AN INTRODUCTION TO

Fire Science & Flame Resistant Fabric Technologies

for Protective Apparel

White Paper Executive Summary
In order to understand flame resistant (FR) fabrics and the engineering behind them, it’s important to understand what they are protecting against. This requires diving deep into the science of a flame, and identifying exactly how and when flame resistant technologies intervene to protect wearers against flammable hazards.

Fire is a complex chemical chain reaction that requires heat, fuel, and oxygen. Three technologies are commonly used to reduce the flammability of fabrics, each based on removing or reducing one of these factors: heat, fuel, or oxygen. Each method is used, to some degree, to produce FR fabric for protective apparel and has unique advantages and disadvantages.

This white paper reviews the benefits and challenges of three technologies to produce FR apparel:

1. Thermally stable fibers
2. Solid-state treatments
3. Gas-state treatments

Thermally stable fibers, also commonly described as “inherent,” are fibers that have a molecular structure that doesn’t burn until reaching extremely high temperatures. Thermally stable fibers are highly durable and are often used in military flight suits, turn-out fire gear, and motorsports. The FR properties of thermally stable fibers are permanent and cannot be washed out. However, thermally stable fibers have a few disadvantages, including high cost, a stiff feel, and color limitations.

Solid-state technologies are chemical solutions that interrupt a flame’s chain reaction on textile surfaces. When exposed to heat, a solid char forms on the fabric, creating a barrier between the flame and its fuel. This removes fuel from the fire while also protecting the underlying material. There are two approaches to solid-state technologies: treated, which remains on the top of a fabric’s surface, and engineered, which is permanently bonded to fabrics to create a structurally-enhanced material.

In addition to FR apparel, solid-state treatments are used in commercial textiles found in public spaces from hotel curtains to bedspreads. Particularly important to FR garments, solid-state treatments, when bonded permanently, allow FR fabric manufacturers to offer products at a more economical price. They also preserve much of the inherent comfort of cotton blends, including breathability, moisture wicking, stain release, and dyeability, without compromising FR performance.

Adding a gas-state or fuel-activated technology is another approach to creating FR fabrics. This method eliminates combustion fuel and stops the flame’s chain reaction. Gas-activated treatments are used in a broad range of products, including televisions, blenders, electrical wire, and mattresses. Modacrylic fibers are the most widely used example of this technology in protective apparel.
Overall, each strategy can provide effective FR protection and reduce injuries in hazardous environments. As such, the choice of fabric for FR apparel is often based on properties other than FR performance, including: comfort, breathability, drape, hand, moisture and heat management, product lifetime, cost, and appearance. Determining the ideal FR fabric for protective apparel in a specific line of work balances all of these properties.

FR technologies are not visible to the eye, so industry standards exist to provide an even comparison across products for specific hazards, including arc flash, flash fire, and others. Even with these assurances and third-party certifications, it is critical to source fabric from reputable manufacturers who have established robust process controls and internal testing procedures to ensure the performance of FR apparel.

This white paper is a nuts-and-bolts look at the “what,” “how,” pros, cons, and applications of each method and industry standards in place to help buyers compare FR fabrics.
AN INTRODUCTION TO
Fire Science & Flame Resistant Fabric Technologies
for Protective Apparel
In order to understand flame resistant (FR) fabrics and the engineering behind them, it is important to understand the nature of fire. After all, you want to know your opponent well in order to exploit his weaknesses. The same goes for fire when engineering flame resistant apparel.

Fire is a complex chemical chain reaction that requires heat, fuel, and oxygen. Strategies to reduce the flammability of fabrics are based on removing or reducing one of these components. Several technologies, or methods, are used to produce FR fabric for protective apparel, and each one has its own advantages and disadvantages. Understanding the science of fire—and the strategies to reduce flammability—are vital assets in engineering the most effective FR fabric.

THE SCIENCE OF A FLAME

Fire is a chemical reaction of oxygen and fuel that produces light and heat. The heat produced feeds the flame in a chain reaction when oxygen in the air reacts with carbon and hydrogen.

Combustion involves three basic steps:

1. Heat causes the material to break down, or decompose, into smaller molecules that are vaporized into the gas state to become fuel.
2. The fuel reacts with oxygen to produce light, heat, and reactive molecules, called radicals.
3. The produced heat and radicals lead to further decomposition of the material and the production of additional fuel.

The combustion process has many intricate layers, but strategies to reduce flammability in protective apparel involve interrupting one or more of these three fundamental steps. This holds true in either the solid or gas state.

FLAME RETARDANTS IN THE SOLID STATE

Solid-state flame retardants prevent the fuel source from entering the gas state. This process stops larger molecules from breaking down into gases, removing the fuel from the gas state and insulating the solid from additional heat exposure.

HOW: Solid-state flame retardants work by redirecting the small molecules produced by decomposition into a reaction that forms a solid char instead of producing fuel. The char
also works as an insulator to protect the layers of material beneath it from being heated. The lack of fuel stops the fire from spreading.

**FLAME RETARDANTS IN THE GAS STATE**

Gas-state flame retardants interrupt the gas state by stopping the chain reaction that causes a flame to spread.

**HOW:** Gas-state flame retardants are composed of halogenated compounds, which break down into bromine or chlorine radicals and react with the radicals produced by decomposition. This method snuffs out a flame by stopping the flame’s chain reaction.

**THE SCIENCE BEHIND FR APPAREL**

Three general technologies and approaches are used to create flame resistant fabric for protective apparel. Below is a nuts-and-bolts look at the “what,” “how,” pros, cons, and applications of each method and industry standards in place to help buyers compare FR fabrics.

**THERMALLY STABLE FIBER TECHNOLOGIES**

**WHAT:** Thermally stable fibers, also commonly known as “inherent,” have a molecular structure that doesn’t decompose until reaching extremely high thermal temperatures. In fact, they can withstand temperatures up to 400 °C (750 °F) without melting or decomposing. The most common classes of thermally stable fibers are aramids, which can be found in Nomex®, Kevlar®, and Kermel®, and also in inorganic fibers such as asbestos and fiberglass.

**HOW:** These thermally stable fibers do not undergo any chemical changes when exposed to heat. Because the fiber does not break down or change at all, the flame doesn’t have any fuel to sustain itself.

**PROS:** Thermally stable fibers have many advantages, a significant one being that the FR properties are permanent and cannot be washed out. The fibers are also incredibly strong and resistant to tearing, which can increase the lifespan of FR apparel.

**CONS:** Although it is very strong, FR garments made with thermally stable fibers feel very stiff and rigid, which can limit a worker’s movement. They are also limited in color options and are very difficult to dye. The fiber structure produces an innate yellow-to-brown tone. Although the garment will not burn, thermally stable fibers can shrink when heated. This decreases the air gap between the fabric and skin, which may result in more severe skin burns.

In addition, thermally stable fibers cost significantly more than other FR technologies, which translates into higher fabric cost. This can be mitigated by blending thermally stable fibers with cotton, rayon, polyester, or nylon, but because those fibers do not have inherent flame resistance, additional FR chemistry is required to create reliable protective clothing fabrics.
Essentially, this means that even fabrics containing thermally stable fibers may need to include solid state or gas-state technologies to adequately protect wearers.

**APPLICATIONS BEYOND INDUSTRIAL FR APPAREL:** Because of their durability and high tear resistance, thermally stable fibers are often used for military flight suits, turn-out fire gear, and motorsports.

**SOLID-STATE FR TECHNOLOGIES**

**WHAT:** Solid-state FR technologies are either chemically treated or engineered fabrics with a phosphorous-based FR solution. There are two groups of solid-state active FR approaches, which are critical to distinguish between: treated and engineered.

- Treated FR technologies do not bond with the fabric they are protecting. Instead, the technology sits on the material’s surface. These surface-level solutions are typically used in paints, polyolefin mixtures, stiff foams, and wood-resin composites. This method does not bond the FR treatment directly to materials so protective fabrics made with this FR approach may encounter durability issues, as the FR treatment can wash out.

- Engineered FR technologies are bonded permanently to fabrics or fibers. This creates a durable and reliable fabric, as it prevents the FR qualities from being washed out when laundered. Base fabrics for engineered FR apparel are cotton, cotton blends, and FR rayon, which offer higher levels of comfort and breathability compared to other FR technologies.

  However, if not manufactured properly, engineered FR can result in reduced fabric strength, shade shifting, and inferior FR protection. As such, it is critical to source FR from a reputable company that uses various process controls and third-party certifications to ensure a consistent, quality FR product.

**HOW:** Solid-state flame retardants work by causing the fabric to char when exposed to heat from flames. The char extinguishes the fire in two ways:

1. It creates a ring-like molecular structure at the flame front, which inhibits reactions that produce fuel for the fire.

2. It protects the underlying material, which decreases heat exposure and thermal decomposition, and therefore, reduces the amount of fuel.

These types of flame retardants are incorporated into fabrics in two ways. In the case of FR rayon, the FR agent is incorporated into the viscose solution when the fiber is produced. For cotton and cotton blend fabrics, woven fabric is exposed to a THP-based solution (a reactive phosphorous compound) and cross-linked with a nitrogen compound to provide a permanent bond with the fiber. The engineered fabric is then washed, dried, and finished with standard textile processing to achieve the look and feel of everyday clothing.

**PROS:** Apparel with solid-state, phosphorous-based FR technologies offer a great deal of benefits.
Compared to other FR approaches, especially in terms of comfort and value. In fact, this approach allows manufacturers to preserve much of the inherent comfort of cotton blends while also providing FR performance. These garments are often more breathable and offer moisture-wicking and stain release properties that other FR technologies cannot.

Manufacturers can also fine-tune various textile properties, such as weight, to optimize protection and comfort. These fabrics can be dyed virtually any color, introducing opportunities for branding. Finally, fabrics that use phosphorous-based FR technology are normally the most economically priced of the various technologies.

**CONS:** Despite many benefits, solid-state FR technologies have disadvantages that should be recognized, based on whether fabrics are treated or engineered. FR qualities can wash out of treated apparel as they are not chemically bonded to the fibers. Though the FR qualities will not wash out of engineered textiles, improper manufacturing can result in reduced fabric strength, shade shifting, and inferior FR protection.

**APPLICATIONS:** Engineered textiles are often used in a variety of FR apparel from denim jeans and jackets to all-weather work coats. Textiles with solid-state, treated FR protection can be found in public spaces in curtains, drapery, couches, and more. However, it is important to note that there are lower FR standards and requirements for these non-apparel applications.

**GAS-STATE FR TECHNOLOGIES**

**WHAT:** Gas-state technologies snuff out flames by interrupting the chemical chain reaction of the fire by trapping radical molecules produced by the flame. This reduces the amount of fuel and stops the flame’s chain reaction. Gas-state active FR technologies often use halogenated compounds. They are extremely stable in their normal state and in normal use but are also extremely effective at snuffing out flames when exposed to fire.

**HOW:** Gas-state active FR technologies use a chemical reaction that activates when a material is heated. When heated, the halogenated organic molecules break down and form radical scavenging molecules in the gas layer above the fabric. These scavengers bind with the radicals produced from the decomposing fibers and greatly reduce their ability to continue the decomposition process that produces fuel.

**PROS:** Unlike thermally stable fibers, FR fabrics created with gas-state treatments are soft to the touch, easy to dye, and retain their color. The FR properties are reliable; you can launder these fabrics without compromising their FR qualities. Because the flame retardant effect is in the gas phase above the fabric, fibers with these types of FR agents can be blended effectively with non-FR fibers and still provide protection. This helps to make these fabrics more reasonably priced than using thermally stable fibers.

**CONS:** Gas-state fabrics do have disadvantages as well. They are relatively weak and therefore, less durable than other FR fabrics, shrink easily, and require blending with other fibers, such as cottons or thermally stable fibers.
The technology also has potential environmental consequences. There is concern that gas-state FR chemistry can transfer to other materials and surfaces in the immediate environment, and there is also a debate over the toxicity of smoke created when modacrylic fibers are burned, as hydrogen cyanide and hydrochloric acid are released.

**APPLICATIONS:** Gas-state treatments are used in a broad range of products, including televisions, blenders, electrical wire, and mattresses. Modacrylic fibers are the most widely used example of this technology in protective apparel.

**INDUSTRY STANDARDS**

It is evident that each strategy used to create FR textiles has distinct advantages and disadvantages, but FR qualities are not visible. To help provide assurance to decision-makers and buyers, industry testing standards allow for an apples-to-apples comparison of FR fabric performance. The most common fabric test standards are NFPA 2112 (assesses flash fire protection) and NFPA 70E (assesses arc flash protection).

Additional certifications by outside testing laboratories, such as Underwriter’s Laboratory, provide another level of assurance that the fabric has been tested by a third-party lab and meets protection and laundry durability standards.

**CONCLUSION**

Ultimately, each method described above can provide effective FR protection and help reduce injuries in hazardous environments. Each method will have its own laundry and care requirements, which need to be followed. No single technology is universally better than the other. Since each of the FR technologies, if properly deployed, can provide durable flame resistance to fabric, the choice of fabric for protective apparel is often based on factors other than the FR performance, like comfort, breathability, drape, feel, moisture and heat management, product lifetime, cost, and appearance. All of these properties are affected by the choice of fabric fiber, finish, and construction.

The final decision on which flame resistant fabric technology to use in protective garments should be based on balancing these properties for the application. Most important, however, is sourcing fabric from reputable manufacturers who have established robust process controls and internal testing plans to ensure the performance of your FR apparel.

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