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## **ENGINEERING AN UNDERGARMENT FOR FLASH/FLAME PROTECTION**

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### **ABSTRACT**

This paper presents a continuation of projects spanning the last two years. In year one, the physical characteristics and medical effects of burns and *Improvised Explosive Device*, IED, blasts were investigated [1]. In year two, the possible use of commercial intumescent materials with fabric was studied [2]. The identified needs for research into the effect of undergarments on burn protection are focused in this study. Additionally, *Thermal Protective Performance*, TPP-(ISO 17492) and *Air Permeability*, AP-(ASTM D737) tests were performed to gather the data needed for the analysis of flame and thermal resistance as well as comfort and breathability. Out of the seven samples evaluated, the *Sample D*, composed of 94% m-aramid, 5 % p-aramid and 1% static dissipative fiber, shirt had the best overall performance in terms of air permeability, average TPP rating, and time to second degree burn. Another finding was that polyester undershirts may be dangerous in the event of a flash fire situation because the fabric could melt and stick to the Soldier's skin causing more severe burn injury. Additionally, an initial framework for a basic mathematical model representing the system was created. This model can be further refined to yield more accurate results and eventually be used to help predict the material properties required in fabrics to design a more protective undergarment.

### **1. INTRODUCTION**

The purpose of this paper is to provide the results of the flash/flame protective clothing research project. The research results presented can lead to further advancements in the thermal protective garments that will ultimately reduce burn

injuries to Soldiers in combat and others in harm's way which include fire fighters and police in their daily work.

#### **1.1 Problem Statement**

The threat of burn injuries to Soldiers in combat due to blasts, flash fires and secondary fires has resulted in the development of the *Flame Resistant Army Combat Uniform*, FR ACU. The FR ACUs provide protection through self-extinguishing properties as well as a level of insulation due to the fact that the material by design balloons out from the body thereby creating an air space due to the intumescent-type effect which occurs when exposed to flame. However, additional insulation provided by undergarments logically would further reduce heat transfer to the body. The goal of this research is to test commercially available undergarments to find a readily available improvement over those currently issued to Soldiers, as well as to mathematically model the system to determine the necessary material properties for new fabrics that can better protect the Soldier. The major design constraint is the trade-off between comfort and protection - an improvement in one category undoubtedly often leads to a reduction in the other.

The customer this design considers is the Dismounted Soldier. His/her primary mission is to close with and destroy the enemy in close proximity. In order to complete the mission in today's wars, the infantrymen need to be mobile. Long range foot patrols are a necessity to interact with local populations and seek out the enemy in counter terrorism operations. To accomplish these in hot conditions and adverse environments, undergarment design must be cool and comfortable. Additionally, the Soldier needs clothing that helps protect from threats, particularly IEDs. The interactive need for mobility, comfort, and protection presents a complex set of design

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constraints that limit possible solutions. To best protect a Soldier from burns, multiple layers of highly insulating material can be combined to completely shield the user from intense heat fluxes associated with blasts and other flash/flame incidents. This is essentially how fire fighters can literally walk through flames with limited to no adverse effects. Soldiers, however, operate for extended periods of time at high levels of physical exertion in hot environmental conditions. The protective insulation would trap body heat and render the soldier mission incapable. The need to be dismounted and mobile also limit possible designs to cool the Soldier with highly insulating clothing. For example, a pilot or tanker can afford the weight of a water cooled vest; a dismounted Soldier, however, may be in a vehicle for a short period of time, but eventually will not be able to carry the extra weight associated with such a design. Therefore, any solution must balance the needs of protection, mobility, and comfort as well as added weight.

## 1.2 Recommended Design Specifications

The purpose of this paper is to provide the findings and results of the *Flash/Flame Protective Clothing* research project. The subject matter in this paper can provide information to help lead to further advancements in thermal protective garments that will reduce burn injuries to Soldiers in combat. Given the two criteria evaluated in the project, the best performing material of those evaluated is Sample D, composed of 94% m-aramid, 5% p-aramid and 1% static dissipative fiber.

Table 1, the Design Specification List, presents the performance of this material compared to the targeted values. All targeted values are based on the performance of Sample E, the Army's standard issue T-shirt, which is readily available to Soldiers which is inexpensive and is commonly worn.

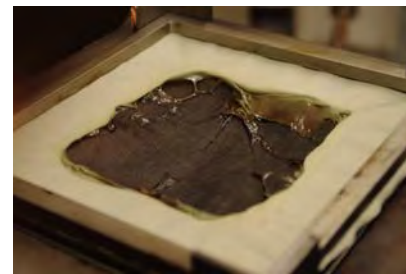
The design met the target values for thickness, air permeability, TPP rating, and time to a second degree burn. Although the weight and density of the design did not meet the target values, they are not significantly greater than the standard T-shirt and should have little effect on the Soldier. Additionally, the air permeability of the recommended design is much greater than the target which is a more comfortable garment under hot operating conditions. Sample D material increases the time to a second degree burn from 8.8 second to 9.1 seconds; this is a 9.34% increase which could be considerable when one is dealing with seconds. More importantly, it is an increase. From the products currently available, this design appears to provide the best protection-comfort combination that will benefit Soldiers in combat based on the factors considered here.

Another finding from test results is the risk of melting with undergarments made of mostly polyester. One of the materials tested, Sample A, was made of 82% polyester and 18% elastane. This material melted when exposed to a high heat flux of the TPP test even though it was protected from direct flame exposure by a layer of the FR ACU uniform fabric. We feel this is an important finding since melted material could

cause harm to the Soldier through additional burning as it drips along the body and enters other wounds. An image of this result can be seen in Figure 1. Although Soldiers are instructed not to wear polyester undershirts with their FR ACU uniforms in theater, this is not easily controlled.

**Table 1. Design Specification List**

| Engineering Characteristic       | Relative Importance | Target                            | Actual                           |
|----------------------------------|---------------------|-----------------------------------|----------------------------------|
| Weight                           | 0.119               | <4.22<br>(oz/sq yd)               | 4.45<br>(oz/sq yd)               |
| Thickness                        | 0.185               | <0.0211<br>(in)                   | 0.0180<br>(in)                   |
| Air Permeability                 | 0.218               | >245.3<br>(ft <sup>3</sup> /min)  | 540<br>(ft <sup>3</sup> /min)    |
| Density                          | 0.163               | <0.151<br>(oz/in <sup>3</sup> )   | 0.191<br>(oz/in <sup>3</sup> )   |
| TPP Rating                       | 0.158               | >17.6<br>(s-cal/cm <sup>2</sup> ) | 18.3<br>(s-cal/cm <sup>2</sup> ) |
| 2 <sup>nd</sup> Degree Burn Time | 0.158               | >8.8<br>(s)                       | 9.1<br>(s)                       |



**Figure 1. Polyester-Elastane Material**

## 2. BUSINESS CASE

From the recommended design specifications of the previous section and the current scope of this research project, the commercially available Sample D shirt provides a readily available protective garment. When coupled with the current Flame Resistant Army Combat Uniform, the Sample D shirt provides the greatest increase in protection over the standard issue T-shirt and various other commercially available undergarments. While offering increased thermal protection, the testing data indicates that this undergarment provides the greatest amount of comfort to the Soldier when compared to other benchmarked materials. Overall, the Sample D shirt seems to provide the best combination of protection and comfort given the criteria considered and evaluated. Each of the engineering characteristics on the design specification list can be grouped under these two categories of thickness, density, weight, and TPP rating contributing to protection aspect, while air permeability provides a measure of comfort. However, only a small selection of commercial undershirt fabrics was evaluated here. Therefore, the Army should consider further evaluation of available flame resistant and non-melting fabrics and consider issuing under garments for

Soldiers who are deploying or are currently deployed to theaters such as Iraq and Afghanistan. Given that Mounted Soldiers such as aircrew and tankers have a formal requirement for certain approved underwear materials, perhaps a list of approved materials could be prepared for all Soldiers who wear flame resistant uniforms.

Finally, this paper provides a solid foundation for further research and development of materials that can provide increased protection against flash/flame situations, while at the same time keeping the Soldier as comfortable as possible. The testing of commercially available products provides a basis of the performance and protection that is achievable today, while at the same time providing a direction in which to advance with continued research.

### 3. BACKGROUND RESEARCH

In order to further define the scope of this project, background research was completed. This research included the social, technological, and economical considerations involved with the project.

#### 3.1 Social Considerations

This project has a direct impact on protecting Soldiers, specifically those that encounter enemy IEDs and other explosives, from burn injury. Based on a 2008 article, personnel at the Brooke Army Medical Center at Fort Sam Houston, Texas, has treated over 700 casualties due to burns sustained in Operation Iraqi Freedom. Lieutenant Colonel Evan Renz, a trauma surgeon at the Fort Sam Houston Burn Center, stated that "Burn injuries comprise about five to 10 percent of all war casualties" [4]. In Afghanistan, insurgent forces have used IED attacks increasingly since 2005. In fact, IED events increased 62% from 2009 to 2010, in which insurgents planted 14,661 IEDs [5]. It has been shown that some explosions reach temperatures between 1,600° and 3,800° C. Because human skin is typically at 32.5°C, and burn injuries can occur at as little as 44°C, these explosions from enemy IEDs can lead to significant burn injuries very quickly. Also, it is stated that a typical flash fire has a heat flux 80 [kW/m<sup>2</sup>] which can cause a burn injury to exposed skin in about one second. These blasts can also ignite fuel and lead to secondary fires that could cause further harm [1]. Therefore, because of the increasing amount of IEDs and the potential of burn injuries that they may cause, equipping Soldiers with the best possible protection has immediate social implications. Greater protection can reduce burn injuries, which can prevent death or allow a casualty to recover more quickly.

#### 3.2 Technological Considerations

Although Sample D exemplifies the best product included in this limited evaluation, more research must be conducted to determine which materials provide the best combination of thermal protection and comfort for the Soldier. The optimum material for this application will exhibit low insulation, high air flow and good moisture management properties at normal

operating conditions for comfort, but can also exhibit high insulation properties and reduce the amount of heat transferred to the skin under extreme conditions, such as during a blast or flash fire. One method of determining the thermal properties of a material that meets these conditions is through numerical modeling. A numerical model that accurately represents the ambient conditions, protective clothing, and skin can estimate the material properties necessary to achieve both comfort and protection. The material properties would then be a function of temperature, and the material would *adapt* based on the ambient conditions. Although such a material may not be currently available due to technological limitations, the first step is developing the model that achieves accurate results.

Mell and Lawson [6] set out to develop a numerical model representing the heat transfer a fire fighter experiences when exposed to flames. To solve this problem, they first developed an experimental apparatus to test the performance of protective clothing under certain conditions. The results from the test provide a thermocouple-based time history of the temperature at the fabric layer surfaces. After collecting experimental data, they developed a one-dimensional heat transfer model to represent the system. They reported that their model differed from the experimental results by 5[°C] in the interior of the system and by 24[°C] in the outer layers. They attribute this inaccuracy largely due to a lack of certain material properties to be used in the model.

Although the experiment described above deals with fire fighter protective clothing, the same method could be used to develop an accurate model for protective clothing for a Soldier. An apparatus could be developed that allows for the testing of under and outer garments that Soldiers wear. Next, a numerical model that most accurately represents the heat transfer through the clothing could be developed and coded in a computer software program. Through adjusting the test and numerical model, the error between the experimental and model results would eventually reach an acceptable value. Once the model is validated, the material properties and ambient conditions could then be varied until the desired results are achieved. Therefore, a validated model is essential to uncovering the material properties necessary to provide the Soldier with optimum protection and comfort. As mentioned before, these material properties, which would be a function of the ambient temperature, could lead a materials engineer to develop new material combinations that could best benefit a Soldier in combat.

One potential issue for this process, as pointed out by Mell and Lawson [6], is determining the material properties of the clothing used in the testing apparatus. This issue is discussed in another one of Lawson's projects, [7]. According to this work, computer modeling and prediction of protective clothing thermal performance requires the use of numerical values of thermo-physical properties for all materials used in garment construction, including thermal conductivity, specific heat, absorptivity, emissivity, and transmissivity. In other words, a computer model can only be validated if the thermal properties

of the materials used in the experimental test are known. Because little or no information is available for making detailed studies of protective clothing thermal performance, more analysis should be conducted on the thermal properties of the materials that Soldiers currently wear, particularly at elevated temperatures consistent with flame incidents. With known material properties, the computer model can be validated with greater accuracy.

Overall, an accurate and operational computer model will allow for the evaluation of different material concepts without testing which can be expensive and time consuming. Also, developing the thermal properties necessary to provide both comfort and protection can lead to advancements in materials that could limit the burn injuries to Soldiers.

### 3.3 Economic Considerations

One issue with conducting material research and implementing more protective clothing is high costs. There are obvious trade-offs between costs and performance of the materials used in the fabrics produced. However, implementing the recommended design may provide the next best alternative based on what is currently available.

### 3.4 Applicable Standards/Regulations

This research used the *Thermal Protective Performance* test, TPP, ISO 17492, to gain a measure of protective performance that each material is able to provide. The TPP test involves exposing a textile material to both convective and radiant heat energy. The current standard set by the Army is based on the percentage of burns resulting from a 4-second burn at a uniform heat flux of  $2[\text{cal}/\text{cm}^2/\text{sec}]$  in a manikin. The exposure time in the TPP test is selected based on the material tested to measure the amount of energy going through the sample and then going through a Stoll curve to predict how long it would take before a second degree burn would be reached. The test method run was, as mentioned above, ISO 17492 in accordance with NFPA 1971, 2007 edition. This test concludes by providing a TPP rating for the textile. The TPP rating is calculated by multiplying the time measured to reach a second degree burn by the uniform heat flux [8]. Intuitively, the larger the TPP rating, the more protective the garment, since the Soldier wearing the garment will have more time to react to the flash/flame incident [9]. The test apparatus is shown in Figure 2 and the resulting sample in Figure 3.

This research also used the *Air Permeability Test*, APT, ASTM D 737, which provides a quantifiable measure of breathability and comfort. In order to make this measurement, a vacuum is used to draw air through the material, Figure 4. The flow rate of the air through the material is measured in cubic feet per minute. This measurement serves as a quantifiable measure of comfort by inferring that the greater the flow of air through the material, the more breathable the material is, thus increasing the comfort of the material [10].

Finally, this research used a standardized method to evaluate the weight of each fabric, ASTM D3776/D3776M.

This standard measures the mass of fabric per unit area. The weight of each fabric combined with the thickness can then be used to calculate the density of each fabric. These three parameters can then serve as indicators as to how protective the material will be [11].



Figure 2. The Thermal Protective Performance Test Apparatus

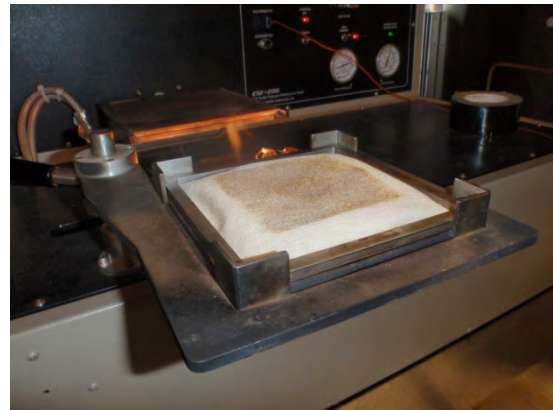


Figure 3. Sample After Thermal Protective Performance Test Burn



Figure 4. Air Permeability Test Apparatus



#### 4. RESULTS

The research followed the design process as taught in mechanical engineering programs and consists of conceptual design, embodiment design and detailed design. Development of the prototype included construction and assembly of components, risk management and testing.

##### 4.1 Conceptual Design

In order to begin the design process, the customer requirements were determined. Information was gathered in the form of a survey conducted and reported in a previous paper [2]. This survey had 264 total responses that identified 50 different attributes that potential customers recognized as important for a flame resistant protective garment. Although this paper went in a very different direction, the survey was still applicable to this new research project. These results were used to create a Pareto chart, Figure 6. A Pareto chart essentially identifies the important attributes from the many trivial attributes. This chart is composed of two parts: a bar chart and a curve. The bar chart uses the left axis and relates to the frequency of responses from the survey. High importance attributes are on the left and low importance attributes are on the right. The curve tracks the cumulative percentage. An 80/20 rule was applied to the Pareto chart to identify the most important attributes for the objectives tree.

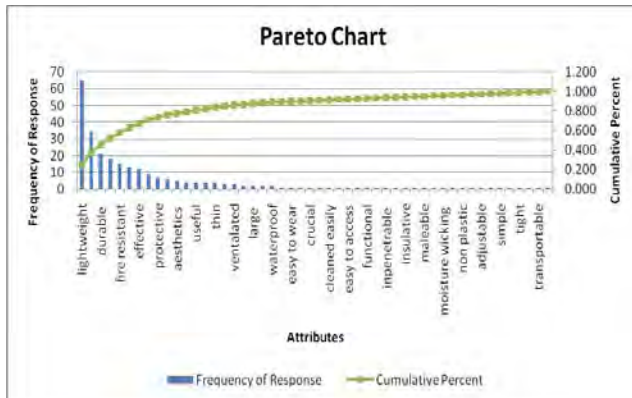


Figure 5. The Pareto Chart

An objectives tree was created to group the top attributes identified in the Pareto chart. In total, eleven attributes were selected. Some attributes were grouped into the categories of comfortable, user-friendly, protective, and sustainable. The groupings reinforce the design constraints of comfort and protection and the difficulty in providing both of these attributes for the Soldier. These three groups and the attribute aesthetics were used in a pairwise comparison. A pairwise comparison is used to prioritize customer requirements by comparing two at a time. A 1 means the row is more important than the column, a 0 means the column is more important than the row, and a 0.5 means they are of equal importance. The output of the pairwise comparison is a relative importance or

weight factor to be used in a Quality Functional Deployment (QFD). The pairwise comparison created in [2] was revised with new rankings to better coincide with recommendations learned from communications and visits to NSRDEC Laboratories. Many of the comfort factors and protective factors have equal importance scores. This is because of the tradeoff between comfort and protection. The relative importance of each customer requirement is as follows: protective is 0.35, comfortable is 0.25, sustainable 0.25, user-friendly is 0.15, and aesthetics is 0 as shown in Table 2.

After the pairwise comparison, the customer requirements were placed into the QFD to determine the desired engineering characteristics. The weight factors used in the QFD were determined in the pairwise comparison, Table 2. The engineering characteristics selected as necessary were weight, thickness, air permeability, density, TPP rating, and time to second degree burn. These characteristics were then ranked on their relevance to the most desired attributes of the device. The ranking is as follows: air permeability, thickness, density, TPP rating and time to second degree burn, and weight. It is important to notice that the most important factor, air permeability, is a comfort factor. This supports the fact that Soldiers must actually want to use the garment.

Table 2. Pairwise Comparison

|               | Comfortable | User-Friendly | Aesthetics | Protective | Sustainable | Sum | Relative Importance |
|---------------|-------------|---------------|------------|------------|-------------|-----|---------------------|
| Comfortable   | X           | 0.5           | 1          | 0.5        | 0.5         | 2.5 | 0.25                |
| User-Friendly | 0.5         | X             | 1          | 0          | 0           | 1.5 | 0.15                |
| Aesthetics    | 0           | 0             | X          | 0          | 0           | 0   | 0                   |
| Protective    | 0.5         | 1             | 1          | X          | 1           | 3.5 | 0.35                |
| Sustainable   | 0.5         | 1             | 1          | 0          | X           | 2.5 | 0.25                |
| 10            |             |               |            |            |             |     | 1                   |

The garment is useless even if it provides the best protection if the Soldier does not want to wear it. Benchmarks and target values were established by testing a standard ACU T-

shirt. Any new product must outperform what the Soldier is currently issued and using. The necessary functions to achieve an overall reduction in burn injuries were identified using a functional decomposition; this describes functions in terms of actions or physical behaviors. The use of action verbs and hierarchical structure allows the designer to describe the ‘what’ and ‘how.’ The two general functions were “interacts with Soldiers” and “interacts with environment.” By using the pairwise comparison, traits for the undergarment deemed important were turned into functions the undergarment must accomplish. Sub-functions and sub-sub-functions were selected to identify a more detailed design picture. Again the importance of comfort and protection are evident based on what the sub-functions provide for both comfort and insulation

The design tool following the functional decomposition is the morphological chart. In this tool, under each function and sub-function of the design, the necessary physics and means necessary to achieve the functions are listed. A morphological chart is typically used for generating design alternatives that will lead to the embodiment of design. However, the goal of this project was not to produce a new product. The means necessary to provide a protective garment are a function of the material

**Table 3. Quality Functional Deployment**

| <b>Problem Statement:</b> To investigate the capabilities of the fire resistant clothing materials against radiant threats and from flames stemming from Improvised Explosive Devices (IED's) as well as explore optimum insulation combinations to complement the fire resistant material. The outcome of this project will help protect Soldiers deployed on the battlefield from sustaining serious burn injuries due to explosions resulting from IED's. |                          |                             |           |                      |                    |                       |                         |                                                                               |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|-----------------------------|-----------|----------------------|--------------------|-----------------------|-------------------------|-------------------------------------------------------------------------------|
| Improvement Direction                                                                                                                                                                                                                                                                                                                                                                                                                                        |                          | Engineering Characteristics |           |                      |                    |                       |                         | Competitor Rankings<br>(Standard Poly-Cotton)<br>1= Poor, 3= OK, 5= Excellent |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                          | ↓                           | ↑         | ↓                    | ↑                  | ↑                     | ↑                       |                                                                               |
| Units                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                          | oz/sq yd                    | in        | ft <sup>3</sup> /min | oz/in <sup>3</sup> | s-cal/cm <sup>2</sup> | sec                     |                                                                               |
| Customer Requirements                                                                                                                                                                                                                                                                                                                                                                                                                                        | Importance Weight Factor | Weight                      | Thickness | Air Permeability     | Density            | TPP Rating            | Time to 2nd Degree Burn |                                                                               |
| Protective                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 0.35                     | 3                           | 3         | 0                    | 3                  | 9                     | 9                       | 3                                                                             |
| Comfortable                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 0.25                     | 3                           | 3         | 9                    | 9                  | 0                     | 0                       | 3                                                                             |
| Sustainable                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 0.25                     | 3                           | 9         | 9                    | 1                  | 0                     | 0                       | 3                                                                             |
| User-Friendly                                                                                                                                                                                                                                                                                                                                                                                                                                                | 0.15                     | 1                           | 1         | 3                    | 1                  | 3                     | 3                       | 3                                                                             |
| Raw Score                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                          | 2.7                         | 4.2       | 4.95                 | 3.7                | 3.6                   | 3.6                     | 22.75                                                                         |
| Relative Importance                                                                                                                                                                                                                                                                                                                                                                                                                                          |                          | 0.119                       | 0.185     | 0.218                | 0.163              | 0.158                 | 0.158                   |                                                                               |
| Rank Order                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                          | 5                           | 2         | 1                    | 3                  | 4                     | 4                       |                                                                               |
| Technical Assessment                                                                                                                                                                                                                                                                                                                                                                                                                                         |                          |                             |           |                      |                    |                       |                         |                                                                               |
| Target Values                                                                                                                                                                                                                                                                                                                                                                                                                                                |                          | <4.22                       | <0.0211   | >245.3               | <0.151             | >17.6                 | >8.8                    |                                                                               |

properties. As was mentioned in [2], this research is really a material design problem; therefore, the end state cannot be achieved by combining different mechanical components. Therefore, the morphological chart and subsequent design tools, such as alternative generation and decision matrix, are not practical to generate design alternatives. Instead, experimental testing and heat transfer modeling must be used to determine new material properties.

## 4.2 Embodiment Design

Two major conclusions come from the testing conducted at Natick Soldier Research, Development and Engineering Center, NSRDEC. First, the commercially available Sample D shirt

performed best under the criteria set for this research project because of its intumescent and ballooning out character towards the flame. Second, the poorest performance was exhibited by Sample A, polyester/elastene. Soldiers enjoy this product because it wicks moisture and is cool in hot environments. However, when tested, results showed that the polyester material in the exposed region completely melted and dripped into the center of the sample due to gravity as shown in Figure 1. When worn as an undershirt, the melted material could drip onto the Soldier's body creating a larger burn injury. Additionally, the melted material could accumulate on the wound and harden. This complicates the wound and makes it harder to treat; surgeons would have to remove the now hardened material, potentially damaging healthy tissue that helps the wound to heal.

## 4.3 Detail Design

All undershirt fabric samples were tested in combination with the standard FR ACU fabric, with the FR ACU fabric toward the flame source and undershirt toward the sensor in the Thermal Protective Performance, TTP, apparatus. Other properties were tested on the undershirt fabrics alone. The following data in Table 4 were obtained from testing and used to determine that Sample D represents the best available solution of the materials tested here.

**Table 4. Experimental Test Data**

| Test                                    | Sample A | Sample B | Sample C | Sample D | Sample E | Sample F | Sample G |
|-----------------------------------------|----------|----------|----------|----------|----------|----------|----------|
| Air Permeability (ft <sup>3</sup> /min) | 287.5    | 80.52    | 370      | 540      | 245.3    | 255.6    |          |
| Weight (oz/sq yd)                       | 5.43     | 6.72     | 6.69     | 4.45     | 4.22     | 5.49     |          |
| Thickness (in)                          | 0.0210   | 0.0212   | 0.0242   | 0.0180   | 0.0211   | 0.0211   |          |
| Density (oz/in <sup>3</sup> )           | 0.200    | 0.244    | 0.213    | 0.191    | 0.151    | 0.210    |          |
| Average TPP Rating                      | 18.0     | 21.3     | 17.8     | 18.3     | 17.6     | 15.9     | 10.0     |
| Time to 2nd Degree Burn (s)             | 9.1      | 10.7     | 8.9      | 9.1      | 8.8      | 8.0      | 5.0      |

The data highlighted in green indicates the best in each category, yellow as second best in each category, and red as worst in each category. Additionally, the categories towards the top are general indicators of comfort where those towards the bottom are general indicators of protection. The first result from testing is that undergarments used in combination with the FR ACU do provide greater protection than Flame Resistant Army Combat Uniforms alone. This is seen by comparing the Thermal Protective Performance ratings and time to second degree burns. The FR ACU material alone only provided 5 seconds to second degree burn with a Thermal Protective Performance rating of 10. The worst combination tested was Sample F, which provided 8 seconds to second degree burn with a Thermal Protective Performance rating of 15.9. The Sample B provided the greatest protection with a Thermal

Protective Performance rating of 18.0 and time to second degree burn of 10.7 seconds. However, this shirt was heavy and had low air permeability results indicating a hot, uncomfortable shirt. Sample D finished second in protective categories and first in air permeability and thickness; in all categories it never finished below second. This suggested it as the best product. Surprisingly, the standard T-shirt, Sample E performed similarly to Sample D in protection, only providing 3/10 of a second less until a second degree burn. At a price of \$12 per three shirts for the standard Sample E undershirt compared to \$99 for the Sample D shirt, it is important to decide if the benefits gained outweighed the cost. Two factors determined that the Sample D shirt was in fact the winner of the experimental results. The first factor was the air permeability; Sample D shirt performed significantly better than the standard T-shirt thus suggesting it may be much more comfortable for Soldiers to wear. Additionally, the second factor was that the standard Sample E T-shirt is not intended as a flame resistant garment.

#### 4.4 Analysis

This paper provides a very basic model as the foundation for a more complex future numerical analysis. The first step in developing this model was making key assumptions. First, an explosion results in a uniform heat flux applied to the outer layer of the material. Because this heat flux is uniform across the entire body, the heat transfer through the system can be considered one-dimensional. Also, the under and outer fabric layers do not typically mesh together completely when worn by a soldier, leaving a small air gap between the two layers. The air within this gap was assumed to be quiescent, so convection through the air gap was also assumed to be negligible. Because the outer layer is in direct contact with the flash or flame, the main mode of heat transfer through the system within the outer boundary is conduction. As a result, radiation across the air gap was assumed to be negligible. Finally, the materials were assumed to be dry. Moist materials would complicate the model, as a high heat flux could lead to a phase change from liquid to vapor within the material coupling both heat and mass transfer effects. These advanced considerations could be incorporated into the model once a base line code has been established. Based on these assumptions, a one dimensional model, as seen in Figure 6, was created.

The four layers of the model, the outer layer, air gap, under layer, and skin were divided into fourteen nodes. The temperatures of these nodes change over time, as the model represents a transient system. The temperature of each node is dependent upon the applied heat flux, material properties, mesh spacing, boundary conditions, and time of exposure. In order to solve for the temperature of each node, an explicit method was used. In this method, the modes of heat transfer at each node are analyzed, and finite-difference equations are developed to represent an energy balance at that node. Once all finite-difference equations are solved for the new temperature at each node, the *unknown* nodal temperatures for the new time

are determined exclusively by the *known* nodal temperatures at the previous time, [12]. In other words, a system of equations is simultaneously evaluated for each time step, resulting in new temperatures at each node until the iteration is complete.

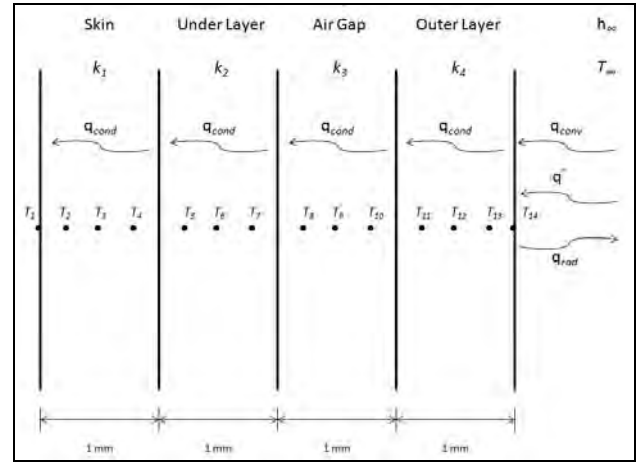


Figure 6. One Dimensional Heat Transfer Model

The energy balance equation used to analyze each node can be seen below in Equation 1.

$$\dot{E}_{in} + \dot{E}_g - \dot{E}_{out} = \dot{E}_{st} \quad [1]$$

The  $\dot{E}_{in}$  component contains the following equations for conduction, convection, and heat flux:

$$q_{cond} = -kA \frac{dT}{dx} \quad [2]$$

$$q_{conv} = hA(T_s - T_{\infty}) \quad [3]$$

$$q'' = \text{heat flux from blast} \quad [4]$$

The  $\dot{E}_{out}$  term is made up of the radiation component:

$$q_{rad} = \epsilon \sigma A (T_s^4 - T_{sur}^4) \quad [5]$$

$\dot{E}_{st}$ , the energy stored, is comprised thermodynamically of the term  $\rho c_p \frac{dT}{dt} V$ , representing the transient nature of the system, as it is dependent on time. Also, two terms, Fourier and Biot numbers, were used to simplify the equations.

$$Fo = \frac{kt}{\rho c_p L^2} \quad [6]$$

$$Bi = \frac{hL}{k} \quad [7]$$

Using this method, the finite difference equations can be derived and solved with computational software such as MATLAB [12].



As mentioned before, this model forms a basic representation of the physical system of a Soldier wearing multiple layers of clothing when exposed to a flash or flame. The model can be further developed to yield more accurate results and once validated it can be used to generate the material properties of an optimum material that can provide more protection to Soldiers without sacrificing comfort.

#### 4.5 Construction/Assembly

After performing an extensive literature review and evaluation of current flame resistant materials that are commercially available, six materials ranging from flame resistant undergarments designed for use by firefighters to popular polyester sportswear were selected for evaluation. This variance in materials helped illustrate the tradeoff between providing thermal protection while at the same time being able to provide a reasonable amount of comfort. The assembly of these materials for testing included, cutting the materials into six by six inch squares. The Thermal Protective Performance test required these dimensions in order for the materials to be compatible with the testing apparatus. Once sized for the testing apparatus, the materials were assembled in such a manner to best replicate an individual wearing the protective garments. The outer portion of the Flame Resistant Army Combat Uniform material was exposed to the applied heat flux. The under garment was then layered behind the uniform material thus simulating an individual wearing the garments together.

#### SUMMARY AND CONCLUSIONS

The design highlights of the Sample D shirt are that it is made of a lightweight material, has a high air permeability which will allow for breathability, and is protective against flash/flame threats. This undershirt could compliment the Flame Resistant Army Combat Uniform and provide improved protection against flash/flame threats for the Dismounted Soldier in combat.

The objectives initially set were to develop a material to provide flash/flame protection. However, it was not practical to research and develop a new material to serve as an undergarment since it was out of the scope for this research due to available time to meet this goal. Despite this fact, the goal was met which was to find a readily available undergarment to compliment the Flame Resistant Army Combat Uniform in order to provide improved protection for Soldiers in the battlefield. Through research and testing the objectives were met and accomplished.

Revisions to the numerical model along with continued numerical analysis will help further research particularly in materials science and smart materials. The ultimate research goal should strive to eliminate burn injuries all together associated with flash/flame threats due to IEDs. It is our hope that research continues with regard to flash/flame protection and ultimately added protection for Soldiers deployed in dangerous environments.

#### NOMENCLATURE

|      |                                                                                |
|------|--------------------------------------------------------------------------------|
| $A$  | area [ $\text{m}^2$ ]                                                          |
| $Bi$ | Biot number [-]                                                                |
| $c$  | specific heat [ $\text{kJ}/(\text{kg}\cdot\text{K})$ ]                         |
| $E$  | energy rate [ $\text{kJ}/\text{s}$ ]                                           |
| $Fo$ | Fourier number [-]                                                             |
| $h$  | convective heat transfer coefficient [ $\text{kW}/(\text{m}^2\cdot\text{K})$ ] |
| $k$  | thermal conductivity [ $\text{kW}/(\text{m}\cdot\text{K})$ ]                   |
| $L$  | length [ $\text{m}$ ]                                                          |
| $q$  | heat transfer rate [ $\text{kW}$ ]                                             |
| $T$  | temperature [ $\text{K}$ ]                                                     |
| $t$  | time [ $\text{s}$ ]                                                            |
| $V$  | volume [ $\text{m}^3$ ]                                                        |
| $x$  | direction [ $\text{m}$ ]                                                       |

#### Greek symbols

|               |                                                                                         |
|---------------|-----------------------------------------------------------------------------------------|
| $\varepsilon$ | emissivity [-]                                                                          |
| $\rho$        | density [ $\text{kg}/\text{m}^3$ ]                                                      |
| $\sigma$      | Stefan-Boltzmann constant, $5.670 \cdot 10^{-8} [\text{W}/(\text{m}^2\cdot\text{K}^4)]$ |

#### Superscripts

|   |                         |
|---|-------------------------|
| " | flux [ $1/\text{m}^2$ ] |
| . | rate [ $1/\text{s}$ ]   |

#### Subscripts

|          |                   |
|----------|-------------------|
| $con$    | conduction        |
| $conv$   | convection        |
| $g$      | generated         |
| $in$     | into the system   |
| $p$      | constant pressure |
| $rad$    | radiation         |
| $s$      | surface           |
| $st$     | stored            |
| $sur$    | surroundings      |
| $out$    | out of the system |
| $\infty$ | free stream       |

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