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Vectran Fiber Time-Dependent Behavior and Additional Static Loading Properties

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Table of Contents

List of Tables

Page

List of Figures

Page

Vectran Fiber Time-Dependent Behavior and Additional Static Loading Properties

Abstract

Vectran HS appears from literature and testing to date to be an ideal upgrade from Kevlar braided cords for many long-term, static-loading applications such as tie-downs on solar arrays. Vectran is a liquid crystalline polymer and exhibits excellent tensile properties. The material has been touted as a zero creep product. Testing discussed in this report does not support this statement, though the creep is on the order of four times slower than with similar Kevlar 49 products. Previous work with Kevlar and new analysis of Vectran testing has led to a simple predictive model for Vectran at ambient conditions. The mean coefficient of thermal expansion (negative in this case) is similar to Kevlar 49, but is not linear. A positive transition in the curve occurs near 100 ºC. Out-gassing tests show that the material performs well within parameters for most space flight applications. Vectran also offers increased abrasion resistance, minimal moisture regain, and similar UV degradation. The effects of material construction appear to have a dramatic effect in stress relaxation for braided Vectran. To achieve the improved relaxation rate, upgrades must also examine alternate construction or preconditioning methods. This report recommends Vectran HS as a greatly improved replacement material for applications where time-dependent relaxation is a major factor.

Introduction

The EOS series launched in recent years used bury spliced loops of Kevlar braided cord to tie down the solar arrays during launch. A requisite tension remaining in the loops became especially critical during the cutting of the loops with thermal knives in orbit to deploy the arrays. Previous testing at NASA Goddard Space Flight Center (GSFC) showed that Kevlar has a high rate of stress relaxation with a wide margin of error in prediction. Additionally, it has complicated environmental response. Similar applications such as the GLAST Tracker Tower which use tensioning cables are also concerned with break strength, relaxation, Ultra-Violet (UV) degradation, abrasion, and ease of termination (splice etc…).[1]

A search was made for a material with better performance characteristics than Kevlar, and the most promising was Vectran. See Table 1 in Appendix A for a comparison of fibers researched. Vectran is a liquid crystalline polymer (LCP). The resin is anisotropic before it is spun through tiny holes producing a highly oriented fiber structure with excellent tensile properties.[2]

Vectran is being considered as a possible replacement material primarily due to improved time-dependent behavior. The manufacturer claims the material exhibits no measurable creep when loaded up to 50% of its breaking load.[2] This statement is contradicted by NASA testing, but the measured and quantified creep is on the order of five times less than Kevlar.

Background

Table 2 in Appendix A reports material properties for Vectran with a direct comparison to Kevlar 49 as reported by available literature. Key points include improved strength, abrasion resistance, and creep performance.

Creep and Stress Relaxation

The time dependent load behavior of materials is characterized by creep and stress relaxation. Creep describes a material that experiences an increasing total strain with time under a constant load. Stress relaxation refers to a material that is initially strained to a fixed dimension, and then over time the stress within the material decreases. This phenomenon is observed to some degree in almost every engineering material with the exception of a perfect single crystal.[3,4]

The activation temperature required to initiate this time-dependent relaxation of the material may be seen as primary driver of the process. Other factors may have an effect on relaxation such as moisture, pressure, and the degree of the applied strain or load. All of these vary greatly with each material and there are also numerous underlying molecular processes. [3,4]

Metallic materials in general relax very slowly and require high activation energies as compared to polymers. Polymers display viscoelastic properties where their behavior can be described as a mix between a pure solid (governed by Hooke's Law) and a pure liquid (governed by the laws of fluid mechanics). Maxwell models consisting of a series of springs and dashpots are often used to describe (at least conceptually) the relaxation of polymers over time. [3,4]

A classical model of the creep behavior of a material has three stages of strain vs. time behavior of creep (constant load). The first stage consists of the initial elastic and plastic effects of loading and an initially high, but rapidly decaying creep rate. This is followed by steady state creep in stage two where the rate is linear with time, and concludes with tertiary creep where the creep rate rapidly accelerates and ends in failure.[5] Figure 1 below represents these three phases.

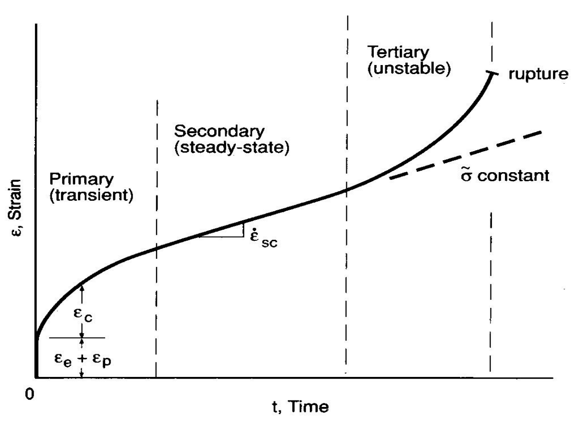

Figure 1. Strain vs. Time Behavior of Creep.[5]

In classic polymer relaxation theory, the time-dependent behavior is governed by highly developed equations often based on Maxwell or Voigt models and governed by a spectrum of relaxation times for the material.[4,6]

To describe real systems, these models become very complicated. In literature and testing at NASA GSFC mathematical fits to creep and relaxation curves proved a better engineering solution for Kevlar relaxation. This allows analysis on a macroscopic level and reliable predictions under the condition that the constants in the mathematical model can be varied to include all pertinent variables.

These mathematical models can be further enhanced if they can be used to predict relaxation after a history of varying conditions. Under the theory of Linear Viscoelasticity, the Boltzmann superposition principle applies. It states that the effects of mechanical history are linearly additive.[4] This may or may not be a valid assumption for Vectran.

Extensive literature review[7-12] and testing with Kevlar suggested that a simple logarithmic creep model might be applied to the results of Creep and Relaxation Testing with Vectran. Therefore, the following equation for steady state stress relaxation is proposed, where Beta is assumed to be negative.

$$\sigma(t) = \sigma_1 \beta \log_{10}(t) + \beta_1 \qquad t > 0 \qquad (1)$$

$\sigma(t)$ = Stress at time (t)
σ_1 = Stress at t = 1
β = Constant
t = time

The practicality of this predictive model will be discussed following the results section. Making a similar assumption that the material is stress independent, a practical mathematical model for creep can be obtained. β becomes the slope of the curve, divided by the total length of the specimen in tension, measured as built. Models from Guimaraes[9] and Blades[12] use the initial strain rather than the initial length to create their constants and models. This study proposes an alternate method because of the difficulty of defining a specific point as being the point of zero strain in a multi-fiber material. Using the total length of the specimen allows a more consistent measure because the margin of error for defining this initial point is smaller. However, the equation is no longer directly comparable to creep, and is insensitive to the load used for testing. Therefore, the constants developed will be specific to a degree of applied load. The result is equation (2) below.

$$e(t) = l_1 \beta \log_{10}(t) \qquad t > 0 \qquad (2)$$

$e(t)$ = elongation at time t
β = Constant
t = time
l_1 = length at t = 0, prior to any loading

These equations presuppose that the item in question has been pre-conditioned sufficiently to remove all construction settling.

Coefficient of Thermal Expansion (CTE)

The CTE is the relationship between expansion in a linear direction and the temperature. The CTE is especially important when working with different materials. The CTE may be used to determine the thermal compatibility of materials that will be bonded together, to make sure that they will expand at a comparable rate. If materials with different CTE values are bonded together, they will expand/contract at different rates as they are heated/cooled and the bond could ultimately fail or the materials could move. The CTE is also used in conjunction with mechanical measure-ments to determine the feasibility of using a material for a project, i.e., whether its properties fit the needs of the project. The CTE (α) is calculated using the formula:

$$\frac{l_f - l_o}{l_o} = \alpha\left(T_f - T_0\right), \qquad (3)$$

l_0 = Initial length
T_0 = Initial temperature
l_f = Final length
T_f = Final temperature.[13]

Experimental

The configuration of tested fibers, the equip-ment, and the specific test methods are all critical factors in this analysis.

Specimens

Previous experience in testing Kevlar braided cord accelerated the development of a suitable test specimen for the braided Vectran. The material tested was Vectran HS type 97 in a 12 strand 1500 denier braid rated at 800 lbs according to the manufacturer of the cordage, Cortland Cable.

A simple bury splice creating an eye loop on each end (Figure 2) proved to be the best method of gripping the cord and placing it in tension, based on previous testing and research into methods during analysis of Kevlar braided cords. The length of the splice was varied to find the shortest splice needed to cause failure in the cord and not splice pullout. A 4 in splice was required, which is similar to that used in pin diameter tests reported by Celanese. Little or no taper zone was used in the relatively thin Vectran specimens.

Direct comparison Kevlar creep specimens were built to the same dimensions, but had a larger taper zone primarily due to necessity in splicing this thicker cordage. They were made from surplus Kevlar 49 braided cordage. The braid weave is not identical to that of the Vectran.

The final specimen configuration is pictured below. A total length of 20 in was chosen to maximize the un-spliced length of material, and also to best fit the environmental chamber included in the test setup.

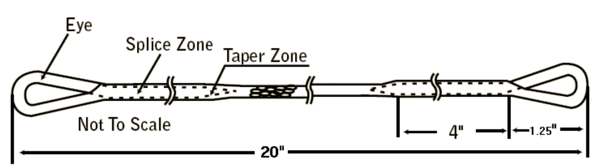

Figure 2. Specimen Diagram [Adapted from Celanese.][2]

Tensile Testing was performed on the specimens to determine the average breaking strength in this configuration. The specimens were loaded through 1/2 in steel pins in mechanical testing machines and tensioned at a rate of 0.5 in/min crosshead speed. The cable was reported to have a strength of 800 lbs. With this configuration the average breaking strength was 760 lbs. Total length of the tensile specimens was 12 in, splice dimensions were identical to those above. Kevlar specimens were tested in a similar manner.

A summary of all tensile testing results including specimens spliced and tested as a complete loop similar to that used in the array tie-downs is included in Appendix A as Table 3 (Vectran) and Table 4 (Kevlar).

Test Methods

In this properties discovery process, a wide variety of test methods were employed.

Creep Test: Creep Testing was performed on a mechanical test machine with a hydraulic actuated ram to achieve precise and virtually instantaneous control over load, along with a convenient method to obtain creep information by analyzing the crosshead displacement. A rapidly moving actuator is especially helpful to match the rapid initial displacements due to construction effects of the braid. An environmental chamber surrounded the specimen during testing and was used to control temperature between 0 and 60 ºC.

Specimens were built by hand, inserted over 1/2 in pins in the mechanical tester, and loaded to the final test load (which varied between 25 and 50% of breaking strength) at a rate of 200 lb/min. No preconditioning was performed for these specimens. It was assumed that the effects of the rope construction would be eliminated over the initial part of the constant load test, in the same way as pre-stressing them.

The data was analyzed by using the logarithmic slope fit function of KaleidaGraph WIN v 3.5x. The data period covered included all points after 5 hours. This point was chosen because it was after the inflection point noted previously and consistently eliminated the area not showing a linear response. The slope constant was the number of interest from this equation.

The units from this result are mils/log(t). This was converted to %e/log(t) (% elongation) by dividing by the total length of the test specimen (loop end to loop end). This number is the slope constant β , referred to in the Equation 2.

Stress Relaxation Test: The second test conducted was a simulation of the stress relaxation test used by an independent testing company to report zero creep for Vectran. Four cables constructed in the same manner as for creep testing were loaded into steel load frames, in line with precision load cells. Two specimens were tensioned to 60% of their breaking strength, and two at 40%. They were allowed to relax for one day, and then re-tensioned to the original load. Over the course of the 10-week test, the cables were re-tensioned once more.

Data was analyzed by taking the logarithmic best fit of the steady state portions of each relaxation curve. This constant was divided by the load applied to obtain the constant β from Equation 1. The slope constants reported were taken from data 2.5 hours after loading where all curves were visually log-linear.

An independent testing company performed a stress relaxation test to infer properties for both stress relaxation and creep. They performed the test at 20% of material strength in a static test fixture, and monitored the load in two load cells at the ends of the sample. Tensions were recorded periodically for 6 months. The material configuration was a single strand wire-lay. This method helps to minimize the construction stretch component as compared to a braided rope. The specimen "was loaded very slowly to 20% using a turnbuckle arrangement, and not subsequently re-tensioned for the entire 6-month period. There was no previous loading on the rope."

CTE Test: The third test conducted was an analysis of the CTE across a specified temperature range for Vectran. The CTE for the Vectran was measured using a TA Instruments TMA 2940 Thermomechanical Analyzer. The samples were prepared by clamping a small piece of the sample at both ends using the film/fiber clamps for the TMA 2940. The CTE of the samples was then measured using the film/fiber accessory, which measures the CTE by holding the sample in tension and measuring the change in length as the sample is heated. Each of the samples was tested over a temperature range of –150 °C to 150° C using a ramp rate of 5 °C/min. Nitrogen was used as the purge gas for the TMA, and liquid nitrogen was used to cool the samples to –150 °C.

Equipment
Creep testing was performed on an INSTRON Model 1350 Dynamic Testing Machine. Thermal control was achieved through an INSTRON Testing Oven Model 3119-409-21. Stress Relaxation Testing was performed in stainless steel fixture formed by fixing square plates at either end of threaded rods. A through hole connected to a 1/2 in pin yoke provides the load path. Turning a fine thread nut tensions the system. Sensotec load cells from Honeywell were calibrated before testing at GSFC. One Model 31 Precision Miniature Load Cell with a range of 500 lbs was employed per fixture.

CTE measurements were performed on a TA instruments Thermo-mechanical Analyzer: TMA 2940. Liquid Nitrogen was used to cool the specimens initially to begin testing.

Results

Creep Testing
Figure 3 depicts four creep data runs taken at 50% of the breaking strength for 20–90 hours, normalized for comparison. The specimens were run at approximately 23 ºC in the lab environment. Temperature and humidity were not controlled. The summary of valid (see discussion) creep constants is found in Table 5.

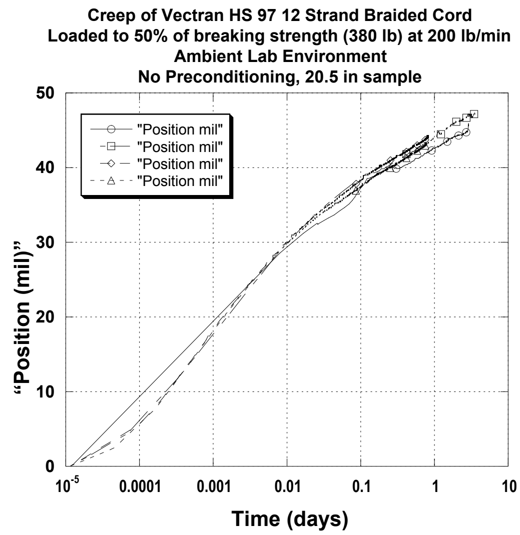

Figure 3. Creep Curves.

Table 5. Summary of Creep Constants.

	Time (hrs)	Creep Rate β(%/log(t))*
Vectran 50% of Breaking Load (23 °C)		
Vectran C2d	20	0.00031
Vectran C2e	20	0.00029
Vectran C2g	90	0.00029
Vectran C2h	70	0.00026
	Average	0.00029
Vectran 25% of Breaking Load (23 °C)		
Vectran C1a	20	0.00048
Vectran C1b	62	0.00032
	Average	0.00040
Kevlar 34% of Breaking Load (23 °C)		
Kevlar C2a	90	0.00122
Kevlar C2b	90	0.00176
		0.00149
Vectran 50% of Breaking Load (60 °C)		
Vectran C6b	20	0.00026
Vectran C6d	20	0.00029
	Average	0.00028
** note that % refers to a weighted %.*		

Stress Relaxation Testing
An independent testing company reported zero creep for Vectran HS wire rope from the data produced in their stress relaxation test. Slight variations were attributed to room temperature fluctuations. This phenomenon is expected because of CTE mismatches with the frame and

sample, and was seen in testing at NASA as well. Their charted results were recreated by Celanese for their Engineering Data Sheet.[2]

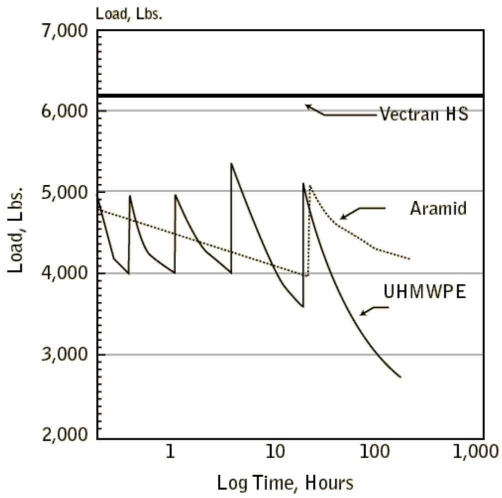

Figure 4. Manufacturer's Creep Data.[2]

A similarly formatted graph of the data generated in testing at GSFC is found as Figure 5, and a normalized graph as Figure 6.

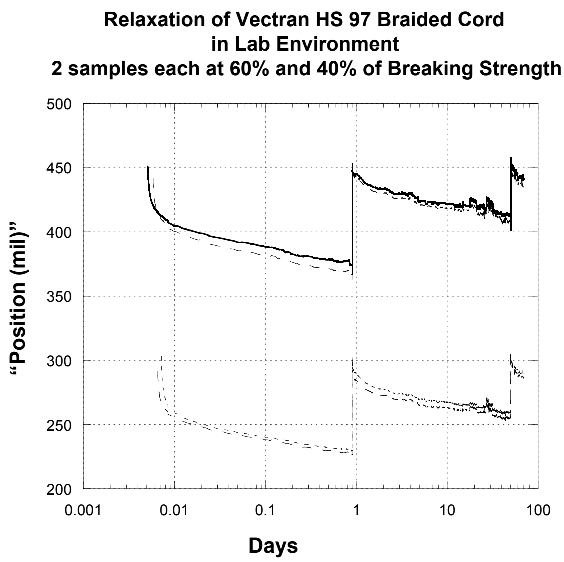

Figure 5. Vectran Relaxation at NASA GSFC.

When the results from Figure 5 are normalized, both for time and load, the results can be better examined. This is depicted in Figure 6, where each re-tensioning has also been reset to t=1. The resulting creep constants are reported in Table 6 and compared with the summary of results from previous Kevlar stress relaxation testing. Table 7 shows an additional comparison test of Kevlar and Vectran relaxation.

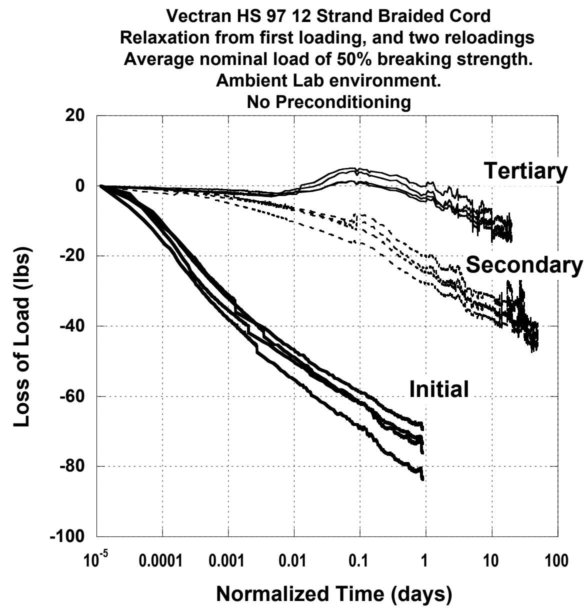

Figure 6. Normalized Vectran Relaxation at NASA GSFC.

Table 6. Summary of Relaxation Constants.

Vectran 10 Week Relaxation Test				
	Strength %*	Initial %/log(t)*	Secondary %/log(t)*	Tertiary %/log(t)*
Fixture 1	0.59	-0.028	-0.025	-0.018
Fixture 2	0.59	-0.031	-0.026	-0.018
Fixture 3	0.39	-0.036	-0.034	-0.027
Fixture 4	0.39	-0.034	-0.035	-0.026
	Average	-0.032	-0.030	-0.022
Kevlar**	0.60	-0.015	-0.011	
** note that % refers to a weighted %.*				
***From previous NASA testing*				

Table 7. Kevlar vs. Vectran Relaxation.

2 Day Direct Comparison Slope after 1 retensioning		
	% break	%/log(t)
Kevlar	0.2	-0.0388
Kevlar	0.2	-0.0398
Vectran	0.2	-0.0658
Vectran	0.2	-0.0612
% is weighted %		

CTE Testing

Each sample was heated from –150 °C to 150 °C, and a mean CTE of -5.78μm/m- °C was found over a range of 125 °C to 0 °C. A CTE of -4.8 μm /m- °C from 20 to 145° C was reported by Celanese, the manufacturer of the Vectran fiber. Additional CTE data provided by an independent company lists a CTE of -4.89 μm/m- °C from 150 to –160 °C.

Out-gas Testing

Standard out-gassing tests were also performed at NASA and the pertinent results are included in Table 8. The results show that the material performs well within the typical limits to qualify it for space flight. IR Spectroscopy showed the cords tested were coated with optional silicon oil, which can be declined for space flight.

Table 8. Out-gassing report.

Micro VCM Out-gassing Test Per ASTM E-595-93, Three runs Vectran HS Type 97 1500 denier 12 std Braid tested as received	
Average Total Mass Lost	**0.06%**
Average WVR @ 50% RH	**0.01%**
Average CVCM	**0.01%**
Test by Dewey Dove and Debbie Thomas, NASA GSFC 1 June 2004.	

Discussion

A variety of differently constructed rope products are compared throughout this report. A primary assumption of this report is that the effects of material construction (yarn twist, weave, braid, and wire rope packing) are eliminated during initial tensioning and the material will subsequently perform similarly to a single fiber. For Creep testing, this break-in period (also known as pre-conditioning) is accomplished during the initial period of constant loading in the test. For stress relaxation, the first loading curve and relaxation constant can be assumed to be dominated by construction artifacts as well.

The validity of this assumption is borne out by testing of Kevlar braided cords during 2003 – 2004 at NASA GSFC where the relaxation constants generated during testing of 12 strand braided Kevlar included fiber results in their margin of error. It is also supported by a rope creep study.[9]

Temperature fluctuations in tests at ambient lab conditions caused disruptions in both creep and stress relaxation curves. These were minor, and are not assumed to have impacted the results.

Creep Testing

The most instructive information on the response of Vectran came from creep testing. Although for most applications at NASA, stress relaxation is the more pertinent test, creep testing allows quicker and more controlled results that can cover a wider range of variables. Also, under certain simplifications, the Boltzmann superposition principle can be used to directly relate creep to stress relaxation.

In creep testing, there was a distinct inflection point observed on many of the test curves of displacement vs. Log (t). The visually distinct inflections generally occurred between 0.5 and 4 hours. Previous testing implies that this may represent the end of a period when fiber lays are aligned and straightened. A graphic depiction of one creep curve with a distinct inflection is represented below.

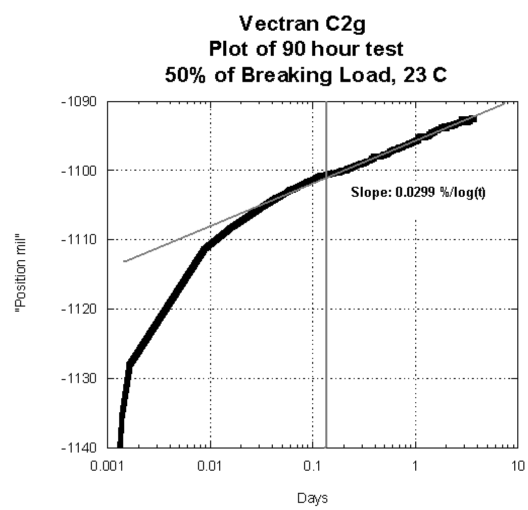

Figure 7. Depiction of Creep Curve with Inflection to Steady State Creep.

Beginning after the inflection is a period of steady state creep, which should demonstrate the material properties of the specimen.
For the reported creep slopes, the only results considered valid were those in tests that covered a period of at least 20 hours. The first factor for this decision was a visual inflection point in the response of Kevlar observed as late as 4 hours into the test. This inflection point appears to represent a change from an initially rapid but declining response over log time before achieving a steady state response. Additionally, observation of initial results showed that the slope constant was lower with a longer test, until reaching a plateau with the 20-hour tests conducted. Test runs demonstrating large environmental interruptions or testing artifacts were also disregarded.

The two long-term tests performed at 60 ºC did not reveal a significant departure from the results at room temperature. Additional testing will be required to determine if the Boltzmann superposition principle will further simplify the results. It is unclear from either stress relaxation or creep testing if the material exhibits a distinctly different rate at different loads.

Stress Relaxation Testing

The results of the stress relaxation test show a decelerating initial reaction tapering to a steady state response as expected. After each re-tensioning there is an additional break-in period or settling before steady state at a logarithmic rate is achieved. This is similar to an inverse of each creep curve reported. Further testing should analyze whether over-loading and the decreasing to a final start load eliminates this issue.

Material Construction Effects

Testing results indicate more rapid creep and relaxation at lower loads. This information could be indicative of construction characteristics of the braided cord still having a significant effect on the material behavior during steady state due to insufficient preconditioning, in contrast with the initial assumption. Further testing should study the effects of relaxation from higher loads and preconditioning by over-loading to elucidate and eliminate any construction effects.

The results of stress relaxation for Vectran when compared to Kevlar show an opposite response than that of creep. The most likely explanation is a change in the way the construction artifacts are eliminated. Kevlar has been demonstrated to overcome the effects of yarn twist and braid after an initial relaxation and re-tensioning as discussed in the assumptions. This may not be applicable for Vectran. Creep testing could be less susceptible to construction effects as it is re-tensioned constantly. The difference in test results for stress relaxation and creep compared for Kevlar and Vectran is shown in Table 9.

Table 9. Creep vs. Stress Relaxation.

Average Ratios of Rates of Kevlar and Vectran Time-Dependent Behavior		
	Creep	
Kevlar		Vectran
4.3	to	1
	Stress Relaxation	
Kevlar		Vectran
0.5	to	1

In light of this information, stress relaxation applications should consider alternate material constructions. E-mail correspondence with Mr. Douglas Bentley (mechanical properties engineer at Cortland Cable) provided some guidance on ways to reduce the construction creep/relaxation. Reducing the twist in the component strands of a braided cord or reducing the helix angle of the braid can significantly reduce the amount of elongation due to construction or geometry of the braid. Braided cords have provided a convenient geometry for terminating the ends with a splice, but there are other options such as continuously wound grommets, or cable terminations such as discussed for the GLAST project.[1]

CTE Testing

Due to the fact that the Vectran cording is formed by braiding 12 strands of fiber, testing was performed on both a single strand from the braid and on the braid as a whole. Testing of a single strand was preferred, as the 12 strands in the braid increases the amount of twist in the fiber and may alter the measured CTE. The effect that the braiding has on the CTE is reflected in the data. Two runs were performed on the TMA 2940 using a single strand of Vectran, and one run was done using the 12-strand braid.

The measured CTE for the Vectran fiber is comparable to the CTE values reported by the independent company; however, the expansion curves from both the TMA 2940 and the independent company show a small transition at approximately 100 °C. For the TMA 2940 measurements, the CTE was calculated from the expansion curve over the range of –125 °C to 0 °C, and was limited by the presence of the transition in the curve. Conversely, the CTE calculated by the independent company included the portion of the expansion curve with the transition by taking the linear regression of the curve. Given that the CTE is often provided as a linear value, the CTE for the Vectran would be more useful if it were provided over a temperature range that excluded the transition in the curve, rather than calculating the CTE using linear regression.

Several different test configurations were used to determine the cause of the transition. In addition to testing the Vectran over the –150 °C to 150 °C range, several samples were also tested from room temperature to 150 °C, and a sample was also run using a weight to provide more tension in the sample. Finally, a sample of the 12-strand Vectran braid was tested over the full –150 °C to 150 °C temperature range. As mentioned previously, because the braid consists of 12 strands, the fibers within the braid are twisted and are therefore not oriented in a linear direction. It was therefore expected that testing the Vectran in this configuration would provide a higher CTE. Analysis of the braid of Vectran found that the CTE for the braid was –12.5μm/m- °C, almost triple the reported CTE value. Figure 8 provides a comparison of the difference in CTE found by testing the entire braided cord as opposed to a single strand.

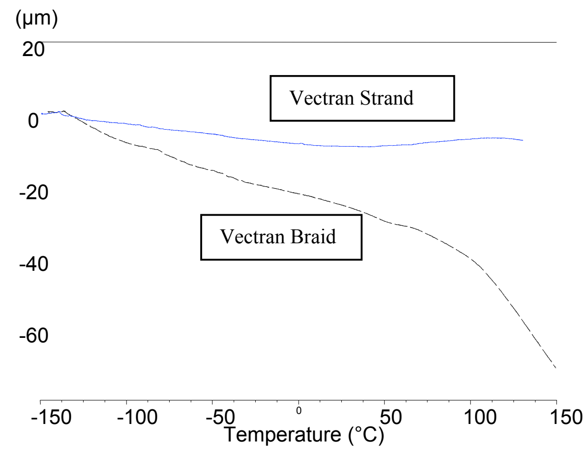

Figure 8. CTE Plot of Vectran HS.

Conclusions and Recommendations

1. Vectran HS type 97 appears from literature and testing to date to be an ideal upgrade from Kevlar Braided Cords for many long-term, static-loading applications such as tie-downs on solar arrays.

2. Key improvements in performance include creep/relaxation, moisture regain, abrasion resistance, and strength properties.

3. Vectran is NOT a zero creep material. This assumption was uncontested and repeated in available literature, based on a stress relaxation test. The material experienced logarithmic creep and stress relaxation.

4. Vectran creeps at a rate four times slower than Kevlar.

5. A mean CTE of -5.78μm/m- °C was found over a range of -125 °C to 0 °C.

6. Vectran braided cord must be pre-loaded to remove the effects of fiber weave and lay before a reliable creep or stress relaxation rate can be expected.

7. Continuing Creep and Stress Relaxation testing should analyze effects of construction artifacts in time-dependent behavior more fully. Contact Whitehill Manufacturing who has offered to help with direct comparison tests between their wire rope product and our braided cord.

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Appendix A

Vectran Properties

Table 1. Comparison of High Strength Fibers.

	Creep	*Strength*	*Modulus*	*CTE*	*density*	*Moisture*	*Elong/Break*	*Max T*	*Other*
Fibers	*%/log t*	*GPa*	*GPa*	*um/m/C*	*g/cm^3*	*%*	*%*	*°C*	
HMPE (6)	Susceptible [16]	Excellent[16]					Very Low[16]	Low[16]	dynamic toughness[16]
Spectra (1000)	creeps	3 [15]	171 [15]		.97 [15]		2.7 [15] 3.3[17]	100 [15]	
Spectra (2000)		3.25 [17]	116 [17]		.97 [17]		2.9[17]		(probably hard splice)
LCP (6)	Zero[16]	Excellent[16]						High[16]	good flex fatigue[16]
Vectran	0.00**[2]	3.2 [15]	91 [15]	-4.8* [2]	1.47 [15]	0.1 [2]	3.3 [2]	150 [15]	easy to splice [2]
Aramid	Negligible[16]	Excellent[16]						Excellent [16]	
Kevlar (49)	0.016	2.9 [15]	135[15]	-4.9 [14]	1.45 [15]	3-4 [15]	2.8 [15]	250 [15]	
Twaron (2200)		3.0 [18]	110 [18]						
Technora		3.3 [15]	70 [15]		1.39 [15]		4.3 [15]	250 [15]	
PBO	Negligible[16]	Best[16]						Best[16]	Poor UV[16]
Zylon									
Comparison									
Steel		7.6 [15]	150 [15]		7.8 [15]		4.8 [15]	500 [15]	

* from 20-145 °C

** up to 50% of ult. Load

Table 2. Summary of Literature Properties for Vectran and Kevlar 49.

Property Comparison of Vectran and Kevlar 49					
	Vectran	**Kevlar 49**		Source	Source
	LCP	Aramid	units	Vectran	Kevlar
Tenacity	2.9	3.0	GPa	*2.*	*14.*
Tenacity	23	24	gpd	*2.*	*14.*
Modulus	65	112	GPa	*2.*	*14.*
Modulus	525	885	gpd	*2.*	*14.*
Yarn Elongation	3.3	2.4	%	*2.*	*14.*
Density	1.47	1.44	g/cm^3	*15.*	*14.*
Max Use Temperature	150	250	ºC	*15.*	*15.*
Moisture Regain	<0.1	3.7		*2.*	*2.*
Melting Point	330	Chars	ºC	*2.*	*2.*
TGA 50% weight loss	550	560	ºC	*2.*	*2.*
% Tenacity at 150 ºC	55	81	%	*2.*	*2.*
CTE (20-145ºC)	-4.8	-4.9	m/m - ºC x 10^6	*2.*	*14.*
Abrasion Resistance*	10	1	Cycle Ratio	*2.*	*2.*
Creep	0.0003	0.0015	%/Log(t)*		
Stress Relaxation	0.033	0.015	%/Log(t)*		
UV Resistance**	similar			*2.*	*2.*
Thermal Conductivity	0.37***	0.04	W/(m x K)	***	*14.*
Cryogenic Strength**	+4.3%	+0.4%	23 to -50ºC	*2.*	*14.*
Cryogenic Modulus*	+40.0%	+12.5%	23 to -50ºC	*2.*	*14.*
Sintech Cut Resistance	3.4	1.1	Relative Load	*2.*	*2.*

* % refers to a weighted percent

* *These are not material properties, but an approximation of results of many varying tests

* * *Number was for a polymer chip coupon sample, not fiber, and from a phone interview

Table 3. Summary Strength testing on Vectran HS type 97 in spliced configurations.

Vectran Strength Testing on INSTRON at 0.5 in/min x-head					
Test	Specimen Description	Length (in)	Failure point	Load (lbs)	
1	4 in eye splice	13	splice transition	894	
2	3 in eye splice	13	splice pullout	793	
3	3.5 in loop splice	12	top of loop, no splice	1370	
4	3.5 in loop splice	12	top of loop, no splice	1473	
5	3.5 in loop splice	12	top of loop, no splice	1296	
6	4 in eye splice	12	splice transition	707	
7	4 in eye splice	12	splice transition	790	
8	4 in eye splice	12	splice transition	766	
9	4 in eye splice	12	splice transition	769	
avg	**4 in eye splice**	**12**	splice transition	**758**	stdev 31
avg	**3.5 in loop splice**	**12**	top of loop, no splice	**1380**	stdev 73

Table 4. Summary Strength testing on Kevlar 49 in spliced configurations.

Kevlar Strength Testing on INSTRON at 0.5 in/min x-head					
Test	Specimen Description	Length (in)	Failure point	Load (lbs)	
1	4 in eye splice & taper	12.5	Center Section	1449	
2	4 in eye splice & taper	12.5	Center Section	1497	
avg	**4 in eye splice & taper**	**12.5**	top of loop, no splice	**1473**	stdev 34

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14. ABSTRACT
Vectran HS appears from literature and testing to date to be an ideal upgrade from Kevlar braided cords for many long-term, static-loading applications such as tie-downs on solar arrays. Vectran is a liquid crystalline polymer and exhibits excellent tensile properties. The material has been touted as a zero creep product. Testing discussed in this report does not support this statement, though the creep is on the order of four times slower than with similar Kevlar 49 products. Previous work with Kevlar and new analysis of Vectran testing has led to a simple predictive model for Vectran at ambient conditions. The mean coefficient of thermal expansion (negative in this case) is similar to Kevlar 49, but is not linear. A positive transition in the curve occurs near 100 ºC. Outgassing tests show that the material performs well within parameters for most space flight applications. Vectran also offers increased abrasion resistance, minimal moisture regain, and similar UV degradation. The effects of material construction appear to have a dramatic effect in stress relaxation for braided Vectran. To achieve the improved relaxation rate, upgrades must also examine alternate construction or preconditioning methods. This report recommends Vectran HS as a greatly improved replacement material for applications where time-dependent relaxation is a major factor.

15. SUBJECT TERMS
Vectran, Kevlar,time-dependent behavior, Goddard Space Flight Center (GSFC), Coefficient of Thermal Expansion (CTE), creep, Boltzman superposition principle, stress relaxation

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