High Performance And High Temperature Resistant Fibers
- Emphasis on Protective Clothing

I. INTRODUCTION

Faster, stronger, lighter, safer ... these demands are constantly being pushed upon today's researchers and manufacturers, including protective clothing - routine or specialized. High performance and high temperature resistant fibers aid enormously in allowing products to meet these challenges. The markets and products which are facilitated by the use of these fibers go far beyond the scope and awareness of most people. This paper intends to provide a solid overview of the definitions, properties, products and end uses associated with some of the most common high performance and high temperature resistant fibers used today. *It is stressed that not all high performance materials are presented.*

Before exploring details these materials, it is important to define the parameters of high performance and high temperature resistant fibers. For this discussion, the latter is classified as ***a synthetic fiber with a continuous operating temperature ranging from 375^0 F to 600^0 F***.

The classification of high performance is less rigid and can be broken down into various segments. Generally speaking, fibers are said to be either ***commodity*** or ***high performance***. Commodity fibers are typically used in a highly competitive price environment which translates into large scale high volume programs in order to compensate for the (often) low margins.

Conversely, high performance fibers are driven by ***special technical functions that require specific physical properties unique to these fibers***. Some of the most prominent of these properties are: tensile strength, operating temperature, limiting oxygen index and chemical resistance. Each fiber has a unique combination of the above properties which allows it to fill a niche in the high performance fiber spectrum.

For comparative purposes carbon, glass and high density polyethylene are also referenced. Although these fibers don't necessarily meet all of the requirements of the stated definitions, they commonly compete in the high performance market and should therefore be referenced.

The following presents some basic characteristics of each classification:

Commodity Fibers	High Performance Fibers
Volume Driven	Technically Driven
Price oriented	Specialty oriented
Large scale, line-type production	Smaller batch-type production

II. BASIC PROPERTIES

Tensile strength is often the determining factor in choosing a fiber for a specific need (see chart 1). A major advantage of high strength fibers over steel, for example, is the superior strength-to-weight ratio that such fibers can offer. Para-aramid fiber offers 6-8 times higher tensile strength and over twice the modulus of steel, at only one-fifth the weight, but in applications where strength is not of paramount importance, other properties must be evaluated.

Temperature resistance often plays an integral role in the selection of a fiber. Heat degrades fibers at different rates depending on the fiber type, atmospheric conditions and time of exposure. The key property for high temperature resistant fibers is their continuous operating temperature. Fibers can survive exposure to temperatures above their continuous operating temperatures, but the high heat will begin to degrade the fiber. This degradation has the effect of reducing the tensile properties of the fiber and ultimately destroying its integrity.

A common mistake is to confuse *temperature resistance* with *flame retardant ability*. Flame retardant ability is generally measured by the Limiting Oxygen Index. LOI, basically, is the amount of oxygen needed in the atmosphere to support combustion. Fibers with a Limiting Oxygen Index (LOI) greater than 25 are said to be flame retardant, that is there must be at least 25% oxygen present in order for them to burn. The LOI of a fiber can be influenced by adding a flame retardant finish to the fiber. FR chemicals are either added to the polymer solution before extruding the fiber or added to the fiber during the spinning (extrusion) process. In addition, impregnating or topically treating the fiber or the fabric, flame retardant properties are often added directly to fabrics (such as FR treating cotton fabrics).

Just as heat can degrade a fiber, chemical exposure, such as contact with acids or alkalis, can have a similar effect. Some fibers, such as PTFE (i.e. DuPont's Teflon), are extremely resistant to chemicals. Others lose strength and integrity quite rapidly depending on the type of chemical and the degree of concentration of the chemical or compound.

III. FIBER FORMS AND PRODUCT FORMS

Fibers are available in several different forms. The most common forms used are:

- Staple Fiber – filaments cut into specific lengths – usually spun into yarn
- Chopped Fiber – coarser, cut to specific, often short, lengths to add to mixture
- Monofilament – a single (large) continuous filament yarn – like fishing line
- Multifilament – extruded continuously with many filaments in the bundle.

These basic forms of fiber are then further processed into one of four major converted forms. These converted forms can be categorized into four groups:

- Spun yarn
- Knitted fabri

- Woven fabric
- Nonwoven fabric

Most are familiar with yarn, woven and knitted fabrics. Nonwoven fabrics may be another story. The most common types of nonwoven fabrics are – based on bonding and manufacturing processes - are:

- Needlefelts – the fibers are mechanically entangled with barbed needles
- Dry-laid – chemical or thermal bond – many different forms, including
- Direct formed - spunbond and melt-blown (may be further bonded or combined)
- Stitch Bond – sewn bond
- Wet-laid – paper making process
- Hydro-entangled (spunlace) – water jet entangled – mechanical bond

Many of the fibers are used in very similar end uses, but based on differences of specific properties, *each fiber tends to find its own niche where it has an advantage over the others.*

IV. FIBER PROPERTIES AND THEIR APPLICATIONS

A. Meta-aramid: Nomex® (DuPont), TeijinConex®, TeijinConex HT® (Teijin)

Perhaps the best known and most widely used of the aramid fibers (Nomex is familiar to many), meta-aramids are best known for their combination of heat resistance and strength. In addition, meta-aramid fibers do not ignite, melt or drip; a major reason for their success in the FR apparel market. In comparison to commodity fibers, meta-aramids offer better long-term retention of mechanical properties at elevated temperatures. Meta-aramids have a relatively soft hand and tend to process very similarly to conventional fibers, giving them a wide range of converted products. Meta-aramids are available in a variety of forms, anti-stat, conductive, in blends (with other high performance fibers), etc.

TeijinConex HT high tenacity type meta-aramid has significantly higher tensile strength of other meta-aramids. This high strength allows it to bridge the gap between meta-aramid and para-aramid fiber when strength is the primary concern.

M-aramid Properties	Value
Tenacity g/de	3.8-7.2
Elongation (%)	25-40
Limiting Oxygen Index	30
Chemical resistance	Mild-Good

Operating temperature 400^0 F

***Typical** Applications for Meta-aramid Fabrics (not an exhaustive list)*

M-Aramid Fabric Form	Application
Needlefelt	Automotive Business machine parts Cushion material Hot gas filtration **Safety & Protective clothing** Thermal insulation Thermal spacers
Woven fabric	Hot gas filtration Loudspeaker components Reinforcement: composites and rubber **Safety & Protective clothing** Thermal insulation
Wet-laid nonwoven	Business machine parts Battery separators Heat shields
Dry laid nonwoven	Business machine parts Electrical insulation Heat shields Hot gas filtration Laminate support base Thermal spacers
Spunlace nonwoven	High temperature filtration **Safety & Protective clothing** Laminate support base

B. Para-aramid: Kevlar® (DuPont), Twaron® (Acordis), Technora® (Teijin)

Due to their highly oriented rigid molecular structure, para-aramid fibers have high tenacity, high tensile modulus and high heat resistance. Para-aramid fibers have similar operating temperatures to meta-aramid fibers, but have 3 to 7 times higher strength and modulus, making them ideal for reinforcement and protective type applications.

There are two types of para-oriented aramid fibers:

- Homo-polymer - Kevlar and Twaron
- Co-polymer - Technora

Although para-aramids are high in strength, there is some problem with chemical resistance. Homopolymer para-aramids have relatively weak resistance to strong acids and bases. Kevlar and Twaron, for instance, cannot be bleached with chlorine and are often not approved for food handling in protective gloves. The fine surface structure of Technora copolymer allows it to have much higher chemical resistance. Kevlar has new forms with increased strength and improved properties.

Co-polymer para-aramids have advantages with increased abrasion resistance and steam resistance – useful properties in many protective applications.

Typical properties of para-aramids are as follows:

Properties	Value
Tenacity g/de	22 - 26
Modulus g/de	460-1100
Elongation	2.4 – 4.4
Continous operating temperature (^{0} F)	375
Limiting Oxygen Index (LOI)	25 - 28
Chemical resistance	Mild - Good

Para-aramids are often blended with other fibers to impart some of their high strength properties to the blend or mix. A 60/40 blend of Kevlar and PBI, is the most widely used material for firemen's premium turn out coats. The Kevlar helps overcome some of the "textile" deficiencies (processing, strength) in the PBI; the PBI's softness, moisture regain, and high temperature properties improves the performance characteristics of the Kevlar. And it reduces the cost of the otherwise expensive PBI fiber – over $70/lb.

Such synergy is often utilized in high performance fiber blends – one fiber contributing unique properties or improving characteristics of specialized materials – such as improved processing of otherwise difficult-to-handle fibers, or to reduce overall cost.

The following table shows typical applications, in fabric form, for para-aramids. The list is not exhaustive.

Form	Application

Needlefelt	☞ Cushion material ☞ **Safety and protective clothing** ☞ Thermal insulation ☞ Thermal barriers
Woven fabric	☞ Reinforcement: composites and rubber ☞ Sporting goods ☞ Thermal insulation ☞ Mechanical rubber goods ☞ **Safety and protective clothing** ☞ Ballistic application
Wet-laid nonwoven	☞ Friction materials ☞ Heat shields
Yarn	☞ Reinforcement: composites and rubber ☞ Sewing thread ☞ Ropes and cables ☞ **Safety and protective clothing** (sewing thread)

C. Fluorocarbon fibers (PTFE) : Teflon® (duPont), Toyoflon® (Toray)

PTFE (polytetrafluoroethylene) fibers offer a unique blend of chemical and temperature resistance, coupled with a low friction coefficient. PTFE is virtually chemically inert, and is able to withstand exposure to extremely harsh environments. The coefficient of friction for PTFE, the lowest of all fibers, makes the fiber suitable for a wide range of applications such as bearing replacement material and release material when stickiness is a concern. The fiber's low friction coefficient, as well as their low tensile strength, makes PTFE fibers difficult to process, and difficult to blend with other fibers. PTFE sewing thread is ideal for a number of PC and harsh applications. *The material is also made into breathable, porous membranes laminated to fabrics for protective uses.*

The following properties area typical of PTFE materials

PTFE Properties	**Value**
Tenacity g/de	2
Elongation (%)	25
Limiting Oxygen Index (LOI)	95
Chemical resistance	Excellent
Friction coefficient	0.2
Operating temperature (^{0}F)	500

The following table lists typical applications for PTFE yarns/fibers.

PTFE Form	Application
Needlefelt	Automotive Bearing replacement Hot gas filtration Release fabrics
Woven fabric	Conveyor belts Mechanical rubber goods Gasket tape
Wet-laid nonwoven	Battery separators Heat shields Liquid filtration
Monofilament	Release fabrics Filtration fabrics
Yarns	Mechanical rubber good Sewing thread
Membranes	Filtration Safety and Protective (vapor barriers, breathable membranes)

D. PPS: Ryton® (Amoco/Successor), Procon® (Toyobo), Toray PPS® (Toray)

Polyphenylene sulfide fibers combine moderate temperature resistance with excellent chemical resistance. PPS fibers also have very good flame resistance thanks to their high LOI. The low moisture regain of PPS often takes away from its use in protective apparel; the fiber has an uncomfortable hand, but the good chemical resistance makes it very attractive for industrial applications, especially for filtration.

PPS Properties	Value
Tenacity g/de	3.5 – 4.5
Elongation (%)	32 - 49
Limiting Oxygen Index (LOI)	34
Chemical resistance	Very Good

Operating temperature (^{0}F)	500

The following represent typical applications for PPS. The list is rather short, but the applications are important.

Form	Application
Needlefelt	Hot gas filtration
Woven fabric	Liquid filtration Laundry materials Rubber industries

E. Melamine: Basofil® (BASF)

Basofil has recently entered the high temperature fiber market, one of the newest fibers to do so, and has made a rapid impact. Compared to fibers with comparable properties, its low cost is an advantage and should result in its being evaluated in a number of areas. Based on melamine chemistry, Basofil offers a high operating temperature and a high LOI and typically targets hot gas filtration and safety and protective apparel markets. Because of its variable denier and staple length, low tensile strength, and difficulty in processing, Basofil is generally blended with stronger fibers such as aramids. It is more often used in needled products or yarns made from wrapped spinning techniques, though recent advances have led to satisfactory ring spun yarns, blended with other fibers, such as para-aramids, suitable for weaving into firemen’s turnout gear. This development may lead the way to its adoption in other areas.

Basofil Properties	Value
Tenacity g/de	2.0
Elongation (%)	18
Limiting Oxygen Index (LOI)	32
Chemical resistance	Mild - Good
Operating temperature (^{0}F)	400

Having only recently been introduced, Basofil has a limited range, but rapidly growing, of on-going applications. Potential looks promising for this high performance, low cost fiber to find its way into a number of existing areas, especially as processing difficulties are overcome.

Form	Application

Needlefelt	Hot Gas Filtration Safety and Protective Applications Thermal Insulation
Woven Fabric	Safety and Protective Applications

F. PBO: Zylon® (Toyobo)

Poly-phenylene benzobisoxazole is another new entrant to the high performance organic fibers market. The only entrant thus far, Toyobo's Zylon has outstanding thermal properties and has almost twice the tensile strength of conventional para-aramid fibers . Its high modulus makes it an excellent candidate for composites reinforcement. Due to its high LOI, PBO has over twice the flame retardant properties of meta-aramid fibers. PBO is still in its pilot plant stages, with commercial production just coming on stream.

PBO Properties	Value
Tenacity g/de	42
Modulus g/de	1300
Elongation (%)	3.5
Continuous operation temp. (^{O}F)	550-600
Limiting Oxygen Index (%)	68
Chemical resistance	Mild-Good

The following lists some of the possible areas of application for PBO materials.

Form	Application
Woven Fabric	Reinforcement composites and rubber Sporting goods Thermal shields **Safety and protective clothing** Ballistic applications Mechanical rubber goods
Needlefelt	Aluminum spacers Heat shields

Yarn	✓ Reinforcement composites and rubber ✓ Sewing thread ✓ Ropes and cables

G. PBI: **PBI (Celanese)**

Polybenzimidazole is an organic fiber with excellent thermal resistant properties and a good hand. PBI does not burn in air and does not melt or drip. The high LOI coupled with its good chemical resistance and good moisture regain make PBI an excellent fiber for fire blocking end uses such as safety and protective clothing and flame retardant fabrics. Its physical properties are relatively low, but PBI is processed on most types of textile equipment. It blends well with other materials such as carbon and aramid fibers and is most often done for performance reasons as well as cost. PBI has had significant success in the fireman's apparel market where, blended in a 60/40 para-aramid/PBI mixture, it has become the standard "premium" material. PBI's characteristic gold color blends well with other materials for a pleasing appearance. Its main drawback is its very high price – over $70 per pound.

PBI Properties	**Value**
Tenacity g/de	2.7
Modulus g/de	32
Elongation (%)	29
Continuous operation temp. (^{O}F)	482
Limiting Oxygen Index (%)	41
Chemical resistance	Good - Excellent

Typical applications for PBI include the following:

Form	Application
Needlefelt	Thermal insulation **Safety and protective clothing** Fire blocking
Woven Fabric	Thermal insulation **Safety and protective clothing**

H. Polyimide (PI): P-84® (Inspec)

P-84 is a polyimide fiber developed by Lenzing AG (Austria) and now produced and marketed by a spin-off company, Inspec Fibres GmbH in Austria. P-84 provides a high operating temperature with very good flame retardant properties and good chemical resistance. P-84 fiber touts a unique multi-lobal irregular cross section. This irregular structure offers greater surface area than a conventional round cross section, and has achieved widespread recognition for P-84 fiber in the hot gas filtration market. Due to its high price however, actual use of P-84 in the filtration market is limited to areas where extreme emission controls are necessary. It has also made inroads in the protective clothing market, especially in Europe.

P-84 Properties	Value
Tenacity g/de	4.2
Elongation (%)	30
Continuous operation temp. (^{O}F)	500
Limiting Oxygen Index (%)	38
Chemical resistance	Good

Typical applications for P-84 polyimide fabrics include the following:

Form	Application

Needlefelt	☞ Thermal insulation ☞ **Safety and protective clothing**
Woven Fabric	☞ Thermal insulation ☞ **Safety and protective clothing**

I. Carbon Precursor: Lastan® (Asahi)

Lastan is a flame-retardant fiber made by pyrolytic carbonization of a modified acrylic fiber. Carbon precursor fibers are partially carbonized fibers which transform into carbon or graphite fiber when they undergo further carbonization in an inert atmosphere at high temperature. Carbon precursor fiber combines a high operating temperature with excellent flame resistance. Since this fiber is relatively weak and has limited abrasion resistance, it is often blended 50%/50% with para-aramid fibers creating a strong durable product still having an LOI of 45. Due to its soft hand, Lastan fiber is desirable in apparel applications as well as certain industrial applications.

Lastan® Properties	**Value**
Tenacity g/de	2
Elongation (%)	15
Continuous operation temp. (^{O}F)	392
Limiting Oxygen Index (%)	60
Chemical resistance	Mild
Electrical resistance	$10^{8} – 10^{10}$ Ω cm

Typical applications for carbon precursor fabrics include the following:

Form	Application
Woven Fabric	Welding blankets Aluminized fabrics Thermal barriers **Safety and protective clothing**
Needlefelt	Welding blankets Thermal barriers **Safety and protective clothing**
Dry Laid Nonwovens	Aluminized fabrics - S&P

J. Carbon fiber: PAN (polyacrylonitrile) and Pitch based

There are different categories of carbon fibers based on modulus, tensile strength, and final heat treatment temperature. In the carbonization process, temperature exposures range from 1000^0 C to 2000^0 C, each different level of exposure creating a different property for the fiber. For example, high-modulus type is processed at 2000^0 C, 1500^0 C for high strength type, and 1000^0 C for low modulus and low strength type. The main carbon fibers are made from polyacrylonitrile (PAN) based and pitch based, and are well known for their composite reinforcement and heat resistant end uses.

Carbon Fiber Properties	PAN	PITCH
Tenacity g/de	18-70	14-30
Modulus g/de	1640 - 3850	1000 5850
Elongation (%)	0.4-2.4	0.2 – 1.3
Continuous operation temp. (^{O}F)	570 - 1000	570 - 1000

Carbon fibers find application in many forms and many areas. Some include the following:

Form	Application

Woven Fabric	- Aircraft and aerospace - Automotive - Sports & recreational equipment - Marine - General engineering
Yarn/Fiber	- Reinforcement composites and rubber - Filtration

K. Glass:

Glass is an inorganic fiber, which is neither oriented nor crystalline. Glass fibers were one of the first "man-made" fibers, commercialized in the late 30's. Widely used as insulation (glass batts in home insulation and industrial insulation in mats and fabric form). It is widely used in reinforcing thermoplastic composites in products from circuit boards to boat hulls. High temperature filtration is another high volume use. The ingredients normally used in making glass fibers are: silicon dioxide, calcium oxide, aluminum oxide, baron oxide, plus a few other metal oxides.

<u>Glass types:</u>

A - alkali-containing glass composition.
AR - alkali-resistant for reinforcing cement.
C - chemically-resistant glass composition.
E - standard uses, this composition has high electrical resistance.
HS magnesium-alumina-silica glass. High strength.
S - composition similar to HS glass.

The following chart is representative of the properties of various glass fibers.

Properties	**E-glass**	**AR-glass**	**S-glass**
Tensile Strength (g/de)	35	46	35
Modulus (g/de)	524	1250	620

Elongation (%)	4.8	2	5.4
Refractive index	1.547	1.561	--
Density (g/cm3)	2.57	2.68	2.46
Coefficient of thermal expansion ($10^{7}\ ^{0}C$)	50-52	75	23-27
Dielectric(10^{10}Hz) Constant	6.1-6.3	--	--

Typical glass applications include:

Form	Application
Woven Fabric	Automotive Filtration Reinforcement - plastic/rubber/cement Thermal insulation Printed circuit boards - electrical
Needlefelts	Aircraft and aerospace Cushion material Filtration Thermal insulation and spacers Acoustic insulation

L. High Density Polyethylene - HDPE: Spectra® (Honeywell), Dyneema® (Dyneema)

HDPE fibers offer strength similar to that of para-aramids. Developed in Japan by Dyneema, and known throughout the world as Dyneema, except in the US where the process is licensed to AlliedSignal and is known as Spectra. Light in weight, the fiber has a specific gravity of less than 1, tough yet lighweight products can be made, including rope and cordage that floats as well as soft and semi-rigid body armor and in cut resistant materials such as gloves that are lighter than competitors, reducing fatigue in use. In addition to high tenacity, HDPE fibers have very good abrasion resistance and excellent chemical and electrical resistance. HDPE fibers are inherently “slick” and difficult to adhere to, a drawback in some areas but not of concern in others. They can be bleached and sterilized and used for food handling gloves, among others. The HDPE fibers have low melting points, however, so their continuous operation temperature is a relatively low 250^0 F. There are a number of volume areas where temperature is not crucial..

HDPE Fiber Properties	Value
Tenacity g/de	30
Elongation (%)	3.
Continuous operation temp. (^{O}F)	250
Modulus g/de	1400
Chemical resistance	excellent

Typical applications and forms of HDPE fibers include:

Form	Application
Yarns	- Marine ropes and cordage - Sail cloth
Woven Fabric	- Marine - **Safety and protective products** - Reinforcement of composites (sport, pressure vessels, boat hulls, implants) - Medical

V. CONCLUSION

High performance fibers and high temperature resistant fibers offer numerous advantages over traditional materials. Higher strength, lighter weight, higher operating temperatures and flame-retardant ability are some of the most prominent features of these fibers. These outstanding properties create opportunities to manufacture products that historically could not be made due to technical constraints. The protective clothing area is one of those markets.

Each of these fibers discussed have their limitations. It is not as easy to take these materials “off the shelf” except for a few well-distributed ones. Surely, some are more readily available than others -- the aramids, HDPE, for instance -- but most are less so and should be considered as engineering or specialized materials to be used where their properties are paramount. Review thoroughly each fiber for the properties it brings to the product.

High performance fibers allow companies to enter niche markets, which typically provide higher profits as well as strong barriers to entry for the competition. Even in the high performance area, many markets have become "commodity" applications, particularly the aramids in protective clothing. The protective clothing market will continue to bring new opportunities for high performance fibers as the fiber manufacturers expand their current product lines as well as create new and exciting specialized materials.

Special notation: ***The original authors of most of this text, from Aramid Ltd, graciously allowed me to edit and revise some of their text and data in order to develop this version for PCC'99. Inquiries concerning the data, and many of the fibers in question, can be forwarded to them or to me. There is no connection between Aramid Ltd and Industrial Textile Associates.***

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