Fire
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Tests of Undergarments Exposed to Fire

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Wildland firefighters produce a lot of body heat when they're working. Because they're working near fires, their bodies produce tremendous amounts of perspiration to keep them cool. Synthetic undergarments are designed to remove moisture, which seemingly could improve firefighters' comfort and might increase productivity.

While firefighters generally understand that they need to wear flame-resistant outer garments, some have been attracted to undergarments made from polyester and polypropylene. Chapter 7 of "The Interagency Standards for Fire and Fire Aviation Operations 2009" says that firefighters should wear only undergarments made of 100-percent natural fibers (such as cotton, wool, or silk), aramid, or other flame-resistant materials. Synthetic materials such as polyester, polypropylene, and nylon are prohibited because undergarments made of these materials may melt—aggravating burn injuries.

Highlights...

- Some firefighters have been tempted to wear synthetic undergarments because synthetics do a better job of wicking moisture than the approved cotton or wool undergarments.
- Laboratory tests showed that firefighters wearing synthetic undergarments may be more likely to suffer burn injuries because the synthetic materials might melt and stick to their skin.
- The 100-percent cotton and 100-percent wool undergarments did not ignite, melt, or char during testing.

The Missoula Technology and Development Center (MTDC) was asked to compare the potential for burn injury for newer synthetic undergarments with that of undergarments made from natural fibers. MTDC contracted with the University of Alberta's Flash Fire Facility to design realistic scenarios for testing undergarments. The testing took place during the fall of 2006.

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Firefighters' undergarments provide an additional layer of material between radiant heat or direct flame contact and the skin. Protection depends not only on the weight of the undergarment, but on other characteristics of the fabric, such as weave. Fabrics of equal weight can be woven into different thicknesses, affecting their thermal resistance. This study compared six undergarment materials shown in table 1.

All of the materials were evaluated underneath a layer of the flame-resistant aramid fabric typically worn by wildland firefighters. The flame-resistant shirts were manufactured to meet Forest Service Specification 5100-91. The pants meet specification 5100-92. This paper presents the results of two tests—full-scale flame engulfment and full-scale radiant exposure.

Table 1—The materials tested included the standard flame-resistant aramid shirt and pants worn by wildland firefighters and undergarments made from six different materials.

Fabric	Fiber content	Structure	Fabric weight	Manufacturer
Cotton	100% cotton	Jersey knit	4.4 ounces per square yard (150 grams per square meter)	Hanes
Silk	100% silk	Jersey knit	2.3 ounces per square yard (78.2 grams per square meter)	Sport Silks
Wool	100% wool	Jersey knit	6.1 ounces per square yard (208 grams per square meter)	SmartWool
Poly/cotton	50% polyester/ 50% cotton	Jersey knit	5.4 ounces per square yard (182 grams per square meter)	Jerzees
Under Armour	79% polyester/ 21% elastane	Warp knit	5.4 ounces per square yard (182 grams per square meter)	Under Armour Performance Apparel
Polypropylene	100% polypropylene	Rib knit	5.5 ounces per square yard (185 grams per square meter)	Indera
Aramid shirt	98% flame-resistant aramid/ 2% carbon	Modified basket weave	5.7 ounces per square yard (193 grams per square meter)	Polkton Manufacturing Company, Inc.
Aramid pants	98% flame-resistant aramid/ 2% carbon	Twill weave	8.5 ounces per square yard (288 grams per square meter)	Various

Full-Scale Flame Engulfment Tests

Clothing systems were evaluated using an instrumented mannequin following the ASTM International F1930 Test Method. The mannequin was exposed to a propane diffusion flame while the temperatures of sensors on the mannequin were monitored. All tests used a combination of a T-shirt (made from one of six different materials) and cotton brief undergarments.

The University of Alberta's test mannequin is a size-40 male form with 110 sensors distributed over the body. Areas highlighted in yellow in figure 1 represent the sensor areas covered by the T-shirt and outer aramid layers.

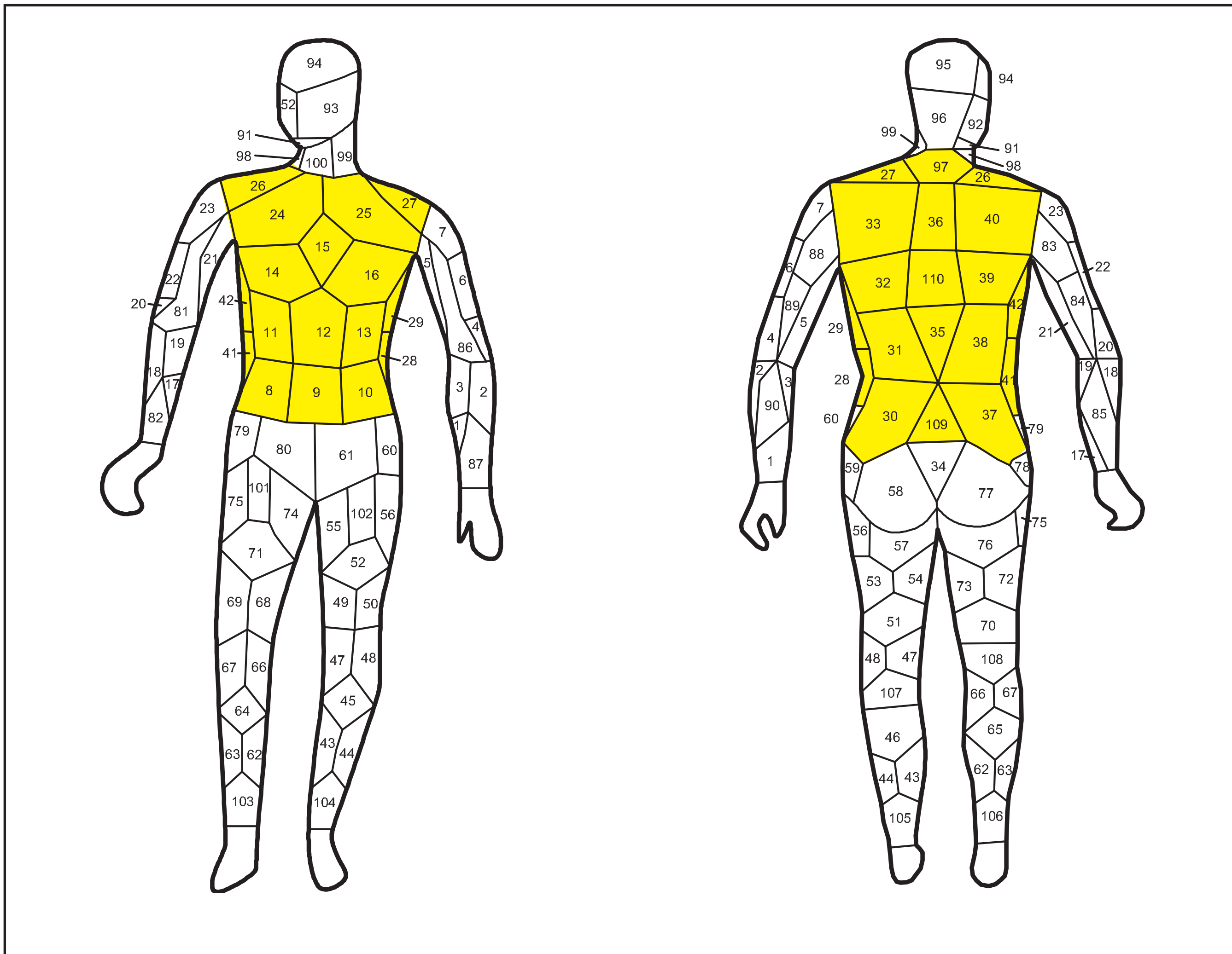


Figure 1—The mannequin's sensor sections highlighted in yellow were covered by the undershirt and aramid shirt.

The mannequin (figure 2) is surrounded by 12 propane burners, each of which emits pure propane through an orifice that can be adjusted to control the temperature. The propane mixes with the surrounding air and burns with a bright orange flame at temperatures of 1,450 to 1,650 degrees Fahrenheit. The burners have been adjusted to ensure a uniform exposure over the surface while the flames fully engulf the mannequin (figure 3). The average heat flux to the nude mannequin form is 84 kilowatts per square meter. The exposure time during tests is 4 seconds.

The 4-second exposure removed most of the dye from the aramid outer garments, shrinking the material around the arms and lower legs (figure 4). In some places the aramid material became brittle.

A video clip showing the flame engulfment and radiant exposure tests is available at *http://www.fs.fed.us/t-d/programs/fire/* (Username: t-d, Password: t-d).

Figure 2—The mannequin was outfitted with a flame-resistant aramid shirt and pants before testing.

Figure 3—The mannequin is fully engulfed in flames during the full-scale flame engulfment test.

Figure 4—The mannequin after the 4-second test.

Because the undershirt covered just part of the mannequin, the maximum possible thermal injury based on the covered sensors would be 27 percent. Each bar in the bar graph (figure 5) is an average of three trials. In all cases, undergarments reduced the thermal injury that would have been predicted if the mannequin was wearing only the aramid layer. For cotton, the most commonly used undergarment, the predicted thermal injury was 6 percent. The predicted injury for firefighters wearing synthetic undergarments was slightly higher.

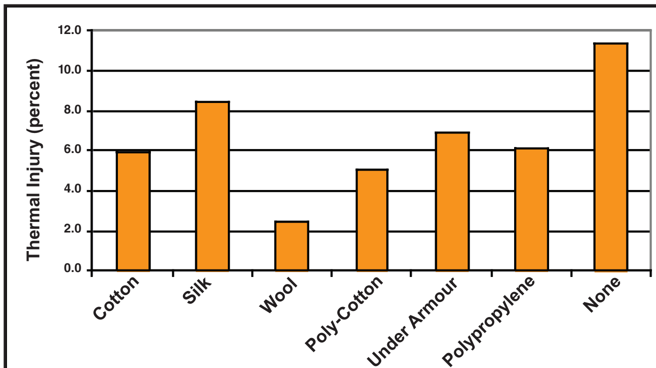
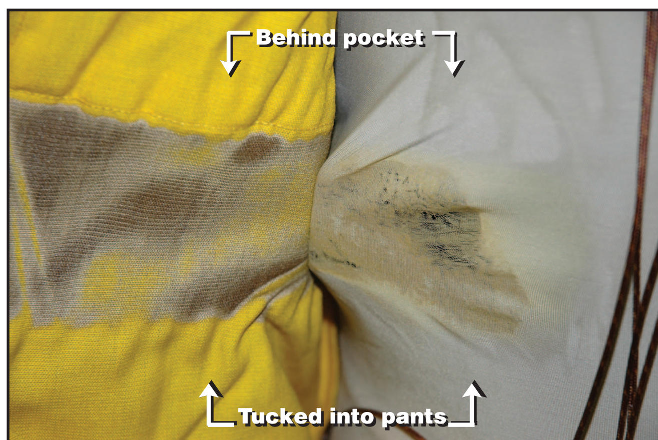


Figure 5—The percentage of the mannequin that would be predicted to have second-degree or more serious burns for each type of undershirt.

Examination of the predicted thermal injury does not present a complete picture. Areas of both the polypropylene and Under Armour T-shirts had melted. Melting materials may stick to the skin, aggravating burn injuries. While the mannequin system can measure energy transferred through the clothing, the mannequin is a hard fiberglass shell that does not stick to melting materials as skin might.

Although the melted synthetic materials seemed to preferentially adhere to the outer aramid fabric, that's no guarantee that melted materials would not adhere to a firefighter's skin. The results from the mannequin system also may be misleading because during these tests synthetic materials absorbed energy as they melted, changing phase from a solid to a liquid. Significant portions of the polypropylene Under Armour T-shirt melted, but even more of the polypropylene T-shirt melted (figures 6a and 6b). Natural fabrics did not melt.

Figure 6a—Much of the polypropylene undershirt (blue) melted during the full-scale flame engulfment test.



Figures 6b—A significant, but smaller, portion of the Under Armour undershirt (off white) melted during the test. The portions of the undershirt that were behind the shirt pocket and tucked into the pants did not melt.

Full-Scale Radiant Exposure Tests

Wildland firefighters are more likely to be exposed to a high radiant heat flux when they're close to the fire than to be engulfed in flames. Tests were conducted with the mannequin placed outside the fire to evaluate the effects of intense, primarily radiant exposure. With the mannequin's back toward the flames, the heat flux on the back was 40 kilowatts per square meter.

The exposure time during these tests was 10 seconds (figures 7a, 7b, 7c, and 7d). Only 10.8 percent of the mannequin's surface (upper torso back) was considered. This was the portion exposed to radiant heat and covered by the T-shirt. The clothing systems in these tests consisted of the same combination of undergarments and outer aramid layers on the torso of the mannequin; the aramid shirt and pants showed signs of exposure to high heat flux (they began smoking and changed color, figure 8).

Figure 7a, 7b, 7c, and 7d—The aramid shirt showed the effects of heat throughout the 10-second radiant heat test.

Figure 8—Large portions of the aramid shirt and pants changed color—a sign of exposure to high levels of heat—after the radiant heat test.

The tests showed burn injury was predicted on a high percentage of the mannequin's surface (figure 9). Polypropylene had the lowest predicted percent of burn injury, while Under Armour and silk fared the worst. Significant portions of the Under Armour and polypropylene garments melted during the radiant exposure tests (figures 10 and 11), as they had during the flame engulfment tests.

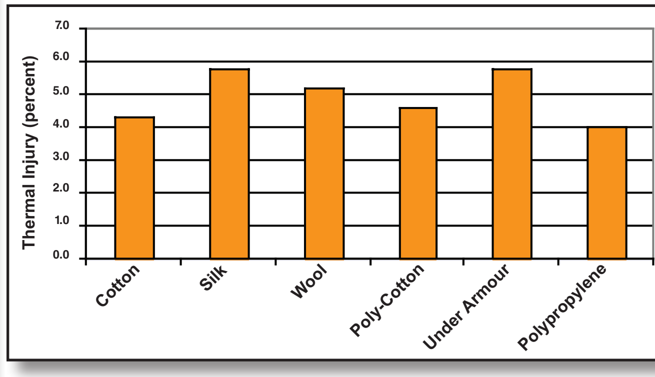


Figure 9—The percentage of the back of the mannequin estimated to have second-degree thermal injury with each type of undergarment. The back represents 10.8 percent of the entire body.

Figure 10—The polypropylene undershirt (blue) after the radiant heat test.

Figure 11—The Under Armour undershirt (off white) after the radiant heat test.

Conclusions

The low melting point of the synthetic materials and the energy they absorbed as they changed from a solid to a liquid significantly decreased the energy transferred to the mannequin. However, based on these tests, synthetic undergarments pose an increased risk of burn injury because of the possibility that they might melt and stick to the skin when firefighters are exposed to high heat. Undergarments of 100-percent cotton or 100-percent wool did not ignite, melt, or char. Silk undergarments weren't readily available (only one source was found during an Internet search). A firefighter wearing the silk undergarment would have a higher predicted thermal injury than a firefighter wearing undergarments made from the other fabrics, probably because the silk fabric was so light. The silk undergarment did not melt, but it did begin to char.

Undergarments made of 50-percent polyester and 50-percent cotton showed no sign of melting.

The predicted burn injury generally relates to the weight and thickness of each undergarment. The heavier and thicker the material, the lower the burn injury predicted during these tests.

Recommendations and Observations

Firefighters should continue to follow the Interagency Standards for Fire and Aviation Operations by wearing undergarments of 100-percent natural fibers, such as cotton, wool, or silk, or flame-resistant material such as aramid.

Even though undergarments made of 50-percent polyester and 50-percent cotton did not melt during these tests, the tests were not comprehensive enough to recommend that firefighters be allowed to wear undergarments made from these materials.

While thicker undergarments provide more protection from flames and radiant heat, they can contribute to heat stress. Firefighters should avoid wearing extra layers of material that insulate or restrict air movement, because they make it harder for the body to cool itself. Cotton T-shirts provide a good balance between increased thermal protection and increased heat stress.

Although female undergarments were not tested, based on these tests bras should contain the highest percentage possible of natural fibers that do not melt, such as cotton.

Firefighters exposed to heat flux levels similar to those used in these tests have been burned during fire entrapments, but the firefighters have survived and recovered. Survival and recovery would probably have been more difficult if the firefighters had been wearing synthetic undergarments or if they had not been wearing undergarments at all.

About the Authors

Tony Petrilli is an equipment specialist for the fire and aviation and safety and health programs at MTDC. He has a bachelor's degree in education from Western Montana College. Petrilli began working for the Forest Service in 1982 and joined MTDC full time in 2000. He has worked as a firefighter for the Lewis and Clark and Beaverhead National Forests and as a smokejumper for the Northern Region. He is a division/group supervisor, type III incident commander, and has served on more than 20 fire entrapment review or investigation teams.

Mark Ackerman is a professional engineer and a faculty service officer in the Department of Mechanical Engineering at the University of Alberta. He is a member of the National Fire Protection Association's 1977 Technical Committee on Wildland Fire Fighting Protective Clothing and Equipment. Mark teaches instrumentation, energy conversion, and design.

Library Card

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Some wildland firefighters have been tempted to wear synthetic undergarments that wick moisture rather than undergarments made of cotton, wool, or other flame-resistant materials approved for firefighters. The Missoula Technology and Development Center worked with the University of Alberta's Flash Fire Facility to test undergarments made of cotton or wool (both approved for firefighters) and silk, polyester, polypropylene, and Under Armour. Tests showed that firefighters wearing synthetic undergarments would be more likely to suffer burn injuries because the synthetic materials might melt and stick to their skin. The 100-percent cotton and 100-percent wool undergarments did not ignite, melt, or char during testing.

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Keywords: clothing, cotton, fabrics, fire fighting, firefighting, laboratory tests, nylon, polyester, polypropylene, safety at work, silk, undershirts, underwear, wool

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