Specialty Fibres for Fire Safety Uniform for Airforce Pilots

R.Sakthi Sree; A.Shakithya; S.Meenakshi,
Department of Fashion Technology,
Coimbatore 641049.

Dr. Bhaarathi Dhurai, Professor,
Kumaraguru College of Technology,
Coimbatore 641049.

Abstract:- Fire safety uniforms are essential in industries like construction, manufacturing, oil and gas, and emergency services, where workers face fire risks, extreme heat, and molten materials. These uniforms are designed to provide thermal insulation, flame resistance, and durability, protecting employees from burn injuries and other hazards. Their use not only ensures compliance with safety regulations but also enhances worker safety and operational efficiency. Comfort in fire safety uniforms is vital for ensuring worker safety and performance. A well-designed uniform that combines protection with comfort allows for better mobility, reduces fatigue, and prevents heat stress. This balance encourages consistent use of safety gear, enhances focus, and reduces the risk of accidents in high-risk environments.

***Keywords**:- Fire Safety Uniform, Flame Resistance, Durability, Operational Efficiency, Comfort, Functionality, Design, Airforce Pilots.*

I. INTRODUCTION

Fire safety uniforms for Air Force pilots are vital for ensuring their protection during flight operations, where exposure to extreme heat, fire, and other life-threatening risks is a constant concern. These uniforms are made from specialized flame-resistant fabrics, designed to protect pilots from injuries caused by cockpit fires, aircraft malfunctions, or ejections. The primary function of these uniforms is to offer thermal insulation and prevent burns, but they must also be durable and capable of withstanding high-speed flights, sudden changes in pressure, and other stressors experienced during flight. [1,2]

Comfort is a crucial factor in the design of these uniforms. Pilots often operate in intense environments where precision and focus are essential for mission success. Uncomfortable gear can restrict movement, cause distractions, and increase fatigue, potentially compromising safety. [3]

Therefore, Air Force fire safety uniforms are crafted with materials that provide both protection and comfort, ensuring that pilots can move freely, maintain focus, and endure long flights without distraction. The design includes lightweight, breathable fabrics that minimize heat stress while allowing maximum mobility. This balance between safety and comfort is critical, as it helps pilots remain fully operational in high-risk situations while minimizing the impact of protective gear on their performance and well-being.

II. FUNDAMENTALS OF FIRE-RETARDANT CLOTHING

Fire retardant (FR) fabrics are engineered to provide protection against fire by inhibiting ignition or slowing the spread of flames. The basic principles of fire involve four key components: heat, fuel, oxygen, and radicals. [4,5] To prevent fire, one of these components must be removed. FR fabrics use various technologies to achieve this, with the three primary technologies being,

A. *Char Forming Agents,*
B. *Gas Phase Radical Scavengers,*
C. *High-Temperature Fibers.*

Each of these technologies plays a unique role in interrupting the fire process and ensuring the protection of individuals in hazardous environments.

A. Char Forming Agents

Char forming agents are phosphorus-based chemicals incorporated into fabrics to enhance their flame resistance, particularly for cellulose Fibers such as cotton, rayon, and lyocell. Cellulose-based Fibers are highly flammable, and when exposed to heat, they break down into gaseous fuel, which sustains the fire. The role of char forming agents is to react with these fuels, transforming them into a stable solid char, which serves as a protective barrier between the flame and the fabric.

When the fabric is exposed to fire, the cellulose Fibers decompose and release volatile gases. This is where the char forming agents come into play. Phosphorus-based compounds react with the gaseous fuel, leading to the formation of a stable solid char. This char is non-combustible and forms a protective layer that acts as a barrier between the flame and the underlying fabric. The char helps to prevent the further breakdown of the fabric, and by doing so, it restricts the release of more flammable gases, depriving the fire of fuel. In essence, the char forming agents work by cutting off one of the essential components (fuel) needed for combustion, thus halting or slowing the fire.

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Char forming agents are particularly effective in cellulose Fibers because they prevent the Fibers from burning and releasing more fuel. These agents can also be applied to synthetic Fibers, although their application differs. For synthetic Fibers, the phosphorus agents are incorporated into the Fibers, forming durable chemical bonds that provide long-lasting flame resistance. These bonds ensure that the flame-resistant properties are permanent and do not degrade over time due to wear or washing. By using char forming agents, manufacturers can produce fabrics that offer effective fire protection for various applications, including protective clothing, industrial workwear, and military uniforms.[6,7,8]

B. Gas Phase Radical Scavengers

Gas phase radical scavengers, often chlorine-based compounds, provide another important mechanism for fire resistance in fabrics. To understand how this works, it is important to know that combustion occurs when fuel breaks down into radical molecules, which then react with oxygen to sustain the fire. Gas phase radical scavengers interfere with this process by interacting with the radicals in the combustion zone.

When exposed to heat, these special molecules, particularly chlorine-based ones, form stable chlorine radicals. These chlorine radicals bond with the fuel radicals, preventing them from reacting with oxygen. By intercepting these radicals, the chlorine radicals reduce the overall energy available for the fire to continue spreading. In this way, the scavengers disrupt the combustion process, stopping the fire from growing or sustaining itself.

The most common fibre used with gas phase radical scavengers is acrylic, which can be modified to form modacrylic Fibers. Modacrylic Fibers are known for their flame resistance and softness, and they are easier to dye than other fire-resistant Fibers. Chlorine atoms incorporated into the acrylic Fibers enhance their flame-retardant properties by activating the protection in the gas phase, this means the flame protection works above the fabric itself, in the zone where combustion occurs.

This technology allows non-FR Fibers to be blended with FR Fibers, which helps provide effective protection at a more affordable price point. The combination of non-FR Fibers with gas phase radical scavengers allows to produce fire-resistant fabrics that are not only cost-effective but also versatile, offering a wide range of applications in industries that require fire safety without compromising on cost or comfort.[9]

C. High-Temperature Fibers

High-temperature Fibers are designed to provide flame resistance through their ability to withstand extreme temperatures. Unlike traditional Fibers, which may break down and combust at relatively low temperatures, high-temperature Fibers maintain their structural integrity up to temperatures of approximately 750°F (400°C). These Fibers are inherently resistant to heat and flames and do not require any additional chemical treatments to maintain their fire-resistant properties.

The primary mechanism of high-temperature Fibers is that they do not decompose or release fuel when exposed to heat. This characteristic deprives the fire of one of the essential components (fuel) thus preventing it from spreading or sustaining itself. High-temperature Fibers are especially effective because they maintain their structure even in extreme heat, effectively isolating the fire from the rest of the fabric and providing a durable barrier.

One of the most used types of high-temperature Fibers is aramid Fibers, such as Kevlar and Nomex. These Fibers are made from synthetic polymers that are engineered to withstand high temperatures. Aramid Fibers do not break apart or release fuel when exposed to heat, which makes them highly resistant to fire. They are often used in applications such as firefighter gear, military uniforms, and protective industrial clothing. Unlike fabrics treated with chemical flame retardants, high-temperature Fibers provide long-lasting protection without the risk of degradation over time, making them particularly suitable for environments where prolonged exposure to heat is a concern.

Moreover, the advantage of high-temperature Fibers is that they do not lose their flame-retardant properties after repeated washing or wear. This makes them a more durable option for workers who require long-lasting protection in high-risk environments. [10,11,12]

III. TRADITIONAL FLAME-RETARDANT FABRIC

Traditional fire retardant (FR) fabrics have been designed to provide essential protection in hazardous environments, but they often come with drawbacks that impact comfort and practicality. Many traditional FR fabrics are heavy, itchy, and uncomfortable to wear, which can deter individuals from fully using protective clothing in critical situations. Wool, while naturally flame-resistant, is heavy when wet and lacks breathability, leading to discomfort. Cotton treated with flame retardant (FR) chemicals can also feel restrictive and reduce airflow, making it uncomfortable for the wearer. As a result, individuals may adjust or remove parts of their gear, such as folding sleeves, which can create serious safety risks in emergency situations. Therefore, the comfort and functionality of FR fabrics are crucial to ensuring they are worn properly when safety is at stake.[13] Traditional FR fabrics are often categorized based on the types of chemicals used to make them flame-resistant. The three main types are:

A. *Inorganic FR*
B. *Halogen-Based FR*
C. *Phosphorous-Based FR.*

A. Inorganic Flame Retardant

Inorganic flame retardants, such as aluminium hydroxide, aluminium trioxide, and magnesium hydroxide, work by absorbing heat and releasing water or cooling the textile when exposed to flames. These substances create a

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cooling effect that helps prevent the material from catching fire. For instance, aluminium hydroxide decomposes when heated, releasing water vapor that cools the fabric and dilutes the oxygen surrounding the flame, reducing the likelihood of combustion. However, while effective, these substances can make fabrics heavier and less breathable.[14]

B. Halogen-Based Flame Retardant

Halogen-based flame retardants, such as chlorine and bromine, act through a radical chain mechanism. When exposed to heat, they release halogen atoms that interfere with the combustion process by reacting with the radicals involved in the fire. While these chemicals are effective at suppressing flames, they pose environmental concerns, as their decomposition products can be toxic and harmful to the environment.[15]

C. Phosphorous-Based Flame Retardant

Phosphorous-based flame retardants work by forming a phosphoric acid compound when exposed to flame. The acid reacts with the Fibers to create a char layer, which acts as a barrier between the fire and the fabric. This char protects the material from further breakdown and helps prevent the release of additional fuel for the fire. Phosphorous-based FRs are commonly used because they provide lasting flame resistance, but the treatment can cause the fabric to become rigid and less comfortable.[16]

IV. ARAMID FIBRES

Aramids are synthetic fibres designed to offer exceptional strength while remaining lightweight. These fibres are made from long chains of synthetic polyamides, which are polymers that consist of repeating units of amide groups. Specifically, para-aramid is a type of aramid fibre, made from a polymer known as poly para-phenyleneterephthalamide (PPTA). The structure of this polymer includes alternating benzene rings and amide groups, giving it a rigid, rod-like shape. This unique molecular arrangement contributes to the fibres' impressive tensile strength and durability, making them ideal for high-performance applications. [17,18,19]

A. Characteristics of Aramid Fibres

Aramid fibres exhibit strong resistance to a variety of solvents and salt, although they can be weakened by exposure to strong acids. While they are challenging to dye and are sensitive to UV light, these fibres are highly flame-resistant. Instead of melting when exposed to heat, they decompose.

Aramid products are available in several forms, such as filament yarn, staple fibre, or pulp. These fibres maintain much of their strength even at high temperatures and are resistant to long-term deformation, also known as "creep," under sustained stress. Their toughness exceeds that of materials like steel, glass fibre, and nylon, and they are highly durable, even under extreme conditions of tension and bending, making them highly versatile for various applications. [20]

B. Para Aramid Fibres

Para-aramid fibres are widely recognized for their high strength and modulus, offering excellent resistance to melting at elevated temperatures. Although they are sensitive to ultraviolet (UV) light, they have a low affinity for water, which makes them ideal for specific applications. These strong and heat-resistant fibres were first introduced by DuPont™ in the early 1960s and have become crucial in protective systems. Para-aramid fibres are a type of synthetic fibre made from polyamides derived from aromatic acids and amines. The strong bonding between amide and aromatic groups enhances their thermal resistance and traction, making them superior to nylon fibres in terms of performance.

Despite their higher cost, fabrics made from para-aramid fibres offer remarkable strength, modulus, and tenacity, which are essential qualities for ballistic applications. As a result, they have increasingly replaced nylon fibres in military Armor. Additionally, aramid materials bring the added benefits of flexibility and lightweight properties, which help create more comfortable ballistic vests without compromising on protection. Today, the most common para-aramid fibres are marketed under the trade names Kevlar® and Twaron®. [21,22,23,27]

➢ *Applications of Para Aramid Fibres*

- *Ballistic Protection:*

Para-aramid fibres are crucial in the production of bulletproof vests, helmets, and other personal protective equipment due to their high tensile strength, which helps absorb and distribute impact energy, providing protection from projectiles.

- *Aerospace:*

In the aerospace sector, para-aramid fibres are used in aircraft components and boat hulls. Their light weight, coupled with exceptional strength, enhances the performance and durability of these structures, ensuring safety and reliability in demanding environments.

- *Automotive:*

These fibres are also used in the automotive industry, where they are incorporated into clutch plates and brake linings. Their ability to resist heat and friction makes them an excellent material for these high-performance components, improving their longevity and efficiency.

- *Sporting Goods:*

Para-aramid fibres are employed in various sporting goods, such as tennis rackets, bicycles, and protective gear. Their lightweight yet strong nature offers enhanced performance and safety for athletes, particularly in equipment that requires high strength-to-weight ratios.

- *Ropes and Cables:*

The fibres are used to manufacture strong ropes and cables, including those for optical communication systems. Their tensile strength and resistance to abrasion and

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chemicals make them ideal for applications where durability and reliability are essential.

- *Aramid Paper:*

Para-aramid fibres can be processed into aramid paper, which is used for electrical insulation and in the construction industry. This paper can withstand high temperatures and electrical stress, providing excellent protection and insulation in various applications.

- *Nano-building Blocks:*

Para-aramid nanofibers can be utilized to produce a range of materials, including films, hydrogels, aerogels, fibres, and composites. These materials can be used in advanced technological applications, such as sensors, medical devices, and energy storage systems, where high-performance materials are crucial.[24]

➢ *Advantages of Para Aramid Fibres*

- *Exceptional Strength:*

Kevlar is renowned for its impressive strength-to-weight ratio. With a relative density of 1.44 and a tensile strength of around 3,620 MPa, it is much stronger than many materials, including steel, yet significantly lighter. This remarkable strength comes from its unique chemical structure, where inter-chain bonds are reinforced by hydrogen bonding. This structure allows Kevlar to have a tensile strength up to 10 times greater than steel when compared by weight, making it an ideal material for demanding applications.

- *Zero Thermal Shrinkage:*

One of Kevlar's standout properties is its ability to retain strength and resilience even in extreme temperatures. It maintains its integrity down to cryogenic temperatures (-196°C), remaining unaffected by the cold without becoming brittle. Additionally, Kevlar can withstand high temperatures up to 450°C, with only a slight reduction in its tensile strength (10-20%) when exposed to heat over time. This makes Kevlar an excellent choice for applications where both cold and hot conditions are encountered.

- *Excellent Heat and Flame Resistance:*

Kevlar demonstrates superior heat and flame resistance. It remains virtually unchanged after prolonged exposure to hot conditions, such as hot water, lasting for over 200 days without degradation. Naturally flame-resistant, Kevlar can endure temperatures up to 800°F (427°C). Even if ignited, Kevlar does not melt or drip, and it will stop burning once the heat source is removed. This makes it a reliable material in environments where exposure to heat or flames is a concern.

- *Resistance to Tearing and Stretching:*

Kevlar is highly resistant to damage from tearing, stretching, or impact. Its well-aligned molecular chains create a robust barrier that resists cuts, scratches, and punctures, which makes it particularly useful in protective clothing and gear. In addition, Kevlar is resistant to most chemicals, enhancing its durability in harsh environments. These properties contribute to Kevlar's widespread use in applications that require high levels of cut and impact resistance.

- *High-Velocity Defence:*

One of the most notable applications of Kevlar is in high-velocity defence, such as in bulletproof vests and helmets. The tightly woven fibres of Kevlar prevent separation upon impact, which allows it to absorb and dissipate the energy from bullets or other projectiles. This ability to absorb and spread the impact energy helps reduce the damage caused by high-velocity impacts, making Kevlar a crucial material in personal protective equipment and other defence applications.[25]

➢ *Disadvantages of Para Aramid Fibres*

- *Absorbing Moisture:*

Kevlar fibres are highly sensitive to moisture, as they absorb water more quickly than many other materials. While short-term exposure does not significantly affect Kevlar, prolonged moisture absorption can gradually degrade its properties. As a result, Kevlar may not be the best choice for environments that are consistently damp or where prolonged exposure to moisture occurs.

- *Minimal Compressive Strength:*

Although Kevlar is known for its high tensile strength, it performs poorly under compression. This means it can withstand stretching and pulling forces but is not as effective when subjected to compressive forces. This limitation makes it difficult to use in applications where compression resistance is essential.

- *Cutting and Drilling Difficulties:*

Kevlar's dense and tough structure makes it difficult to cut and drill through. Dry Kevlar fabric requires specialized scissors for cutting and cured Kevlar laminates need special drill bits to pierce them. The material's resilience to cutting tools can pose challenges during manufacturing or in applications where it needs to be altered.

- *Ultraviolet Light Sensitivity:*

Kevlar is more sensitive to ultraviolet (UV) light compared to materials like polyester. Prolonged exposure to UV light causes Kevlar to degrade and lose strength at a faster rate, roughly twice as fast as polyester. This UV sensitivity can lead to a reduction in the material's overall durability and performance when exposed to sunlight over time.[25]

C. Meta Aramid Fibres

Kevlar is a strong and heat-resistant synthetic fibre that belongs to the aramid family, which also includes materials like Nomex and Technora. It was invented by Stephanie Kwolek at DuPont in 1965. Kevlar's exceptional strength and heat resistance led to its commercial use in the early 1970s, initially as a replacement for steel in racing tires. The fibre is often spun into ropes or fabric sheets, which can be used directly in various applications or incorporated into

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composite materials to enhance their strength and durability. [26,28]

➢ *Applications of Meta Aramid Fibres*

- *Protective Clothing:*

Meta-aramid fibres are commonly used in the production of protective clothing, including bulletproof vests, body Armor, and helmets. Their ability to withstand high temperatures and provide resistance to impact makes them ideal for these safety applications.

- *Electrical Insulation:*

Due to their high thermal stability, meta-aramid fibres are used as electrical insulation. They help prevent overheating in wires and other electrical components, ensuring the safe and efficient operation of electrical systems.

- *Automotive Applications:*

In the automotive industry, meta-aramid fibres are used in various components, such as hoses for hot air delivery to the intake manifold and turbochargers. They are also incorporated into racing suits and other protective clothing to improve fire resistance and enhance safety for drivers.

- *Insulation:*

These fibres are used in insulation materials due to their ability to withstand extreme temperatures. Meta-aramid fibres provide excellent thermal protection, making them suitable for use in high-performance insulation applications.

- *Garments:*

In addition to industrial uses, meta-aramid fibres are also used in clothing due to their soft texture. The fibres are woven into fabrics that combine comfort with performance, offering durability and heat resistance in garments.

➢ *Advantages of Meta Aramid Fibres*

- *High Tensile Strength:*

Aramid fibres are much stronger than steel in terms of tensile strength, which makes them ideal for applications where weight is a concern, but high strength is still required. This property allows them to provide excellent performance without adding unnecessary weight.

- *Low Density:*

Aramid fibres are lighter than glass fibres, which gives them an advantage in applications where reducing weight is essential, such as in aerospace, automotive, and sporting goods.

- *Insulation Properties:*

These fibres are excellent insulators, providing effective protection against both heat and electrical currents. This makes them useful in industries where thermal or electrical insulation is needed, such as in protective clothing and electrical components.

- *Resistance to Impact and Damage:*

Aramid fibres are highly resistant to impacts and physical damage. Their strength and durability make them ideal for protective gear, such as bulletproof vests and helmets, as well as in other applications where resistance to wear and tear is critical.

- *Low Moisture Absorption:*

Aramid fibres have a very low tendency to absorb water, which helps maintain their strength and integrity even in humid or wet environments. This characteristic ensures they remain durable and reliable, even when exposed to moisture, unlike many other materials that degrade when wet.

➢ *Advantages of Meta Aramid Fibres*

- *Sensitivity to UV Rays:*

Aramid fibres are vulnerable to ultraviolet (UV) radiation, which causes them to degrade when exposed to sunlight over time. This can lead to a reduction in their strength and durability, limiting their use in outdoor applications without UV protection.

- *Poor Compression Strength:*

Compared to other materials like carbon fibre, aramid fibres have relatively low compressive strength. This makes them unsuitable for structural applications, such as bridge construction, where the material needs to withstand compressive forces.

- *Moisture Absorption:*

Aramid fibres tend to absorb moisture, making them more sensitive to environmental changes than some other materials. To protect their integrity, aramid fibres are often combined with moisture-resistant materials, like epoxy resins, to prevent damage caused by water absorption.

- *Difficulty Cutting:*

Cutting and processing aramid fibres can be challenging. They require specialized equipment, such as special scissors or drill bits, to cut or grind them effectively, which can increase manufacturing costs and complexity.

- *Corrosion:*

Although aramid fibres are resistant to many environmental factors, they can suffer from corrosion under certain conditions, which can weaken the material and limit its lifespan in some environments.

- *Limited Customization:*

Unlike carbon fibres, aramid fibres have fewer grades and finishes available, which can limit their versatility in specific applications. This makes them less customizable for certain specialized uses.

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- *Expensive:*

Aramid fibres are generally more costly than many other materials, such as polyester or nylon, which can make them less accessible for mass-market applications or industries that are highly cost sensitive.

- *Sensitivity to Acids, Bases, and Chlorine:*

Aramid fibres are vulnerable to damage from exposure to acids, bases, and chlorine. As a result, products made from aramid fibres require special care, such as different laundering techniques, to maintain their performance and longevity.

D. Comparison Between Para-Aramid And Meta-Aramid

Table 1 COMPARISON BETWEEN PARA-ARAMID AND META-ARAMID

S. No	PROPERTY	PARA-ARAMID	META-ARAMID
01.	Flame retardancy rate	Withstand upto 800°F (420°C)	Withstand upto 700°F(370°C)
02.	Durability	It is 5 times stronger than steel and lasts upto 5 years.	Extremely durable and lasts upto 5 years.
03.	Comfort	Great comfort	Great comfort
04.	Breathability	Good	Highly breathable
05.	Air permeability	35-50L/m²/s	35-50L/m²/s
06.	Tensile strength	3620 megapascals (MPa)	340 megapascals (MPa)
07.	Melting point	930° F (500° C)	660° F (350° C)
08.	Shrinkage	Low thermal shrinkage	Very little and retain shape after washing.
09.	Weave	Twill and plain weave	Twill weave
10.	Fabric when wet	Less ballistic performance	Better even when wet.
11.	Adhesion	Less	Less
12.	Exposure to sunlight	Can degrade	Damage in 3 days

V. CONCLUSION

When considering the ideal fabric for Air Force pilot fire safety uniforms, Nomex fabric stands out as a superior choice over Kevlar due to its specialized properties that align more effectively with the specific needs of pilots operating in high-risk environments. Both Nomex and Kevlar are well-known for their strength and heat-resistant capabilities, but Nomex offers several advantages that make it the better option for fire safety uniforms.

Nomex, a flame-resistant aramid fibre, is specifically designed for heat and flame protection. It is highly effective at withstanding extreme temperatures, offering excellent thermal insulation and preventing the fabric from igniting, even in direct contact with fire. This property is crucial for Air Force pilots, who may be exposed to the risk of aircraft fires, crashes, or sudden emergencies. Nomex is known for its ability to self-extinguish, meaning that it doesn't continue to burn once the flame source is removed. This feature significantly enhances pilot safety during fire-related incidents, offering them the critical time needed to escape or receive help. In contrast, Kevlar, while extremely strong and used primarily for ballistic protection, is not designed with heat resistance as its primary function. Kevlar's high tensile strength makes it suitable for protective gear like bulletproof vests, but it does not offer the same level of fire protection as Nomex. While Kevlar can withstand certain levels of heat, it is more prone to degradation when exposed to high temperatures or flames for extended periods. This makes it less suitable as a primary material for fire safety in aviation, where the threat of fire is a significant concern.

Moreover, Nomex is lighter and more flexible than Kevlar, allowing for greater comfort and mobility, which are essential for pilots during flight. The ability to remain agile and unencumbered while wearing protective clothing is crucial in the cockpit, as pilots need to perform complex tasks under stressful conditions. Nomex's lightweight nature ensures that it does not restrict a pilot's movement or cause fatigue, which is an important consideration during long flights or in emergency scenarios.In addition to its heat-resistant properties, Nomex also excels in its durability and ability to maintain its protective qualities over time. While Kevlar may lose its strength or effectiveness in extreme conditions, Nomex remains consistent in its performance even after prolonged exposure to heat, wear, and tear. This makes it a more reliable and long-lasting choice for pilots who require consistent protection.

Nomex is the superior fabric for Air Force pilot fire safety uniforms. Its exceptional flame resistance, flexibility, durability, and comfort make it the ideal material to ensure pilot safety in hazardous environments. The combination of these factors positions Nomex as the more suitable choice for the specialized demands of military aviation, providing pilots with the necessary protection and confidence to perform their duties in the most dangerous situations.

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