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Dinesh Bhatia, Priya Jaswal, S.K. Sinha

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# A Review of Emerging Technologies and Future Fabrics for Extreme Cold

Dinesh BHATIA<sup>1\*</sup>, Priya JASWAL<sup>1</sup>, S.K. SINHA<sup>2</sup>

<sup>1</sup>Department of Textile Engineering, Jawaharlal Nehru Govt. Engineering College, Sundernagar (Himachal Pradesh), India

<sup>2</sup>Department of Textile Technology, Dr B.R. Ambedkar National Institute of Technology, Jalandhar (Punjab), India

\*dineshbhatia55@rediffmail.com

## Review

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## ABSTRACT

*Human comfort, safety, and performance are severely hampered by extremely cold environments, necessitating the ongoing development of innovative fabric technologies. The ability of materials to keep people warm is crucial, but conventional fabrics frequently have drawbacks in terms of comfort, durability, and thermal performance. To trace the development of fabric technologies insights from historical perspectives are drawn to trace the evolution of fabric technologies and key challenges highlighting their crucial impact on fabric performance in extremely cold situations. Design considerations are explored to improve comfort, movement, and protection by emphasizing the importance of layering systems. Standardized testing methods for the evaluation of fabric performance in cold environments are delved into. These evaluation criteria will be reliable and effective for future fabric solutions in extremely cold environments. Finally, the actual case studies are presented to show how emerging technologies can be successfully used in extremely cold environments.*

## KEYWORDS

*extreme cold, thermal performance, fabrics, phase change materials, carbon nanotubes*

## INTRODUCTION

Extreme cold environments are recognized for their low temperatures, low humidity, and high winds. These conditions can lead to frostbite, hypothermia, and other cold-related injuries [1]. The creation of unique fabrics designed for extremely cold environments has attracted more attention in recent years, aiming to provide adequate protection and comfort for individuals facing these unique challenges [2-4]. This focus has led to the development of cutting-edge technologies and novel fabric designs to improve thermal insulation, moisture management, breathability, durability, and overall performance in frigid environments. In addition, these developments not only address the demands of people working in extremely cold environments, such as arctic explorers, military personnel, and cold-weather athletes, but they also have the potential to positively impact various industries, such as aerospace, energy, and transportation [5-6].

A variety of human organs and systems experience considerable alterations in activity when exposed to cold. The extent of these alterations depends on specific climatic variable values, the duration of time spent in low-temperature situations, and the design of the cold protection procedures used [7-8]. Considering the characteristics of the various clothing layers and how they combine to create a layered cold-protective clothing system is necessary for making an appropriate clothing selection. Cold-protective clothing creates a microclimate around the wearer and the wearer needs to maintain a thermal balance while ensuring that this microclimate prevents harmful cooling. It is crucial to recognise the adverse impacts of clothing on physical performance, energy consumption, manual dexterity, sensory function, and restrictions on movement, visual field, and comfort even though cold-protective clothing and equipment are necessary to prevent the effects of cold on the body [9-13]. Since ancient times, wool and woollen pile fabric have been the most common materials used to make insulation against the cold. Following the development of synthetic fibres, several kinds of acrylic and polyester fibres were used to create cold-protective apparel. Systematic and thorough research on polyester batting, wool, acrylic pile, and extreme cold temperatures revealed that polyester batting has a good insulation-to-weight ratio against the cold, making it an important component in protective clothing where the weight of the garment is a key consideration, particularly for protective clothing used in glacier and Siachin regions [14].

The transfer of heat and water vapour through fabrics is an important consideration when determining how well they are suitable for use in protective garments. The fabric's thermal resistance is the primary variable in determining body heat loss in a cold environment [15]. Multilayer fabrics are mostly used in cold weather conditions because they offer adequate thermal insulation. Generally, multilayer fabric ensembles are often preferable to single-layer clothing in that the insulation offered by multiple layers can be adjusted easily. A thermal protective garment usually consists of three layers: an inner layer, a middle layer, and an outer layer [16-17]. The inner layer aims to enhance comfort near the skin by wicking away sweat from the skin's surface for improved evaporative cooling and quicker drying. The middle layer's main function is to act as insulation. The outer layer's function is to shield humans from the elements (such as heat, flame, wind, and precipitation) and to allow water vapour to diffuse into the surrounding air.

Numerous significant challenges like insulation, moisture management, wind resistance, flexibility and ease of movement, durability, weight and bulkiness, and compatibility with layering must be overcome when designing winter clothing textiles for extremely cold temperatures [18]. Addressing such challenges requires a combination of cutting-edge materials, fabric structures, and design methodologies. These problems can be resolved for winter wear textiles that offer the best protection, comfort, and performance in extremely cold temperatures, created with the help of advancements in synthetic fibres, specialised finishes, and garment construction techniques. Several novel approaches

are being researched and developed to improve the performance of fabrics in extremely cold environments. These innovations are meant to increase insulation, moisture management, durability, and overall comfort.

The aerogel materials have a very porous structure, low density, a large specific surface area, and excellent thermal insulation properties [19-20]. Aerogel-based materials, when compared to other insulation materials, have significantly lower thermal conductivity and higher thermal resistance, even at extremely high temperatures. The aerogel component in aerogel blankets significantly affects the blanket's thermal properties [21]. These products are starting to become more prevalent and open the way to the development of fabrics with improved thermal insulation performance levels.

PCMs are outstanding materials for thermal management solutions since they store and release thermal energy throughout the process of melting and freezing (changing from one phase to another). To increase thermal resistance or store excess heat from sporadic renewable sources during the day for use at night, lightweight prefabricated PUF-insulated shelters used by security forces can make use of the special feature of PCM-based latent heat storage systems. This will help to maintain a comfortable temperature inside the shelters. These PCM characteristics can be effectively used in several other applications where thermal management or temperature control is crucial.

In the early 1980s, [22] researchers investigated the use of phase change material (PCM) microcapsules to enhance the thermal performance of textile structures. William Tong and Alan Tong [23] invented a novel design of thermo-regulating smart textiles merged with solar-absorbing metamaterial microcapsules of phase change materials (PCMs) intended for coats or clothing, especially for use in space or cold climates on Earth. These metamaterial microcapsules could provide new ways to improve thermoregulating fabrics by giving them unique qualities and value.

The creation of a wearable heating system with a controlled e-textile-based thermal panel is explained by Senem Kurşun Bahadır and Umut Kivanc Sahin [24]. The system consists of a wearable heating vest, an electronic control module, and an e-textile-based thermal panel. The e-textile-based thermal panel is stitched into the fabric of the wearable heating vest. The system was put through several power levels of testing, and the outcomes demonstrated that it could offer a consistent and comfortable heating experience. The paper concludes the potential uses of the system, including the provision of warmth for people working in extreme cold conditions or for those who have medical issues and have to remain warm.

Shape memory alloys (SMA) are capable of spontaneous and reversible shape changes when exposed to temperature stimuli. This thermoelastic martensitic transformation is what causes the shape-memory effect, which is accompanied by heat exchange. The two-way shape memory effect, which occurs from properly carried out thermomechanical treatment, is a significant characteristic of shape memory alloys that can be employed in smart protective equipment [25-27]. Several researchers have

studied the creation of active textile systems incorporating SMA components for protection against the cold [25,28-29]. Yoo et al. incorporated SMA components into clothes in between the lining and the exterior laminated fabric [25]. They demonstrated that it is feasible to produce an air layer that acts as a heat insulator in clothes using SMAs.

The review paper delves into the historical development of fabrics for cold environments, which also offers insights into the evolution of the materials and design ideas used to address the challenges faced in extreme cold conditions. The next generation of cold-weather fabrics is also discussed in this review article, along with upcoming trends and predictions. This paper also explores the possibilities of new materials, such as phase-change materials and nanofibers, as well as the incorporation of advanced features like adaptive thermal regulation and self-healing capabilities. Various performance testing and evaluation methods are also explained for the evaluation of fabric performance in extreme conditions. The paper also includes pertinent case studies highlighting successful applications in real-world scenarios.

## **HISTORICAL PERSPECTIVE**

The traditional method of protecting individuals from the extreme cold has a long history. In the past, humans protected themselves from the cold by using natural materials. Animal skins and furs [30-31] were frequently used because of their natural insulating qualities. Animals with thick fur, such as bears, seals, and beavers, were exceptionally warm and wind-resistant.

These furs were used to create accessories, including mittens, caps, and coats. To offer insulation and retain body heat, inner layers were made of plant fibres like cotton and wool. The use of synthetic fibre and textile solutions, or mixtures of both, has replaced natural material solutions (fur, down), owing to advancements in textile technology [32]. Throughout history, wool has been a popular cold-weather fabric [33]. It is made from sheep's fleece and is appreciated for its superior insulating properties. Wool fibres naturally have crimps and scales that form air pockets and keep warm air near the body [34-35]. When wet, this aids in maintaining heat. In colder climates, woollen clothing such as sweaters, coats, and socks has been consistently popular.

People used animal furs and down feathers as insulation in regions with extreme cold. To create warm outer layers, fur from animals such as foxes, wolves, and seals was used. Fur-lined parkas and coats provide excellent defence against arctic conditions and brisk winds [31,36]. Due to their lightweight and high warmth-to-weight ratio, down feathers, obtained from ducks and geese, have become popular for filling quilted jackets, sleeping bags, and insulated clothing [37-38].

In the middle of the 20th century, synthetic fibre development led to substantial improvements in cold-weather garments [39]. Among the first synthetic fibres to be introduced were nylon and

polyester. Compared to natural fibres, they provided better insulation, the capacity to wick away moisture, durability, and quicker drying times. These synthetic materials quickly gained popularity for outerwear, mid-layers, and base layers [40-41].

Advancements in insulation technologies led to the development of high-performance fabrics for extremely cold conditions. Thinsulate, PrimaLoft, and Polartec are a few examples of synthetic insulations that were created to give warmth without significantly increasing weight or bulk [42-43]. These materials effectively trap heat using thin fibres or small air pockets. They are lightweight, and breathable, and still maintain their insulating properties in a compressed state.

In the context of smart adaptive systems for cold weather apparel, nowadays use of both shape-memory polymers, with their thermally sensitive response qualities, and phase-change materials, with their rapid phase-change responses to environmental changes for extremely cold weather is growing. The use of bionic climate membranes, adjustable insulation systems, and silver-based fabrics in cold-weather apparel is growing in popularity. However, more research is required to enhance the wearability, cost, and behaviour of these garments in terms of temperature control.

These developments have made it easier for people to survive in extremely cold situations by significantly enhancing the comfort, safety, and functionality of cold-weather clothing and are still in progress. A timeline diagram illustrating the evolutionary process of extreme cold weather fabric is depicted in Figure 1.

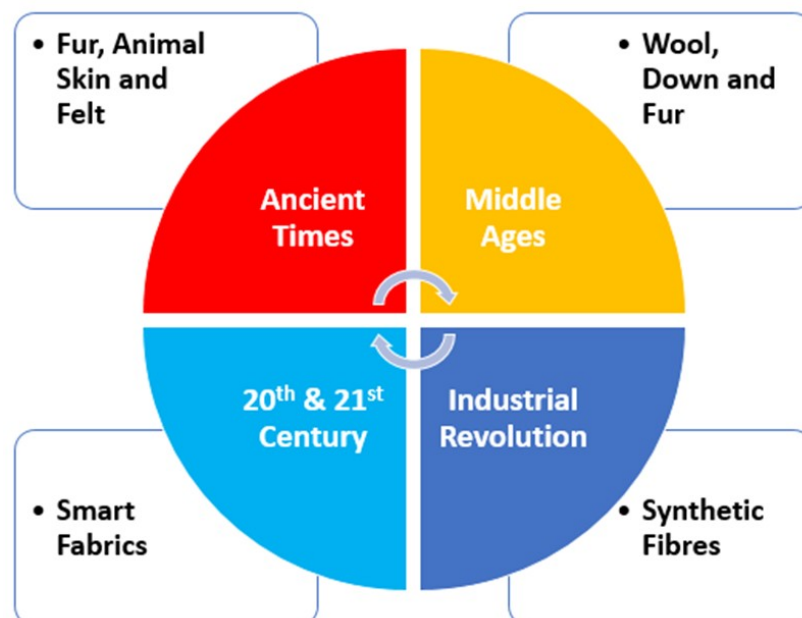


Figure 1. Timeline diagram for the evolutionary process of extreme cold weather fabric

## KEY CHALLENGES FOR FABRICS IN EXTREME COLD CONDITIONS

Fabrics used in extremely cold environments confront several significant obstacles due to the severe climate and specific requirements. Some of the main challenges include:

- ❖ *Insulation*: Under extremely cold conditions, maintaining adequate insulation is crucial. Body heat must be efficiently trapped by fabrics to keep it from escaping into the outside environment [44]. Rapid heat loss from inadequate insulation can raise the chance of hypothermia [45].
- ❖ *Moisture management*: Sweating is still possible, even in cold conditions, especially when engaging in vigorous activity. To keep the body dry, fabrics must wick away moisture from the skin because damp clothing has significantly reduced insulating capabilities and makes the wearer feel colder.
- ❖ *Breathability*: The fabric being worn needs to allow the skin to breathe while preventing the accumulation of moisture. An illness called frostbite can result from excessive sweat and moisture that is trapped adjacent to the skin.
- ❖ *Wind resistance*: Wind in cold conditions can significantly increase the chilling effect by removing the insulating layer of warm air around the body. To avoid this, fabrics must have strong wind resistance.
- ❖ *Durability*: Fabrics can be harshly affected by extremely cold conditions, becoming fragile and vulnerable to tearing or damage. Fabrics must be sufficiently durable to resist abrasion from cold or rough surfaces.
- ❖ *Weight and bulk*: Individuals need a dress with multiple layers in cold weather for improved insulation. To keep the clothes comfortable and not too restricting, high warmth-to-weight and warmth-to-bulk ratio fabrics are desired.
- ❖ *Flexibility and comfort*: To maintain safety and productivity in cold conditions, mobility is crucial. Fabrics should be comfortable, and flexible enough to allow easy movement.
- ❖ *UV protection*: Harmful UV ray exposure is more prevalent in high-altitude, cold environments. UV-protective fabrics can aid in preventing skin problems such as sunburn [46].
- ❖ *Freeze resistance*: In extremely cold conditions, fabrics must resist freezing and become stiff or brittle. To avoid discomfort and potential injury, flexibility and softness are crucial [31].
- ❖ *Thermoregulation*: There could be a difference in temperature between day and night in some extremely cold conditions. The wearer can be comfortable in a variety of environments with the aid of fabrics that have thermoregulating properties.

## DESIGNS FOR EXTREME COLD FABRICS

Cold weather products include several occupational and recreational activities, but we first examine some general design factors for cold weather protective equipment. Putting on and taking off layers of clothes, altering posture, moving, or taking shelter are some examples of thermoregulation behaviour [47]. Outer shell; liner (insert with watertight property); thermal liner (a layer with a watertight property providing additional thermal insulation); thermal lining (nonwatertight layer providing thermal insulation); and lining (innermost material without watertight properties) are the component layers for cold weather ensembles listed in BS EN342 (2004) [48]. To suit occupational and recreational needs, these components may be combined in many ways (BS EN343, 2003) [49]. The selection of materials for each of the system's layers is crucial to the design and development of these garments, which are intended to protect the body's extremities and the core. Shaw [50] outlines a practical approach. However, the approach includes no reference to the requirement to reduce environmental effects as stated in the standard BS EN340 (2004). A three-layer system consists of a base layer that is worn next to the skin for moisture management, a mid-layer that provides thermal insulation, and an outer layer, or shell, that protects the system's microclimate [18]. A common clothing method for cold weather is a three-layer system that offers the best insulation, moisture management, and weatherproofing. The three-layer method is further developed in a four-layer system for extremely cold weather conditions adding layers for improved insulation and protection. The foundation layer, middle layer, insulating layer, and outer layer (shell) are the four layers as shown in Figure 2.



Figure 2. A four-layer system with a thick belay jacket layer preferably for an expedition [51]

*Base Layer:* The base layer, which is worn near the skin, is the same as in the three-layer system. Its main purpose is moisture management, wicking sweat from the body and keeping the skin dry. Base layers are often constructed of synthetic textiles such as polyester or polypropylene or moisture-wicking and quick-drying materials such as merino wool.

*Mid-Layer:* The mid-layer also remains unchanged as in the three-layer system and continues to offer additional insulation. Its function is to retain body heat and create warm air pockets near the skin. Fleece, down, or synthetic insulating materials such as Thinsulate™ or PrimaLoft® are frequently used for mid-layers.

*Insulation Layer:* Another insulation layer is designed to enhance warmth in extremely cold environments. To provide additional loft and warmth, this layer might be made from heavier, thicker insulating materials. High-quality down or cutting-edge synthetic insulating technologies are frequently used in insulation layers.

*Outer Layer (Shell):* The final barrier against wind, water, and snow is the outer layer, or shell, which is the same as in the three-layer system. To prevent moisture from entering and allowing extra heat and sweat to escape, it needs to be windproof, waterproof, and breathable. Typically, Gore-Tex®, nylon, or other technical textiles with water-resistant coatings are used to create the outer layer.

## **EMERGING TECHNOLOGIES FOR EXTREME COLD FABRICS**

Innovations in textile technology have played a pivotal role in the relentless pursuit of comfort and safety in extremely cold situations. The need for effective solutions to protect people from extreme cold is growing as our planet experiences more severe weather conditions. This has inspired scientists, engineers, and textile designers to explore new emerging technologies and develop innovative materials with unmatched insulation and temperature regulation properties.

Traditional cold-weather clothing is somewhat effective but often falls short of providing the requisite warmth and protection in the worst environments. To develop a new generation of extremely cold materials, the emphasis has now shifted towards cutting-edge technologies in fabric design. Currently, emerging fields of science and engineering are all involved in the development of fabrics that can withstand extremely low temperatures. Among the most encouraging developments are:

### **Phase Change Materials (PCMs)**

During temperature changes, these materials can store and release thermal energy. They can assist in controlling body temperature when included in fabrics, ensuring that the wearer is comfortable in both extremely cold and relatively warm conditions. Instead of choosing a material for clothing based on the weather, the textile industry, by changing the garment, can boost responsiveness, where comfort

is of primary importance so that it would change unavoidably in response to an environmental stimulus [52-54], as shown in Figure 3.

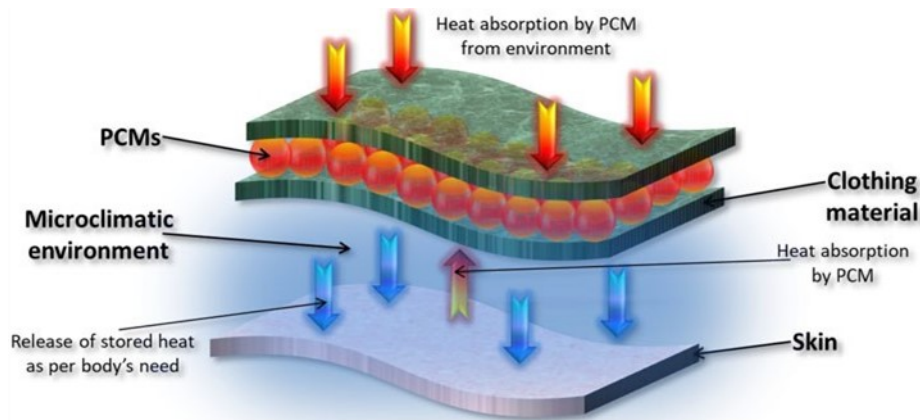


Figure 3. PCMs were integrated into textiles for thermoregulating properties [52]

The encapsulated PCM can be used directly to make various textile items such as gloves, socks, jeans, shirts, jackets, and earmuffs from fabrics (cotton or polyester) [55], foams (polyurethane foams) [56], and fibres (polyacrylonitrile, polyamide, etc.) [57].

### Aerogels

Fabrics made of aerogels have become a ground-breaking solution for extremely cold weather since they provide unmatched insulation and thermal regulation qualities [58-59]. One of the best insulators known to science is the family of materials known as aerogels because of their open-pored structure and very lightweight [21]. They produce a revolutionary insulating layer when incorporated into fabrics, making them resistant to the coldest conditions.

A prototype of aerogel clothing is compared with commercial clothing for thermal performance with thermal images captured using infrared (IR) photography [60]. IR comparisons at various suit orientations are displayed in Figures 4-7. A human test subject who was wearing clothing stood in a dry test chamber with the ambient temperature conditioned to 10 °C for 30 minutes before taking these IR pictures. Comparing the garment made from microfibrinous polypropylene batts that are readily accessible commercially to the aerogel-infiltrated materials, it has been observed that the aerogel-infiltrated materials offer higher thermal protection.

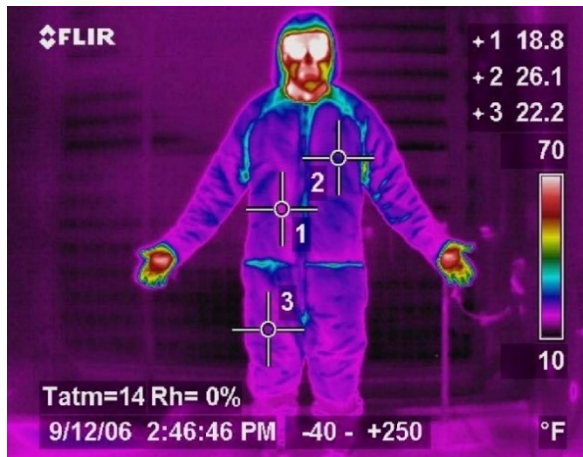


Figure 4. Frontal view of prototype aerogel garment.

Typical surface temperatures are 18-26°F [60]

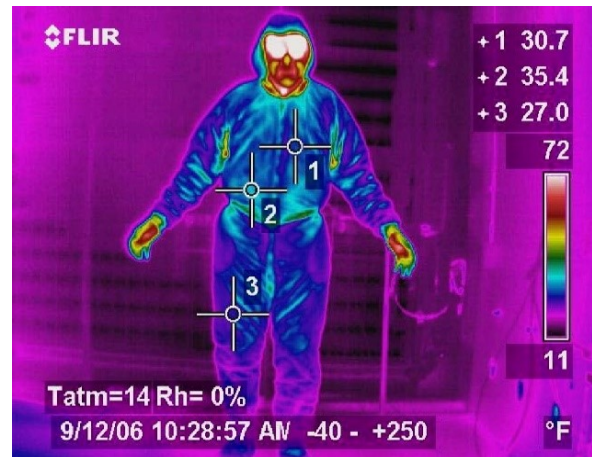


Figure 5. Frontal view of 400-weight Thinsulate garment.

Typical surface temperatures are 27-35°F [60]

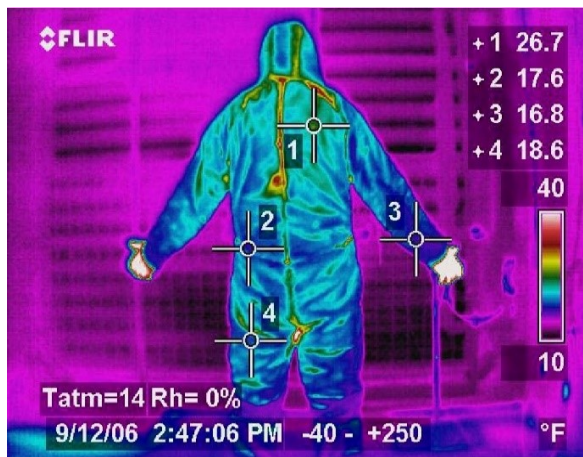


Figure 6. Back view of aerogel garment. Typical surface temperatures 17-27°F [60]

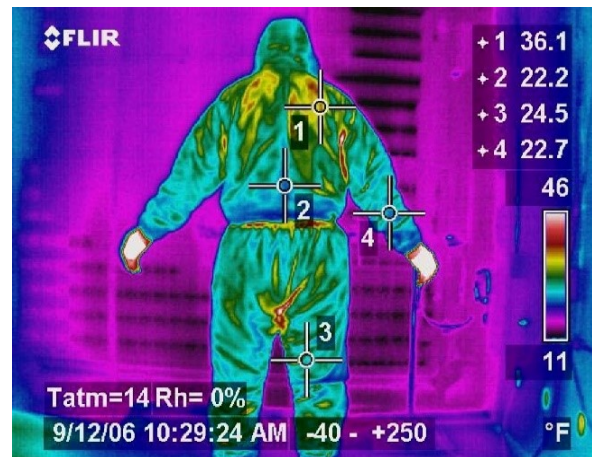


Figure 7. Back view of 400-weight Thinsulate garment (surface temperature range 22-36°F) [60]

### Shape memory materials

Shape memory materials have shown potential for designing fabrics for extremely cold weather conditions. When exposed to specific stimuli, such as temperature fluctuations, these materials have the extraordinary capacity to "remember" their previous shape and return to it [61].

There are few studies on how shape memory alloys (SMAs) can boost the effectiveness of cold-protective apparel. For intelligent insulation that responds to the environment, cold weather jacket systems were built with Ni-Ti SMA helical coils with two different deformation heights, 10 mm and 15 mm [25].

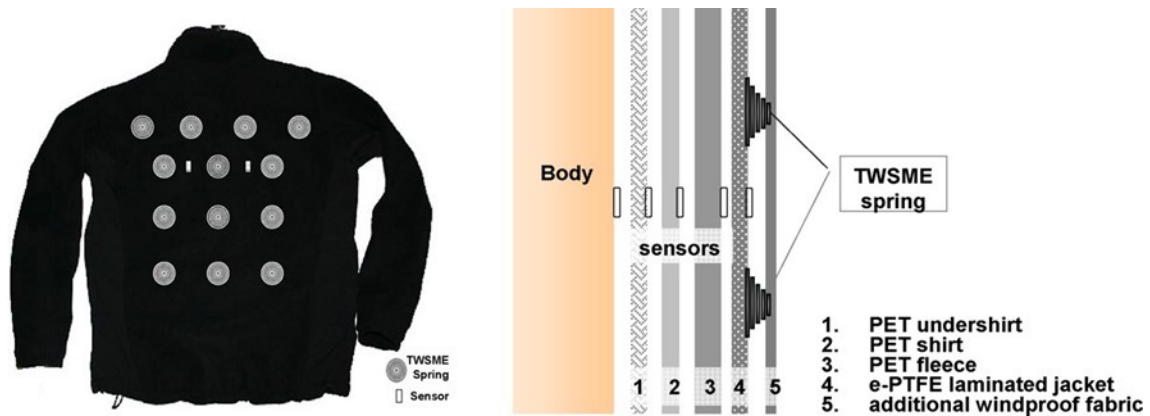


Figure 8. TWSME coils/sensors on the jacket and a cross-section of the jacket [25]

It was discovered that SMA helical coils increased the air space between layers of clothing as a result of SMA self-activation in cold environments, which improved thermal insulation and buffering capabilities for people under temperature fluctuations. As spring height increased, this buffering effect also increased. The wearer felt warmer with jackets having SMA coils, as shown in Figure 8; however, other than at the transition point, subjective thermal sensation ratings did not change significantly.

### Graphene-Coated Textiles

Graphene consists of a single layer of carbon atoms arranged in a two-dimensional lattice. Enhancing the thermal conductivity of fabrics with graphene coatings may enhance their efficiency in maintaining heat. The thermal insulation properties of multilayer fabric heating elements based on graphene were studied by Kim et al. [62]. Figure 9 shows the surface temperature of multilayer fabric heating elements based on graphene with different fabric types and layers. Figure 9a shows the cotton fabric with graphene/polymer coating (below GR) and the double layer for each fabric used to measure surface temperature. According to Joule's rule, Figure 9b demonstrates that the surface temperatures of each sample increased as the applied voltage increased from 5 to 30 V. According to the IR image (Figure 9c), the surface temperature of the Lining/GR was approximately 85.2 °C when 30 V was applied, and the surface temperature after layering the brushed waterproof polyester fabric (below WPF\_B) under GR by lining tended to be approximately (4.0-5.0) °C higher than when GR was used as a single layer after 25 V.

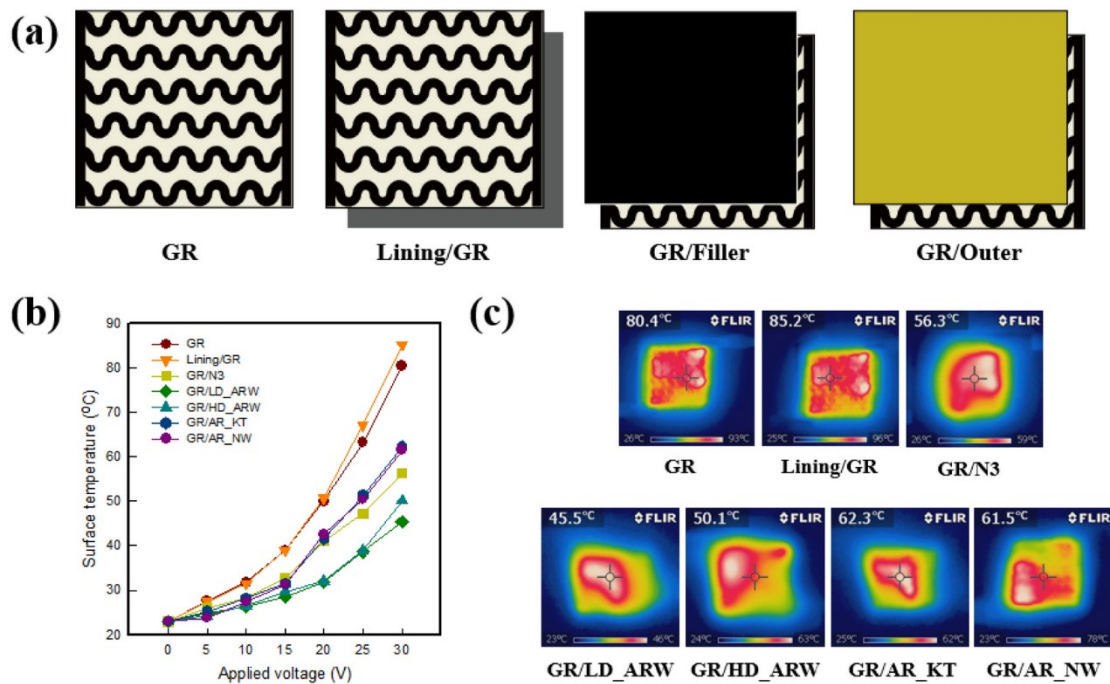


Figure 9. (a) Measuring layer, (b) surface temperature of single layer and double layer of graphene-coated fabric-based heating element with various applied voltages, and (c) IR images at 30 V [62]

The paper concludes that multilayer fabric heating elements based on graphene have the potential to be employed in a variety of environments where thermal insulation is crucial, including materials for insulation and protective equipment.

### Carbon Nanotubes (CNTs)

Carbon nanotubes (CNTs) are examples of carbon-based materials that have been developed into many forms and exhibit features such as flexibility, high mechanical strength, high electrical conductivity, and good thermal stability [63-64]. CNTs are currently a research topic as additions to improve the insulation of cold-weather fabrics because of their outstanding thermal properties. They could assist in more efficient body heat retention.

Researchers investigated the electrothermal behaviour of the developed CNT fibre fabrics (CNTFFs) in an open-air environment for wearable heaters by considering the exceptional joule heating characteristics of CNT fibres and yarns [65-66]. The temperature versus time curves for CNTFF-6-5/2000Y are shown in Figure 10a. CNTFFs produced heat immediately and reached saturation temperature in less than 10 seconds after receiving a voltage.

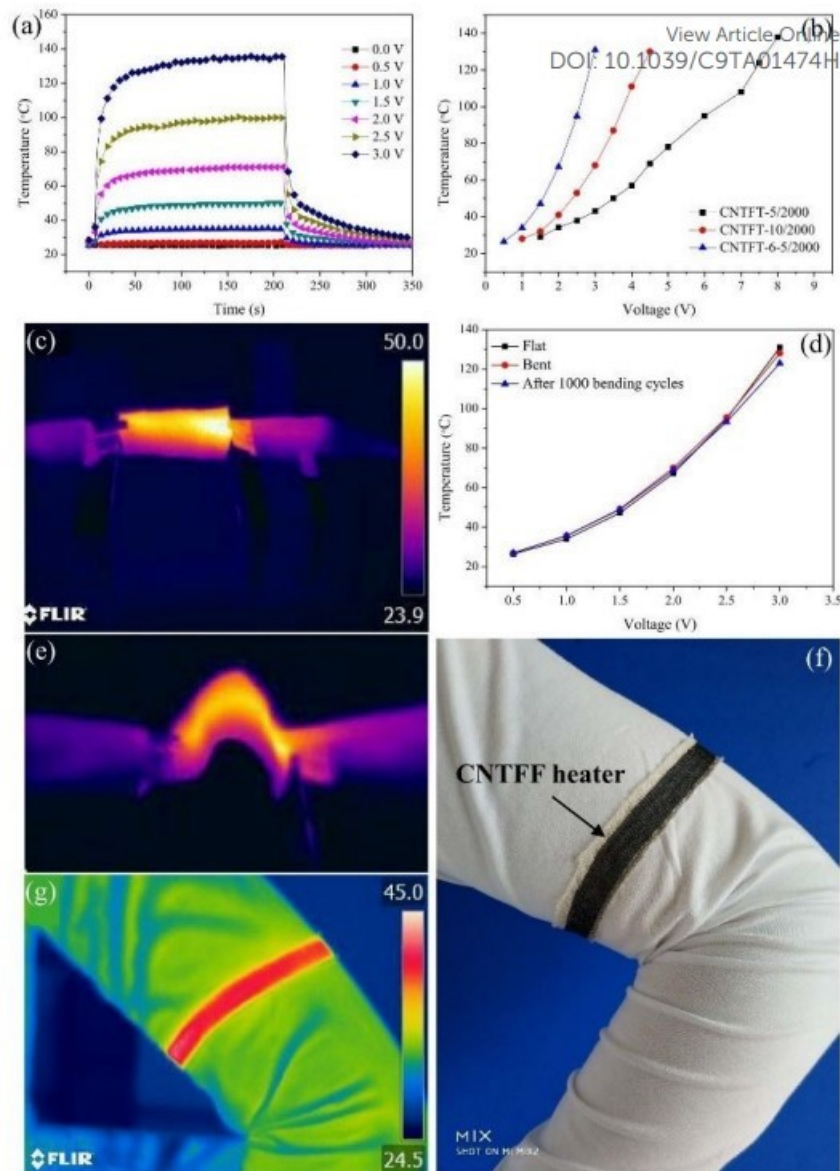


Figure 10. Electrothermal performance of CNTFFs. (a) Temperature versus time curves, (b) saturated temperature versus input voltage, (c) infrared image at 1.5 V, (d) saturated temperature at a different voltage, (e) infrared image in bending state, (f) optical image showing a CNTFF heater sewn on the sleeve of a T-shirt and (g) corresponding infrared image at 9 V [68]

The diameter, number of CNT yarns, and input voltage (Figure 10b) increased saturation temperature. The voltage needed to obtain CNTFF-6-5/2000Y at a suitable body temperature (core 37 °C and skin 33 °C) was 1.5 V (47 °C, Figure 10c) [68]. The saturation temperature remained almost the same in both the flat condition and the bending state, as illustrated in Figure 10d. The difference in saturation temperature remained minimal even after 1000 cycles of bending. Figure 10e demonstrates through infrared images that the temperature distribution on the CNTFFs was uniform and free of blind spots in both the flat and bent states. In addition, the current free-standing, flexible CNTFF heaters are easily incorporated into clothing by straightforward sewing. A sizable CNTFF with an area of 280 x 15 mm<sup>2</sup>

was sewn onto a T-shirt's sleeve as a proof of concept (Figure 10f). The temperature climbed quickly from the ambient temperature to 42 °C in 10 s when it was exposed to a voltage of 9 V (Figure 10g) [68].

### Bio-Inspired Insulation

Researchers are investigating the natural insulating properties of animals that live in extremely cold climates. Innovative fabric designs can result from mimicking the design and structure of fur and feathers on Arctic animals.

A polar bear, which has an excellent ability to survive in severe Arctic conditions, is depicted in the photograph shown in Figure 11a. The scanning electron microscopy (SEM) images in Figure 11b and c (axial and radial cross-sections of a single hair, respectively) demonstrate the unusual microstructure of the hollow core and aligned shell that gives polar bear hairs their high reputation as thermally insulating materials. Figure 10 d illustrates an example of a "freeze-spinning" procedure that combines directional freezing and solution spinning [69-71]. Figure 11(e) illustrates a fibre roll obtained by the above-mentioned method. The optical and SEM images in Figures 11(f) and 11(g), respectively, show how the biomimetic fibres can be further weaved into a textile.

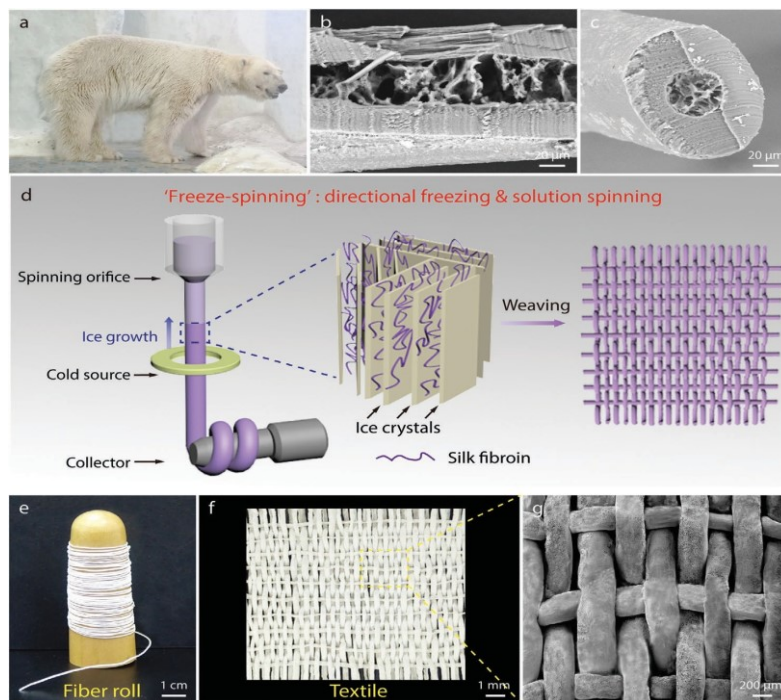


Figure 11. Fabrication of biomimetic porous fabric. a) Picture of a polar bear. b,c) SEM images of a polar bear's hair, respectively. d) Illustration of the "freeze-spinning" technique, e) Optical image of fibre roll. f,g) Optical image and SEM of biomimetic woven textile respectively [69]

Such biomimetic fibres produce a textile with great thermal insulation, high breathability, and wearability. When a textile is doped with electro-heating components, such as carbon nanotubes, it can act as a wearable heater in addition to passively insulating heat loss. This allows the textile to produce a quick thermal response and uniform electroheating while retaining its soft and porous properties for pleasant wear.

## **PERFORMANCE TESTING AND EVALUATION: ASSESSING FABRIC PERFORMANCE IN COLD ENVIRONMENTS**

Fabrics intended for extremely cold weather are designed to be used at temperatures below 5-10 °C, potentially even well below 0 °C. As a result, the primary characteristic of these fabrics is to offer protection against cold, specifically preventing heat loss. Protection against water becomes more relevant when temperatures are expected to be above zero or when working in environments where liquids are present. Even a slight deviation in core body temperature, even just a degree, can lead to significant problems for the human body. The term 'hypothermia' refers to a condition where the body's temperature drops below the level required for normal metabolism and bodily functions to occur. Humans typically maintain their core body temperature at or near a constant level through biological homeostasis. However, when exposed to cold, the body's internal mechanisms may struggle to replenish the heat lost to the surroundings. This goes beyond simply feeling cold; even a slight drop in temperature can severely impact brain function and impair judgment.

Therefore, the vapour permeability of the fabrics used is crucial, as well as considering the layering of clothing, allowing for ventilation, and ensuring ease of donning and doffing to adapt to changing conditions. Additionally, excessive moisture accumulation within the clothing system can affect cold protection, especially when activity levels are reduced. This can lead to the phenomenon known as 'after chill', where accumulated moisture evaporates and significantly cools the person when they are less active. Such cooling increases the risk of hypothermia and is a significant risk factor to consider. To address these concerns effectively, the following measures are recommended: thermal insulation, vapour resistance, water tightness, air permeability, wind resistance, and wicking [72].

### **Thermal insulation**

The purpose of cold-weather clothing is to regulate the user's body temperature by effectively managing heat exchange amidst changing environmental conditions and metabolic changes. The thermal insulation of a material is influenced by various physical factors, including (i) the material's thermal conductivity, (ii) its thickness, (iii) the density of the fibres, (iv) the temperature of the surrounding environment, (v) the heat transfer coefficient of the external air, and (vi) the air space between the material and the skin. [14]. To assess the thermal insulation of fabric, the guarded hot

plate method is employed and tested in accordance with ASTM-F1291-05. This method is often referred to as a "skin model" as it replicates the heat and moisture transfer from the body surface through the layers of clothing to the surrounding environment. Figure 12 provides a visual representation of the setup and the thermal resistances involved. The thermal resistance is calculated using the following equation:

$$R = \frac{A \times t_p - t_a}{Q} \quad (1)$$

where R is the total thermal resistance in  $\text{m}^2\text{°C/W}$ .

A is the area of the tested sample, in  $\text{m}^2$

$t_p$  is the temperature of the heating plate, in  $^{\circ}\text{C}$

$t_a$  is the temperature of the air in the test chamber, in  $^{\circ}\text{C}$

Q is the heating power supplied to the measuring unit, in W.

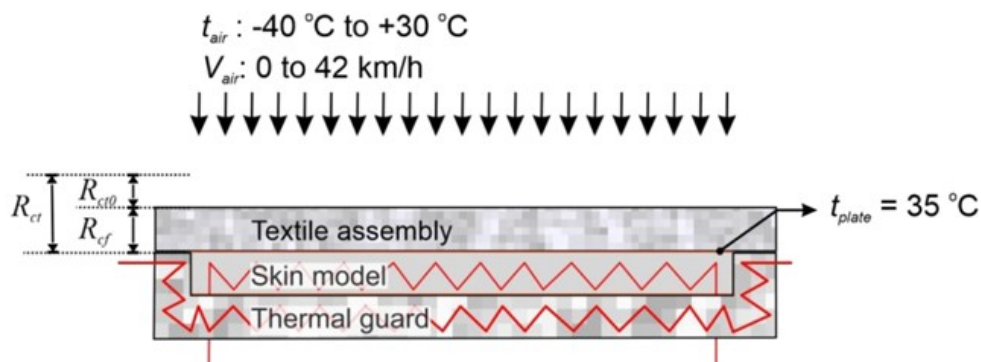


Figure 12. Schematic view of the apparatus and the thermal resistances [73]

In research conducted by [14], the Thermolabo-II thermal tester, designed by Prof. Kawabata from Japan, was employed to measure the thermal insulation value (TIV). This instrument compares the electricity consumed in maintaining a specific temperature on the hot plate with the fabric sample to the electricity consumed in maintaining the same temperature on the hot plate without the sample. The resulting ratio is then expressed as a percentage to determine the thermal insulation value. In a research study aimed at developing a testing procedure for measuring thermal insulation in extremely cold environments [73], the researchers investigated the influence of temperature, humidity ratio, and wind speed on thermal insulation. The findings revealed that vertical wind orientation had a notable impact on thermal insulation. Irrespective of the type of insulation and assembly, the thermal resistance (R) of the textiles decreased to below 15% of its initial value with an average wind speed of 16 km/h. The study also determined that the effect of wind remained consistent regardless of changes in ambient temperature or humidity. Additionally, slightly higher humidity ratios in the environment

resulted in minor increases in thermal resistance. Interestingly, the range of temperatures tested (from 40 °C to -30 °C) did not significantly affect the thermal insulation performance of the examined assemblies.

Thermal Insulation of Clothing Using a Heated Manikin was carried out by Oliveira et al. [74]. The manikin was divided into 16 parts, and for each body section, temperature and heat flux were measured. The measurements were carried out in a climate chamber with four autonomous air-handling units and several capabilities to control air temperature, humidity, and air velocity. Three thermal insulation calculation methods - serial, global, and parallel - were examined, and the results were compared for total, basic, and effective clothing insulation. Different clothing ensembles, including a summer ensemble, a business suit, and a cold-protective ensemble, were studied. The serial method consistently yields the highest results, regardless of the manikin regulation mode. The thermal comfort regulation mode generally provides higher values, while the constant heat flux regulation mode yields lower values. The relative differences between the serial and global methods range from 7.0% to 23.1% for the various ensembles. The global and parallel methods show smaller differences, mostly negative [74].

### **Vapor resistance**

Evaporative resistance (or vapour resistance) can be determined by using a thermal manikin since they are usually fast, cost-effective, and repeatable. Engineers have created numerous types of manikins since the first thermal manikin was created in 1941, including male and female manikins as well as baby, child, adult, and segmental body manikins. Modern thermal manikins can simulate human walking and perspiration in addition to being used to forecast how humans will react physiologically under various thermal circumstances [75]. The study carried out by Wang focuses on the thermal insulation measurement of clothing using sweating thermal manikins [76]. Various factors, such as fabric 'skin', sweating rate, fabric thickness, and body segments, were studied. It was observed that the fabric 'skin', which simulates human sweating, significantly impacts the measured clothing evaporative resistance. The choice of fabric material, thickness, and moisture content affects the apparent 'wet' thermal resistance of the fabric 'skin'. Current sweating thermal manikins do not control the fabric 'skin' surface temperature, leading to discrepancies between the manikin surface temperature and the fabric 'skin' surface temperature. To improve test accuracy, the fabric 'skin' temperature should be considered for calculating total evaporative resistance. The fabric 'skin' should fit tightly to the manikin body without air gaps, possess good moisture management properties, and maintain a fully saturated surface. A recommended fabric 'skin' consists of a blend of hygroscopic or hydrophilic fibres (e.g., cotton) and spandex with a medium thickness (e.g., 0.50 mm) [77].

In another study, the moisture vapour resistance of different fabric specimens was compared using the ISO 11092 method, which utilizes a sweating-guarded hot plate apparatus. The results showed distinctive trends among fabric groups, with fabrics having larger pore sizes exhibiting lower moisture vapour resistance and superior breathability. Fabrics composed of spun yarns in the weft direction generally had higher moisture vapour resistance than those with sheath/core and hi-multi-PET filaments, attributed to smaller pore diameters and higher hygroscopicity of the bamboo fibres. The study also highlighted the difference between the sweating-guarded hot plate method and the upright cup method in measuring moisture vapour transmission, with the former being more suitable for coated/laminated fabrics and the latter for non-coated ordinary fabrics [77-78]. ASTM F1868-02 and ASTM F2370-05 standard test methods can be used for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate and Sweating Manikin respectively.

### **Wicking**

Wicking is the ability of the fabric to draw moisture (such as sweat) away from the skin and transport it to the outer surface of the clothing, where it can evaporate. This is a crucial feature for cold weather clothing because when humans engage in physical activities, their bodies generate heat and sweat, which can make them feel wet and uncomfortable. If the moisture stays close to your skin, it can lead to a drop in body temperature and increase the risk of hypothermia. In a study conducted by Fangueiro et al. [79], the wicking behaviour and drying capability of different plated knitted functional fabrics were analysed, which were produced using functional fibres and either polypropylene (PP) or polyester (PES). The wicking behaviour of the fabrics was mainly influenced by the effective capillary pore distribution, pathways, and surface tension. The drying capability was found to be related to the macromolecular structure of the fibre. Furthermore, when comparing fabrics made with PP face yarn and those made with face PES yarn combined with other functional fibres, it was found that the functional knitted fabrics with PP face yarn had worse wicking ability but better drying capability compared to those using face PES yarn.

The innermost layer, i.e., the base layer, takes on the role of wicking moisture away from the skin. With its high permeability, it effectively draws moisture away from the body and transfers it to the layer above. Base layer materials, such as polypropylene, Polartec®, and polyester microfiber, are commonly chosen for their quick-drying properties. This quick drying helps enhance the wearer's comfort by keeping the skin dry. The wicking buffer effect can be evaluated using different methods. One such method involves using a sweating-guarded hot plate to measure moisture loss when liquid water comes into contact with the fabric. Another approach is to measure the microclimate response during a short sweating burst in a laboratory setting and examine the wicking of liquid into vertically hanging fabric strips over fixed periods or observe the dispersion of a liquid drop on fabric through a

visual test [73]. A study carried out by Kicklighter et al. investigated the peak evaporative heat flux of 1 mL of isothermal water that was correlated with direct assessments of fabric wickability and water vapour permeability [80]. Six wicking fabric samples were tested using a Sweating Guarded Hot Plate (SGHP) to measure their thermal properties and heat flux responses to water application. Wickability was assessed using a longitudinal strip wicking test. The study found that *im/clo* (clothing insulation) showed the strongest correlation with peak evaporative heat flux, except for one outlier, suggesting that *im/clo* alone may not fully indicate a fabric's evaporative cooling capacity.

### **Air permeability**

Consideration of air permeability in cold-weather apparel is crucial for comfort and effective thermoregulation. Air permeability, which allows for the passage of air between the inside and outside of garments in cold situations, aids in controlling body temperature and moisture management. The test method employed for measuring air permeability is EN ISO 9237.

The body produces heat during exercise to keep itself at a comfortable temperature when it's cold outside. Air that is unable to escape between layers of clothes might cause excessive sweating and moisture to build up. The wearer may feel cold and uneasy as a result of this retained moisture, especially when at rest or during periods of low activity when heat generation is reduced. By allowing heat and moisture from the clothes to escape, air permeability keeps the wearer dry and lowers their chance of being uncomfortable. Additionally, it inhibits the accumulation of moisture that would cause condensation, which would reduce insulation, possibly make the clothes feel damp, and less effectively trap heat.

However, while thinking about air permeability in cold-weather apparel, it is crucial to establish a balance. A fabric's air pockets can affect a variety of things, such as warmth, and protection against wind, and rain. The wearer experiences decreased comfort when wearing garments made of high-permeability fabric [81]. Too much air permeability may lead to excessive heat loss, making the clothing insufficient to protect against cold temperatures. As a result, cold-weather clothing is frequently made of permeable materials or features strategic ventilation to allow moisture to evaporate while still offering enough insulation to retain body heat.

European standard EN 342 is employed for ensembles and garments for protection against cold. A cold environment is defined in this standard as less than -5 °C. Details of requirements for cold weather fabrics are shown in Table 1.

Table 1. Details of requirements for cold weather fabrics

S.No	Type of Requirement	Property
1.	Ergonomics (Size and Dimensional Change)	
2.	Comfort and Efficiency	Water Vapour Resistance < 55 m <sup>2</sup> PA/W
3.	Design Strength	Tear Resistance > 25 N
4.	Complete PPE	Thermal Insulation I <sub>cle</sub> and I <sub>cler</sub> > 0.310 m <sup>2</sup> (= 2 clo) K/W
5.	Air Permeability	3 Classes
6.	Resistance to Water Penetration	2 Classes

## CONCLUSION

Extreme cold environments present unique challenges, necessitating continuous innovation and progress in fabric technologies. This study's article elucidates critical issues and promising avenues for addressing these challenges through a comprehensive review of future textiles designed for extreme cold and emerging technologies. The historical perspective showcased the continuous evolution of fabric engineering, progressing from fundamental materials to intricate multi-layered systems. This journey provided a foundation for the current situation of fabric development today and encouraged the search for ever more efficient alternatives. The importance of focused research and development is highlighted by numerous challenges, including thermal insulation, moisture management, durability, and flexibility. Designing materials that give the best protection and comfort in extremely cold conditions requires a thorough understanding of these challenges. The future of fabric engineering is illuminated by emerging technologies such as phase-change materials, aerogels, shape-memory materials, graphene-coated textiles, carbon nanotubes, and bioinspired insulation. These innovations provide fabric designers with exciting opportunities to craft inventive solutions for extremely cold conditions. A thorough foundation for completely evaluating fabric characteristics is provided by performance testing and evaluation procedures. Standardized tests ensure accuracy and consistency in measuring fabric performance, enabling designers to improve their approaches and tailor them to specific requirements. Moving forward, interdisciplinary collaboration, sustained research efforts, and continuous innovation will be pivotal in overcoming challenges and pushing the boundaries of fabric design for extreme cold environments. The development of fabrics that provide superior protection, comfort, and performance in extremely cold temperatures will undoubtedly contribute to the well-being and safety of individuals working and living in such challenging conditions.

### *Author Contributions*

Conceptualization – Bhatia D, Jaswal P, Sinha SK; Writing-original draft preparation – Bhatia D, Jaswal P, Sinha SK; Writing-review and editing – Bhatia D, Jaswal P, Sinha SK; Supervision – Bhatia D. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

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