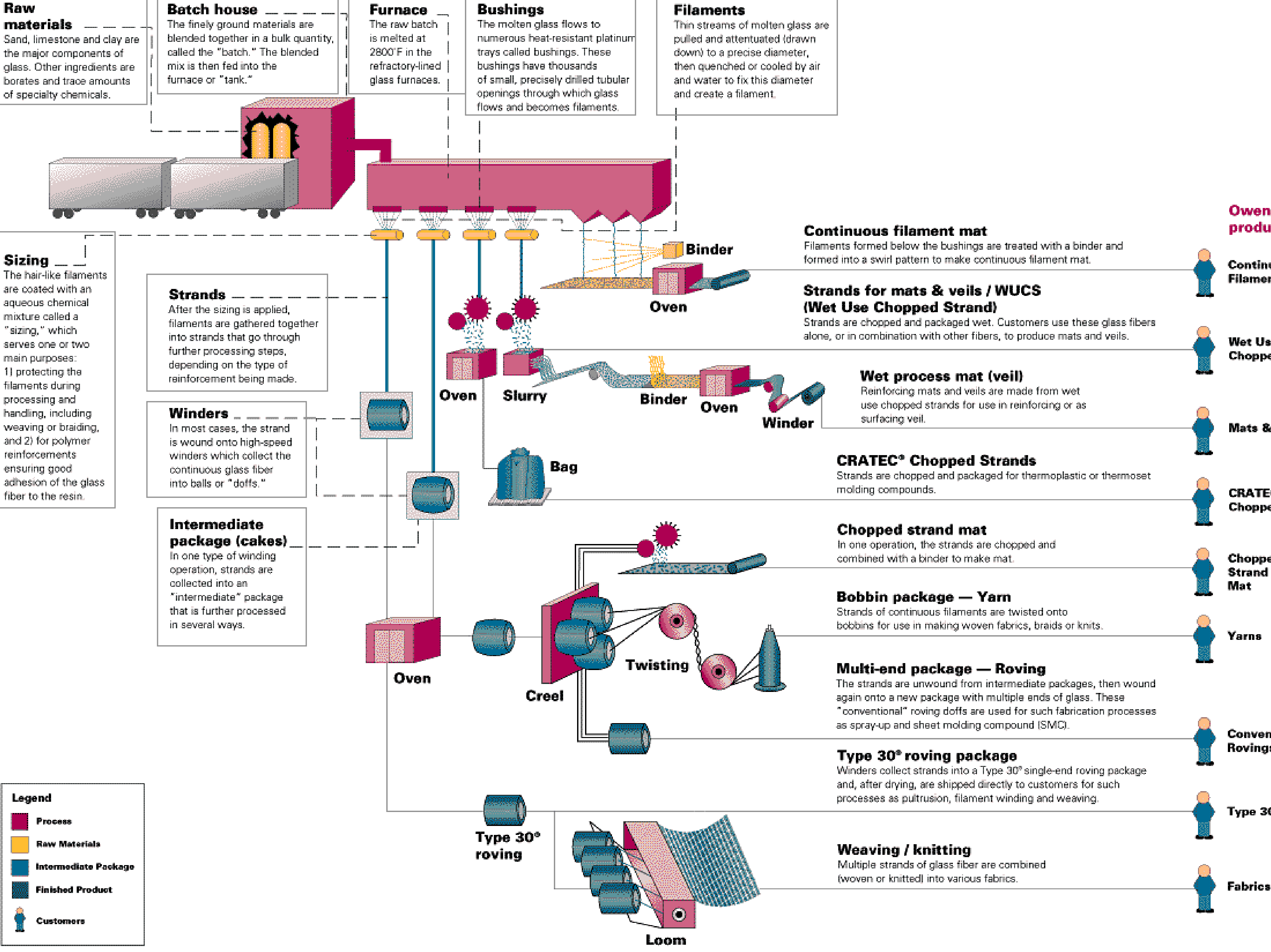

Raw materials
Sand, limestone and clay are the major components of glass. Other ingredients are borates and trace amounts of specialty chemicals.
Batch house
The finely ground materials are blended together in a bulk quantity, called the "batch." The blended mix is then fed into the furnace or "tank."
Furnace
The raw batch is melted at 2800°F in the refractory-lined glass furnaces.
Bushings
The molten glass flows to numerous heat-resistant platinum trays called bushings. These bushings have thousands of small, precisely drilled tubular openings through which glass flows and becomes filaments.
Filaments
Thin streams of molten glass are pulled and attentuated (drawn down) to a precise diameter, then quenched or cooled by air and water to fix this diameter and create a filament.
Sizing
The hair-like filaments are coated with an aqueous chemical mixture called a "sizing," which serves one or two main purposes: 1) protecting the filaments during processing and handling, including weaving or braiding, and 2) for polymer reinforcements ensuring good adhesion of the glass fiber to the resin.
Strands
After the sizing is applied, filaments are gathered together into strands that go through further processing steps, depending on the type of reinforcement being made.
Winders
In most cases, the strand is wound onto high-speed winders which collect the continuous glass fiber into balls or "doffs."
Intermediate package (cakes)
In one type of winding operation, strands are collected into an "intermediate" package that is further processed in several ways.
Binder
Oven
Oven
Slurry
Binder
Oven
Winder
Bag
Oven
Creel
Twisting
Type 30® roving
Loom
Continuous filament mat
Filaments formed below the bushings are treated with a binder and formed into a swirl pattern to make continuous filament mat.
Strands for mats & veils / WUCS (Wet Use Chopped Strand)
Strands are chopped and packaged wet. Customers use these glass fibers alone, or in combination with other fibers, to produce mats and veils.
Wet process mat (veil)
Reinforcing mats and veils are made from wet use chopped strands for use in reinforcing or as surfacing veil.
CRATEC® Chopped Strands
Strands are chopped and packaged for thermoplastic or thermoset molding compounds.
Chopped strand mat
In one operation, the strands are chopped and combined with a binder to make mat.
Bobbin package — Yarn
Strands of continuous filaments are twisted onto bobbins for use in making woven fabrics, braids or knits.
Multi-end package — Roving
The strands are unwound from intermediate packages, then wound again onto a new package with multiple ends of glass. These "conventional" roving doffs are used for such fabrication processes as spray-up and sheet molding compound (SMC).
Type 30® roving package
Winders collect strands into a Type 30® single-end roving package and, after drying, are shipped directly to customers for such processes as pultrusion, filament winding and weaving.
Weaving / knitting
Multiple strands of glass fiber are combined (woven or knitted) into various fabrics.
Strand
Mat
Yarns
Fabrics
Legend
Process
Raw Materials
Intermediate Package
Finished Product
Customers

# Raw Materials

- More than half the mix is silica sand, the basic building block of any glass.
- Other ingredients are borates and trace amounts of specialty chemicals.

Return

# Batch House & Furnace

- The materials are blended together in a bulk quantity, called the "batch."
- The blended mix is then fed into the furnace or "tank."
- The temperature is so high that the sand and other ingredients dissolve into molten glass.

Return

# Bushings

- The molten glass flows to numerous high heat-resistant platinum trays which have thousands of small, precisely drilled tubular openings, called "bushings."

Return

# Filaments

- This thin stream of molten glass is pulled and attenuated (drawn down) to a precise diameter, then quenched or cooled by air and water to fix this diameter and create a filament.

Return

# Sizing

- The hair-like filaments are coated with an aqueous chemical mixture called a "sizing," which serves two main purposes:
  1) protecting the filaments from each other during processing and handling, and
  2) ensuring good adhesion of the glass fiber to the resin.

Return

# Winders

- In most cases, the strand is wound onto high-speed winders which collect the continuous fiber glass into balls or "doffs.“

**Single end roving**

- Most of these packages are shipped directly to customers for such processes as pultrusion and filament winding.
- Doffs are heated in an oven to dry the chemical sizing.

Return

# Intermediate Package

- In one type of winding operation, strands are collected into an "intermediate" package that is further processed in one of several ways.
- For most intermediate packages, the fibers are unwound, then wound again onto a new package with **multiple ends of glass**.
- These "conventional" roving doffs are used for such fabrication processes as spray-up and sheet molding compound (SMC).

Return

# Strands

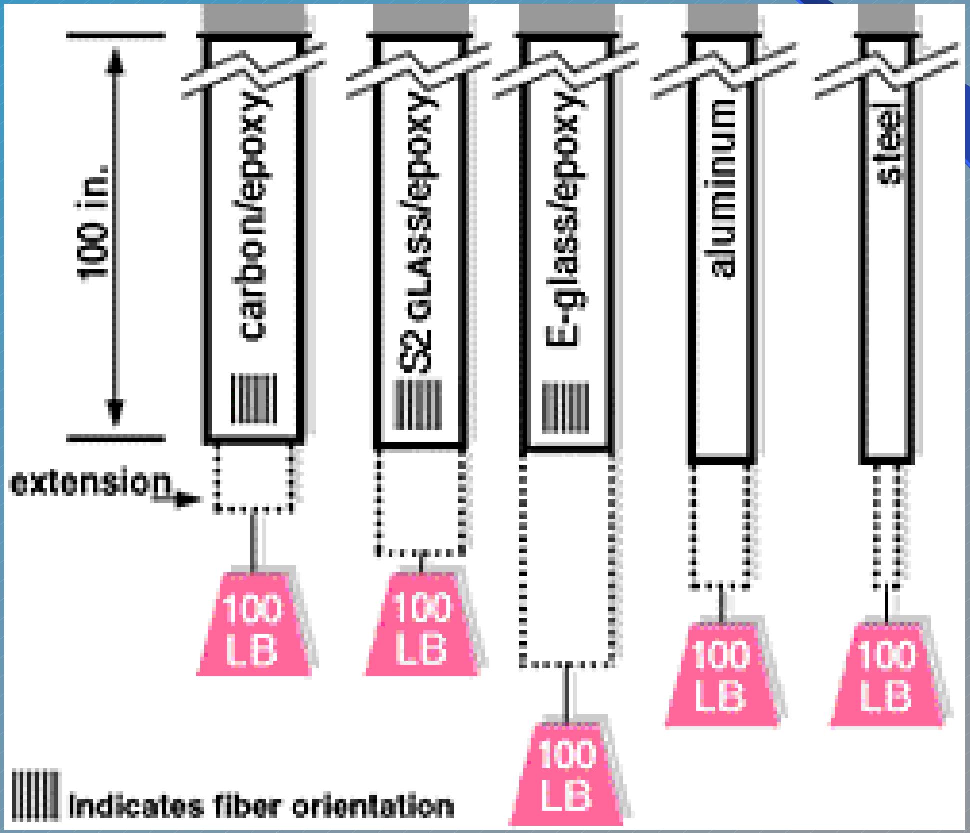
- After the sizing is applied, filaments are gathered together into twine-like strands that go through one of three steps, depending on the type of reinforcement being made.

Return

# Types of Glass Fibers

- A-glass: High **alkali** glass (bottle glass); most common composition, high alkali content degrades electrical properties.
- E-glass: Low alkali glass (alumino-borosilicate); excellent **electrical** insulation properties; constitutes the majority of the textile glass production ($1.50/lb.)
- C-glass: Sodium borosilicate glass (**corrosion** resistant); excellent chemical resistance properties.
- S-glass: Magnesium borosilicate glass; excellent tensile **strength** (40% higher than E-glass); most common is S2-glass at ~$6/lb (used for ballistic protection.)

# Properties of Glass Fibers



# Advantages and Disadvantages of Glass Fibers

- **Advantages**
  - Cost per weight or volume is chief advantage
  - Chemical or galvanic corrosion resistance
  - Electrical properties
  - Wide range of available product forms
- **Disadvantages**
  - High CTE compared to carbon fibers
  - Low modulus compared to carbon fibers
  - Aramid fibers have higher tensile modulus but lower compression & shear properties, as well as problems with moisture pick-up.

# Quartz Fibers

- Very pure (99.95%) fused silica glass fibers.
- Coated with an organic binder containing a silane coupling agent which is compatible with most resin systems.
- Highest strength-to-weight ratio of all high temperature materials (850 ksi, that's 5900 MPa)
- Service temperatures up to 1920°F possible
- Chemical stability of quartz makes them resistant to halogens, and most common acids, but poor in environment with high alkalinity.
- Quartz fibers also offer low dielectric constant and loss tangent, make excellent insulators.
- Relatively expensive at $5-150/lb.

# Boron Fibers

- Boron fiber is commercially made by chemical vapor deposition (CVD) of boron on a substrate, that is, boron fiber as produced is itself a composite fiber.
- In view of the fact that rather high temperatures (1000° C) are required for this deposition process, the choice of substrate material that goes to form the core of the finished boron fiber is limited.
- Generally, a fine tungsten wire is used for this purpose.
- A carbon substrate can also been used.

# Boron Fibers

- Boron fiber fabrication, jumpstarted in 1959 Talley used the process of halide reduction to obtain amorphous boron fibers of high strength.
- Since then, the interest in the use of strong but light boron fibers as a possible structural component in aerospace and other structures has come and gone.
- Interest has periodically waxed and waned in the face of rather stiff competition from other so-called advanced fibers, in particular, carbon fibers.

# Boron Fibers

- The structure and morphology of boron fibers depend on the conditions of deposition:
  - temperature, (crystallization is T dependant)
  - composition of gases, (effects defects)
  - gas dynamics, and so on.
- While theoretically the mechanical properties are limited only by the strength of the atomic bond, in practice, there always are present structural defects and morphological irregularities that lower the mechanical properties.
- Temperature gradients and trace concentrations of impurity elements inevitably cause process irregularities.
- Even greater irregularities are caused by fluctuations in electric power, instability in gas flow, or any other operator-induced variables.

# Boron Fibers

- Boron fibers have inherent residual stresses that have their origin in the process of chemical vapor deposition which can have a considerable influence on the fiber mechanical properties.
  - Growth stresses in the nodules of boron,
  - Stresses induced by the diffusion of boron into the tungsten core,
  - And stresses generated by the difference in the coefficient of expansion of deposited boron and tungsten boride core.
- The compressive stresses on the fiber surface are due to the quenching action involved in pulling the fiber out from the chamber.
- Morphologically, the most conspicuous aspect of these internal stresses would appear to be the frequently observed radial crack, from within the core to just inside the outer surface, in the transverse section of these fibers.

# Boron Fibers

- Boron is an inherently-brittle material.
- Brittle materials show a distribution of strengths rather than a single value.
- Imperfections in these materials lead to stress concentrations much higher than the applied stress levels.
- Because the brittle material is not capable of deforming plastically in response to these stress concentrations, fracture ensues at one or more such sites.
- Cracks often originate at pre-existing defects located at the boron-core interface or at the surface.

# Boron Fibers

- The average tensile strength of boron fiber is 3-4 GPa, while its Young's modulus is between 380 and 400 GPa.
- Boron has a density of 2.34 g/cc (about 15% less than that of Al).
- Boron fiber with the tungsten core has a density of 2.6 g/cc for a fiber of 100 micron diameter.
- The melting temperature of Boron is 2040 °C and it has a thermal expansion coefficient of 8.3 x 10-6 $°C^{-1}$ up to 315° C.
- Boron fiber composites are in use in a number of U.S. military aircraft, notably the F-14 and F-15, and in the Space Shuttle. Also used for repair of metallic structures.
- Big obstacle to the widespread use of Boron fiber is its high cost compared to that of other fibers.
  - A major portion of this high price is the cost of the tungsten substrate.

# Boron Fibers

Boron prepreg from Specialty Materials

# Hybrid Materials

- Hy-Bor from Specialty Materials

# Carbon Fibers

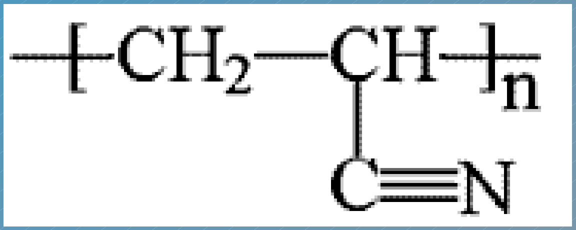
- Carbon fiber is a high strength, high stiffness synthetic fiber that is used in a variety of structural and electrical applications.
- Carbon fiber composites are 10x stronger than steel, yet are 5x lighter.
- In comparison to aluminum, carbon fiber composites are 8x stronger, 2x stiffer, yet 1.5x lighter.
- Carbon fiber composites have superior fatigue properties to all known metallic structures.
- Coupled with the proper resins, carbon fiber composites are one of the most corrosion resistant materials available.

# Carbon Fibers

- In electrical applications, carbon fibers can be used to tailor the electrical properties of injection molding compounds, paints, and adhesives.
- When used in adhesives, the electrical conductivity of carbon can be used to enhance cure times in RF environments by an order of magnitude.
- The electrical properties of carbon fiber and the ability to configure the material into a semi-permeable membrane with defined mass transport properties makes carbon an ideal choice for Next Generation fuel cell engines.
- In friction applications, carbon fiber is used to create materials that can withstand extremely high temperature coupled with brutal abrasive wear.

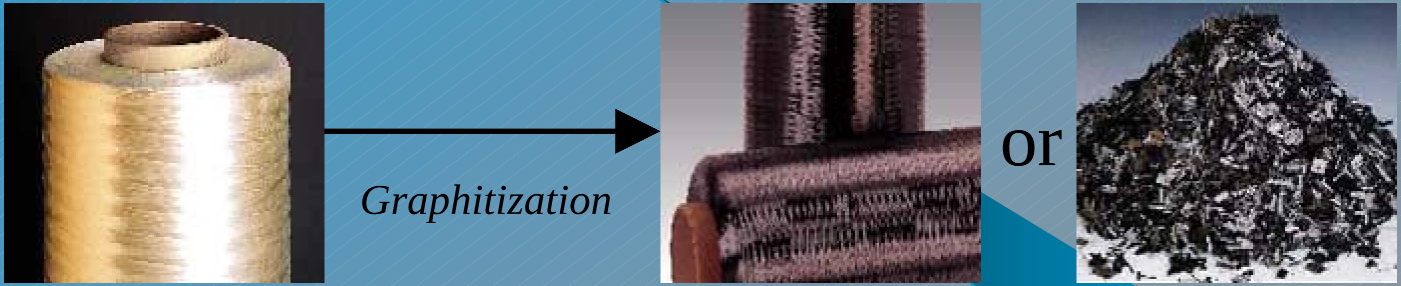
# PAN based Carbon fibers

➢PAN based carbon fibers are produced in a continuous operation in which the polyacrylonitrile (PAN) precursor undergoes a series of precisely controlled processes.



- a vinyl polymer, and a derivative of the acrylate family of polymers.
It is made from the monomer acrylonitrile by free radical vinyl polymerization.

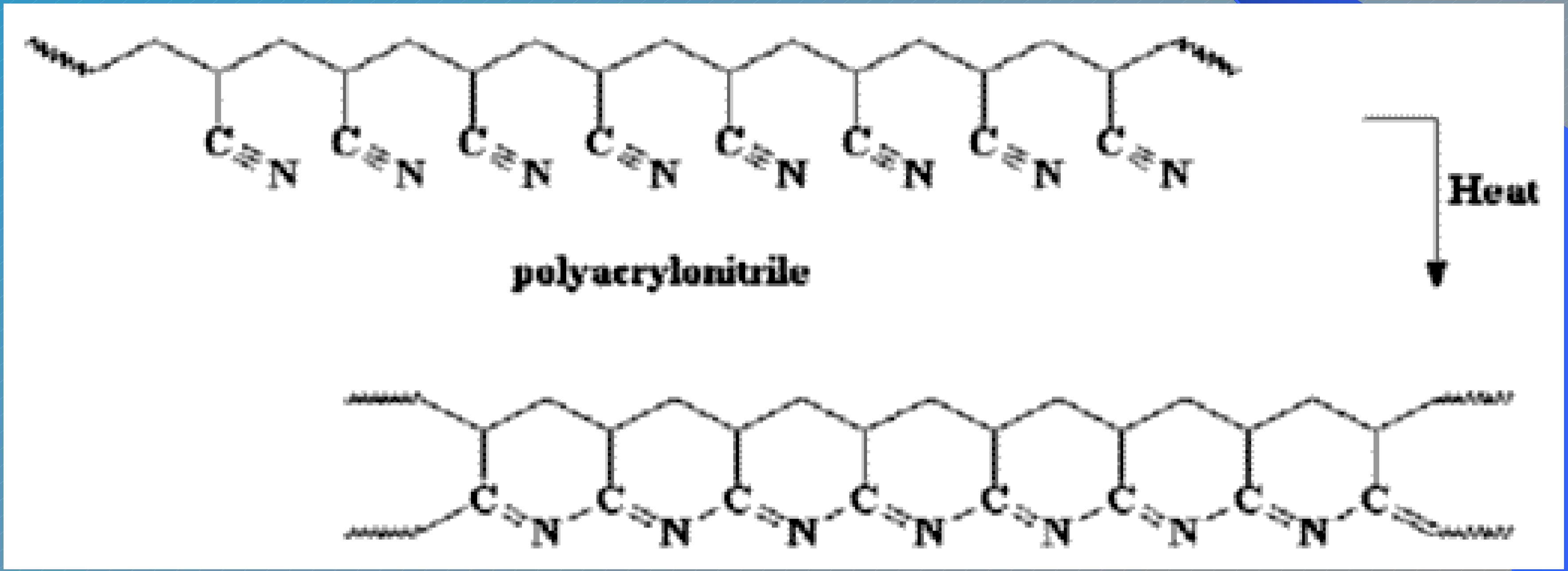
# PAN based Carbon fibers




- Exposure to extremely high temperatures chemically changes the precursor, yielding high strength-to-weight and high stiffness-to-weight properties through oxidation, carbonization and graphitization.
- The successive surface treatment and sizing stages improve bonding and handleability. The resulting carbon fiber is stronger than steel, lighter than Al and as stiff as Ti.

# Carbonization of PAN based Carbon Fibers

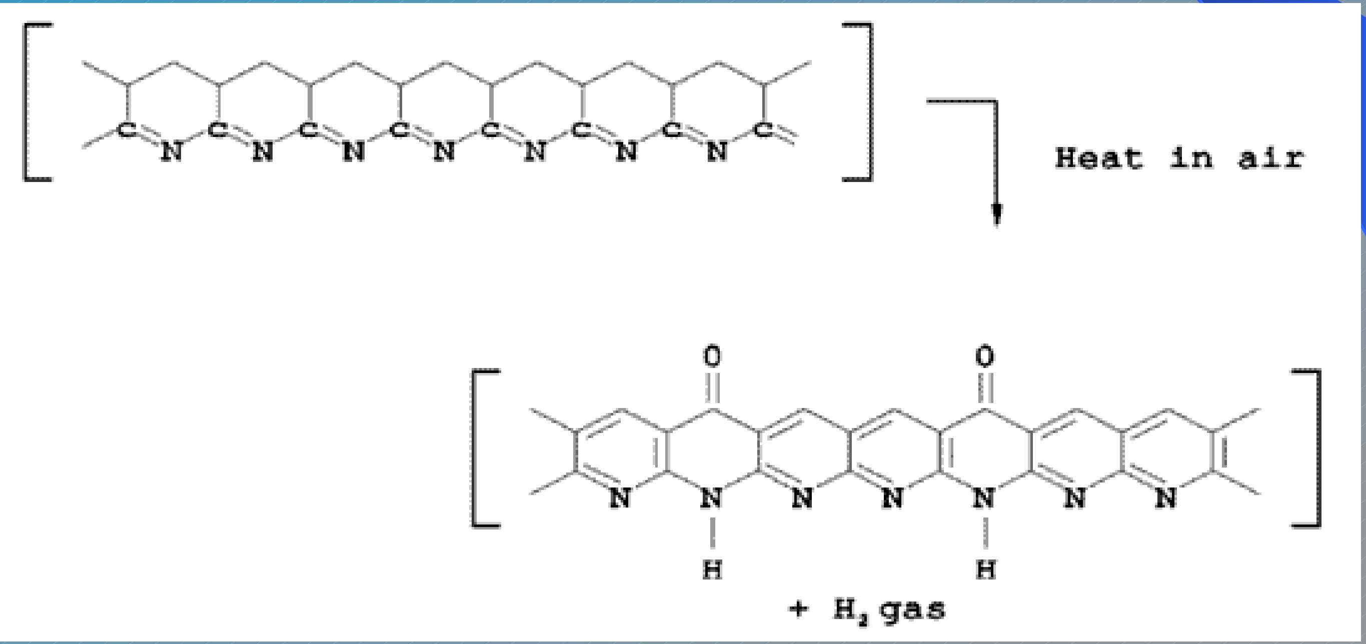
First, the PAN fiber is heated in air (200-300° C.) The heat causes the cyano sites within the PAN polymer chain to form repeat cyclic units




The ladder molecule (tetrahydropyridine )

# Carbonization of PAN based Carbon Fibers

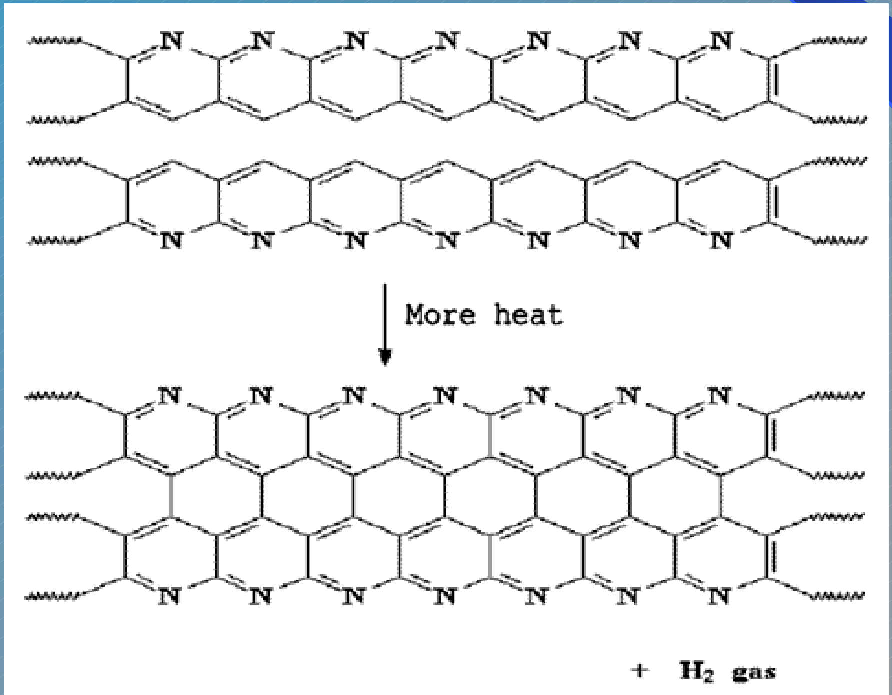
- Continuing the heating process in air (up to 700° C), oxidation occurs. This process causes the carbon atoms to kick off their hydrogen atoms, and the rings become aromatic.




Forms a series of fused pyridine-pyridone rings.

# Carbonization

- The heating process is continued in the absence of air. The heating process is now called carbonization, where the heat is raised to above 1300°C.



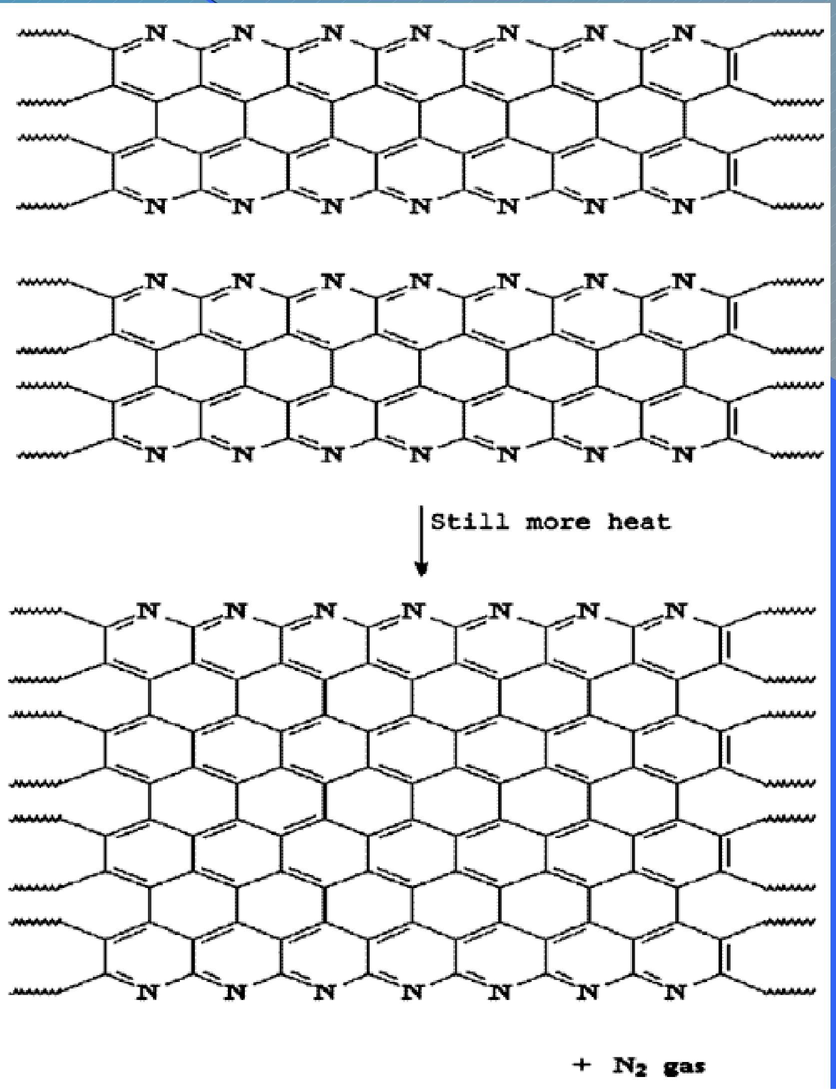

Adjacent polymer chains are joined together to give a ribbon-like fused ring polymer.

# Carbonization

- The newly formed ribbons continue to condense together to form the lamellar, basal plane structure of nearly pure carbon.

- The polymer has nitrogen atoms along the edges of the basal planes and which are expelled as Nitrogen gas.

- These basal planes will stack to form microcrystalline structures. The size and orientation of these crystallites will alter the properties of the final carbon fiber product.



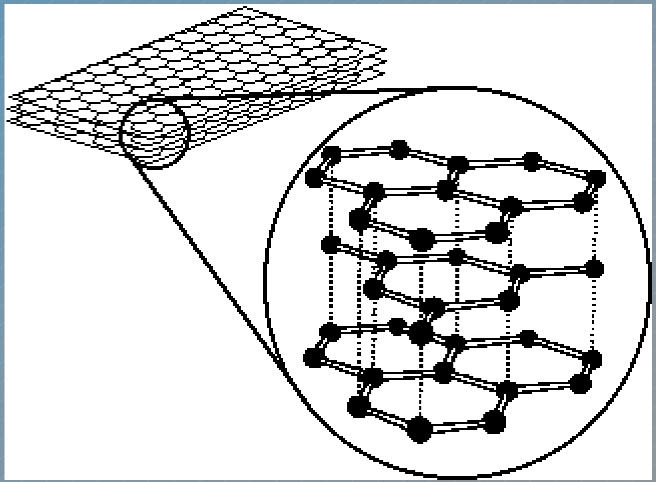
# Whoops

- If during the treatment process the temperature is raised above 2500 °C, graphite will be formed instead of carbon fibers!

- Why?
  - Because graphite is more stable than carbon fibers.
  - When higher temperatures are applied to the carbon fibers, eventually enough energy is present to break the bonds in the carbon fibers, allowing them to reorganize to the more stable graphite form.

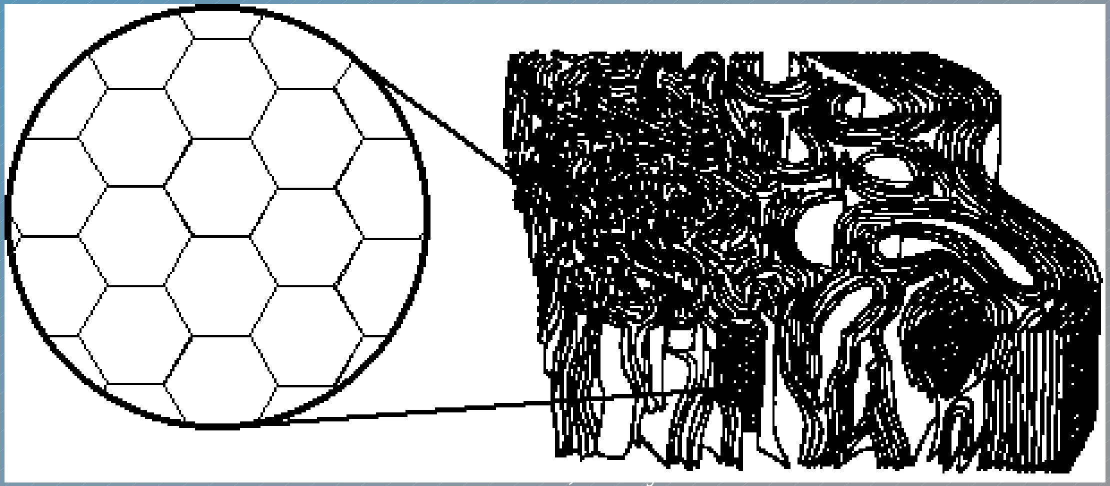
# Structure of Graphite

- The atomic structure of graphite has been determined by x-ray diffraction and other analytical techniques and is shown below.
- Parallel sheets of hexagonal rings are spaced 3.35 Å apart. Bonds within the chickenwire-like sheets are very strong, but interactions between the sheets are weaker and can be broken easily.

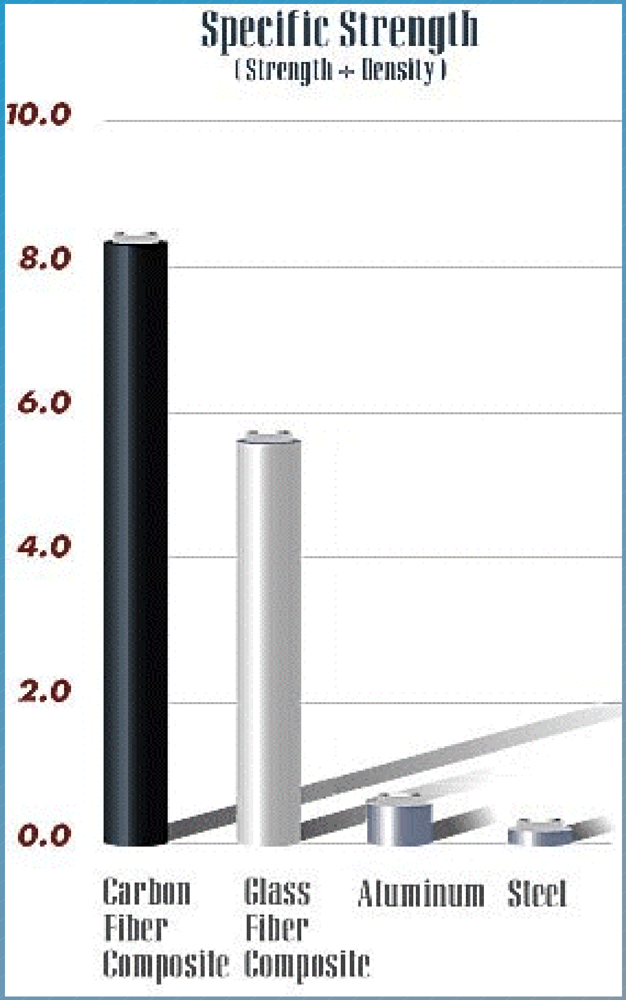


# Carbon Fiber Structure

- Carbon fibers have less long-range ordering.
- Instead of the planar layers of carbon atoms which are found in graphite, carbon fibers consist of ribbons of carbon atoms aligned parallel to the axis of the fibers.
- Although the ribbons are essentially parallel on the surfaces of a carbon fiber, the fiber's inner layers fold in a "hairpin“ fashion as seen in the Figure. This is a stark contrast to graphite in which the carbon sheets remain parallel on a long range scale.
- It is believed that the great strength of carbon fibers is due to the interlocking and folding of ribbons (the sheets of carbon atoms can not slide past each other as they did in graphite).



# Carbon Fiber Properties



# Pitch based carbon fibers

(First introduced in 1976)

- Made from coal tar or petroleum pitch, which is converted to anisotropic mesophase or liquid crystal state for spinning.
- Spinning and drawing process creates a highly oriented fiber, which obtains its superior modulus from the essentially flat aromatic polymer molecules which lie parallel to the fiber axis.
- Fiber is then oxidized and carbonized, much as PAN based carbon fibers (no need for tensioning to maintain preferred orientation.)

# Pitch Based Carbon Fibers

| Property | Units | **P-55S** | **P-75S** | **P-100S** |
|---|---|---|---|---|
| Density | g/cc | 1.90 | 2.00 | 2.16 |
| Tensile Strength | GPa<br>ksi | *1.9*<br>*275* | *2.1*<br>*300* | *2.41*<br>*350* |
| Tensile Modulus | GPa<br>Msi | **379**<br>**55** | **517**<br>**75** | **758**<br>**110** |
| CTE | $°F^{-1}$ | -0.7E-6 (L)<br>15E-6 (T) | -0.8E-6 (L)<br>15E-6 (T) | -0.8E-6 (L) |
| Thermal Conductivity | W/m-K | 120 | 185 | 300* |

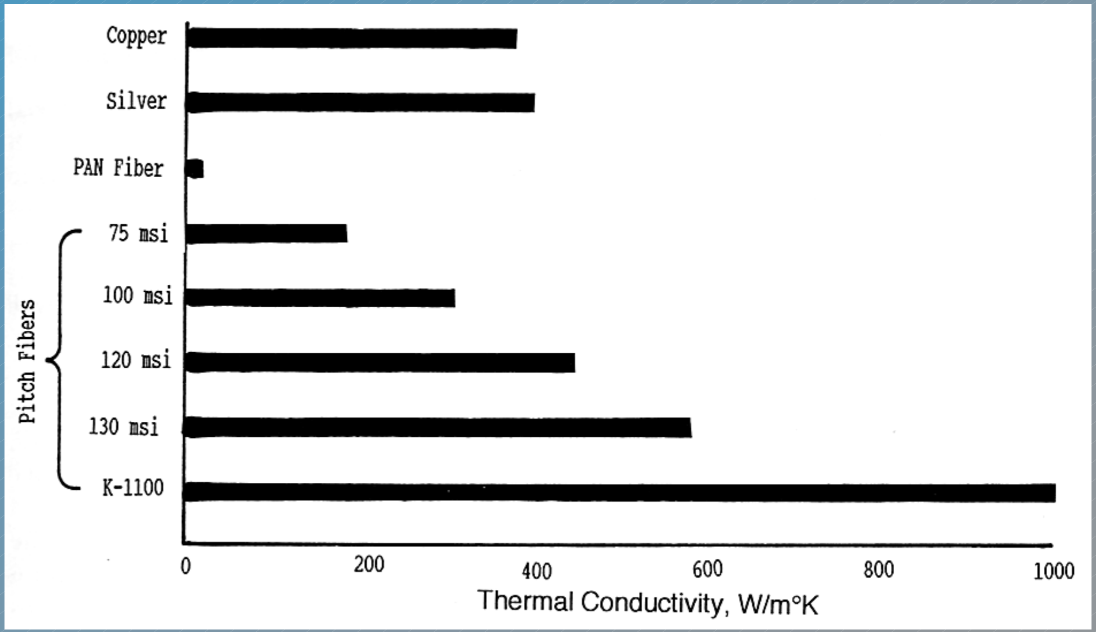
(Cytec Engineered Materials website)

# Pitch Based Carbon Fibers

- Low strength attributed to:
    - Fused filaments,
    - Voids,
    - And inorganic inclusions (stress concentrations.)
- Although many stiffness critical applications could accommodate fibers of low tensile strength, high modulus, low strength fibers pose manufacturing problems.
- With care pitch based fibers can be prepregged, filament wound. . .
- Surface treatments have led to significant increase in shear strength (x 2)
- Potential applications include:
    - Carbon/carbon composites
    - Metal Matrix Composites
    - Rocket Launcher Tubes and Hubs
    - Automotive Drive Shafts
    - Helicopter Fuel Pods
    - Space Antennas, Arrays and Structures
    - Outerspace Telescopes
    - Push Rods for High Performance Autos

# Pitch Based Carbon Fibers

- In addition to high stiffness and zero CTE, pitch based carbon fiber also exhibits superb heat transfer capabilities.
- High modulus pitch fibers in particular have incredibly high thermal conductivity (K-1100 from Amoco.)



# Property Comparison

| | Units | **T-300** | **P-55S** | **P-75S** |
|---|---|---|---|---|
| Density | g/cc | 1.76 | 1.90 | 2.00 |
| Tensile Strength | GPa<br>ksi | 3.75<br>545 | 1.90<br>275 | 2.10<br>300 |
| Tensile Modulus | GPa<br>Msi | 231<br>33.5 | 379<br>55 | 517<br>75 |
| Thermal Conductivity | W/m-K | 8 | 120 | 185 |

(Cytcc Engineered Materials website)

Tensile, flexural, and compressive properties of pitch based fiber composites are lower than expected for the fiber properties???

# Heavy Tow

- Walsh et al. compared filament wound tubes of 48K carbon fiber/EPON 826 with 12K carbon fiber/EPON 826.
  - Phase I – Drop-In Conversion to 48K
  - Phase II – Proper Conversion
  - Phase III – Downselect and Optimization

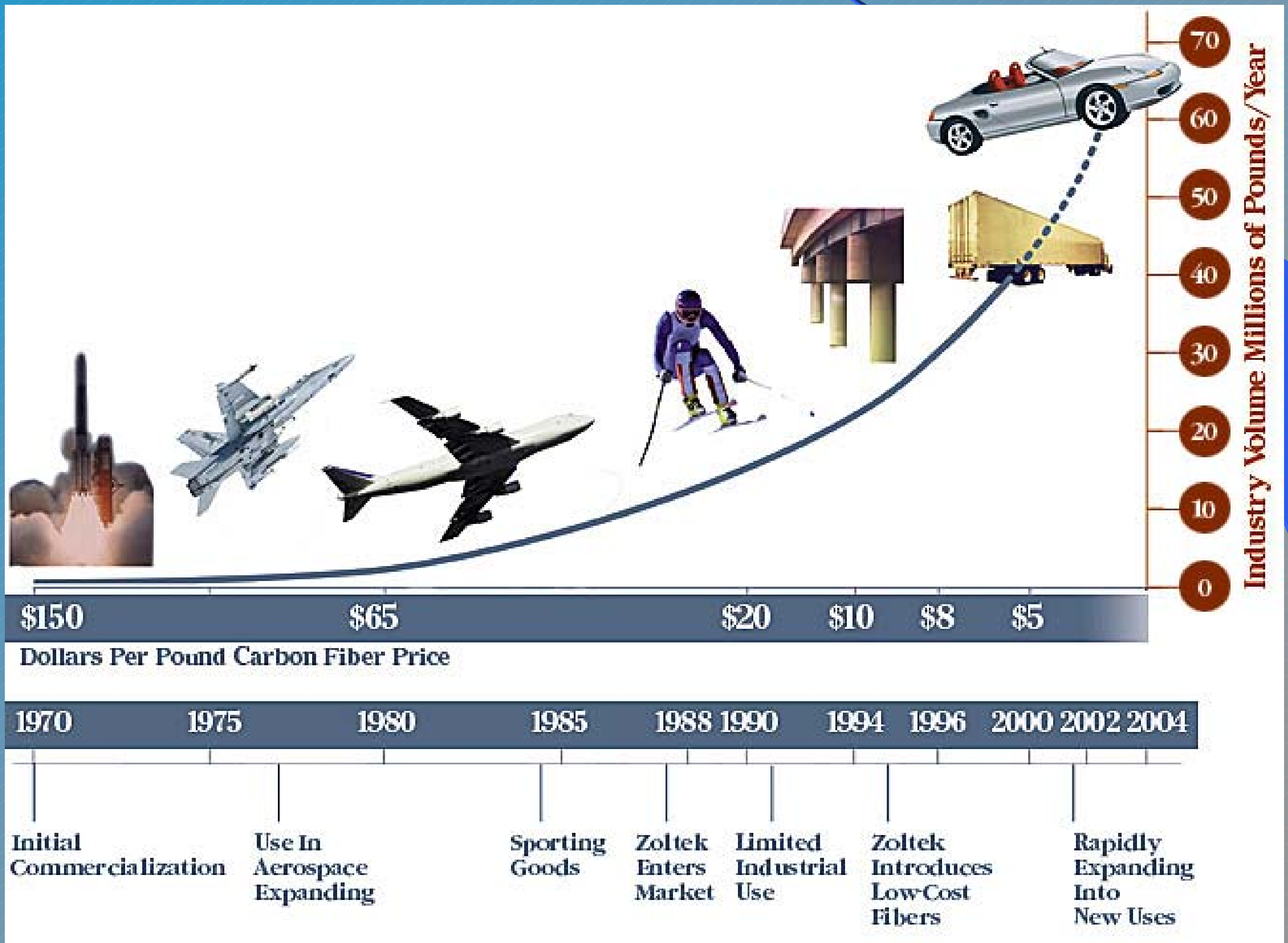
| | Tensile Strength | Tensile Modulus |
|---|---|---|
| **12K** | 650 ksi | 34.0 Msi |
| **48K** | 550 ksi | 32.5 Msi |

# Heavy Tow

- Low cost equipment solutions devised to acheive
  - 30% increase in bandwidth, translates to more uniform filament tension and improved strength
  - Low void content (comparable to 12K technology)
  - Improved homogeneity
  - Maintained 12K production rates

# Carbon Fibers – the Future

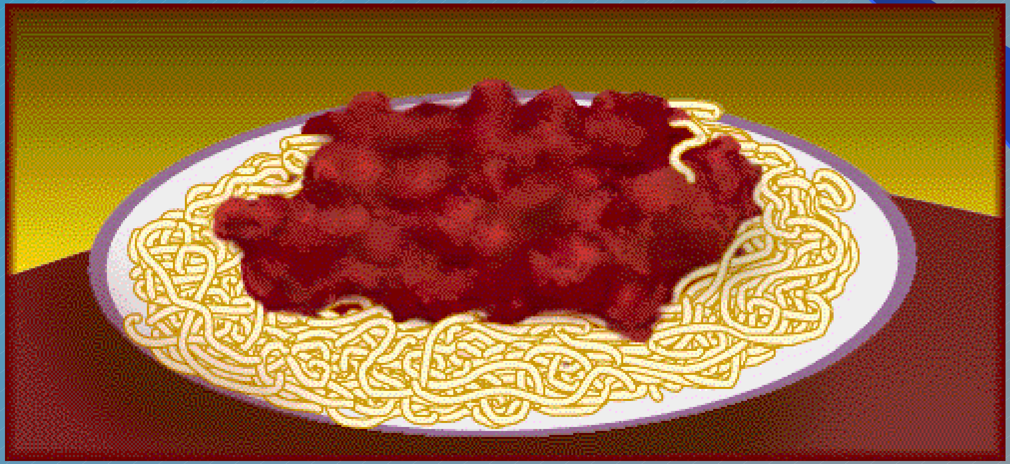
*(according to Zoltek)*



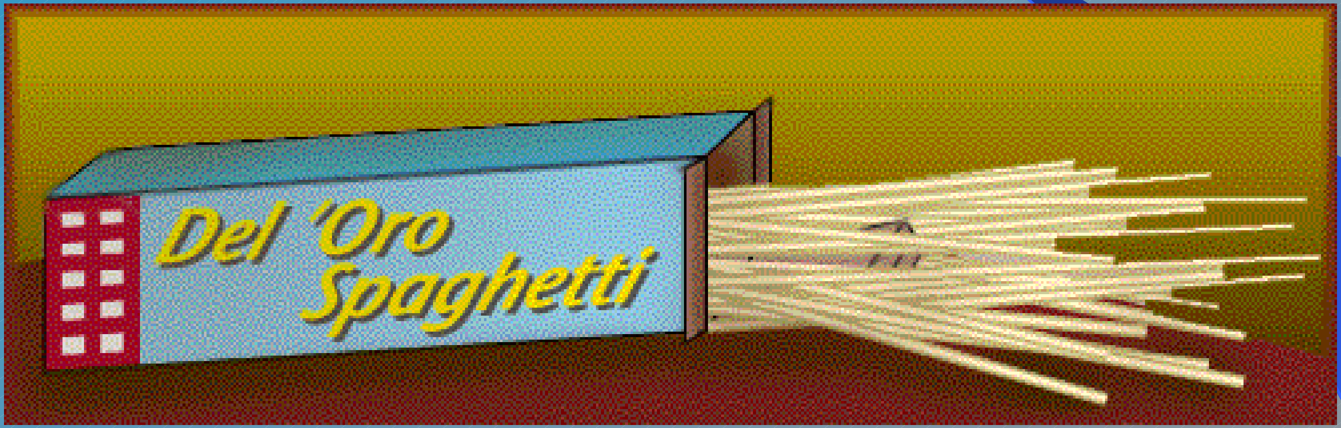
# Polymer Fibers

- Nylon (polyamide), Polyester
- Aramid (Kevlar, Twaron)
- Polyethylene (Spectra, Dyneema)
- Poly(p-phenylene-2,6-benzobisoxazole) [PBO]
- Liquid crystal polymers (Vectran)
- M5

# Polymer Fibers



# Polymer Fibers

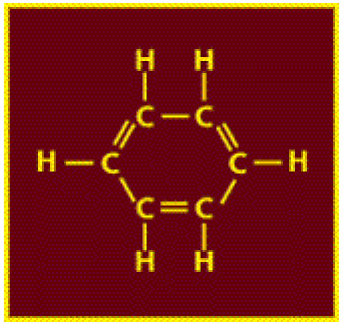


# What is Kevlar?

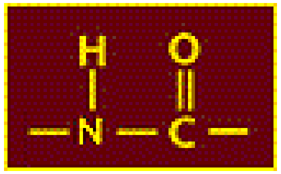
- Kevlar first discovered in 1965 by Dupont
- Immediately commercialized by DuPont in the 1970s. It was the first organic fiber with sufficient tensile strength and modulus to be used in advanced composites. Originally developed as a replacement for steel in radial tires, Kevlar is now used in a wide range of applications.
- Kevlar is an aramid, a term invented as an abbreviation for aromatic polyamide. The chemical composition of Kevlar is poly para-phenyleneterephthalamide, and it is more properly known as a para-Aramid.
- Also Twaron (Dutch, 1978 recently acquired by Japanese, Teijin Twaron)
- Aramids belong to the family of nylons. Common nylons, such as nylon 6,6, do not have very good structural properties, so the para-aramid distinction is important. The aramid ring gives Kevlar thermal stability, while the para structure gives it high strength and modulus.

# What Makes Kevlar so Strong?

- Kevlar is a polyaromatic amide. That is, it contains aromatic and amide groups.



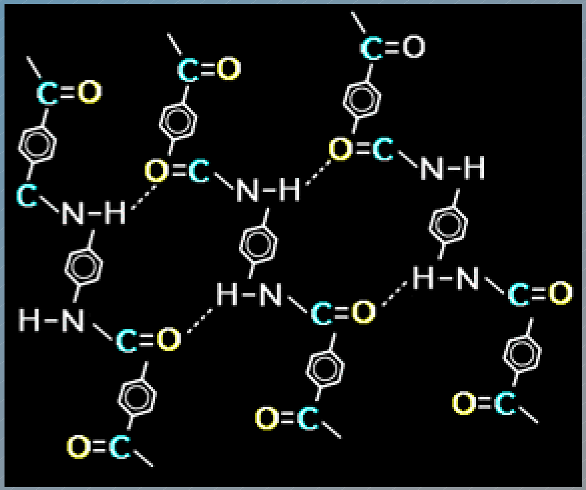

Benzene ring




Amide group

# What Makes Kevlar so Strong?

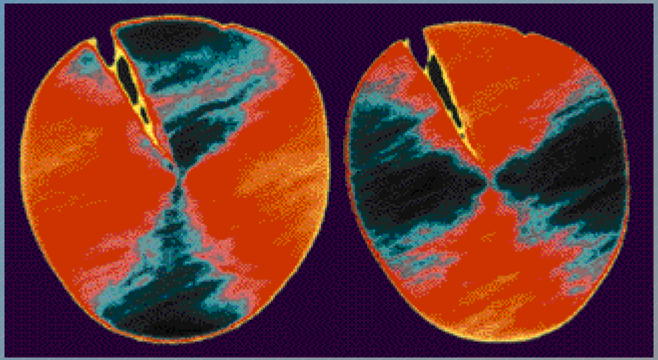
- The individual polymer strands of Kevlar are held together by hydrogen bonds that form between the polar amide groups on adjacent chains.




Hydrogen bonding

# What Makes Kevlar so Strong?

- The aromatic components of Kevlar polymers have a radial (spoke-like) orientation, which gives a high degree of symmetry and regularity to the internal structure of the fibers.
- **This crystalline-like regularity is the largest contributing factor in the strength of Kevlar.**
- Only with bright synchrotron radiation could the secret strength of Kevlar be revealed.



# Kevlar Fibers

- There are 3 grades of Kevlar available, Kevlar 29, Kevlar 49, and Kevlar 149.

| Grade | Density (g/cc) | Tensile Modulus (GPa) | Tensile Strength (GPa) | Tensile Elongation (%) |
|---|---|---|---|---|
| 29 | 1.44 | 83 | 3.6 | 4.0 |
| 49 | 1.44 | 131 | 3.6-4.1 | 2.8 |
| 149 | 1.47 | 186 | 3.4 | 2.0 |

# Kevlar Fibers

- KEVLAR® is 5x stronger than steel on an equal weight basis.

# Kevlar fibers

- Modulus and strength comparable to glass fibers.  S-2 glass has strength comparable to carbon fibers.
- Density is approximately half that of glass.
- Kevlar is significantly more expensive than glass.
- Negative CTE, makes Kevlar thermally stable.
- Very resistant to impact and abrasion.
- Fibers absorb moisture.
- Poor compressive strength and modulus.
- Difficult to cut fabric, machine cured laminates.

# Kevlar Fibers

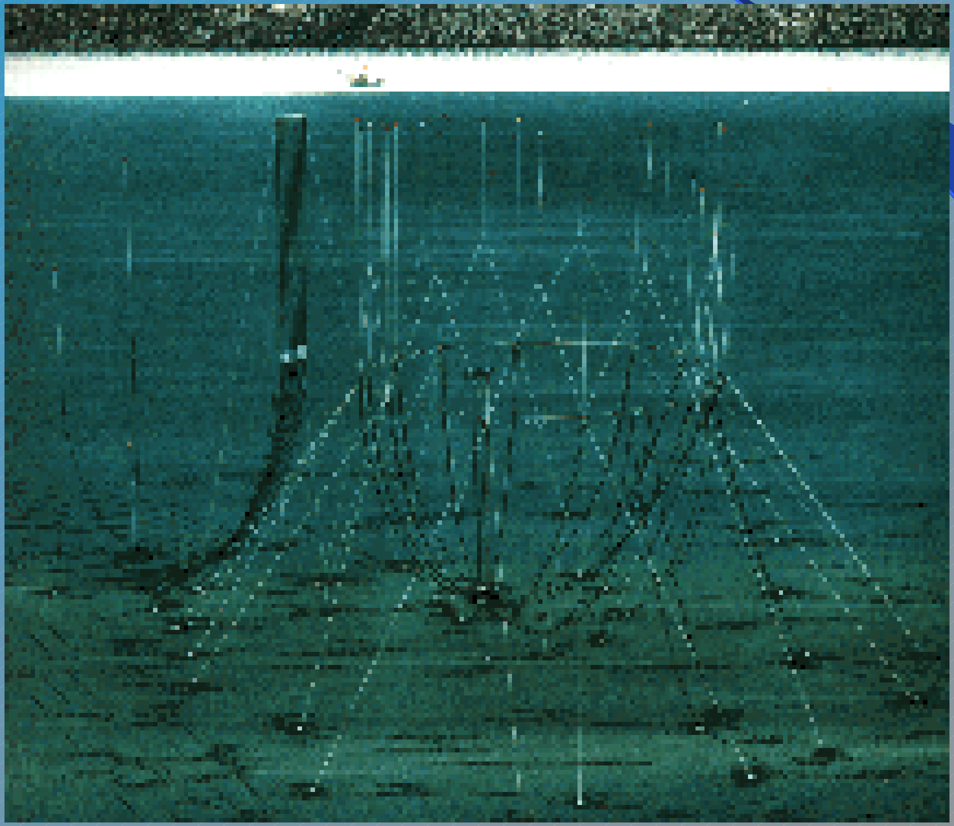
- Kevlar is produce in only one fiber size.
- These fibers are used to produce yarns of various weights, or “denier” grades
  - 195 denier (bundle with 134 individual fibers)
  - 7100 denier (bundle with 4879 individual fiber)
- Nobody uses the denier system except DuPont
  - Defined as the weight in grams of 900 meters of strand.
  - *9000 meters is the approximate length of a single strand of silk spun by a silk worm.*

# Diverse Applications of Kevlar

- Body armor for military, law enforcement, even personal recreation.
- Ropes that secure the airbags in the crucial landing apparatus of the Mars Pathfinder
- Small-diameter, lightweight ropes that hold 22,000 pounds and help moor the largest U.S. Navy vessels
- Shrapnel-resistant shielding in jet aircraft engines that will protect passengers in case an explosion occurs
- Run-flat tires that allow for greater safety because they won't ruin the rim when driving to the nearest assistance
- Gloves that protect hands and fingers against cuts, slashes and other injuries that often occur in glass and sheet metal factories
- Kayaks that provide better impact resistance with no extra weight
- Strong, lightweight skis, helmets and racquets that help lessen fatigue and boost exhilaration

# Body Armor

# Kevlar Cables



# Sails

# High Strength, Lightweight Polyethylene fibers (Spectra, Honeywell)

- Spectra commercialized in 1985 by Allied Signal.
- **UHMWPE** has a **M**olecular **W**eight > 3E6
- Comprised of highly oriented chains (fully extended)
- Spectra fiber has the highest strength to weight ratio of any man made fiber (competitive at $16-80/lb.)
- 8 to 10x stronger than steel and 40% stronger than Kevlar.
- With its outstanding toughness and extraordinary visco-elastic properties it can withstand high-load strain-rate velocities.
- Light enough to float, it also exhibits superior resistance to chemicals, moisture and UV.
- Low dielectric makes it virtually invisible to radar.

# Advantages and Limitations of UHMWPE Fiber

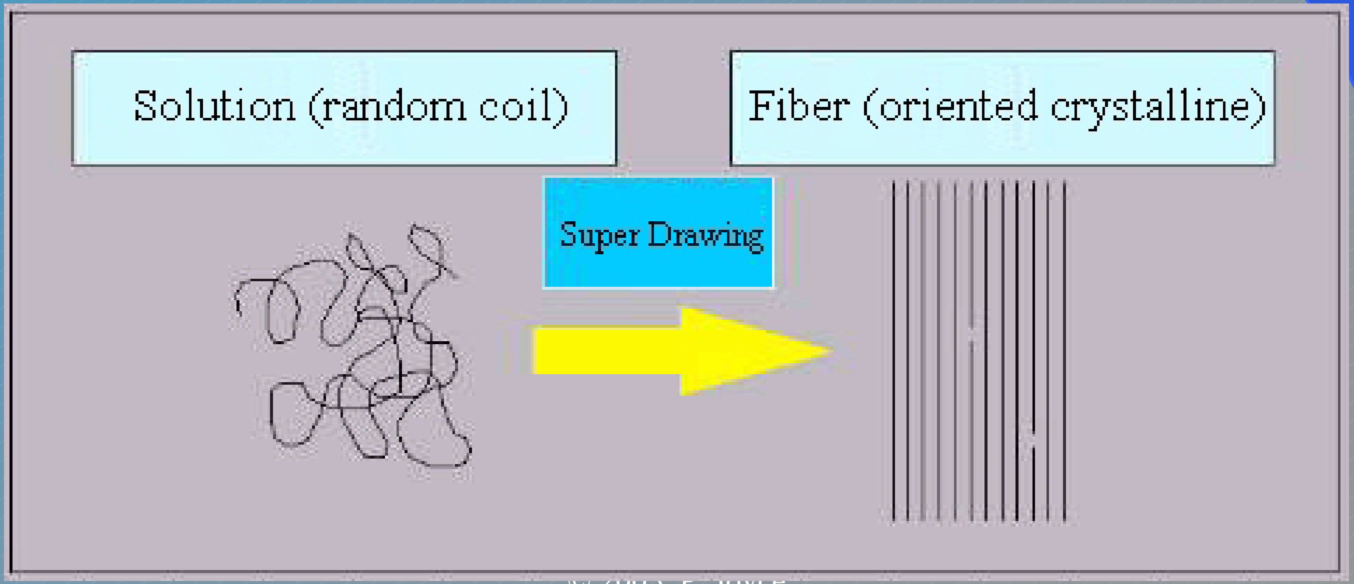
- Best strength to weight ratio (density = 0.97 g/cc)
- Outstanding impact strength (prime candidate to replace aramids in body armor)
- Hydrophobic character makes it extremely resistant to moisture effects, also good UV resistance
- The main drawback is poor temperature performance, $T_m$ = 300°F, max. $T_s$ = 230 °F
- The upper processing limit of UHMWPE coincides with the recommended cure temperature of many commercially popular structural resin systems (350 °F cures not possible.)
- Creep is also a problem, even at room temperature
- Bonds poorly to most matrices (chemical inertness and low surface energy); **few laminate applications are possible.**

# Ultra High Strength Polyethylene (Dyneema, Toyobo)

- Extremely High Strength and High Modulus
- Light Weight (low specific gravity)
  - Dyneema SK60 is the only super-fiber with a density below 1.0 (the fiber can float on water).
  - Dyneema SK60 has the highest level value of the specific strength among commercialized organic strong fibers.
- Dyneema SK60 has an extremely high impact strength. Due to its very high energy absorption characteristics, Dyneema SK60 is a suitable material for protective applications or sport composites applications.
- Dyneema SK60 exhibits excellent flexibility and excellent abrasion resistance. Easy fabrication offers various textile applications.
- With no degradation due to water absorption, Dyneema SK60 is the ideal material for ropes or nets used in marine and off-shore applications.
- Dyneema SK60 has excellent light stability and chemical resistance in a wide pH range.

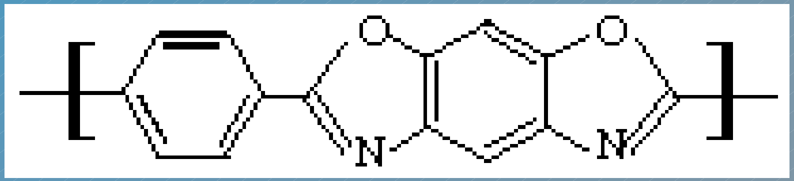
# Making Dyneema fibers

- Ultra-high molecular weight polyethylene is dissolved in a solvent and then spun through small orifices (spinneret).
- Successively, the spun solution is solidified by cooling, which fixes a molecular structure which contains a very low entanglement density of molecular chain. This structure gives an extremely high draw ratio and results in extremely high strength.
- The gel-like appearance of the solidified fiber is the origin of the name of this technology. The highly drawn fiber contains an almost 100% crystalline structure with perfectly arranged molecules, which promotes its extremely high strength, modulus, and other excellent properties.



# PBO (Zylon) fibers

- PBO is a rigid-rod isotropic crystal polymer.

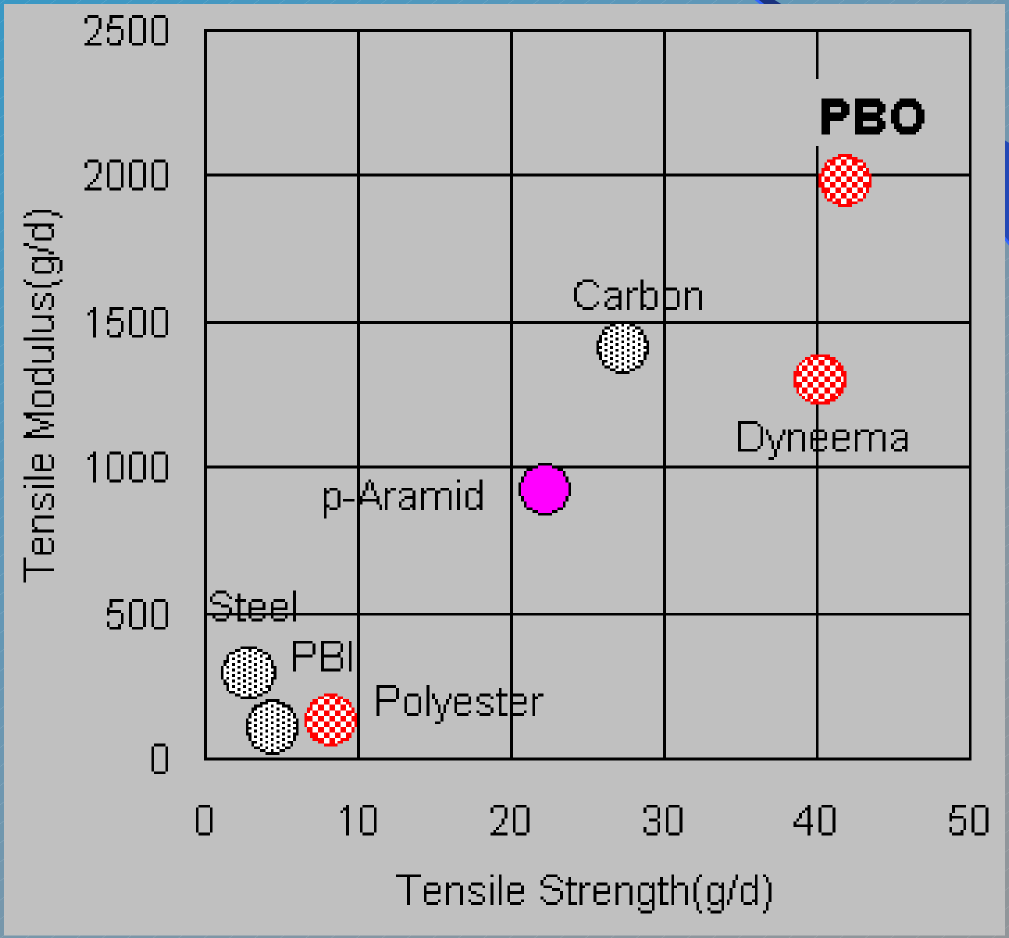



- Zylon is a new high performance fiber developed by TOYOBO using the latest material science and state of the art fiber technology

# PBO (Zylon) fibers

- Zylon has superior tensile strength and modulus compared to p-Aramid fibers.
- It also has outstanding high flame resistance and thermal stability among organic fibers.
- Zylon shows excellent performance in such properties as creep, chemical resistance, cut/abrasion resistance and high temperature abrasion resistance, that far exceeds p-Aramid fibers.
- Zylon's moisture regain is low(0.6%) and it is dimensionally stable against humidity.
- **Extremely light sensitive** (winding in the dark)

# PBO – modulus & strength



# LCP Fibers (Vectran)

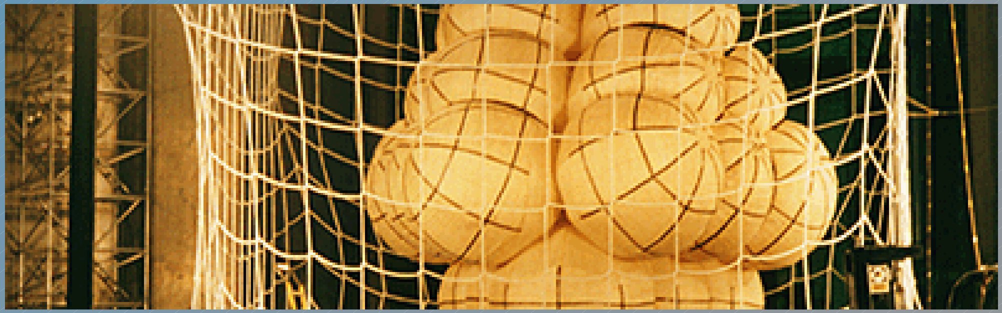
- Vectran is a high-performance thermoplastic multifilament yarn spun from Vectra ® liquid crystal polymer (LCP).
- Vectran is the only commercially available melt spun LCP fiber in the world.
- Vectran fiber exhibits exceptional strength and rigidity.
- Pound for pound Vectran fiber is 5x stronger than steel and 10x stronger than aluminum.

# Vectran Fibers

- 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 Fibers

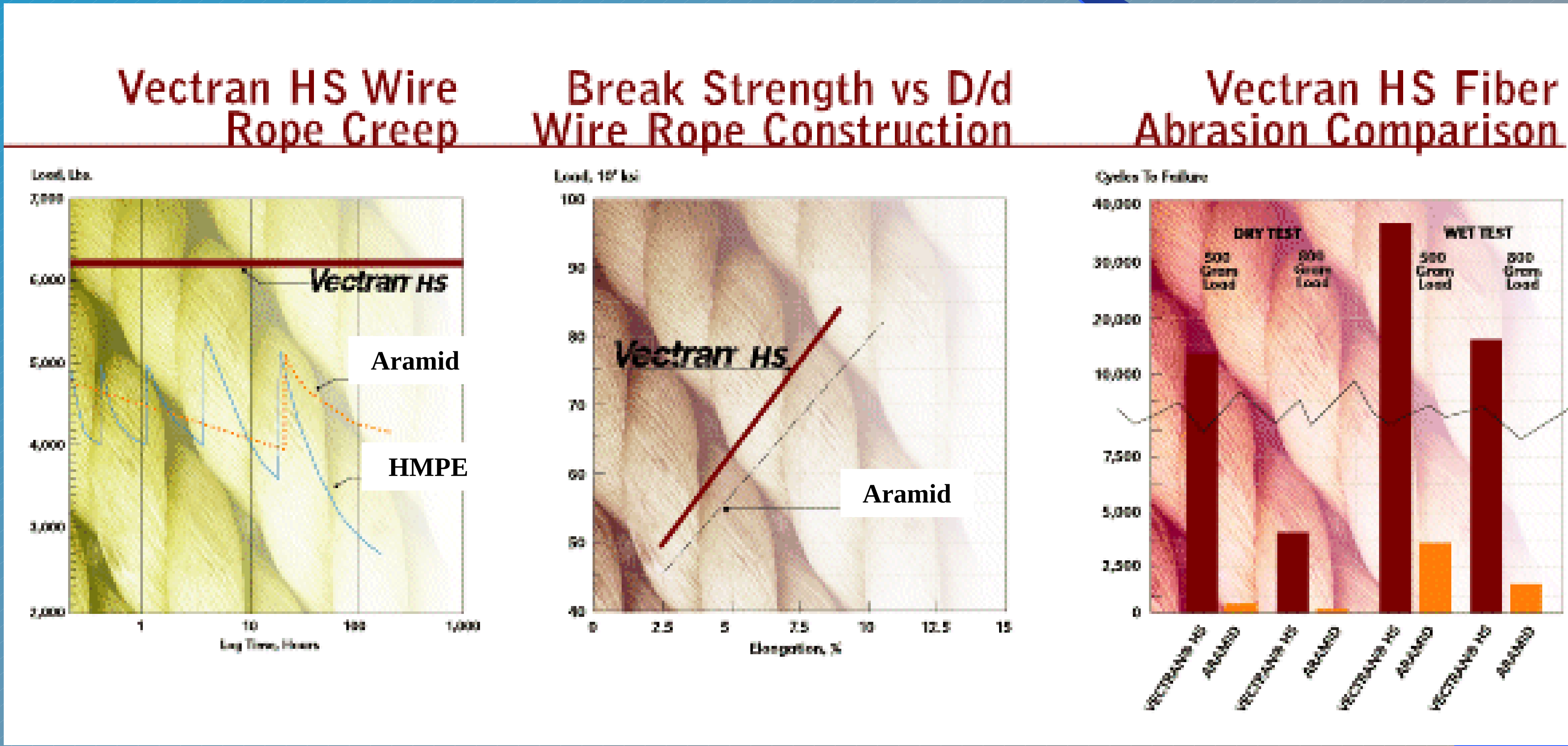
- The first use of Vectran fiber was for demanding and specialized military applications.
- In July 1997, the airbags used to cushion the Pathfinder's successful landing on the surface of Mars, were made with Vectran fibers .
- A stellar-strength fiber, Vectran is lightweight and stable providing superior load handling characteristics for tow ropes, cargo tie-downs and inflatables.



# Vectran Fibers

| | Vectran HS | Vectran M |
|---|---|---|
| Density | 1.4 g/cc | 1.4 g/cc |
| Tensile Strength | 412-465 ksi | 161 ksi |
| Tensile Modulus | 9.4-10.5 Msi | 7.6 Msi |
| % Elongation | 3.3-3.7% | 2.00% |
| Moisture Absorption | <0.1% | <0.1% |
| Melting Point | 625°F | 529°F |

# Property Comparisons



# Basalt Fiber

- Developed in Soviet Union, available in the West since 1991 ~ 1000 lbs/yr
- High tensile strength, 506 ksi
- Very high heat resistance (1800°F)
- Alkali resistance
- High impact strength
- Low moisture absorption

# Basalt Fiber

- Poor availability
- Poor quality control
- Basalt Technologies, Medford, NJ, Oct. 2001
- Anticipated cost of $1.25-1.50/lb
- Hybrid carbon/basalt wakeboard under development
- Envision applications ranging from automotive composites to housing products, even structural concrete for starters. . .

# Comparison

| | E-Glass (Corning) | S-Glass (Corning) | Boron (Specialty Materials) | Carbon (T-300 Cytec) | Aramid (Kevlar-49 DuPont) | PBO (Zylon AS Toyobo) | LCP (Vectran HS Celanese) |
|---|---|---|---|---|---|---|---|
| Density (g/cc) | 2.54 | 2.49 | 2.57 | 1.76 | 1.44 | 1.54 | 1.4 |
| Modulus (GPa) | 72.5 | 85.6 | 400 | 231 | 131 | 180 | 65-72 |
| Strength (MPa) | 3450 | 4480 | 3600 | 3750 | 3600-4100 | 5800 | 2840-3200 |
| CTE ($°F^{-1}$) | $6.3 \times 10^{-6}$ * | | $2.5 \times 10^{-6}$ | $-0.30 \times 10^{-6}$ | $-2.7 \times 10^{-6}$ * | $-6 \times 10^{-6}$ | $-2.7 \times 10^{-6}$ |

# Advantages & Disadvantages of Reinforcing Fibers

| **Fiber** | **Advantages** | **Disadvantages** |
|---|---|---|
| Glass | High strength<br>Low cost | Low stiffness<br>Short fatigue life<br>High temperature sensitivity |
| Boron | High stiffness<br>High compressive strength | High cost |
| Carbon | High strength<br>High stiffness | Moderately high cost |
| Synthetics | High tensile strength<br>Low density | Low compressive strength<br>High moisture absorption |

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