Vectran®

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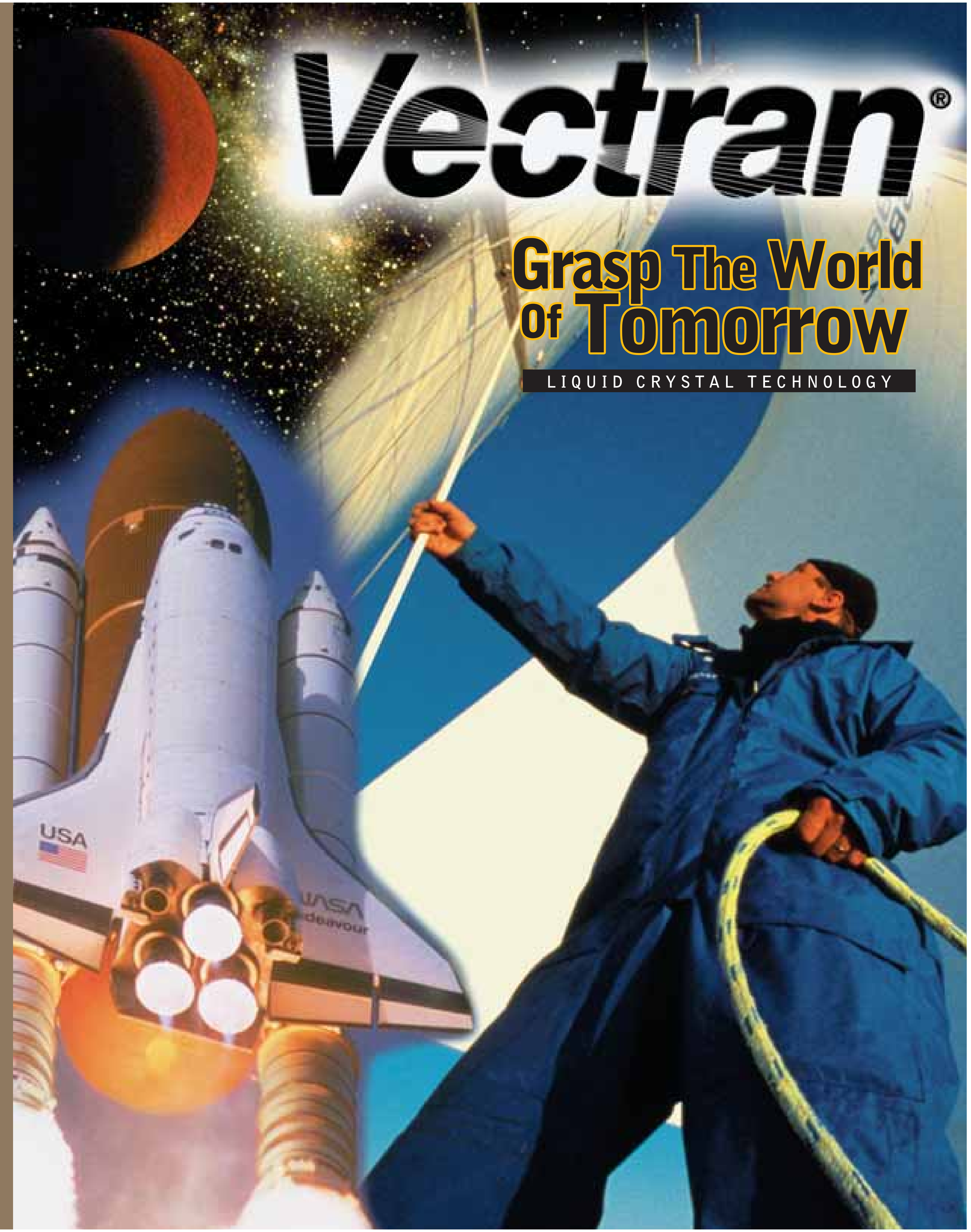


# KURARAY AMERICA, INC.

**Kuraray America, Inc. is a subsidiary of Kuraray Co., Ltd. Kuraray America's product lines include *Vectran*® liquid crystal polymer (LCP) fiber.**

TABLE OF CONTENTS



Vectran® LIQUID CRYSTAL POLYMER FIBER

KURARAY AMERICA, INC.

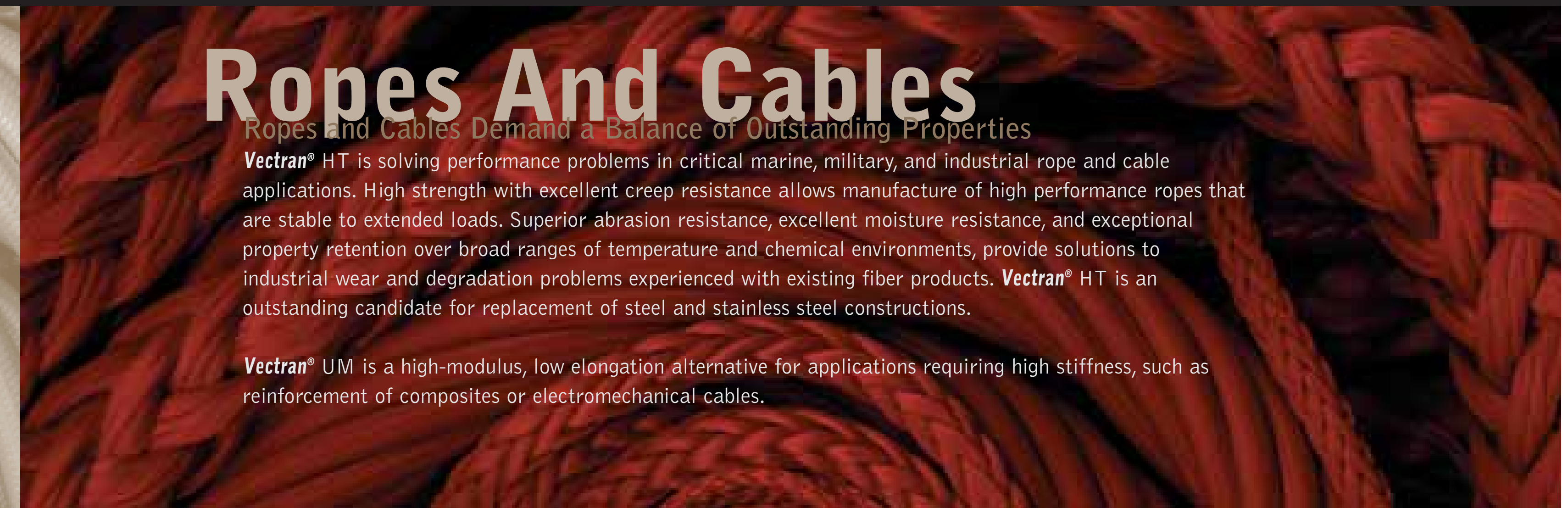
## *Vectran*® Fiber
## A Unique Combination of Properties For The Most Demanding Applications

Day in, and day out, whether at home or in the office, we are surrounded by products from the Kuraray group. This is because the specialty products which our company produces worldwide are primarily used as important constituents in building and coating materials and in adhesives, high-performance composites, home textiles and man-made leather, dental materials, carpets, in furniture finishes or in laminated safety glass.

An industry-leading textile fiber manufacturer, Kuraray has been providing innovative technical and industrial textile solutions for over 45 years.

***Vectran*®** is a high-performance multifilament yarn spun from liquid crystal polymer (LCP). ***Vectran*®** is the only commercially available melt spun LCP fiber in the world. ***Vectran*®** fiber exhibits exceptional strength and rigidity. Pound for pound ***Vectran*®** fiber is five times stronger than steel and ten times stronger than aluminum. These unique properties characterize ***Vectran*®**:

- High strength and modulus
- Excellent creep resistance
- High abrasion resistance
- Excellent flex/fold characteristics
- Minimal moisture absorption
- Excellent chemical resistance
- Low coefficient of thermal expansion (CTE)
- High dielectric strength
- Outstanding cut resistance
- Excellent property retention at high/low temperatures
- Outstanding vibration damping characteristics
- High impact resistance



# Vectran® Liquid Crystal Polymer Fiber: A Unique Combination of Properties For Demanding Applications

Photo Courtesy of Cargolifter AG.

### Where Existing Materials Fail to Perform

A unique combination of properties differentiates ***Vectran®*** fiber from other high-performance fibers and makes it the material of choice in demanding applications where other fibers fail to meet performance requirements. Vectran's remarkable mechanical performance combined with the other unique properties permit it to be used for a variety of purposes. ***Vectran®*** fibers are used in aerospace, ocean exploration and development, electronic support structures, the recreation and leisure industry, safety materials, industrial applications, ropes and cables, composites, protective apparel and high-pressure inflatables.



## Ropes And Cables

### Ropes and Cables Demand a Balance of Outstanding Properties

***Vectran®*** HT is solving performance problems in critical marine, military, and industrial rope and cable applications. High strength with excellent creep resistance allows manufacture of high performance ropes that are stable to extended loads. Superior abrasion resistance, excellent moisture resistance, and exceptional property retention over broad ranges of temperature and chemical environments, provide solutions to industrial wear and degradation problems experienced with existing fiber products. ***Vectran®*** HT is an outstanding candidate for replacement of steel and stainless steel constructions.

***Vectran®*** UM is a high-modulus, low elongation alternative for applications requiring high stiffness, such as reinforcement of composites or electromechanical cables.

**Vectran® fiber can be found on yacht ropes and sails powering Americas Cup vessels and high-performance yachts.**

## Recreation & Leisure

### Recreation and Leisure

***Vectran®*** fibers are an excellent option for recreation and leisure products such as sailcloth, reinforced hulls, fishing poles and lines, golf clubs, bicycle forks, skis, bowstrings, tennis racquets, snowboards, and paragliders. Performance is critical in many specialty sporting goods applications. Of particular importance are the unique vibration damping characteristics of ***Vectran®*** fiber combined with high strength, minimal moisture absorption and excellent flex/fold/abrasion/impact resistance.

Photo Courtesy of ILC Dover.

## Aerospace & Military

### Aerospace and Military

The first use of ***Vectran®*** fiber was for demanding and specialized military applications. The unique properties of this high-performance fiber satisfy many of the military and aerospace needs of today. In fact, the airbags above made with ***Vectran®*** fiber successfully cushioned the Mars Pathfinder, Spirit, and Opportunity landings on the surface of Mars. A stellar-strength fiber, ***Vectran®*** offers exceptional flex fatigue resistance, providing superior load handling characteristics for tow ropes, cargo tie-downs and inflatables.

# Composite Options

### New Textile and Composite Options

The ***Vectran®*** fiber family is available in a range of deniers for textile and composite processing and offers new options in design and material selection. ***Vectran®*** HT fiber offers benefits for applications requiring high strength, vibration damping, low moisture absorption, and low CTE. ***Vectran®*** NT fiber is a high modulus thermoplastic matrix fiber for applications requiring high impermeability, excellent property retention over a broad temperature range, and low moisture absorption. ***Vectran®*** UM offers the highest modulus without sacrificing tensile strength.

# Industrial Applications

### Industrial Applications For The 21st Century

***Vectran®*** Fiber brings unique solutions to industrial applications. Stability to most chemicals allows the manufacture of chemically resistant packings and gaskets. Users of protective apparel such as gloves and workwear benefit from excellent cut and stab resistance, elevated temperature resistance, outstanding flex/fold resistance, and durability to multiple wash/dry cycles even in the presence of bleach.

For example, the meat processing industry suffers from some of the highest incidents of hand cuts and abdominal stabs. Worker safety is improved when garments provide increased cut resistance or stab resistance. Because of the high cost of safety apparel and the high costs of injuries, meat processing companies are sensitive to cost/performance of safety workwear. Aramid fibers have poor resistance to bleach and HMPE fibers are sensitive to high temperatures associated with drying. Therefore, the cost/performance of safetywear improves when garments can resist exposure to bleach and are durable enough to resist multiple wash/dry cycles without loss of strength or shape due to shrinkage. ***Vectran®*** fiber workwear is meeting the cost/performance needs of this industry.

# Specialized Electronic Uses

### Specialized Electronic Uses Require a Unique Fiber

***Vectran®*** HT fiber is an excellent candidate for printed circuit boards, fiber optic strength members, and conductor reinforcements. High dielectric strength coupled with elevated temperature resistance and outstanding moisture resistance provide new levels of electrical efficiency in prevention of current leakage. This combination along with excellent dimensional stability and low CTE provide a unique fiber for specialized electronic uses.

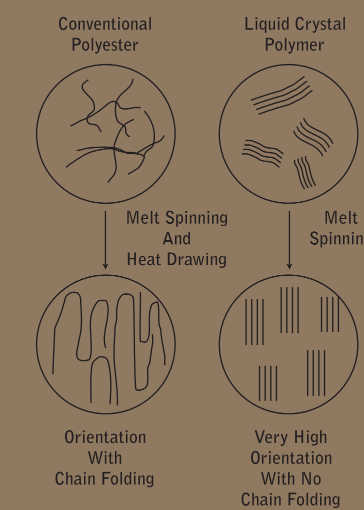


# Fiber Chemistry

***Vectran®***, a liquid crystal polymer (LCP) fiber, offers a balance of properties unmatched by other high performance fibers. This unique fiber's history spans 30 years of research and development in thermotropic (melt-processable) LCP's.

LCP polymer molecules are stiff, rod-like structures organized in ordered domains in the solid and melt states. These oriented domains lead to anisotropic behavior in the melt state, thus the term "liquid crystal polymer." ***Vectran®*** fiber is formed by melt extrusion of the LCP through fine diameter capillaries, during which the molecular domains orient parallel to the fiber axis. The structure's high degree of orientation, illustrated schematically in Figure 1, translates to excellent fiber tensile properties.

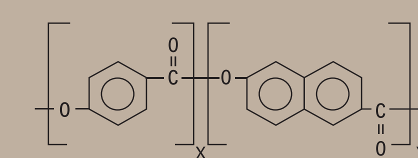
Figure 1: Schematic Of Molecular Chain Structure Of Fiber




# Molecular Structure

The molecular structure of LCP, a wholly aromatic polyester, is shown in Figure 2.

Figure 2: LCP Molecular Structure



With conventional polyesters, the molecular chains are random and flexible. Fibers spun from such materials must be further oriented, generally through a combination of extrusion speed and post-spin drawing, to obtain higher tensile properties. Vectran's highly oriented structure is locked in directly during the melt-spinning process, thanks to the molecular structure and liquid crystalline nature of the starting polymer.

***Vectran®*** is different from other high-performance fibers such as aramid and ultra-high molecular weight polyethylene (HMPE). ***Vectran®*** fiber is thermotropic, it is melt-spun, and it melts at a high temperature. Aramid fiber is lyotropic, it is solvent-spun, and it does not melt at high temperature. HMPE fiber is gel-spun, and it melts at a low temperature.

# Tensile Properties

***Vectran***® offers a distinct advantage over traditional metals in terms of strength-to-weight ratios. This is demonstrated in Table 1, which lists the tensile properties and densities of various reinforcing materials. Table 2 gives the mechanical properties of ***Vectran***® yarn. Even higher tensile strengths are characteristically associated with lower deniers.

Table 1: Comparison of Properties of Various Engineering Materials

| Material | Density (g/cm3) | Tensile Strength (GPa) | Specific Strength (km*) | Tensile Modulus (GPa) | Specific Modulus (km**) |
|---|---|---|---|---|---|
| ***Vectran***® NT | 1.4 | 1.1 | 79 | 52 | 3700 |
| ***Vectran***® HT | 1.4 | 3.2 | 229 | 75 | 5300 |
| ***Vectran***® UM | 1.4 | 3.0 | 215 | 103 | 7400 |
| Titanium | 4.5 | 1.3 | 29 | 110 | 2500 |
| Stainless Steel | 7.9 | 2.0 | 26 | 210 | 2700 |
| Aluminum | 2.8 | 0.6 | 22 | 70 | 2600 |
| E-Glass | 2.6 | 3.4 | 130 | 72 | 2800 |
| Graphite (AS4) | 1.8 | 4.3 | 240 | 230 | 13000 |

*Specific strength = Strength/Density (also divided by force of gravity for SI units). Also known as breaking length, the length of fiber that could be held in a vertical direction without breaking.
** Specific modulus = Modulus/Density (also divided by force of gravity for SI units). This measure increases with increasing stiffness and decreasing density.

(KAI data)

Table 2: Average of Mechanical Properties of ***Vectran***® Filament Yarn

| | HT | | | UM | | |
|---|---|---|---|---|---|---|
| | GPa | g/denier | ksi | GPa | g/denier | ksi |
| Break Strength | 3.2 | 25.9 | 465 | 3.0 | 24.4 | 440 |
| Initial Modulus | 75 | 600 | 10760 | 103 | 838 | 15020 |
| Elongation at break, % | 3.8 | | | 2.8 | | |

(KRC data)

# Finishing Options

***Vectran***® fiber is available with three sizing options.

T-97 A silicone oil finish applied at a level of ~5.0% Oil-on-Yarn to optimize fiber-to-fiber abrasion resistance. Used for dynamic applications primarily in cordage and cable industry.

T-117 An ester-based finish applied at a level of ~1.5% Oil-on-Yarn for improved fiber-to-fiber abrasion resistance without the use of silicone.

T-150 A weaving finish applied at a level of ~0.5% Oil-on-Yarn to assist processing (e.g.: rewinding, twisting, braiding, weaving), which can be easily scoured off.



# Thermal Properties

***Vectran***® HT shows robust performance in a broad spectrum of responses to thermal loading. These responses are summarized below and in Table 3:

- Good LOI (equivalent to aramids) and low smoke generation
- Low thermal shrinkage (hot air, boiling water and laundry)
- No dripping in vertical flammability tests
- Good strength retention after hot air and radiant energy exposures
- Low, negative coefficient of thermal expansion
- Excellent property retention in a broad temperature range
- No measurable volatile condensable mass (VCM) and 0.3% maximum weight loss (TML or TWL) in testing for aerospace applications (see also "Offgassing/Outgassing")

Table 3: Fiber Thermal Properties

| | ***Vectran***® | | Aramid | |
|---|---|---|---|---|
| | HT | UM | Standard | High Modulus |
| LOI | 28 | 30 | 30 | 30 |
| M.P., °C | None | 350 | None | None |
| HAS (Hot air shrink, 180°C, 30 minutes), % | <0.2 | <0.1 | <0.2 | <0.1 |
| BWS (Boiling water shrinkage, 100°C. 30 minutes), % | <0.2 | <0.1 | <0.2 | <0.1 |
| 50% Strength Retention Temperature[1], °C | 145 | 150 | 400 | 230 |
| TGA (20% weight loss), °C | >450 | >450 | >450 | >450 |

1 Estimated from Figure 3

(KAI data)

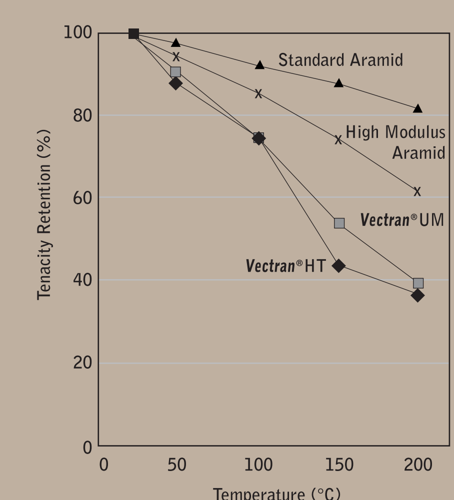
Table 4: Equilibrium Moisture Regain

| Temperature (degree °C) | Relative Humidity (%) | ***Vectran***® HT | ***Vectran***® UM | Aramid(PPT) Standard | Aramid(PPT) High Modulus |
|---|---|---|---|---|---|
| 20 | 65 | <0.1 | <0.1 | 4.2 | 4.1 |
| 20 | 80 | <0.1 | <0.1 | 4.8 | 4.8 |
| 20 | 90 | <0.1 | <0.1 | 5.4 | 5.5 |

(KRC)

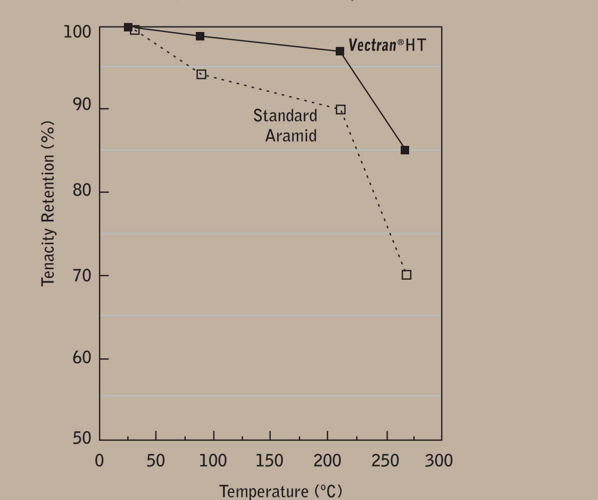
Mechanical property retention during or after thermal exposure is a key concern in many applications. Most commonly, high temperatures are encountered during a downstream processing step, such as coating or laminating. Care must be taken to minimize line tensions or other mechanical loads during the high temperature step. Figure 3, which describes Vectran's tensile strength at temperature, should be used as a reference in selecting process conditions. For high temperature processing at low mechanical load, Figure 4 shows that ***Vectran***® will have excellent strength after processing, in fact, superior to aramids.

Figure 3: Strength At High Temperatures:
Simultaneous Mechanical and Thermal Loading




(KRC)

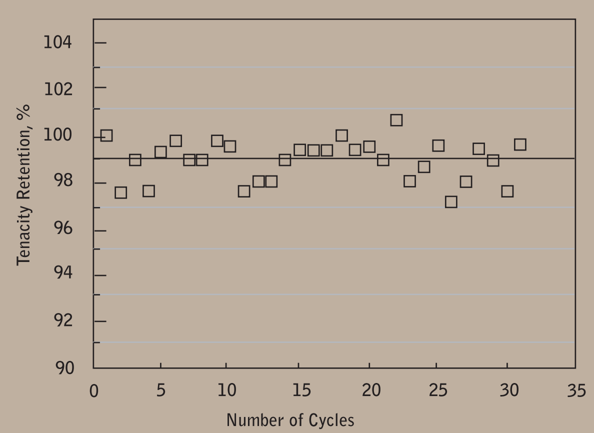
Figure 4: Strength After Thermal Exposure
24 Hour Exposure To Temperature, Followed by Testing at Ambient Temperature




(KAI)

For end uses that call for longterm or cyclic thermal exposure, ***Vectran®*** can also offer increased product lifetimes. Figure 5 illustrates that ***Vectran®*** has little to no strength loss in cyclic exposures to 120˚C. Vectran's resistance to cyclic thermal loads is confirmed at higher temperatures in Figure 6, which also illustrates Vectran's superiority to aramids in this respect. Note that the aramid in Figure 6 suffered 30% strength loss in roughly a dozen 8-hr cycles, or 4 days of exposure (in total). Similar trends are observed when ***Vectran®*** is held at 250°C continuously (Figure 7) and after 120°C steam exposure (Figure 8).

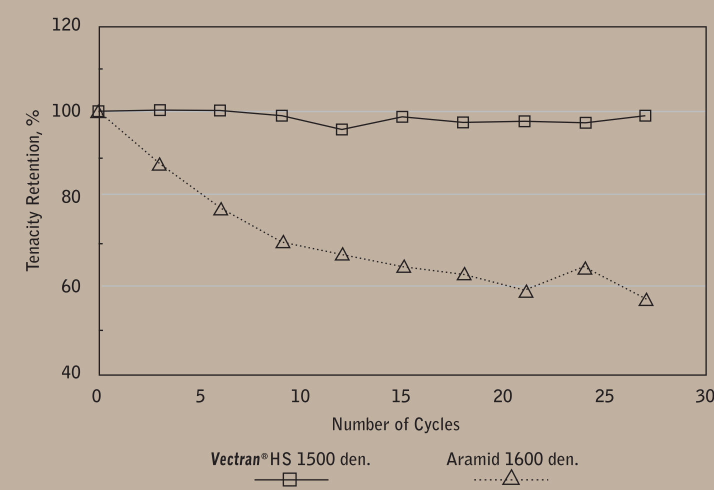
Figure 5: ***Vectran®*** HT Tenacity vs Cycles At Temperature




Each Cycle = 8 hours @ 120C followed by testing at ambient temperature

(KAI)

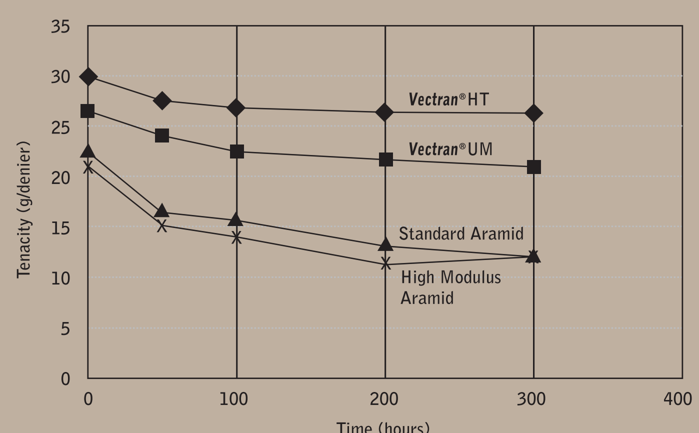
Figure 6: ***Vectran®*** HT 1500/300 Filament Yarn Tenacity – Cycles at 195°C




Each Cycle = 8 hours @ 195C; testing at ambient temperature

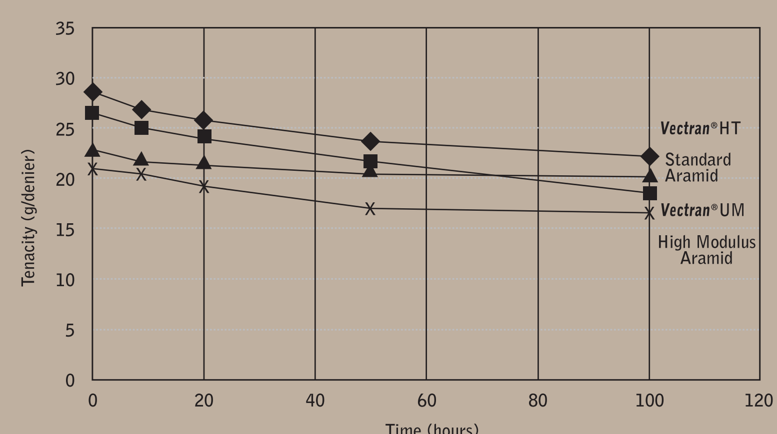
(KAI)

Figure 7: Tenacity After Thermal Exposure (250°C)




(KRC)

Figure 8: Tenacity After Steam Exposure (120°C)

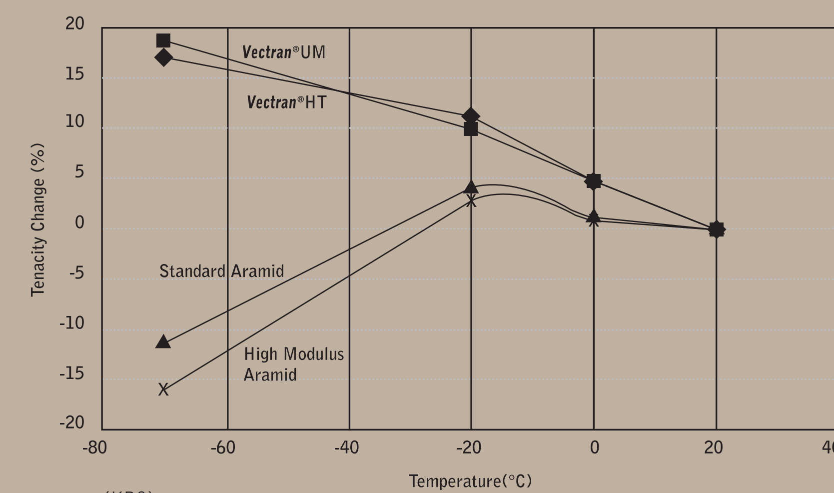



(KRC)



***Vectran®*** fiber's performance at low temperature was evaluated by ILC Dover during the design of the airbag system for the 1997 Mars Pathfinder mission. ILC reported that ***Vectran®*** actually increased in strength in tests at -62˚C, leading to its selection for the airbag fabric and external assembly tendons (Development and Evaluation of the Mars Pathfinder Inflatable Airbag System, D. Cadogen et al, ILC Dover, Inc., 49th International Astronautical Congress, 1998.) This distinguishing characteristic of ***Vectran®*** is shown in Figure 9.

Figure 9: Low Temperature Properties of ***Vectran®*** Fiber




(KRC)

***Vectran®*** has a low, negative coefficient of thermal expansion (Table 5). This is particularly beneficial for dimensional control of composites. Thermal conductivity properties are given in Table 6.

Table 5: ***Vectran®*** HT CTE at Various Temperatures

| | Fiber Longitudinal Direction CTE (m/m-°C X 10$^{-06}$) | |
|---|---|---|
| Temperature Range | ***Vectran®*** HT | Standard Aramid |
| -150 to 100°C | -4.8 | -4.9 |
| 100 to 200°C | -11.6 | -5.8 |

(KRC)

Table 6: Thermal Conductivity of ***Vectran®*** HT

| | Direction | Temperature °C | Density g/cm$^3$ | Specific Heat J/kg-°K | Thermal Conductivity W/m-°K | Thermal Conductivity 10$^{-3}$cal/cm-sec-°C |
|---|---|---|---|---|---|---|
| ***Vectran®*** HT | Longitudinal | 23 | 1.4 | 1100 | 1.5 | 3.5 |
| | | 100 | 1.4 | 1420 | 2.0 | 4.7 |
| Standard Aramid | Longitudinal | 23 | 1.44 | 1230 | 2.5 | 5.9 |

(KRC)

# Offgassing/Outgassing

In aerospace applications, material candidates are often screened for outgassing and offgassing properties. Outgassing is the release of chemicals from non-metallic substances under vacuum conditions. Test method ASTM E595 is routinely used to assess material outgassing characteristics. In this test, a material is held at 125˚C for 24 hours in vacuum, and condensing volatiles are collected on a cooled plate. Test results include the sample's percent total mass loss (TML%), the percent collected volatile condensable materials (CVCM%), and percent water vapor regained (WVR%).

Offgassing refers to the release of chemicals from materials at ambient or higher pressure. Test method NHB 8060.1C (Test 7) is commonly used to measure offgassing characteristics. In this test, the candidate material is held at 125˚C and ambient pressure for 72 hours. Gas sample analysis yields offgassed product identities and their concentration. For each species, the ratio of the sample concentration to its SMAC (spacecraft maximum allowable concentration) is calculated. The sum of these ratios is the T value of the material, or the Toxic Hazard Index.

***Vectran®*** fiber with either T97 or T150 finish provides excellent offgassing and outgassing characteristics (Table 7) in a wide variety of aerospace applications.

Table 7: Offgassing and Outgassing Test Results for ***Vectran®*** HT Fiber

| ***Vectran®*** Fiber with: | TML% | CVCM% | WVR% | T |
|---|---|---|---|---|
| No finish | * | 0.00 | 0.00 | 2.226** |
| T97 finish | * | 0.00 | 0.00 | 0.009 |
| T150 finish | 0.30 | 0.00 | 0.00 | 0.015 |

* Test results exceeded precision limits required to produce a statistically meaningful average. Individual samples measurements: fiber without finish, 0.21 and 0.07%; fiber with T97 finish, 0.13 and 0.19%.

** The contribution of benzyl alcohol to this T-value is 2.214. The concentration in the sample was 0.31μg/g; no measured SMAC value was available, therefore a conservatively low value of 0.14 μg/g was assumed.

(KAI)

# Chemical Resistance

***Vectran®*** fiber has good strength retention in chemical exposures covering a wide range of aggressive chemicals, concentrations, exposure times, and temperatures. The fiber is resistant to organic solvents, some acids of >90% concentration, and bases of <30% concentration. Specific exposure results are provided in Table 8.

Chemical resistance is an important consideration in protective apparel use, garment care, and upkeep. Bleach resistance, strength retention, and dimensional stability (i.e., shrinkage) determine the launderability of protective garments, which, of course, affects the cost and performance of safety wear. For example, HMPE fibers are sensitive to high temperatures associated with drying, while ***Vectran®*** offers minimal shrinkage in hot water or air (Table 3). Figure 10 demonstrates Vectran's superior bleach resistance compared to aramid fiber. ***Vectran®*** fiber's dimensional and chemical stability simplify garment care and further allow the use of chlorine as a cleaning agent in various applications.

Figure 10: Tenacity Retention ***Vectran®*** HT vs Aramid

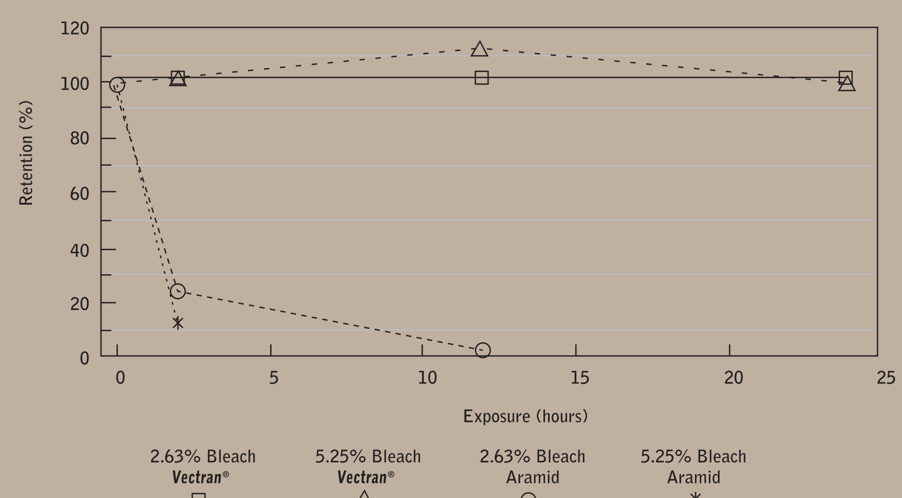



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Table 8: Chemical Resistance Of ***Vectran®*** Fiber

| Reagent | Formula | Concentration (%) | Temperature °C | Time (Hours) | Fiber Strength Retention (%) ***Vectran®*** HT | ***Vectran®*** UM | Standard Aramid |
|---|---|---|---|---|---|---|---|
| **Acids** | | | | | | | |
| Hydrochloric Acid | HCI | 1 | 50 | 100 | 100 | 96 | 93 |
| | | 1 | 50 | 1,000 | 93 | - | 34 |
| | | 1 | 50 | 10,000 | 84 | - | 16 |
| | | 10 | 70 | 1 | 96 | - | 73 |
| | | 10 | 70 | 10 | 93 | - | 26 |
| Sulfuric Acid | $H_2SO_4$ | 1 | 50 | 100 | 99 | 99 | 98 |
| | | 1 | 50 | 1,000 | 93 | - | 88 |
| | | 1 | 50 | 10,000 | 85 | - | 28 |
| | | 10 | 20 | 100 | 100 | - | 94 |
| | | 10 | 20 | 1,000 | 95 | - | 90 |
| | | 10 | 20 | 10,000 | 90 | - | 69 |
| | | 10 | 50 | 100 | 98 | - | 86 |
| | | 10 | 50 | 1,000 | 98 | - | 65 |
| | | 10 | 50 | 10,000 | 82 | - | 12 |
| | | 10 | 70 | 10 | 94 | - | 79 |
| | | 10 | 70 | 100 | 93 | - | 19 |
| | | 10 | 100 | 10 | 96 | - | 40 |
| Nitric Acid | $NHO_3$ | 1 | 50 | 100 | 99 | 100 | 83 |
| | | 1 | 50 | 1,000 | 97 | - | 29 |
| | | 1 | 50 | 10,000 | 86 | - | 14 |
| | | 10 | 70 | 1 | 95 | - | 60 |
| | | 10 | 70 | 10 | 95 | - | 23 |
| | | 10 | 70 | 100 | 92 | - | 5 |
| Phosphoric Acid | | 10 | 70 | 100 | 93 | - | 46 |
| | | 10 | 100 | 100 | 91 | - | 20 |
| Formic Acid | | 90 | 20 | 100 | 96 | - | 93 |
| | | 90 | 70 | 100 | 93 | - | 42 |
| Acetic Acid | | 40 | 70 | 100 | 94 | - | 37 |
| | | 40 | 100 | 100 | 90 | - | 22 |
| **Bases** | | | | | | | |
| Sodium Hydroxide | NaOH | 10 | 20 | 100 | 97 | - | 68 |
| (Caustic Soda) | | 10 | 70 | 20 | 66 | - | 21 |
| | | 10 | 70 | 40 | 37 | - | 19 |
| | | 10 | 70 | 60 | 32 | - | 17 |
| | | 10 | 100 | 10 | 28 | - | 17 |
| Calcium Hydroxide | $Ca(OH)_2$ | saturated | 50 | 100 | 96 | 86 | 93 |
| | | saturated | 50 | 1,000 | 85 | - | 60 |
| | | saturated | 50 | 10,000 | 9 | - | 20 |
| Cement Extract | | - | 20 | 10 | 99 | - | 98 |
| | | - | 20 | 100 | 100 | - | 94 |
| | | - | 20 | 1,000 | 95 | - | 90 |
| | | - | 20 | 10,000 | 90 | - | 69 |
| | | - | 50 | 1 | 100 | - | 98 |
| | | - | 50 | 10 | 99 | - | 94 |
| | | - | 50 | 100 | 97 | - | 90 |
| | | - | 50 | 1,000 | 79 | - | 59 |
| | | - | 50 | 10,000 | 6 | - | 20 |
| **Organic Solvents** | | | | | | | |
| Acetone | $Ch_3CoCH_3$ | 100 | 20 | 100 | 100 | 100 | 99 |
| | | 100 | 20 | 1,000 | 100 | - | 98 |
| | | 100 | 20 | 10,000 | 99 | - | 99 |
| Benzene | $C_6H_6$ | 100 | 20 | 100 | 97 | - | 96 |
| | | 100 | 70 | 100 | 95 | - | 93 |
| Carbon Tetrachloride | | 100 | 20 | 100 | 96 | - | 95 |
| Ether | | 100 | 20 | 100 | 98 | - | 95 |
| Ethyl Acetate | | 100 | 20 | 100 | 98 | - | 96 |
| Toluene | $C_6H_6CH_3$ | 100 | 20 | 100 | 100 | 100 | 96 |
| | | 100 | 20 | 1,000 | 99 | - | 98 |
| | | 100 | 20 | 10,000 | 98 | - | 99 |
| Methanol | $CH_3Ch_2OH$ | 100 | 20 | 100 | 96 | - | 94 |
| Perchloroethylene | | 100 | 20 | 100 | 95 | - | 96 |
| Formaldehyde | | 37 | 20 | 100 | 96 | - | 98 |
| Ethylene Glycol | $HOCH_2CH_2OH$ | 50 | 100 | 10 | 92 | - | 90 |
| | | 50 | 100 | 100 | 79 | - | 74 |
| Ammonia Solution | $NH_3$ | 10 | 70 | 24 | 35 | - | 95 |
| **Salts** | | | | | | | |
| Sodium Carbonate | $Na_2CO_3$ | 1 | 50 | 100 | 96 | 100 | 100 |
| | | 1 | 50 | 1,000 | 95 | 100 | 96 |
| | | 1 | 50 | 10,000 | 80 | 100 | 67 |
| Sodium Chloride | NaCI | 1 | 50 | 100 | 100 | 99 | 100 |
| | | 1 | 50 | 1,000 | 97 | 99 | 98 |
| | | 1 | 50 | 10,000 | 95 | 99 | 97 |
| Copper Sulfate | $CuSO_4$ | 1 | 50 | 100 | 101 | 100 | 100 |
| | | 1 | 50 | 1,000 | 95 | 100 | 98 |
| | | 1 | 50 | 10,000 | 90 | 100 | 68 |
| Zinc Chloride | $ZnCI_2$ | 1 | 50 | 100 | 98 | 99 | 99 |
| | | 1 | 50 | 1,000 | 98 | 99 | 98 |
| | | 1 | 50 | 10,000 | 95 | 99 | 97 |
| **Oils** | | | | | | | |
| Mineral Oil | | 100 | 20 | 100 | 100 | 100 | 100 |
| | | 100 | 20 | 10,000 | 100 | - | 100 |

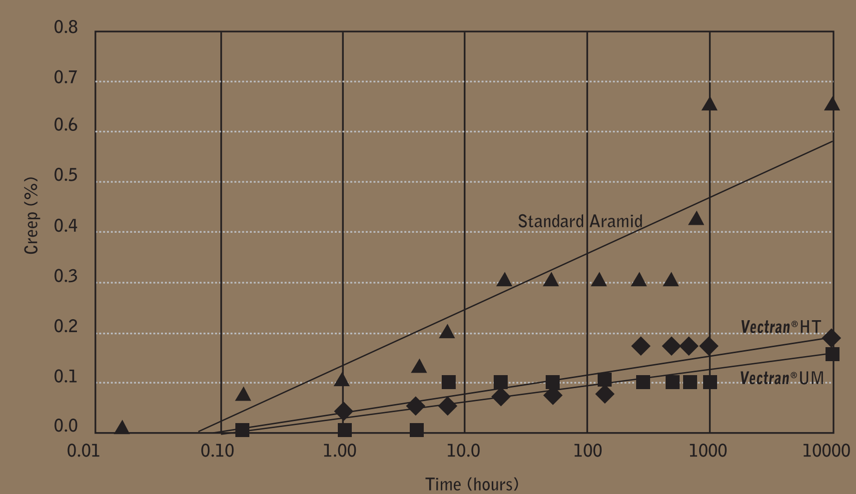
(KRC)

# Creep

Creep is the continued extension of a material when subjected to long-term static loading. Resistance to creep (or its static-strain complement, stress-relaxation) is a critical design consideration in material selection for many applications requiring long-term dimensional stability (e.g. sailcloth, halyards, bowstring, marine cables, robotic tendons, etc.).

In experiments on yarns and small braids, minimal creep was observed with loads up to 30% of rated breaking load. These tests ran for as long as 10,000 hours at ambient temperatures, as shown in Figure 11.

Figure 11: Creep Behavior At Ambient Temperature (30% of Break Load)

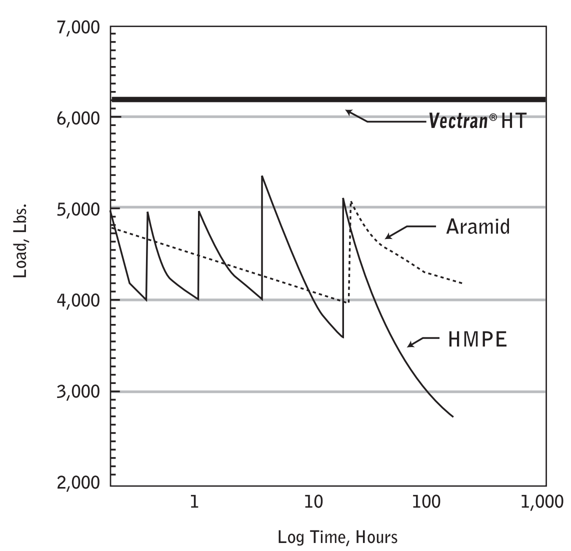



(KRC)

# Stress Relaxation

A manufacturer of high performance ropes measured stress relaxation on ***Vectran®***, aramid, and HMPE. In this test, ropes are tensioned to a known load using a turnbuckle configuration (i.e., a fixed strain). As relaxation occurs, the load decreases until the sample is retensioned using the turnbuckle. Test results are shown in Figure 12.

Figure 12: Stress Relaxation (1/2″ dia wirelay rope)



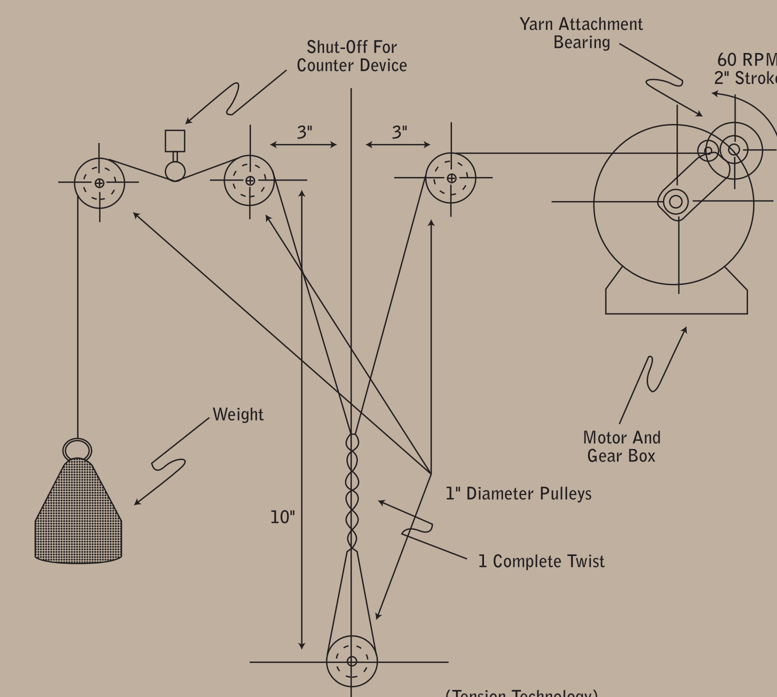

(KAI)



# Yarn-on-Yarn Abrasion Resistance

One measure of fatigue resistance used in the rope and cordage industry is the yarn-on-yarn abrasion test (e.g. Cordage Institute Test Method CI-1503). This test simulates abrasion of adjacent yarns inside a rope or rope splice during flexure. The typical test configuration is shown in Figure 13.

Figure 13: Yarn-On-Yarn Abrasion Test Set-Up




(Tension Technology)

Using this test, samples of ***Vectran®*** HT 1500/300 fiber with various finishes were evaluated versus a wide range of aramid yarns and HMPE. Results are shown in Table 9. ***Vectran®*** clearly outperforms aramids and is equivalent to or superior to HMPEs in dry testing. The performance of ***Vectran®*** and HMPE were improved by wet conditions; in contrast, aramid abrasion resistance was lower when tested in water.

Table 9: Comparative Testing of Yarn-on-Yarn Abrasion Resistance

| | Average Cycles-to-Failure | |
|---|---|---|
| Yarn | Dry | Wet |
| ***Vectran®*** T97, 1500D | 16672 | 21924 |
| Aramid 1, 1500D | 1178 | 705 |
| Aramid 2, 1500D | 1773 | 759 |
| Aramid 3, 1500D | 974 | 486 |
| PBO, 1500D | 2153 | – |
| HMPE, 1600D | 8518 | 23619 |

Test Method CI-1503: 1.5 wraps, 500g load, 66 cycles/min, no twist
(KAI)

Using a third party's proprietary marine finish, an independent rope and cordage industry test facility confirmed Vectran's exceptional abrasion resistance in comparison to aramids. Vectran's CTF was consistently an order of magnitude higher than that of the aramid at each set of test conditions (see Table 10).

Table 10: Yarn-on-Yarn Abrasion of **Vectran**® HT

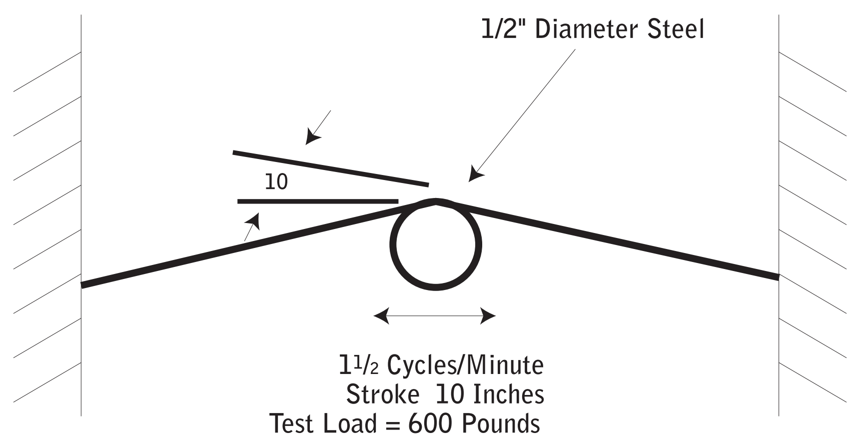
| | Cycles-to-failure* | | | |
|---|---|---|---|---|
| | Dry Test | Wet Test | Dry Test | Wet Test |
| Test Load | 500 g | 500 g | 800 g | 800 g |
| **Vectran**® HT | 12987 | 30519 | 3581 | 16524 |
| Aramid | 939 | 3029 | 422 | 1719 |

*1500 denier yarns, no twist, 1 wrap.
(KAI)

# External Abrasion Resistance

Abrasion test comparisons of **Vectran**® and aramid braids were conducted by a high-performance rope and cable company using the test shown schematically in Figure 14. Without marine finish on the braid, **Vectran**® outperformed aramid (Table 11). With marine finish applied to both **Vectran**® and aramid braids, **Vectran**® again showed superior abrasion resistance.

Figure 14: Rope Abrasion Test Set-up




Note: Samson Ocean Systems
Abrasion Test

Table 11: Braid Abrasion of **Vectran**® HT*

| | Cycles-to-Failure | |
|---|---|---|
| | **Vectran**® HT | Aramid |
| 600 lbf Load | | |
| Without marine finish | 286 | 83 |
| With marine finish applied | 1250 | 93 |

*Eight-strand plain braid, 64X1500 denier threadlines, All tests dry
(KAI)



# Flex Fatigue

Flexural fatigue is a critical concern in many applications where yarns or fabrics are subject to repeated bending or creasing. Examples include ropes, sailcloth, inflatable and/or temporary structures, etc. Improving the service life of products by increasing flex fatigue resistance is an important driver for the use of **Vectran**® fibers in a variety of applications.

The actual mechanism of flex fatigue has been a subject of considerable study, due to the significant variability in flexural failure resistance of fibers made from linear chain polymers. For example, typical polyesters, **Vectran**® (wholly aromatic liquid crystalline polyester), and aramids (wholly aromatic liquid crystalline polyamide) all exhibit a microfibrillar structure. In addition, the ultimate compressive strength of high modulus organic fibers is generally about 1/10 of the ultimate tensile strength, and for all of the examples above, the first visual manifestation of flex damage is the appearance of kink bands in the fiber. Kink bands, often explained as dislocations (buckling or breaking) in the molecular chains, could involve the entire microfibril, or propagate through the microfibril with repeated flexing or compressive strain at the same location.

In spite of these structural commonalities, these fibers differ considerably in their resistance to flexural fatigue. Typical polyester can not provide the tensile and thermal stability of high performance fibers, but it does offer higher flex fatigue resistance when cycled at a similar percentage level of its ultimate breakload. **Vectran**® routinely outperforms aramids when tested for fatigue resistance and tenacity retention in yarn, rope/cable, and fabric forms.

Comparative data for yarns appear in Table 12 and were collected using the Folding Endurance Tester (Figure 15). While aramid results varied considerably with type, **Vectran**® clearly outperforms the aramid class as well as PBO. Flexural test data should always be considered as a tool to rank various materials since controlled component testing can not mirror actual results in the fully constructed product's environment. However, relative material rankings are consistent from test to test, as seen in Table 13. These rope testing data, generated by a high performance rope and cable company, show a range of lifetimes observed for aramids and PBO, with clearly the best results obtained from the **Vectran**® sample.

Figure 15: Folding Endurance Tester
(Tinius Olsen/M.I.T.)

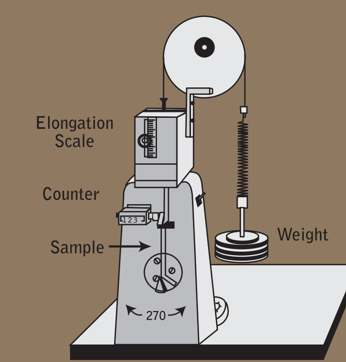



Table 12: Flex Fatigue Results on 1500D Yarn

| Material | Cycles-to-failure |
|---|---|
| **Vectran**® T97 | 115113 |
| Aramid 1 | 5114 |
| Aramid 2 | 40666 |
| Aramid 3 | 1383 |
| PBO | 23821 |

Test Conditions: Tinius Olsen tester, ASTM D2176-97a, modified for yarn, 4.5 lb weight
(KAI)

Table 13: Flex Fatigue Results on 0.085″ Ropes

| Material | Cycles-to-failure |
|---|---|
| **Vectran**® T117 | 41909 |
| Aramid 1 | 2115 |
| Aramid 2 | 14963 |
| Aramid 3 | 8143 |
| PBO | 25158 |

Construction: Parallel core/extruded jacket
Test conditions: 0.085″ dia. samples, 1.78″ dia pulley, 100lb test load, 58 cycles/min., 5 tests/sample on cyclic test machine
(KAI)

An aerospace company compared flexural fatigue resistance of ***Vectran***® to aramids in coated fabric form. In this study, base fabrics of aramid and ***Vectran***® were coated in an identical fashion with the company's proprietary formulation. Specimens 1″ (weft direction) x 60″ were cut and tested to simulate hard creasing and folding in a cyclic fashion. Each cycle consisted of folding the sample in half, dragging a 10 lb. steel roller over the fold, refolding the specimen at the same point but in the opposite direction, and again dragging the roller over the fold. Strength losses were compared using a test compliant with FED-STD-191, Test Method 5102. As Table 14 illustrates, Vectran's tenacity losses were minimal after 100 cycles, with the tensile failure point occurring away from the fatigued fold line. Aramid strength losses were significant, with tensile failures occurring at the fold line.

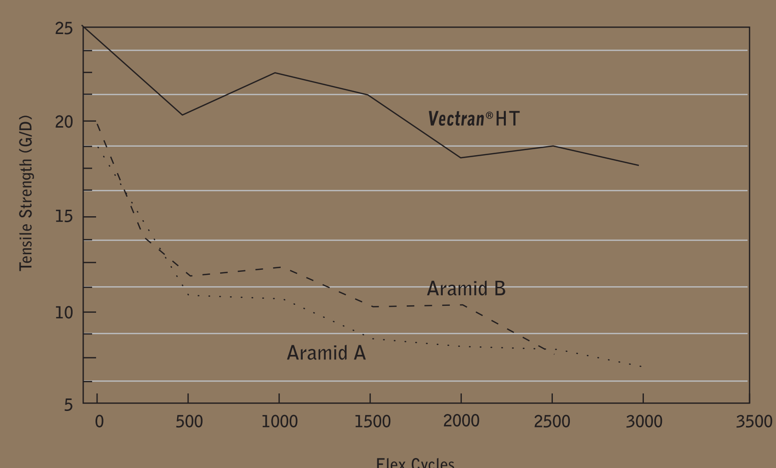
Table 14: Fatigue Testing of Coated Fabrics

| Base Material | Tenacity Loss at 100 Cycles, % | Failure Location |
|---|---|---|
| ***Vectran***® | 0.8 | Away from Fatigued Crease |
| Aramid | 22.9 | At Crease |

(KAI)

Vectran's higher load bearing capability after equivalent fatigue levels is also demonstrated in Figure 16. In this comparison, 400 denier ***Vectran***® and aramid yarns were subjected to the indicated cycle level in a Tinius Olsen tester, after which the samples were removed and tested for strength. In this study, Vectran's load bearing capability was twice that of the aramid after as few as 500 cycles, and the gap appears to widen as cycling continues. Fiber samples for each material and cycle level were examined by microscopic techniques in an effort to compare kink band formation. ***Vectran***® samples showed kink band formation increasing with cycle level as expected; however, the most noted observation for aramid samples was the presence of split and fibrillated fibers, even at the 500 cycle level. Possibly, kink band formation in the aramids was initiated at much lower cycle levels, but catastrophic failures later masked or interfered with microscopic examinations.

Figure 16: Tensile Strength vs Flexural Fatigue




(KAI)

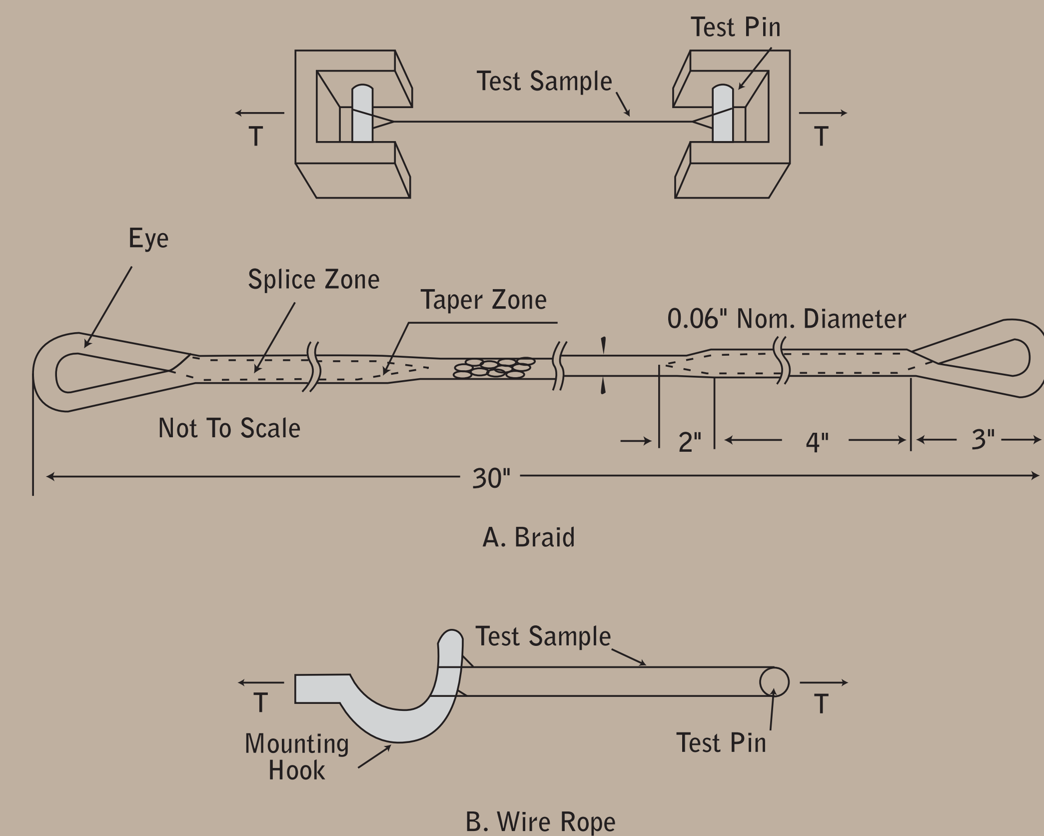
Flexural fatigue failure and differences between the resistance of various fibers is not a simple mechanism. However, one relevant consideration might be the relative extent of crystalline order in these three fibers. For example, standard polyesters are ordered along the axis with considerable amorphous content. ***Vectran***® is a liquid crystalline fiber oriented along the axis with no amorphous regions and no observed three-dimensional crystallinity. Aramids are liquid crystalline fibers in which three-dimensional crystals have been observed. While each of these fibers has exhibited kink band formation in response to compressive strains, lower degrees of dimensional order may more effectively block damage propagation across microfibrils and/or fibers.



# Bend Tolerance

Tolerance to bending around small radii is important in ropes and cables, as it allows the use of smaller running gears or termination hardware. Aerospace and rope manufacturers conducted pin diameter tests on ***Vectran***® braid and wire rope, respectively. The test configurations are shown in Figure 17.

Figure 17: Cord Test Sample Dimensions

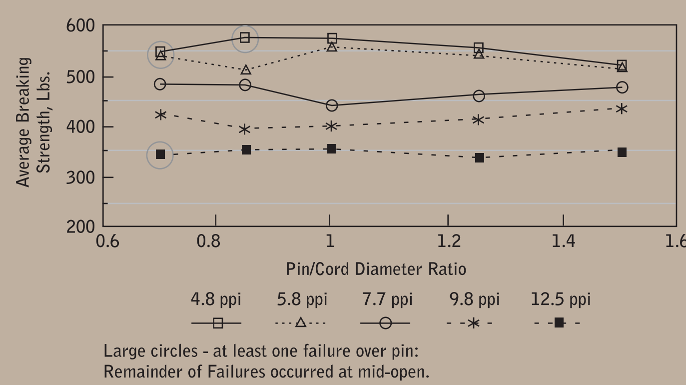



(KAI)

For the braid tests, each sample was 30 inches long and eye spliced on both ends with a long taper to minimize stress concentration where the splice begins. Each sample was tensioned three times to half its breaking strength to remove construction slippage before being tensioned to break. Pin diameters ranged from 0.110 inches to 0.31 inches. D/d (pin diameter/rope diameter) ranged from 1.5 down to 0.7. For the larger wire rope tested, each sample was cycled five times 0-5,000 lbs., five times 0-10,000 lbs. and tensioned to break. The rope diameter was 0.5 inches; D/d ranged from 7.56 down to 2.28.

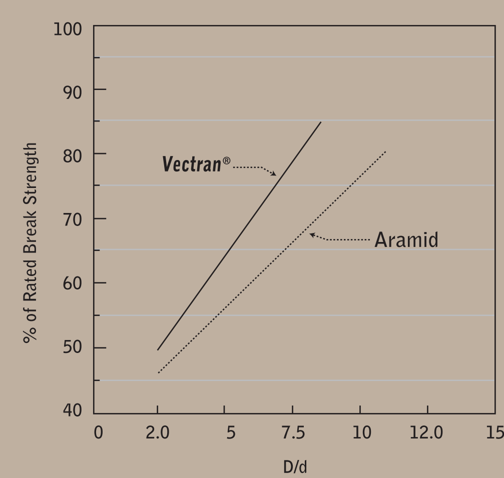
The break strength of ***Vectran®*** braids did not decrease with decreasing D/d, as shown in Figure 18. Furthermore, breaks occurred in the middle of the sample and not at the pins. For the 0.5 inch diameter wire rope construction, ***Vectran®*** had a higher break strength than aramid over the range of pin diameters tested (Figure 19). While no change in ***Vectran®*** braid break strength was observed with decreasing pin diameter, a decrease was observed for the ***Vectran®*** wire rope construction.

Figure 18: Breaking Strength vs Pin/Cord Dia.Ratio 8x1500/1 Construction




(KAI)

Figure 19: Break Strength vs D/d Wire Rope Construction




(KAI)

# Impact Resistance

In composite applications, ***Vectran®*** offers a unique balance of properties rarely found in synthetic fibers: minimal moisture regain, thermal stability, and excellent impact resistance. Dynatup impact tests were conducted on 1500 denier ***Vectran®*** HT and aramid fabric samples. Both samples contained 13 X 13 plain weave constructions within Dow Derakane 411 resin (***Vectran®*** sample thickness: 0.0474 in.-0.0488 in., aramid sample thickness 0.040 in.). A 12.09 lb. load cell attached to a 5/8 in. tup dropped 36 inches through a metal tube before impact (Figure 20). Table 15 compares the impact energy required for sample penetration.

Figure 20: Dynatup Impact Test

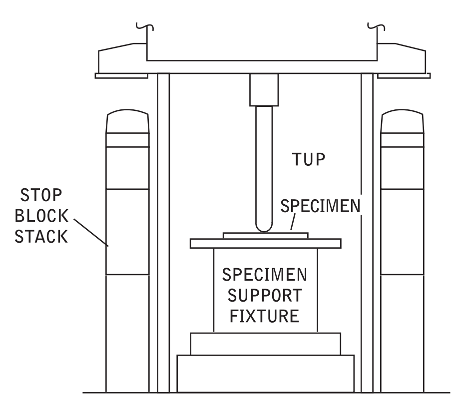



Table 15:
Impact Resistance Comparison of High-performance Fabrics

| Impact Energy (inch lbs.) | ***Vectran®*** | Aramid |
|---|---|---|
| 25 | No | No |
| 30 | No | No |
| 50 | No | Penetration |
| 75 | No | Penetration |
| 100 | No | Penetration |
| 125 | Penetration | Penetration |

(KAI)



# Vibration Damping

A vibration damping measurement system and a comparison of vibration damping characteristics for glass fiber, carbon fiber, aramid fiber, and ***Vectran®*** fiber are found in Figures 21 and 22. Table 16 lists performance characteristics of various metals and composite materials used by a manufacturer of audio components. The differences are apparent and demonstrate that ***Vectran®*** fiber is ideal for vibration damping in sporting goods and audio applications.

Figure 21: Measurement System For Vibration Damping

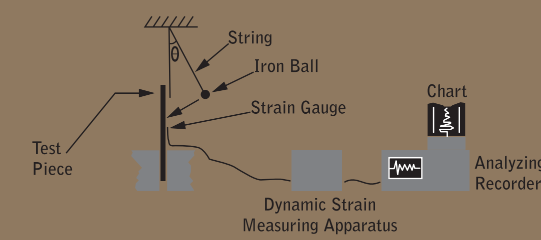
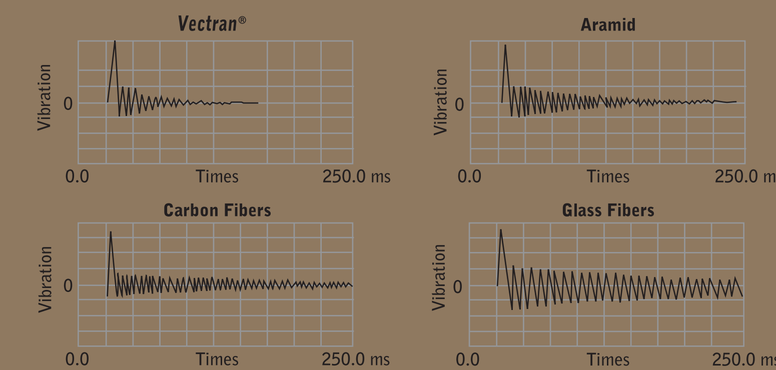



Figure 22: Vibration Damping




Periodic Damping of Single Fibers Reinforced Composite
(Matrix Resin: Epoxy)
(KRC)

Table 16: Audio Engineering Data For Various Metals and Composites

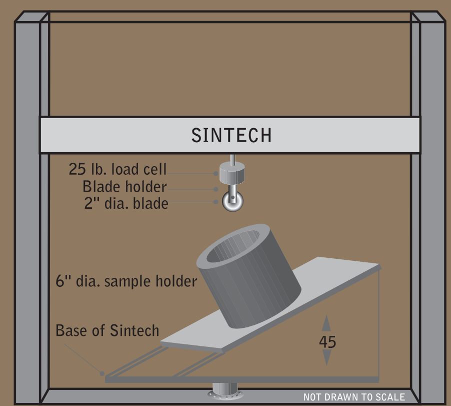
| Material | Speed of Sound m/s | Density g/cm3 | Elastic Modulus GPa | Modulus Rigidity E/ρ3 | Internal Loss Tanδ |
|---|---|---|---|---|---|
| Carbon Fiber* | 6902 | 1.42 | 68 | 23.6 | 0.035 |
| Paper (typical) | 1781 | 0.50 | 2 | 12.7 | 0.040 |
| Magnesium | 5000 | 1.74 | 44 | 8.3 | 0.004 |
| ***Vectran®*** ** | 4288 | 1.50 | 28 | 8.2 | 0.070 |
| Glass | 3216 | 2.00 | 21 | 2.6 | N/A |
| PET | 1802 | 1.38 | 4 | 1.7 | 0.010 |
| Titanium | 4773 | 4.54 | 103 | 1.1 | 0.002 |
| Stainless Steel | 5125 | 7.90 | 207 | 0.4 | 0.002 |

*woven fabric within epoxy resin
**woven ***Vectran®*** HT and NT blend within epoxy resin
(KAI)

# Cut Resistance

Cut resistant tests are many and varied, and uniformity of test sample and cutting edge is critical in all tests. In-house cut-resistance comparisons have used a Sintech tensile testing machine modified as shown in Figure 23 to accept a fixture holding a knitted hoseleg.

Figure 23: Sintech Tensile Testing Machine




Tension is adjusted in hoseleg samples to allow a specified deflection at a given load. Inspection of the round blade to assure a clean cutting edge is critical. Table 17 compares the cut resistance of various fibers.

Table 17: Sintech Cut Resistance

| Material | Denier | Relative Load |
|---|---|---|
| ***Vectran®*** HT | 1500 | 3.4 |
| ***Vectran®*** NT | 1500 | 2.2 |
| Aramid | 1500 | 1.1 |
| HMPE | 1500 | 1.0 |

(KAI)

Kuraray method tests, utilizing fixed blades, yield similar results with knitted spun yarn samples (Figure 24). Table 18 compares these results.

Figure 24: Kuraray Test Method

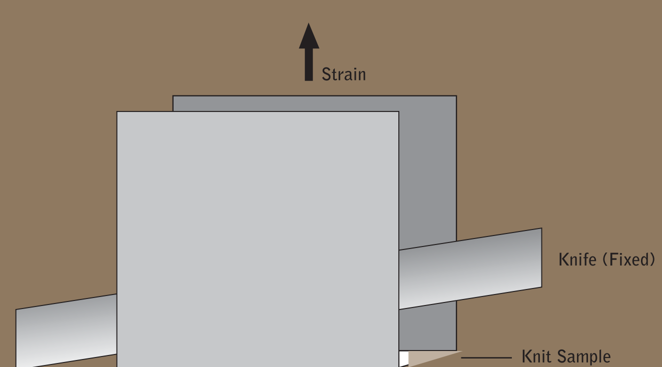



Table 18: Cut Resistance Of Spun Yarn (Knit Samples From 20s/2s)

| Material | Relative Load |
|---|---|
| ***Vectran®*** HT | 100 |
| Standard Aramid | 73 |
| Polyester | 4 |

(KRC)

# Twist

Twisting is the process of combining filaments into yarn by twisting them together or combining two or more parallel singles yarns (spun or filament) into plied yarns or cords. Twisting improves uniformity and smoothness, and can be used to optimize strength and elongation. Note that overtwisting can significantly lower tensile properties.

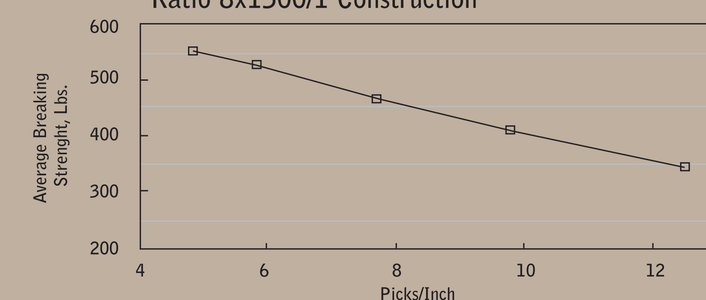
Many high performance yarns benefit from the improved load sharing that twisting allows. Optimum twist level varies with the material, fiber size, yarn size, end use, etc. Table 19 illustrates Vectran's tenacity response to varying twist level, suggesting tenacity optimums of 2.5 TPI for 400 denier and 1.5 TPI for 1500 denier yarns. Similar tests determine ideal cord and cable pick levels (Figures 25, 26).

Table 19: ***Vectran®*** HT Tenacity vs. Twists per Inch (TPI)

| TPI | 400 denier tenacity gpd | 1500 denier tenacity gpd |
|---|---|---|
| 0 | 25.6 | 25.6 |
| 0.5 | 26.5 | 26.7 |
| 1.0 | 27.8 | 27.6 |
| 1.5 | 27.8 | 28.6 |
| 2.0 | 28.6 | 27.9 |
| 2.5 | 28.8 | 27.6 |
| 3.0 | 28.1 | 25.8 |
| 3.5 | 28.3 | 24.0 |
| 4.0 | 28.3 | 21.8 |
| 4.5 | 27.8 | N/A |
| 5.0 | 27.8 | N/A |

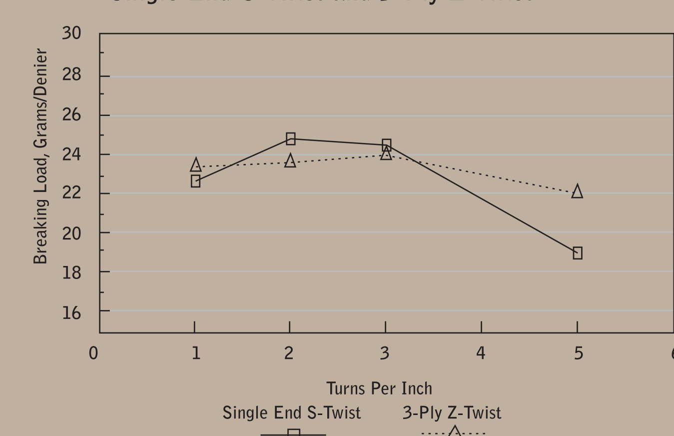
(KAI)

Figure 25: Breaking Strength vs Picks/Inch
Ratio 8x1500/1 Construction




(KAI)

Figure 26: 1500/300 ***Vectran®*** HT
Single End S-Twist and 3-Ply Z-Twist



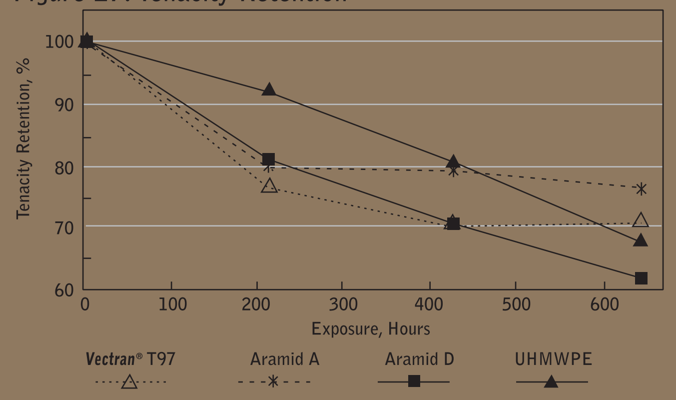

(KAI)

# UV Resistance

The UV resistance of products made from high performance fibers is highly dependent upon a number of variables, including final product form (for example, rope or fabric, filament and yarn size, finishes/coatings, twist/pick levels, etc). The impact of UV on braided cords made from high performance fibers is illustrated in Figure 27.

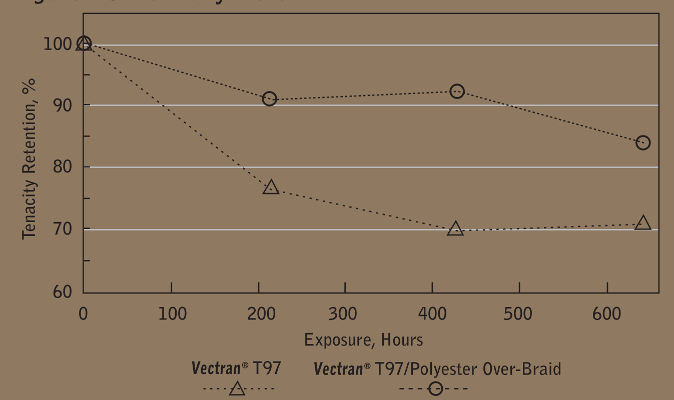
Figure 28 shows that UV damage can be mitigated with simple protective measures – in the worst case (e.g. single fiber, low twist, no coatings or external protection), ***Vectran®*** and other high performance fibers will not retain acceptable performance after long-term UV exposure (Figure 29).

Figure 27: Tenacity Retention



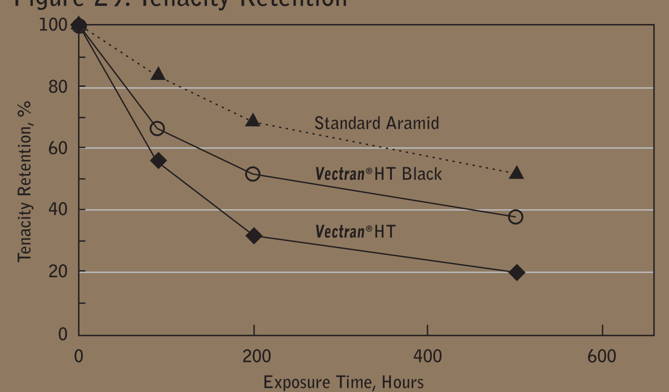

Rope: 1/4" Diameter, 12x1 Braid
Test Method: AATCC #16E (Xenon-Arc Lamp)
(KAI)

Figure 28: Tenacity Retention




Rope: 1/4" Diameter, 12x1 Braid
Test Method: AATCC #16E (Xenon-Arc Lamp)
(KAI)

Figure 29: Tenacity Retention




Light Source: Carbon-arc Lamp
Samples: 1500 Denier, 2tpi twist
(KRC)



# Radiation Exposure

LCP's are transparent to microwave energy and are virtually unaffected by high levels of radiation. ***Vectran®*** fiber is likewise stable in high X-ray exposure environments (Table 20).

Table 20: ***Vectran®*** Radiation Exposure

| Sample | Twist (t/m) | Denier (dtex) | Before Exposure<br>Tenacity (g/d) | Elongation (%) |
|---|---|---|---|---|
| ***Vectran®*** HT | 80 | 1,696 | 28.9 | 3.8 |
| ***Vectran®*** UM | 30 | 1,589 | 23.9 | 2.6 |
| Standard Aramid | 30 | 1,748 | 22.7 | 4.5 |

| Sample | Twist (t/m) | Denier (dtex) | After Exposure X-ray<br>Tenacity (g/d) | Elongation (%) | Strength<br>Resistance (%) |
|---|---|---|---|---|---|
| ***Vectran®*** HT | 80 | 1,691 | 28.4 | 4.3 | 98 |
| ***Vectran®*** UM | 80 | 1,599 | 26.3 | 3.1 | 110 |
| Standard Aramid | 80 | 1,705 | 24.4 | 4.3 | 108 |

Source: Soft X-ray
Amount of radiation exposure: 9.6xE+06 (mR/h at 1m)
This energy is equivalent to the 1800 times levels used in medical soft X-ray photography
(KRC)

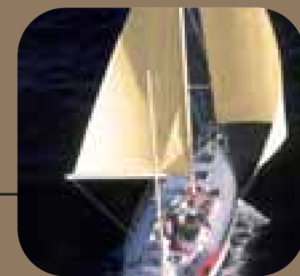
# Applications

## Ropes and Cables

Sonobuoy Cables
Seismic/Magnetometer Tow Cables
Sidescan Sonar Cables
Towed ASW Sensor Systems
Thermistor Cables and Strings
Aircraft Geophysical Tow Cables
Drill Hole Logging Cables
Pumped Water Sampler Cables
Environmental Ocean Sensors
Aerial Camera Tethers
Fishing System Sensors
Divers Comm/Strength Members
Air Tow Cables (Countermeasures)
Array Cables
Subsea Mooring Lines
Balloon Tethers
Parachute Cords
Taglines-River/Canyon
Helicopter Sling Legs
Aircraft Target Tow Cables
Astronaut Safety Tethers
Center Core Strength Members
Pull Through Cables
Ship Handling Cables
Helicopter Rescue Hoist Cables
Choker/Snatch Cables
Fish Net Trawl Ropes
Stainless Wire Replacement
Optical Fiber Tension Members
Deep Sea Winch Systems
Aircraft Cable
Deck Pendants
Robotic Cables
Automotive Cables

## Industrial/Military/Aerospace

Heat Resistant Belting
High Pressure Inflatables
Tape Reinforcement
Abrasion Resistant Baggage
Chemically Resistant Packings
Chemically Resistant Gaskets
Cut Resistant Gloves
Fragmentation Fabric
Prison Industry Garments
Oil Well Tension Members
Chain Saw Chaps
Cut Resistant Clothing
Concrete Reinforcement
Pressure Vessels
Electronic Reinforcement
Sewing Thread
Radome Composites
Aerostats
Dirigibles
Airbeams
Pneumatic Muscles
Cryogenic Applications
Specialized Value Composites
Nonwovens
Adhesive Reinforcement
Speaker Cones
Voice Coil Wraps
Geotextiles
Filtration Applications



## Sporting Goods

Sailcloth
Mountaineering Ropes
Skis and Snowboards
Fishing Pole Reinforcement
Bow Strings
Bicycle Components
Reinforced Hulls
Golf Clubs
Tennis Racquets and Strings
Mainstays
Backstays
Running Rigging
Standing Rigging
Fishing Line
Hockey Sticks