exposure of extracted yarns is shown in table 4-4. The data is graphically displayed in figure 4-6 for strength and figure 4-7 for tensile modulus. A comparison to Toyobo data shows no surprises regarding the Light Kevlar. However, the Zylon degradation in this study was slightly greater than the Toyobo data (the slight increase in retained strength from 1 to 2 weeks exposure is not significant). The reasons for this may include the ambient moisture in the laboratory environment. The RH in the chamber was normally around 40% to 50% at a temperature of 126ºF. The chamber runs warm during normal operation due to the heat generated by the xenon lamp. Although the effects of this were not investigated at the time of the investigation, the difference between the Boeing data of this study and the Toyobo data (80% degradation in tensile strength versus 70% respectively) would make no difference in the basic conclusion in regard to Zylon fabric exposed to light. The Zylon must be protected with a covering that prevents light exposure.

TABLE 4-4. SUMMARY DATA OF UV-EXPOSED YARN

	Temperature (°F)	Warp Strength (cN/dtex)	Warp Modulus (cN/dtex)
Tested at RT after 1-week exposure to xenon light at RT			
Baseline Zylon	RT	3.5	--
Light Kevlar	RT	12.2	626
Tested at RT after 2-week exposure to xenon light at RT			
Baseline Zylon	RT	3.8	--
Light Kevlar	RT	9.3	486
Tested at RT after 4-week exposure to xenon light at RT			
Baseline Zylon	RT	2	--
Light Kevlar	RT	8.9	489

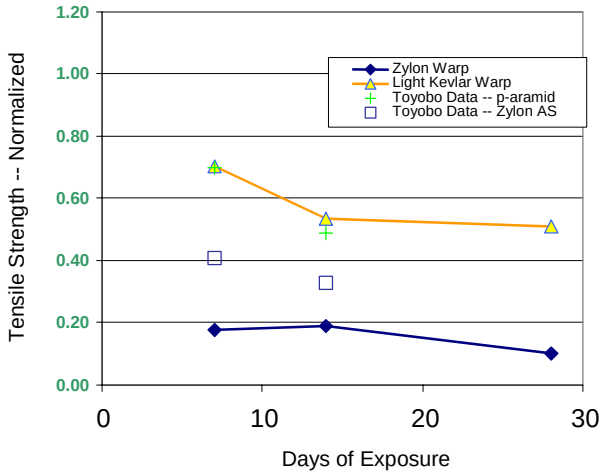

FIGURE 4-6. NORMALIZED YARN TENSILE STRENGTH AS A FUNCTION OF UV EXPOSURE

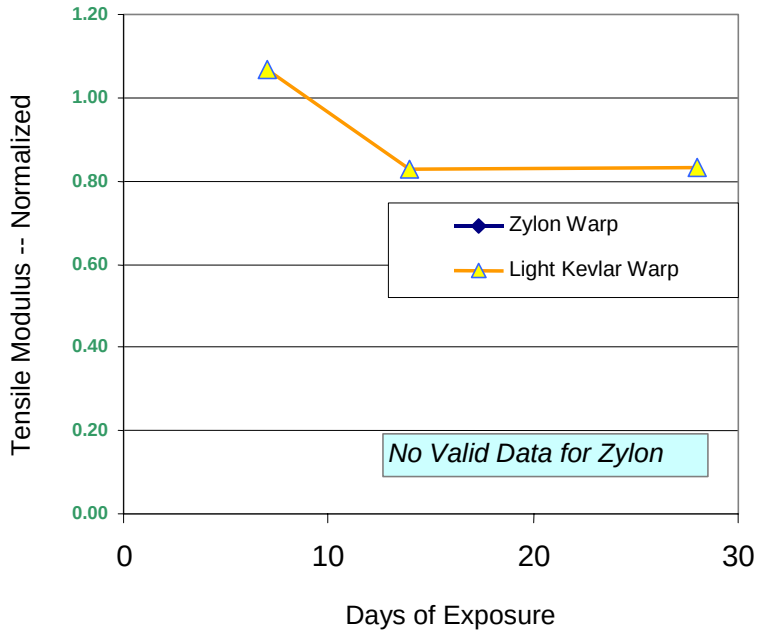

FIGURE 4-7. NORMALIZED YARN TENSILE MODULUS AS A FUNCTION OF UV EXPOSURE

4.3 EXPOSURE TO HUMIDITY.

The humidity exposure data are presented in table 4-5, and the data plots are shown in figures 4-8 and 4-9. There was difficulty when comparing the Toyobo data because their data was at 80% RH, whereas this study used 100% RH.

There was a way to indirectly compare the data generated at Boeing with Toyobo data. The data point for 85% RH at 160ºF after 21 days of exposure exhibited the same trend as exposure in 100% RH at 120ºF. The correlation between 85% RH exposure and 100% RH exposure appeared to be approximately a 40ºF decrease in the 100% RH environment to achieve tensile strength degradation similar to exposure in an 85% RH environment. In other words, exposure at 85% RH and 160ºF for 21 days is equivalent to 100% RH and 120ºF for 21 days. If this correlation is valid, then the Toyobo data point for 80% RH and 176ºF should lie near the 100% RH and 120ºF trend, and in fact, it does, as shown in figure 4-8.

The humidity exposure effects of this study seem to be in rough agreement with the published Toyobo data.

TABLE 4-5. SUMMARY DATA OF HUMIDITY-EXPOSED YARN

	Temperature (°F)	Warp Strength (cN/dtex)	Warp Modulus (cN/dtex)	Fill Strength (cN/dtex)	Fill Modulus (cN/dtex)
Tested at RT after 48-hour exposure to 100% humidity at 120°F					
Baseline Zylon	RT	18	943		
Light Kevlar	RT	16.2	519		
Tested at RT after 48-hour exposure to 100% humidity at 120°F					
Baseline Zylon	RT	17.3	971		
Light Kevlar	RT	17.5	571		
Tested at RT after 1-week exposure to 100% humidity at 120°F					
Baseline Zylon	RT	18.1	955.8		
Light Kevlar	RT	16.7	552		
Tested at RT after 1-week exposure to 100% humidity at 160°F					
Baseline Zylon	RT	16.6	885		
Light Kevlar	RT	16	555		
Tested at RT after 3-week exposure to 85% humidity at 160°F					
Baseline Zylon	RT			20.8	973
Tested at RT after 4-week exposure to 100% humidity at 120°F					
Baseline Zylon	RT	13.5	842		
Light Kevlar	RT	13.9	534		
Tested at RT after 4-week exposure to 100% humidity at 160°F					
Baseline Zylon	RT	10.8	746		
Light Kevlar	RT	5.2	443		

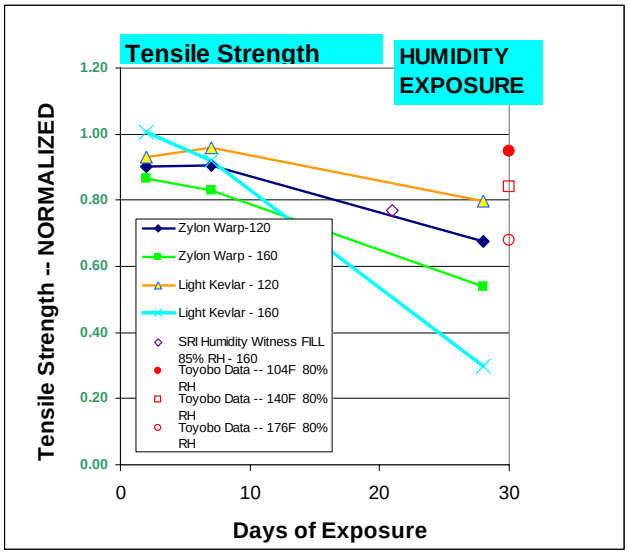

FIGURE 4-8. NORMALIZED YARN TENSILE STRENGTH AS A FUNCTION OF HUMIDITY EXPOSURE

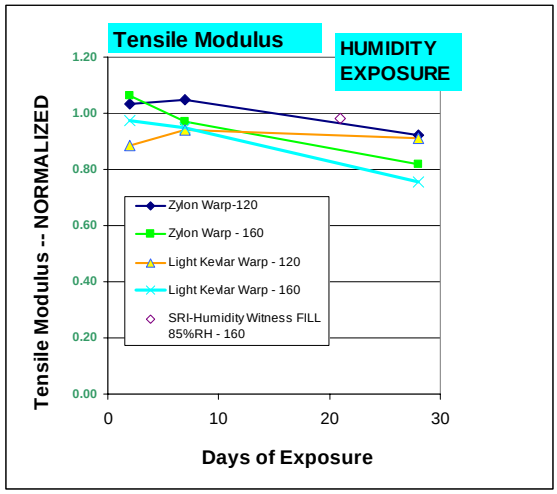

FIGURE 4-9. NORMALIZED YARN TENSILE MODULUS AS A FUNCTION OF HUMIDITY EXPOSURE

4.4 EXPOSURE TO FLUIDS AND SOLVENTS.

Extracted yarn exposure to aircraft fluids showed no surprises for Zylon, and in fact, it performed significantly better than the Light Kevlar after immersion in jet fuel.

Neither Zylon nor Kevlar were appreciably affected by immersion in the fluids, even the hot Skydrol hydraulic fluid. The data are listed in table 4-6, and the graphical presentation is shown in figures 4-10 and 4-11.

TABLE 4-6. SUMMARY DATA FOR FLUID-EXPOSED YARNS

	Temperature (°F)	Warp Strength (cN/dtex)	Warp Modulus (cN/dtex)
Tested at RT after 2-week immersion in jet fuel at RT			
Baseline Zylon	RT	20.5	978
Light Kevlar	RT	13.3	471
Tested at RT after 2-week immersion in MEK at RT			
Baseline Zylon	RT	19.1	925
Light Kevlar	RT	17.2	616
Tested at RT after 2-week immersion in deicing fluid at RT			
Baseline Zylon	RT	19.2	858
Light Kevlar	RT	17.6	598
Tested at RT after 2-week immersion in Skydrol at RT			
Baseline Zylon	RT	17.9	955
Light Kevlar	RT	17.9	574
Tested at RT after 48-hour immersion in Skydrol at 160°F			
Baseline Zylon	RT	19	876
Light Kevlar	RT	17.7	568

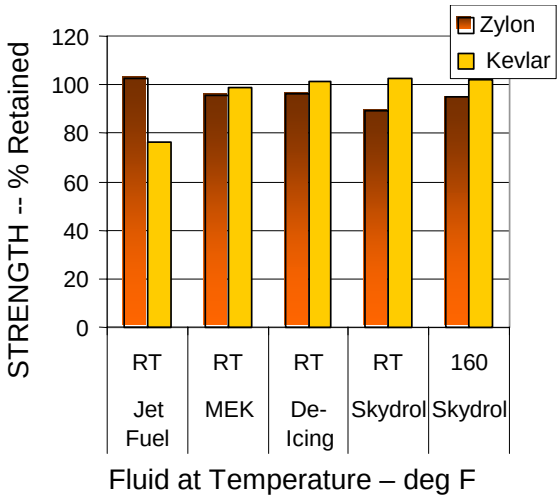

FIGURE 4-10. PERCENT YARN TENSILE STRENGTH RETAINED AS A FUNCTION OF FLUID EXPOSURE

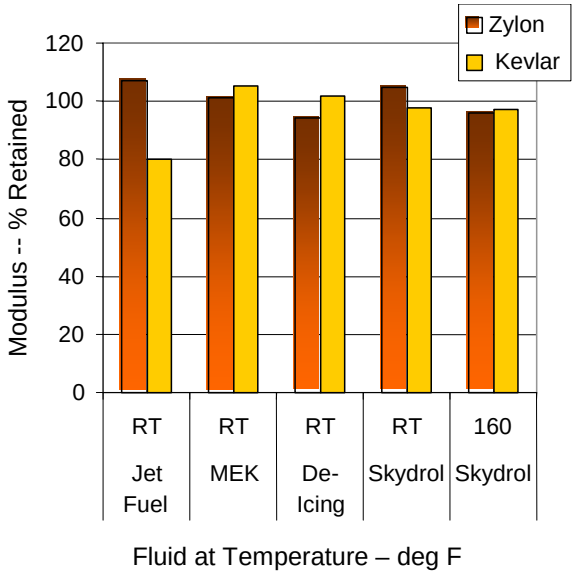

FIGURE 4-11. PERCENT YARN TENSILE MODULUS RETAINED AS A FUNCTION OF FLUID EXPOSURE

4.5 FLAMMABILITY AND SMOKE AND TOXICITY.

Zylon passed the requirements for all tests by a wide margin and was less affected by flame than the Light Kevlar samples. This was not altogether surprising because of Zylon's inherent resistance to thermal degradation.

The Zylon and Kevlar samples were tested for flammability according to 14 CFR Part 25, Appendix F, and passed robustly, as shown by the data in table 4-7.

TABLE 4-7. SUMMARY OF FLAMMABILITY TESTING FOR FABRICS

		Average for Three Samples		
Values	Time Over Burner	Zylon AS	Light Kevlar	Requirement
Extinguish time	F1 – 60 secs	0.0 second	0.0 second	15 seconds
Burn length	F1 – 60 secs	0.1 inch	0.5 inch	6 inches
Drip extinguish time	F1 – 60 secs	0.0 second	0.0 second	3 seconds
Extinguish time	F2 – 12 secs	0.0 second	0.0 second	15 seconds
Burned length	F2 – 12 secs	0.1 inch	0.3 inch	8 inches
Drip extinguish time	F2 – 12 secs	0.0 second	0.0 second	5 seconds

The results for the Boeing NBS Smoke Chamber optical density are listed in table 4-8.

TABLE 4-8. SUMMARY OF SMOKE DENSITY TESTING FOR FABRICS

	Specific Optical Density							
	Time in Minutes						Maximum in First 4 min.	Time of Maximum
Fabric	1:00	1:50	2:00	3:00	4:00	5:00		
Zylon	0.15	0.1	0.25	0.11	0.1	0.18	0.69	1.33
Light Kevlar	0.62	0.64	0.65	1.09	1.86	2.98	1.96	3.92

The toxicity data for the two fabrics were based on ion chromatography analysis and are provided in table 4-9.

TABLE 4-9. SUMMARY OF SMOKE DENSITY TESTING FOR FABRICS

	Analysis by Ion Chromatography Concentration in ppm							
Component	HF	HCl	HCN	H_2S	No_x	HBr	PO_4	SO_2
Zylon AS	2	1	--	--	1	--	--	1
Light Kevlar	2	1	2	--	1	1	--	1

4.6 FOLLOW-ON TESTING OF ZYLON YARN AT ELEVATED TEMPERATURES.

In examining the Zylon yarn strength and modulus results at elevated temperature reported in tables 4-1 to 4-3 and figures 4-2 to 4-4, significant differences between the Boeing test results (conducted in 2002) and data reported by Toyobo were observed. Questions were raised about the material properties of the acrylic resin used to impregnate the ends of the yarn samples prior to extraction from the fabric and tensile tests and the 5-minute epoxy used to pot the ends of the specimens so that the grips of the tensile test machine could grip them. To resolve this issue, tensile tests of extracted Zylon yarn samples were repeated (in 2003) for elevated temperatures up to 220°F with a high-temperature epoxy resin used in place of the 5-minute epoxy used in the earlier tests. An epoxy resin was chosen with a glass transition temperature above 220°F and a Young's modulus great enough that elongation of the epoxy at the ends of the test specimens

was negligible to that of the test specimens themselves. Tests with and without the aid of acrylic resin applied to the ends of the specimens prior to their extraction from the woven fabric were tested. Only warp yarn specimens were considered for this series of tests. The test configuration for the extracted Zylon yarn specimens was the same as for the previous, with the exception of the resin used to treat the ends of the yarns—the reader is referred to figures 2-2 and 2-3. In addition, tensile tests were conducted on 1.5-in.-wide strips of Zylon fabric. The mounting configuration for these tests is illustrated in figure 4-12.

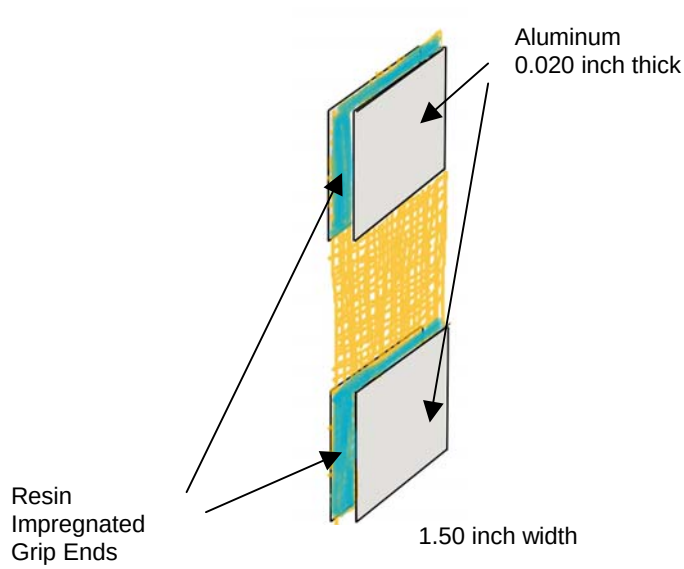

FIGURE 4-12. TENSILE TEST CONFIGURATION FOR ZYLON FABRIC STRIPS

The results for the tensile tests of the Zylon yarn specimens with the high-temperature epoxy treatment appear in table 4-10 and in figures 4-13 to 4-16. Note that results for the Zylon yarn tensile strength and elastic modulus are reduced at 70°F over the corresponding values measured during the original series of tests conducted in 2002. The change of approximately 10% is attributed to degradation of the Zylon material over nearly 1 year of storage under nonideal conditions; it was kept in a dark closed container, but was not hermetically sealed. Note that the results for strength and elastic modulus at elevated temperatures exhibit similar reductions from the corresponding values originally measured. Figures 4-14 and 4-16 indicate that the new high-temperature mounting system did make a difference and that the values for strength and elastic modulus reported in table 4-1 for elevated temperatures are somewhat in error. Note also that the strengths and elastic moduli for the specimens extracted with nail polish applied to the ends to prevent loss of fibers in the yarns yield consistently greater values for strength and elastic modulus than those which were extracted without nail polish applied to their ends. This indicates that Zylon fibers are lost from the untwisted yarns if nail polish is not used, and that it greatly aids the extraction of intact yarn specimens with weaving damage. Degradation in tensile strength for the yarns is observed to be approximately 20% over the 75°-220°F temperature range, rather than nearly 40% as reported in section 4.1.2. Similar tests on Kevlar yarns were not conducted in this series of tests.

TABLE 4-10. TENSILE STRENGTHS AND ELASTIC MODULII FOR ZYLON YARN SAMPLES WITH HIGH-TEMPERATURE EPOXY END TREATMENT

Warp Direction	Yarn Tensile Tests 2003 High-Temperature Resin Mount		Yarn Tensile Tests 2002 5-Minute Epoxy	
Test Temperature (°F)	Ultimate (cN/dTex)	Modulus (cN/dTex)	Ultimate (cN/dTex)	Modulus (cN/dTex)
70	17.6 n = 15; s = 1.4	953 n = 15; s = 67	20 n = 10; s = 2.1	912 n = 20; s = 32
160	15.6 n = 15; s = 1.2	861 n = 15; s = 70	16.1 n = 10; s = 1.4	733 n = 10; s = 56
220	13.6 n = 15; s = 0.8	847 n = 15; s = 59	12.2 n = 9; s = 1.6	--
70	18 n = 9; s = 1.0	1024 n = 9; s = 34		
220	15.3 n = 10; s = 1.7	877 n = 10; s = 73		

Note: Nail polish was applied to shaded tests to ensure no loss of fibers during extraction.

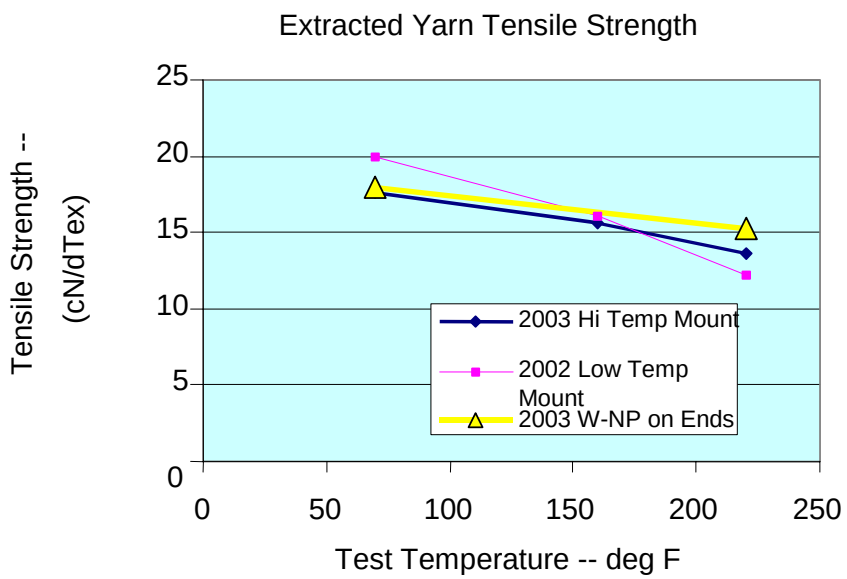

FIGURE 4-13. ZYLON YARN TENSILE STRENGTH AS A FUNCTION OF YARN TEMPERATURE WITH HIGH-TEMPERATURE EPOXY MOUNT

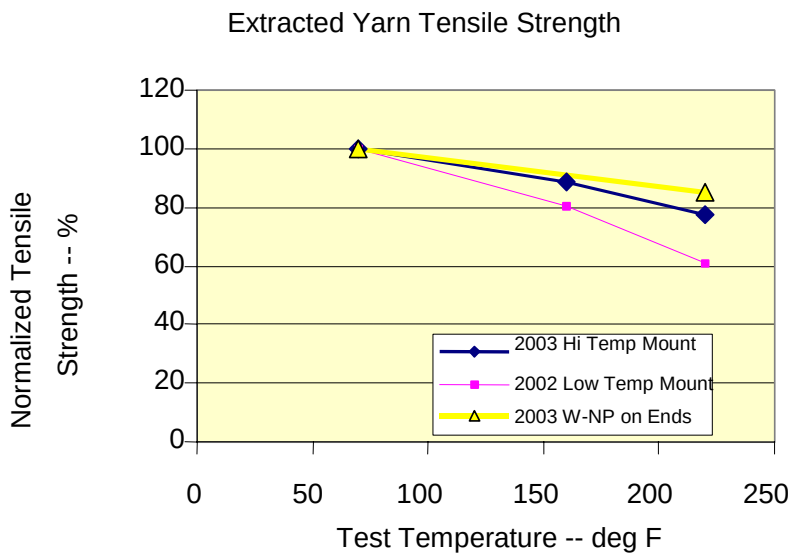

FIGURE 4-14. NORMALIZED ZYLON YARN TENSILE STRENGTH AS A FUNCTION OF YARN TEMPERATURE WITH HIGH-TEMPERATURE EPOXY MOUNT

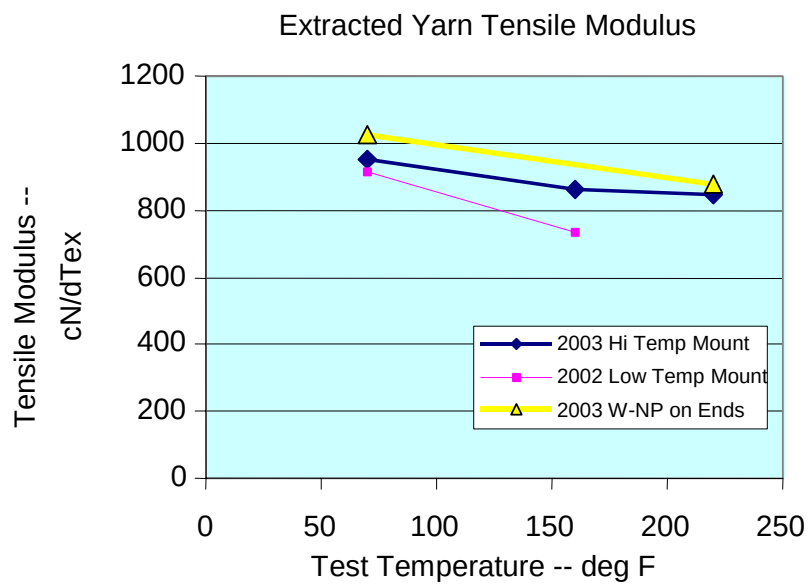

FIGURE 4-15. ZYLON YARN ELASTIC MODULUS AS A FUNCTION OF YARN TEMPERATURE WITH HIGH-TEMPERATURE EPOXY MOUNT

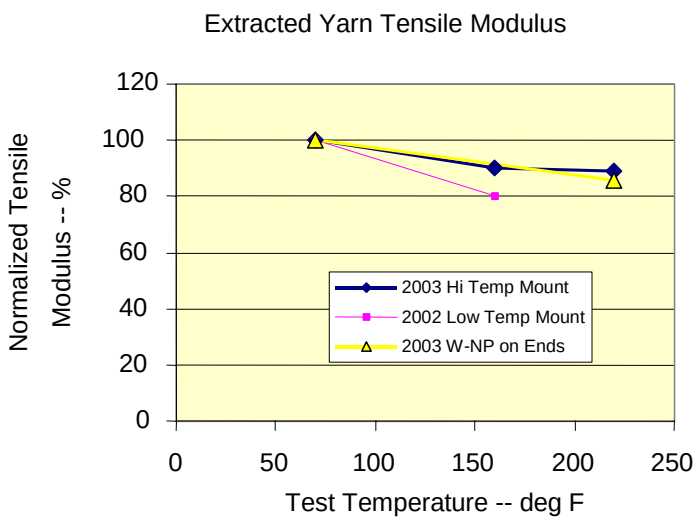

FIGURE 4-16. NORMALIZED ZYLON YARN ELASTIC MODULUS AS A FUNCTION OF YARN TEMPERATURE WITH HIGH-TEMPERATURE EPOXY MOUNT

An additional series of tensile tests were conducted on 1.5-in.-wide strips of Zylon fabric. These tests were conducted on dry Zylon specimens at RT (75°F) and were intended to provide comparison between Boeing's laboratory tests and similar tests of Zylon fabric strips conducted by Arizona State University (ASU) [3]. The results from these tests are shown in figures 4-17 and 4-18. Figure 4-17 indicates that very similar load deflection curves were obtained when the test was repeated at Boeing, as the data are observed to cluster tightly about their mean value. The results obtained in the fabric strip tensile tests conducted at Boeing agree closely with the corresponding results obtained by ASU; these are shown in figure 4-18 with the appropriate ASU results labeled swath1 and swath2.

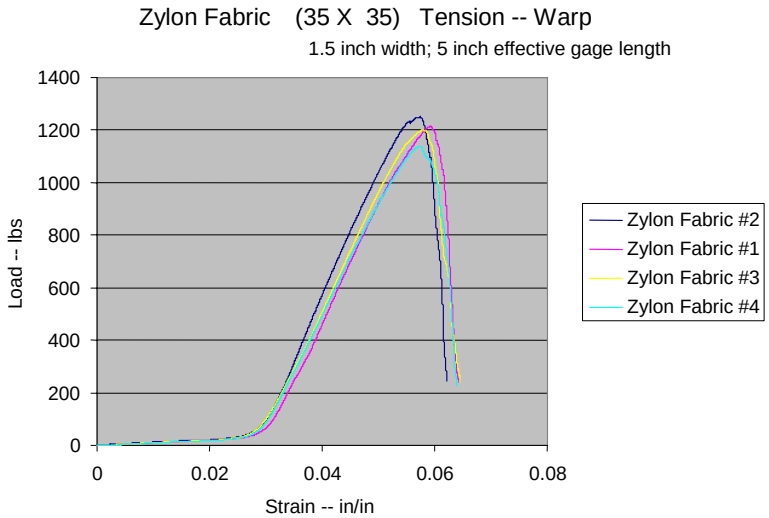

FIGURE 4-17. ZYLON FABRIC STRIP TENSILE STRENGTH AS A FUNCTION OF YARN TEMPERATURE

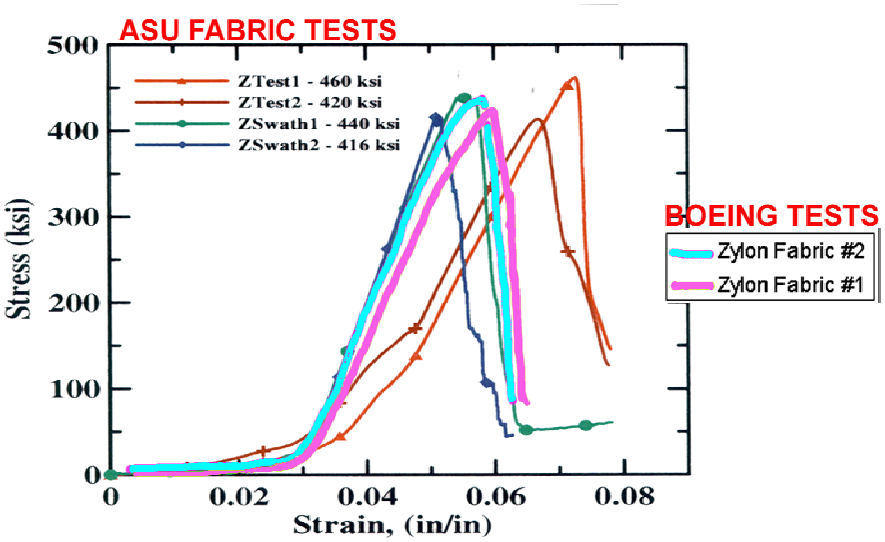

FIGURE 4-18. ZYLON FABRIC STRIP TENSILE STRENGTH AS A FUNCTION OF YARN TEMPERATURE: COMPARISON OF BOEING TEST DATA WITH RESULTS FROM SIMILAR TESTS PERFORMED BY ASU

5. SUMMARY, ISSUES, AND RECOMMENDATIONS.

5.1 SUMMARY.

Over 800 individual yarn tests were performed in developing the methods and in the actual test matrix to generate the comparison data for baseline numbers and for values (1) at temperature, (2) in various fluids as a function of temperature, (3) in an accelerated UV exposure environment, (4) as a function of humidity and temperature, and (5) flammability in a vertical burner.

The results, on equivalent weight fabrics, indicate that extracted Zylon yarn is over 60% stronger than extracted Kevlar yarn and nearly 75% stiffer.

The effects on properties at temperature were not clear and the reason was probably due to sample preparation. However, it was clear that there was little, or no, nonreversible effect of temperature up to 220ºF for a 30-minute exposure on either Zylon or Kevlar.

In section 4.6, the high-temperature tests were repeated in 2003 for Zylon with improved sample preparation. The results now agree with the Toyobo Web site Zylon data for strength reduction at elevated temperatures.

The Zylon tensile yarn tests run in 2003, which was almost 1 year after the initial tests in 2002, showed a 10% drop in tensile strength at RT. The Zylon had been stored in a dark closed container in the laboratory. This raised the question about any long-term effects this might have in an aircraft environment. However, it was out of the scope of this study to evaluate long-term environmental effects of the Zylon.

In various fluids and solvents, neither yarn was seriously affected, with just one exception—the Kevlar yarn suffered over a 20% loss in strength (and a 20% loss in modulus) in jet fuel.

UV light exposure was dramatically destructive to Kevlar yarns and even more so for the Zylon. After 28 days in the accelerated UV test, the Kevlar lost nearly 50% strength and the Zylon lost 80%. This was not totally unexpected because the light sensitivity of both these materials was appreciated. However, neither of these materials would be used in a UV environment unless protected from light and humidity. Currently used Kevlar for fan blade containment is protected from light and humidity, and one would expect Zylon to be similarly protected.

In 100% humidity environments, the Kevlar retained more tensile strength at a temperature of 120ºF than Zylon—80% versus 68% respectively. However, at 160ºF, the Zylon was significantly better—53% versus 30% retention of tensile strength.

Flammability of Zylon is significantly less than for Kevlar—the burn length for Zylon is only 20% to 30% of Kevlar. Smoke density and toxicity tests elicited no problems—both Zylon and Kevlar passed easily. Zylon was superior due to its inherent thermal stability.

From the tests performed in this study, there were no major impediments found for Zylon fabrics in a commercial aircraft environment. However, not enough is known about the long-term effects of humidity and temperature on the strength of Zylon.

5.2 ISSUES AND RECOMMENDATIONS.

The main issues that surfaced in the Zylon property tests were the drop-off in tensile properties at temperature and the permanent loss of strength over time.

- The tensile values for the yarn tested at temperature were considerably lower than Toyobo data had indicated. The reason for this is believed to be that the yarn-mounting epoxy resin may not have had a T_g sufficient for testing at the elevated temperatures (160º and 220ºF) of interest. Retesting was performed in 2003 using a high-temperature epoxy resin, and the results did match the Toyobo data.

- The Zylon used in 2003 lost 10% strength after 1 year of storage. This is an area of concern for what the long-term effects of having Zylon installed on an aircraft.

Another issue that was not addressed due to a change in the original scope was the question of gage length effects on the statistics of tensile strengths of extracted yarns. The issue is the distribution of damage in the fabric from the weaving process.

The following recommendations are suggested for future research:

- Perform longer-term environmental tests on Zylon to determine what safety factors or life limits may have to be used for Zylon in an aircraft application.

- Perform Zylon yarn tests using virgin yarn that is mounted with the new high-temperature mounting system.

  – Validate method by comparing the results for RT tests for the new method to the results using the older method.

  – Perform elevated temperature tests on yarns with new mounting method.

- Investigate the effect that a significantly greater or shorter gage length may have on the distribution of tensile strengths for Zylon yarn. As the gage length shortens, the probability of damage from weaving would be expected to lessen. Testing shorter gage lengths of extracted yarn and comparing the results to a large number of test samples for several larger gage lengths would aid in understanding the statistical distribution of damage within the yarn length.

6. REFERENCES.

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3. Rajan, S.D., Mobasher, B., Sharda, J., Yanna, V., Deenadayla, C., Lau, D., and Shah, D., "Explicit Finite Element Modeling of Multilayer Composite Fabric for Gas Turbine Engine Containment Systems, Part 1: Static Tests and Modeling," FAA report DOT/FAA/AR-04/40, P1, November 2004.