ABSTRACT

ENI, Egbe U. Developing Test Procedures for Measuring Stored Thermal Energy in Firefighter Protective Clothing. (Under the direction of Roger L. Barker.)

This research studied stored thermal energy in fire fighter’s turnout systems. It developed a novel laboratory apparatus and test protocols for measuring the contribution of both transmitted and discharged stored energy on thermal protective performance. It examined the effects of thermal exposure conditions, as well as material variables and applied moisture on thermal energy stored in firefighter turnout materials exposed to heat intensities ranging from 0.06 to 0.50 cal/cm²·sec. This research provides a useful preliminary basis for further development of laboratory test methods to measure phenomenon associated with the discharge of stored thermal energy from materials used in the construction of firefighter turnouts. It demonstrates the complexity of factors affecting these phenomena in turnout materials.
DEVELOPING TEST PROCEDURES FOR MEASURING STORED THERMAL ENERGY IN FIREFIGHTER PROTECTIVE CLOTHING

by

EGBE U. ENI

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science

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APPROVED BY

Dr. Roger L. Barker
Chair of Advisory Committee

Dr. Sujit K. Ghosh
Member of Advisory Committee

Dr. Hechmi Hamouda
Member of Advisory Committee
DEDICATION

This work is dedicated to my family and church whose love, support, and prayer have ensured its success.
BIOGRAPHY

EGBE U. ENI was born in Little Rock, AR on August 8th, 1979. In 1997, he graduated with honors from Millbrook High School in Raleigh, NC. Egbe began his college career at North Carolina State University (NCSU) in Textile Materials Science. When the degree program was phased out in 1999, he transferred to Textile Engineering and received a Bachelor of Science degree from NCSU in 2001. Upon graduating, Egbe remained at NCSU to pursue a Master of Science degree in Textile Engineering.
ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Roger Barker, for his guidance and support. I also thank Dr. Hechmi Hamouda and Dr. Sujit Ghosh for being a committee member and for discussions. Mr. Rob Grimes and Dr. Guowen Song has been an invaluable asset who has made this work possible. Finally, I would like to thank God who has been a constant shield and fortress for me during this time in my life.
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1. INTRODUCTION

1.1. Introduction

Structural firefighters can receive second degree burns while working in thermal exposures that are considerably lower than flashover conditions. These exposures typically last for several minutes, and usually do not degrade the turnout shell fabric. There is considerable interest, therefore, in understanding thermal phenomena that may contribute to firefighter injury in these low level heat exposures. One potential source is the thermal energy stored in the firefighter’s protective turnout assembly as a result of prolonged exposure in a structural fire within a room that has not reached a flashover condition.[3]

The research sought to develop a laboratory test method to measure the thermal energy stored in turnout materials during prolonged exposure to low flux levels. This test method is intended to provide information on the potential for burn injury associated with a firefighter compressing his heated turnout system against his body due to either a flexing action of his limbs or the action of compressing his turnout garment against a structural wall or other fixed surface. The intent of the research was to determine the utility of this test method, and to study the effects of critical variables on the thermal energy stored and transmitted through firefighter turnout composites. Variables studied
included the moisture barrier permeability, thermal liner thickness, moisture present in fabric layers, and the intensity of the heat exposure. [3]
2. EXPERIMENTAL

2.1. Stored energy Test (SET)

Song et. all illustrated the stored energy test concept as follows [13]:

This procedure measures the thermal energy stored and transmitted by turnout ensembles following exposure to a heat source producing thermal energy ranging from 0.06 to 0.50cal/cm²·sec. For tests at the 0.50 cal/cm²·sec level, the TPP tester was used as the basic testing platform. (Figure 2.2).
For this study a device was specially constructed to permit compression of the sample (Figure 2.3). Details of these testing apparatus can be found in Appendix A.
The testing protocol proceeded as follows: A test sample is exposed to a 0.5 cal/cm\(^2\)-sec (21 kW/m\(^2\)) radiant heat source for an amount of time determined by the investigator (step 1). The sample is mounted in the sample holder to provide a spacing of 0.25 inches between the test sample and thermal sensor. The spacing provides an insulating air layer on the inner surface of the turnout sample thus increasing the amount of energy stored in the sample during exposure. After the sample is exposed it is removed from the heat source and allowed to cool (step 2). Seventy-five seconds after the start of test, the sample is compressed using an insulating compression plate and data are collected for a period of 150 seconds. If a second degree burn is not predicted during compression (step 3), the exposure time is increased and the test is repeated using a new sample. This iterative process is continued until a second degree burn is predicted following the compression step. The minimum exposure time (MET) is measured and defined as the exposure required to just predict a second degree burn. If a second degree burn is predicted in the last sequence, the exposure time is decreased and the test is repeated using a new sample. This process is continued until a second degree burn is predicted following the compression step. The final exposure time which produced the second degree burn result is recorded as the MET value.

The experimental procedure can be summarized as follows:

- Cut and assemble 6 inch x 6 inch square samples of turnout systems.
- Condition samples in a lab environment for 24 hours.
- Start the heat source and calibrate to a heat flux level of 0.5 cal/cm\(^2\)-sec. Only the quartz tubes are used.
- Place the sample in the TPP tester and start the software.
  (The standard TPP tester was reprogrammed to for this procedure)
• Move the sample over the heat source, activate the shutter, and start data acquisition.
• Expose the sample to the 0.5 cal/cm²·sec heat source for the pre-selected exposure time.
• Stop the exposure at the end of the exposure time and remove the sample-sensor system from the heat source. Continue data acquisition.
• After 75 seconds of data collection, compress the sample using the insulated compression plate and a pressure of 6 kPa (1.0 psi). Keep the sample compressed and continue data acquisition.
• After 150 seconds from the start of testing, stop data acquisition.
• Calculate burn damage and determine if a second degree burn was predicted during compression.
• If a second degree burn was not predicted during compression, increase the exposure time and repeat the test using a new sample. Continue retesting until a second degree burn is predicted. The exposure time used in this last test becomes the Minimum value of Exposure Time or MET.
• If a second degree burn was predicted during compression, reduce the exposure time and repeat the test using a new sample. Continue retesting until no second degree burn is predicted. The last exposure time that generated a second degree burn prediction becomes the Minimum value of Exposure Time or MET.

Song et. al described the stored energy index as follows [13]:

The MET value may be used in conjunction with the turnout garment’s RPP burn time value to generate a Stored Energy Index value for a turnout composite [13]. The index is dimensionless and can be expressed as follows:

\[
\text{Stored Energy Index} = \frac{(\text{RPP burn time} - \text{MET})}{\text{MET}}
\]

The stored energy index indicates the stored energy or capacity discharge of the turnout system. In generating a RPP burn time value, the entire amount of thermal energy used to predict a second degree burn comes from heat transmission through the turnout. In
other words, no thermal energy stored in the turnout during exposure is transferred to the thermal sensor. Therefore, the energy used to predict a second degree burn comes from both heat transferred during the exposure and from stored energy discharged following compression with the turnout system. The difference between the RPP burn time and the MET burn time is an indication of the impact of the discharged stored energy on the predicted time to second degree. These concepts, as they were described by Song et. al; are illustrated below.

![Figure 2.4 Comparison of RPP burn time and MET burn times](image)

**Skin Burn Model**

The Henriques burn algorithm was used to predict time to second degree burn [6]. The parameters used the integral and thermal properties in skin heat transfer model are described in Appendix B.
2.2. Test Variables

2.2.1. Turnout Materials

A series of experiments were performed to examine the relationship between the total heat loss (THL) and the weight of the thermal liner component of the turnout system. Total heat loss (THL) is a measurement associated with the thermal comfort of a turnout composite. It is measured using the ASTM standard test method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate (F1868) in NFPA 1971 [2]. THL is influenced by the moisture vapor permeability of the moisture barrier and the insulation of the thermal liner component of the turnout layers. Three thermal liners, having different weight and thickness, and moisture barriers with different levels of moisture vapor permeability were selected for this study. All the test systems used the same outer shell fabric (Table 2.1).

<table>
<thead>
<tr>
<th>Table 2.1. Turnout Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Shell Fabric</td>
</tr>
<tr>
<td>60% Kevlar ®/ 40% PBI (254 g/m²)</td>
</tr>
<tr>
<td>Moisture Barrier</td>
</tr>
<tr>
<td>Thermal Liner (g/m²)</td>
</tr>
</tbody>
</table>

2.2.2. Preconditioning

Experiments were performed on both dry and wet turnout systems. For the dry tests, test samples were preconditioned in a standard atmosphere at 21°C ± 2°C and 60% ± 5% relative humidity for 24 hours. For the wet condition, the samples were preconditioned using a procedure that attempted to simulate the introduction of moisture by sweat produced by an active firefighter. The procedure includes one hour preconditioning in
standard atmosphere. Water was sprayed directly onto the face cloth side of the thermal liner component. Spray application was adjusted to introduce 15% of sample weight water into the thermal liner. Turnout systems, wetted in this manner, were then sealed in a plastic bag and allowed to condition for 24 hours.

2.2.3. Heat Exposure

In order to select appropriate thermal exposures, the conditions under which firefighter protective clothing will be used must be considered. As mentioned by Barker et al., it is quite difficult to completely define the firefighter environment [3]. This is because of the many environmental, physical, physiological and psychological factors that affect a firefighter’s interaction with the fire scene. Nonetheless, data has been collected and information is available to provide a range of common thermal environment conditions that are classified into three general categories. These classifications are identified as routine, hazardous, and emergency. The summary provided in Table 2.2 has been presented by Barker et al. [3].
Table 2.2. Firefighter’s thermal environments. [3]

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Air Temperature (°F/°C)</th>
<th>Radiant Flux (cal/cm²·sec)</th>
<th>Tolerance Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foster &amp; Roberts[6]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Routine</td>
<td>100°C</td>
<td>0.02</td>
<td>25 min</td>
</tr>
<tr>
<td>Hazardous</td>
<td>120°C</td>
<td>0.07</td>
<td>10 min</td>
</tr>
<tr>
<td>Emergency</td>
<td>160°C</td>
<td>0.10</td>
<td>1 min</td>
</tr>
<tr>
<td>Abbott [1]</td>
<td>160-235°C</td>
<td>0.23</td>
<td>&lt;1 min</td>
</tr>
<tr>
<td></td>
<td>&gt;235 deg C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coletta [4]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Routine</td>
<td>20-70°C</td>
<td>&lt;0.04</td>
<td>10-20 minutes</td>
</tr>
<tr>
<td>Hazardous</td>
<td>70-300°C</td>
<td>0.04-0.30</td>
<td>1-5 minutes</td>
</tr>
<tr>
<td>Emergency</td>
<td>300-1200 °C</td>
<td>0.30-5.0</td>
<td>15-20 seconds</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Routine</td>
<td>140°F (60°C)</td>
<td>0.03</td>
<td>5-60 minutes</td>
</tr>
<tr>
<td>Hazardous</td>
<td>572°F (300°C)</td>
<td>0.20</td>
<td>5-20 minutes</td>
</tr>
<tr>
<td>Emergency</td>
<td>1832°F (1000°C)</td>
<td>2.50</td>
<td>5-20 seconds</td>
</tr>
</tbody>
</table>

Routine Conditions: These conditions are applicable to firefighters who are operating hoses or otherwise fighting fires from a distance, where no special clothing is necessary. According to Foster et. al. [6], the limits proposed are 25 minutes at 100°C and a thermal radiation limit of 0.024 cal/cm²·sec(1kW/m²). Abott et. al. [1] associates conditional limits of 20-70°C with thermal radiation of <0.04 cal/cm²·sec (1.67kW/m²).

Hazardous Conditions: These conditions (described as “ordinary” by Abbott et al.) are typical of those that would be encountered outside a burning room or small burning building. According to Hoschke [8], the lower bounds of this region are similar to firefighters ventilating a fire without water support, while the upper limits are applicable to those who are first into a burning building. Nonetheless, a “turnout” uniform is necessary to provide burn protection and to minimize thermal stress the firefighter may encounter. The range set by Foster et. al. [6] has been taken to be at least 1 minute at 160°C and a thermal radiation of 0.096 cal/cm²·sec (4kW/m²) and can be tolerated up to
10 minutes. Abbott et al. [1] describe this condition as lasting 10 – 20 minutes with air temperatures of 70°C - 300°C with thermal radiation of 0.04cal/cm²·sec to 30cal/cm²·sec (4.0 to 12.56kW/m²).

**Emergency Conditions:** These conditions may be encountered during “flashover” of a large building fire. These conditions have been taken to be above the range of “Hazardous” conditions and ranging to beyond 235°C and 0.23cal/cm²·sec (10 kW/m²) by Foster et. al.[6]. Severe thermal problems and life threatening injuries are associated with these conditions. Abbott et. al. [1] describe these conditions as having temperatures of 300°C to 1200°C and 0.30 cal/cm²·sec to 5.0 cal/cm²·sec (12 to 209 kW/m²).

Since it was impractical to test all possible heat exposure scenarios, this research performed preliminary experiments to determine a range of thermal exposures that does not produce significant visible damage, or charring, to the outer shell fabric layer of the turnout system. On this basis, the following conditions were tested for this study:

- 0.06 Cal/cm²·sec
- 0.25 Cal/cm²·sec
- 0.50 Cal/cm²·sec

These exposures were selected to represent a reasonable range of thermal conditions that could be encountered by fire fighters working in thermal environments within a room that has not reached a flashover level [3].
3. RESULTS AND DISCUSSION

3.1. RESULTS

A series of experiments were conducted to investigate the effects of moisture barrier permeability (THL), thermal liner weight, attached reflective trim and applied moisture on heat transmitted and stored by selected turnout systems. The following discussion describes the results of experiments conducted at 0.50 cal/cm²·sec (21 kW/m²). These data are also described in reference 13.

3.1.1. Effect of the Thermal Liner Component

Three turnout systems, representing thick, thin and mid range thermal liner components were tested. For these tests, the same high THL moisture barrier was incorporated in the three systems. The turnouts were tested using the standard TPP test apparatus set to produce a radiant flux of 0.5 cal/cm²·sec (21 kW/m²). The time to predict a second degree burn was determined (RPP). The systems were then tested using the stored energy procedure to determine the MET time to a second degree burn times. Results for turnout systems tested in the dry condition are shown in Figure 3.1. These data show that thick systems exhibit a higher RPP burn time than the mid and thin system, due to their greater weight and thickness. However, no significant differences in MET burn times are observed for the mid and thick systems. This result indicates the heavier and thicker system, while providing a greater value of thermal insulation, also stores a greater amount of thermal energy. This is indicated in the stored energy index values shown in Table 3.1. This finding demonstrates that a turnout system utilizes a
thicker thermal liner may not necessarily provide the additional thermal protection indicated by a RPP type test. This is because an RPP test measures transmitted thermal energy. It does not account for the concentration of thermal energy stored in the turnout during the exposure. If stored energy is accounted for, the thicker system thermal protective performance is compatible to the middle weight ensemble.

### Table 3.1 Store Energy Index

<table>
<thead>
<tr>
<th>Turnout Systems</th>
<th>Thick System</th>
<th>Mid-Range System</th>
<th>Thin System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored Energy Index (SEI)</td>
<td>0.93</td>
<td>0.71</td>
<td>0.62</td>
</tr>
</tbody>
</table>

#### Figure 3.1 Comparison between MET and RPP Indexes measured in dry condition
3.1.2. Effects of Moisture

The middle and thick turnout systems were preconditioned with 15% moisture by weight using the method described in the experimental section of this thesis. The two moist preconditioned systems were evaluated to measure the MET and RPP. Results comparing moist with dry conditions are shown in Figure 3.2 and Table 3.2. These data show that the addition of 15% moisture to the turnout systems decreased RPP burn time, but has no effect on MET. The decrease in RPP value can be attributed to the decrease in thermal conductivity caused by the introduction of moisture into the turnout system. As a result, the store energy index, as indicated in Table 3.2, is significantly reduced. The reduction in thermal store energy index value suggests that more thermal energy is transmitted than is stored by the turnout system. In the MET approach, adding moisture to the turnout system has no effect on thermal protective performance. The difference in the store energy index, measured both in dry and wet states, indicates that the burn injury associated with moisture in the turnout is mainly caused by transmitted thermal energy. In comparison the burn injury predicted in the dry turnout is undoubtedly a result of the discharge of stored thermal energy from the turnout material.

Figure 3.3 compares the MET and RPP values with different moisture barriers in dry and wet conditions. The results indicate both moisture barriers exhibit the same trend in values made using MET and RPP approach.
Figure 3.2 MET and RPP values in Dry and Wet Conditions for thermal liners of different thickness

Figure 3.3 Moisture Barrier (THL) on MET and RPP Index in Dry and Wet Conditions
Table 3.2 Stored Energy Index in Turnout Systems Wet and Dry

<table>
<thead>
<tr>
<th>Turnout System</th>
<th>Mid-Thickness Thermal Liner</th>
<th>Higher-Thickness Thermal Liner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored Energy Index (SEI) Dry</td>
<td>0.71</td>
<td>0.93</td>
</tr>
<tr>
<td>Stored Energy Index (SEI) Wet</td>
<td>0.33</td>
<td>0.36</td>
</tr>
</tbody>
</table>

3.1.3. **Effect of Attached Reflective Trim**

A series of experiments was conducted to investigate the effect of attached reflective trim on the measured MET and RPP indexes. This was done by sewing a three inch piece of reflective trim to the outer shell component of the turnout composite. The trim layer was positioned directly under the thermal sensor in the stored energy test.

Figure 3.4 and Table 3.3 show the effect of a trim component on measured MET and RPP indexes for turnout systems having different THL indices. Results are shown for tests made on dry and moist turnout systems. Each of these systems incorporated the same mid weight thermal liner.
Figure 3.3 and Figure 3.4 show that the addition of the reflective trim increased both the RPP and the MET values when tests are conducted in dry condition. When the turnout is moisture preconditioned, a significant decrease in RPP and MET value is observed in turnout systems having higher THL values. No significant change in MET and RPP value is observed on the turnout system with lower THL moisture barrier. Since

<table>
<thead>
<tr>
<th>Turnout Composite</th>
<th>Middle Weight Thermal Liner High THL (no Trim)</th>
<th>Middle Weight Thermal Liner High THL (with Trim)</th>
<th>Middle Weight Thermal Liner Low THL (with Trim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored Energy Index (SEI) Dry</td>
<td>0.71</td>
<td>0.65</td>
<td>0.71</td>
</tr>
<tr>
<td>Stored Energy Index (SEI) Wet</td>
<td>0.33</td>
<td>0.62</td>
<td>0.79</td>
</tr>
</tbody>
</table>
THL is an indication of the vapor permeability of the moisture barrier, these results suggest that the moisture distribution established in the moisture preconditioning stage, in the turnout system may play a role in stored thermal energy phenomena. Table 3.3 shows the store energy index calculated from system with different moisture barrier in wet and dry conditions. These test results also show that the addition of reflective trim to the dry system does not significantly change stored energy performance in comparison to the system without trim. On the contrary, reflective trim increases the store energy in turnout systems that have been wet preconditioned.

3.2. Effects of the Heat Exposure Intensity

Similar experiments were conducted to investigate material and moisture effects at lower heat flux intensities specifically at the, 0.25 and 0.06cal/cm²·sec levels. Additional modifications to the testing apparatus were required to conduct test at the 0.06cal/cm²·sec exposure. The apparatus used for the lowest intensity exposure is described in detail in appendix B.

At the 0.25cal/cm²·sec thermal exposure level, moisture applied to the turnout system was observed to have a greater effect on the protective performance measured in the stored energy test. Therefore, moisture becomes more critical in affecting the MET value. In figure 3.5, one can see a slight change in MET due to moisture which was not evident at the 0.50cal/cm²·sec thermal exposure level. As expected, moisture decreases the protective performance of the system, as was observed with the results obtained from the RPP approach. In figure 3.6, one can see the negative impact moisture has on systems despite differences in THL of the moisture barrier components used in the turnout composite. At this level, moisture appears to have a larger effect on the systems
with the higher THL moisture barriers. When comparing the change in MET from wet to dry conditions, the higher THL shows a larger difference. The results indicate both moisture barriers exhibit the same trend in MET and RPP values.

Figure 3.5 MET and RPP values in Dry and Wet Conditions for thermal liners of different thickness at 0.25 cal/cm$^2$-sec

Figure 3.6 Effect of Moisture Barrier (THL) on MET and RPP Index in Dry and Wet Conditions at 0.25 cal/cm$^2$-sec
Figure 3.7 shows that, at the 0.25 calorie exposure level, turnout systems with high and lower THL show a significant drop in protection due to the combination of moisture and trim in the RPP and MET tests. The system having the lower THL continues to exhibit a longer protection time under dry and moist conditions. Table 3.4 shows that the higher THL system with trim goes through larger changes in Store Energy Index, whereas the lower THL remains relatively high during all conditions. The results indicate that the addition of reflective trim to the dry and wet system does significantly change the stored energy performance over the system without trim.

![Figure 3.7 - Effect of Trim on measured MET and RPP Indexes at 0.25 cal/cm\(^2\) sec](image)

**Table 3.4 Stored Energy Index of System with Trim and without Trim in Dry and Wet Conditions at 0.25 cal/cm\(^2\) sec**

<table>
<thead>
<tr>
<th>Turnout System</th>
<th>Middle Weight System without Trim (High THL)</th>
<th>Middle Weight System with Trim (High THL moisture Barrier)</th>
<th>Middle Weight System with Trim (Low THL moisture Barrier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored Energy Index (SEI) Dry</td>
<td>0.49</td>
<td>1.13</td>
<td>0.95</td>
</tr>
<tr>
<td>Stored Energy Index (SEI) Wet</td>
<td>0.31</td>
<td>0.63</td>
<td>0.94</td>
</tr>
</tbody>
</table>
At the 0.06 cal/cm²·sec exposure level, the variation in protective performance due to thermal liner and added moisture were even more apparent. The same patterns and results seen at the half and quarter calorie level are evident here, but are more pronounced in the 0.06 cal/cm²·sec exposure. Figure 3.8 shows that there is almost a 100 second difference in MET between the mid weight system in both dry and wet condition. The thick thermal liner alone provided a 55 seconds increase in protection time, which was expected from earlier results, but not necessarily to that degree. At the 0.25 calorie level the largest difference in MET was only ten seconds. The differences in protection time between the RPP and MET approach are no longer 40 and 60 seconds, but in the hundreds. These results clearly show that the discharge of stored energy can have significant impact on the protective performance of turnout systems.

![Figure 3.8 MET and RPP values in Dry and Wet Conditions for thermal liners of different thickness at 0.06 cal/cm²·sec](image)

When comparing the moisture barriers in figure 3.9 the difference between dry and wet MET conditions are clearly seen. As shown in figure 3.6, at the prior level moisture was more influential to the higher THL system resulting in a larger range between the dry and wet conditions.
wet MET. At the 0.06 calorie level when the effect of stored energy is not being measured under the RPP approach. The Lower THL system is apparently even more affected by the presence of moisture when compared to the dry and wet RPP of the higher THL system. This study generally confirms previous studies [3, 9] that have shown that moisture, present in the thermal liner component of a firefighter turnout can have a major effect on transmitted thermal energy and potential for skin burn injury.

Figure 3.9 Effect of Moisture Barrier (THL) on MET and RPP Index in Dry and Wet Conditions at 0.06 cal/cm²·sec

Results shown in figure 3.7 are consistent with those in figure 3.10 that indicate larger protection times for lower THL turnout systems in comparison to their higher THL counterparts in wet turnouts, tested with attached trim. The RPP of the lower THL dry trim condition is hundreds of seconds greater than its higher THL counterpart. Under dry conditions in Table 3.5 for the first time the system without trim, barely shows any evidence of stored energy affecting its performance whatsoever. The higher THL is consistent with the previous results revealing that adding trim to the system increases the systems’ dependence on store energy. The stored energy index(SEI) in itself is a measure
of the difference between the RPP and MET approach. The SEI is an observation of the variation in performance of a turnout system when only the transmitted heat is considered compared to its performances when, not only its transmitted abilities are analyzed, but its ability to release thermal energy in the presence and absence of force. The larger the SEI the larger the drop in thermal performance will be due to the discharge of stored energy. At this level moisture increased the stored energy index suggesting that a large part of the burn injuries were caused by discharging the store energy. The lower THL system reverses this pattern decreasing the effect of stored energy at the 0.06 level.

![Figure 3.10 - Effect of Trim on measured MET and RPP Indexes at 0.06 cal/cm²·sec](image)

**Figure 3.10 - Effect of Trim on measured MET and RPP Indexes at 0.06 cal/cm²·sec**

**Table 3.5 Stored Energy Index of System with Trim and without Trim in Dry and Wet Conditions at 0.06 cal/cm²·sec**

<table>
<thead>
<tr>
<th>Turnout System</th>
<th>Middle Weight System without Trim (High THL)</th>
<th>Middle Weight System with Trim (High THL moisture Barrier)</th>
<th>Middle Weight System with Trim (Low THL moisture Barrier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored Energy Index (SEI) Dry</td>
<td>0.13</td>
<td>0.24</td>
<td>0.69</td>
</tr>
<tr>
<td>Stored Energy Index (SEI) Wet</td>
<td>0.32</td>
<td>0.66</td>
<td>0.33</td>
</tr>
</tbody>
</table>
4. CORRELATION BETWEEN RESULTS AT DIFFERENT HEAT FLUX LEVELS

Analysis was conducted to assess the relationship between MET values measured at different heat exposure intensities. Figures 4.1 to 4.3 show the correlation of turnout systems tested in the dry conditions at exposure levels 0.50, 0.25 and 0.06 cal/cm²·sec. Figures 4.4, 4.5, and 4.6 show the correlation of turnout systems tested in the moist conditions at exposure levels 0.50, 0.25 and 0.06 cal/cm²·sec. The effect of trim on the correlation study can be observed in Figures 4.7 to 4.9, dry conditions, and 4.10 to 4.12, wet conditions.

These data indicate a high degree of correlation amongst the various heat flux levels considered for systems tested in dry conditions.

Figure 4.1 – MET values measured at 0.25 and 0.50 cal/cm²·sec (Dry turnout systems)
Figure 4.2 – MET values measured at 0.06 and 0.50 cal/cm²·sec (Dry turnout systems).

Figure 4.3 – MET values measured at 0.06 and 0.25 cal/cm²·sec (Dry turnout systems).
Figures 4.4 to 4.6 show that moisture present in the turnout systems tended to reduce the level of correlation between MET values measured at different levels of heat exposure. This is probably due to the movement of moisture within the turnout systems during extended periods of testing. Further studies, at heat exposure levels lower than the 0.06cal/cm²·sec, have shown that moisture tends to move from the thermal liner into the moisture barrier and outer shell region. Figures 4.5 and 4.6 indicate that the movement of moisture, associated with the 0.06cal/cm²·sec, decreases the correlation between the MET values measured at 0.50 and 0.25cal/cm²·sec. In addition to the movement of moisture, the rate of evaporation and condensation at the low heat flux exposure levels should be different significantly impacting the overall storage and transmittance of thermal energy.

Figure 4.4 – MET values measured at 0.50 and 0.25 cal/cm²·sec, (Wet turnout systems).
Figure 4.5 – MET values measured at 0.50 and 0.06 cal/cm$^2$·sec (Wet turnout systems).

Figure 4.6 – MET values measured at 0.25 and 0.06 cal/cm$^2$·sec (Wet turnout systems).
The application of trim on the dry systems provided no additional significant variation. According to the R-squared values trim appears to provide a high degree of correlation between MET values measured at exposure levels 0.50, 0.25 and 0.06 cal/cm²·sec.

![Graph showing MET values measured at 0.50 and 0.25 cal/cm²·sec (Dry turnout systems with trim).](image1)

Figure 4.7 – MET values measured at 0.50 and 0.25 cal/cm²·sec (Dry turnout systems with trim).

![Graph showing MET values measured at 0.50 and 0.06 cal/cm²·sec (Dry turnout systems with trim).](image2)

Figure 4.8 – MET values measured at 0.50 and 0.06 cal/cm²·sec (Dry turnout systems with trim).
The combination of moisture and trim decreases the correlation at every exposure level compared to the dry trim analysis above, Figure 4.7, 4.8, 4.9. In Figure 4.5 and 4.6 the application of moisture proved to be generally detrimental to the correlation of the 0.06cal/cm²·sec level. Trim decreased the correlation between MET values measured at the 0.50 and 0.25cal/cm²·sec level compared to its wet value in Figure 4.4. However, trim improved the correlations between 0.50 and 0.06cal/cm²·sec as well as 0.25 and 0.06cal/cm²·sec.

Figure 4.9 – MET values measured at 0.25 and 0.06 cal/cm²·sec (Dry turnout systems with trim).
Figure 4.10 – MET values measured at 0.50 and 0.25 cal/cm$^2$·sec (Wet turnout systems with trim).

Figure 4.11 – MET values measured at 0.50 and 0.06 cal/cm$^2$·sec (Wet turnout systems with trim).
At lower heat flux levels the difference between Minimum Exposure Times increased from about 11 percent at 0.50cal/cm$^2$.sec to about 30 percent at 0.06cal/cm$^2$.sec. Minimum Exposure Times at the 0.06cal/cm$^2$.sec level varied anywhere from 1 to five seconds.

It should be noted that testing at the 0.06cal/cm$^2$.sec level was highly sensitive and taxing on the operator. A slight gust of wind in front of the test setup could vary the results. Test runs lasted anywhere from 400 seconds to 24 minutes. At the conclusion of the test a majority of the moisture had escaped the system leaving the thermal liner moist. Due to the fact that the exposure times were so long, a five to ten second variation in MET may or may not be enough to introduce an error in the measured differences in MET due to thickness, moisture, moisture barrier, and trim.

Figure 4.12 – MET values measured at 0.25 and 0.06 cal/cm$^2$.sec (Wet turnout systems with trim).
5. EFFECT OF INTERACTING VARIABLES ON STORED ENERGY

A multiple linear regression analysis was conducted to better qualify the effect of material variables, including thermal liner, moisture barrier, as well as the effects of trim and applied moisture on the stored energy test results. The effects of the intensity of the thermal exposure were also analyzed. For this analysis, two of the independent variables, moisture and trim, were assigned a numerical value of zero or one, this indicating their absence or presence in the test. Variables such as thermal liner, moisture barrier, and heat flux level were assigned values of one, two, and three signifying type or intensity level. Table 5.1 provides the minimum, maximum, median, 1st and 3rd quartiles, as well as the mean value for each variable. This study assessed the statistical significance of each variable in predicting the MET value during testing.

<table>
<thead>
<tr>
<th>Variable</th>
<th>MET</th>
<th>Thermal Liner</th>
<th>Moisture Barrier</th>
<th>Trim</th>
<th>Heat Flux Level</th>
<th>Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>30.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1st Qu.</td>
<td>58.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>100.0</td>
<td>2.0</td>
<td></td>
<td></td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>212.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd Qu.</td>
<td>375.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td>945.0</td>
<td>3.0</td>
<td>2.0</td>
<td>1.0</td>
<td>3.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Combining all the data from the three thermal levels resulted in large variations in MET. Due to the differences associated with the MET values a transformation of the original data was conducted using the log function.

\[
\log(\text{MET}) \sim (\text{Thermal Liner} + \text{Moisture Barrier} + \text{Trim*Water})
\]
Tables 5.2 to 5.4 show the result from the linear regression study on MET. Each table contains degrees of freedom, sum of square value, mean square value, and both F and p values for exposure levels 0.50, 0.25 and 0.06cal/cm\(^2\).sec. According to table 5.2 the only significant factors affecting MET at the 0.50 cal/cm\(^2\).sec exposure level were moisture and trim.

<table>
<thead>
<tr>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL</td>
<td>2</td>
<td>0.09605</td>
<td>0.048025</td>
<td>1.5082</td>
</tr>
<tr>
<td>MB</td>
<td>1</td>
<td>0.122398</td>
<td>0.122398</td>
<td>3.844</td>
</tr>
<tr>
<td>Trim</td>
<td>1</td>
<td>0.001593</td>
<td>0.001593</td>
<td>0.05</td>
</tr>
<tr>
<td>Water</td>
<td>1</td>
<td>0.234948</td>
<td>0.234948</td>
<td>7.3787</td>
</tr>
<tr>
<td>Trim:Water</td>
<td>1</td>
<td>0.196337</td>
<td>0.196337</td>
<td>6.1661</td>
</tr>
<tr>
<td>Residuals</td>
<td>9</td>
<td>0.286574</td>
<td>0.031842</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 Linear Regression Study at 0.50 cal/cm\(^2\).sec

Table 5.3 shows that varying the thermal liner and moisture barrier at the 0.25 cal/cm\(^2\).sec exposure level fails to produce any significant differences in MET. Whereas, trim and moisture, according to their p-value, increases in significance from 0.50 to 0.25 cal/cm\(^2\).sec exposure levels.

<table>
<thead>
<tr>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL</td>
<td>2</td>
<td>0.058597</td>
<td>0.029299</td>
<td>3.4901</td>
</tr>
<tr>
<td>MB</td>
<td>1</td>
<td>0.01977</td>
<td>0.01977</td>
<td>2.355</td>
</tr>
<tr>
<td>Trim</td>
<td>1</td>
<td>0.067167</td>
<td>0.067167</td>
<td>8.001</td>
</tr>
<tr>
<td>Water</td>
<td>1</td>
<td>0.294391</td>
<td>0.294391</td>
<td>35.0683</td>
</tr>
<tr>
<td>Trim:Water</td>
<td>1</td>
<td>0.166958</td>
<td>0.166958</td>
<td>19.8883</td>
</tr>
<tr>
<td>Residuals</td>
<td>9</td>
<td>0.075553</td>
<td>0.008395</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3 Linear Regression Study at 0.25 cal/cm\(^2\).sec

At the 0.06 cal/cm\(^2\).sec exposure level the type of moisture barrier contained in the turnout system becomes a significant factor in determining MET. Trim and moisture continues to be a significant factor at the 0.06 cal/cm\(^2\).sec exposure level.
Table 5.4 Linear Regression Study at 0.06 cal/cm².sec

<table>
<thead>
<tr>
<th></th>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL</td>
<td>2</td>
<td>0.17719</td>
<td>0.08859</td>
<td>3.2671</td>
<td>0.09179</td>
</tr>
<tr>
<td>MB</td>
<td>1</td>
<td>0.16586</td>
<td>0.16586</td>
<td>6.1166</td>
<td>0.038519*</td>
</tr>
<tr>
<td>Trim</td>
<td>1</td>
<td>0.0228</td>
<td>0.0228</td>
<td>0.8407</td>
<td>0.386003</td>
</tr>
<tr>
<td>Water</td>
<td>1</td>
<td>0.55141</td>
<td>0.55141</td>
<td>20.3346</td>
<td>0.001977 **</td>
</tr>
<tr>
<td>Trim:Water</td>
<td>1</td>
<td>0.3132</td>
<td>0.3132</td>
<td>11.5499</td>
<td>0.009381 **</td>
</tr>
<tr>
<td>Residuals</td>
<td>8</td>
<td>0.21694</td>
<td>0.02712</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to the results at all the thermal exposure intensities the effect of trim on MET is dependent on the presence or absence of moisture within the turnout system. The plots located in Figure 5.1 and 5.2 below show the changes in mean MET values due to variations in moisture and heat flux in the absence and presence of trim. In the presence of trim and moisture MET decreases. In the absence of trim MET is not as variable with the addition of moisture. In the absence of moisture adding trim to the turnout system increases MET.

Figure 5.1 – Average MET due to variations in Moisture with and without trim.
Lower heat exposure intensities result in larger MET differences due to the presence and absence of trim. A decrease in thermal exposures intensity results in an increase in material variable significance, seen in table 5.4. At the 0.06cal/cm².sec level on average turnout systems with trim tend to have higher MET values.

Figure 5.2 – Average Log(MET) due to variations in Flux with and without trim.
6. CONCLUSIONS

Turnout systems used in fire fighters protective clothing are capable of storing thermal energy when exposed to low heat flux conditions. The MET procedure for all test conducted predicted 2\textsuperscript{nd} degree burn times prior to all the RPP transmittance study without compression. In the absence of moisture and trim, turnout systems having thicker liners typically have higher stored energy. Thicker thermal liners without the presence of trim had larger SEI values, suggesting a greater ability to store and discharge more thermal energy than thinner systems. The application of moisture on all systems with and without trim consistently reduced the MET values. Moisture also decreased the stored energy for most systems. In general, moisture increased the amount of thermal energy transmitted and decreased the amount of thermal energy stored. Differences in thermal performance were primarily dependent on the large variation of thickness associated with the moisture barriers. The application of trim resulted in an increase in MET for dry systems. Trim also typically increased the SEI. The addition of trim for most cases increased the overall thermal protection for all dry systems. The degree of impact trim and moisture had on a composite varied depending highly on the THL and thermal liner. Trim combined with moisture resulted in the largest drop in MET for all the systems except for the Low THL system. Moisture without trim was the worst case for low THL systems. The MET analysis demonstrated that the protective performance indicated by MET was consistent in different low level thermal radiations. However, the difference of moisture, thickness and trim was pronounced in lower levels of radiation (for example: 0.06 cal/cm2.sec) The SEIs were generally lower at the lower heat flux levels, implying that discharging the stored energy at a higher flux level would be more
influential on the thermal performance. At every flux level the dry thermal liner ranking remained consistent. There is a high degree of correlation amongst the three heat flux levels under dry conditions. At lower heat flux levels the difference between Minimum Exposure Times increased from 1 and 2 seconds at the 0.50cal/cm\(^2\).sec to hundreds of seconds at the 0.06cal/cm\(^2\).sec level. The statistical significance of all the material factors increases as the thermal exposure intensity decreases.
7. RECOMMENDATIONS

Additional research is needed to further develop these test procedures. This research should be focused on the goal of developing and demonstrating a method that can produce reliable results when used by different testing laboratories. This includes improving the apparatus used to apply compression to test samples and redesigning the test platform. Work is also needed to qualify the effects of the moisture preconditioning protocol, and to fully define optimum testing variables, including exposure time and the intensity of the heat exposure. The turnout materials selected for this study represents a small cross-section of all the possible composite materials used in the construction of firefighter turnouts. A wider range of turnout materials and attachments needs to be studied to better qualify material effects. Consideration also needs to be given to the performance levels that are used with stored energy tests. Ideally these performance levels should be defined with input from firefighters. Finally, research is needed to provide a fundamental basis for understanding the stored energy phenomena in firefighter turnouts.
8. BIBLIOGRAPHY


7. Henriques, F.C., Jr., "Studies of Thermal Injuries V. The Predictability and the
   Significance of Thermally Induced Rate Processes Leading to Irreversible

   April 1981, pp. 125-137.

   and Security Systems Division 3M Center, St. Paul, MN

10. Lawson, J.R., “Fire Fighters’ Protective Clothing and Thermal Environments of
    Structural Fire Fighting,” *Performance of Protective Clothing: Sixth Volume,
    SATM STP 1273*, Jeffrey O. Stull and Arthur D. Schwope, Eds. American Society

11. Morse, H., Tickner, G., and Brown, R., “Burn Damage and Burn Depth Criteria,”
    Aerotherm Projects 6269 and 6393, Aerotherm TN-75-26, 1975.


    Energy And Clothing Thermal Protective Performance" Proceedings of the IFAI
    Symposium on Safety and Protective Fabrics, Industrial Fabrics Association,
    Roseville, MN.
A. Experimental Apparatus (0.50 & 0.25 cal/cm²·sec)

TPP (F1060-01) test apparatus

The radiant quartz tube, water cooled shutter, copper calorimeter, ¼ inch spacer, sample and sensor holder, everything excluding the Meker burners from ASTM F1060-01 were used to subject the samples to a thermal energy composed solely of radiant heat. The TPP apparatus was created by Custom Scientific Instrument.

Sensors

The water cooled Medtherm Schmidt-Boelter heat flux transducer was used to calibrate the heat source and measure transmitted flux at the 0.25 cal/cm²·sec and 0.06 cal/cm²·sec flux level. The sensor assembly consisted of a 5.95 in. x 5.95 in. x 2 in. Medtherm mounting block constructed of a machineable ceramic. The TPP copper calorimeter (ASTM F1060-01) was used for calibration and measuring heat flux at the 0.50 cal/cm²·sec level.
B. Experimental Apparatus (0.06cal/cm².sec)

Black Body

A 12 in. x 6 in. x 3 in. Black Body Radiant Heat Panel was used to provide a heat flux of 0.06 cal/cm² sec (2,500 W/m²).

Sample Holder

The specimen holder assembly was made from 1/8 inch Stainless Steel. Its overall dimensions were 8 in. x 8 in. x 1 in. The holder included a 4 in. x 4 in. exposure hole in its center. The holder had two stainless .25 in. x .25 in. x 1.5 in. steel wings welded onto its sides which enabled it to slide from exposure to compression positions in a fluid manner. The wings traveled on two stainless steel 12.5 in. x 1 in. x 1 in. tracks which were bolted directly onto the TPP sample stand (ASTM F1060-01). The heat source and sample holder can be seen in the figure below.
Compression Apparatus

During the compression stage of the experiment the sample was compressed by two 2.3 in. x 2.96 in. x 1 in. insulation blocks stacked on top of each other providing an overall force of 1psi onto the outer shell of the specimen. The compression apparatus was a large 11 in. x 6.75 in. x 6.75 in. C channel made of cold roll steel (CRS). The C channel contained a large 7.5 in. x 6 in. x 2.11 in. CRS box which traveled up and down the channel. The box was moved into compressed and uncompressed positions using a 13.66 in. x 1 in. x .5 in. CRS bar. The bar was held in its compressed position using a rectangular 2.07 in. x 1.66 in. x .5 in. steel block. The compression apparatus was designed to provide a consistent force independent of the user performing the test. All detail design specifications on the compression Apparatus along with the new sample holder assembly for the 0.06 Cal/cm².sec level can be found below.
Figure 9.2 Test setup with Compression apparatus
Appendix C. Skin Burn Model [11]

The skin heat transfer model used in this study adopted Pennes’ approach to model heat conduction in human skin [3]. The model consists of three tissue layers: the epidermis, dermis, and subcutaneous layers which accounts for cooling blood perfusion in the subcutaneous layer. Therefore,

\[
\rho_s c_{p,s} \frac{\partial T}{\partial t} = \nabla \cdot (k_s \nabla T) + (\rho c_{p,b})_o \alpha_b (T_a - T) \quad x > L_s, \ t > 0 \quad (3).
\]

In equation (3), \(\rho_s, c_{p,s}\) and \(k_s\) are the density, specific heat and thermal conductivity of human tissue and \(\rho_b\) and \(c_{p,b}\) are the density and the specific heat of blood. \(\alpha_b\) is the rate of blood perfusion and is taken to be 0.00125 \(m^3/s/m^3\). The boundary condition at the base of the subcutaneous layer is set at a constant basal temperature of 37°C. As an initial condition, linear distribution of skin temperature is assumed between a surface temperature of 34°C and the basal temperature of 37°C. The skin layer thermal physical properties are summarized in Table 4.

Once the temperatures within the skin are determined, Henriques’ burn integral [4] is used to estimate the times required to first, second and third degree burn.

\[
\Omega = \int_0^t P \exp \left( -\frac{\Delta E}{RT} \right) dt
\]

(4)

where \(\Omega\) - a quantitative measure of burn damage at the basal layer or at any depth in the dermis,

- \(P\) – frequency factor, \(s^{-1}\),
- \(\Delta E\) – the activation energy for skin, \(J/mol\),
- \(R\) – the universal gas constant, 8.315 \(J/kmol.K\)
- \(T\) – the absolute temperature at the basal layer or at any depth in the dermis, \(K\), and
- \(t\) – total time for which \(T\) is above 44°C (317.15K).

The values of \(P\) and \(\Delta E\) in equation (4) are from Stoll and Takata [5]:

<table>
<thead>
<tr>
<th>Epidermis</th>
<th>(T &lt; 50^\circ C)</th>
<th>(P = 2.185 \times 10^{124} \ s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(T \geq 50^\circ C)</td>
<td>(P = 1.823 \times 10^{51} \ s^{-1})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dermis</th>
<th>(T &lt; 50^\circ C)</th>
<th>(P = 4.32 \times 10^{64} \ s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(T \geq 50^\circ C)</td>
<td>(P = 9.39 \times 10^{104} \ s^{-1})</td>
</tr>
</tbody>
</table>

\(\Delta E/R\) for different layers:

- **Epidermis**
  - \(\Delta E/R = 93,534.9 \ K^4\)
  - \(\Delta E/R = 39,109.8 \ K\)

- **Dermis**
  - \(\Delta E/R = 50,000 \ K\)
  - \(\Delta E/R = 80,000 \ K\)
The integration is performed from the time when the temperature of the basal layer of the skin, $T$, exceeds or equals $44^\circ C$. Henriques found that if $\Omega$ is less than, or equal to, 0.5 no damage will occur at the basal layer. If $\Omega$ is between 0.5 and 1.0, first-degree burns will occur, whereas if $\Omega > 1.0$, second-degree burns will result. The damage criteria can be applied to any depth of skin provided the appropriate values of $P$ and $\Delta E$ are used. Mathematically, a second-degree burn injury has been defined as an $\Omega > 1.0$ at the epidermis/dermis interface and a third-degree burn injury as an $\Omega > 1.0$ at the dermis/subcutaneous tissue interface.

### Table 9.1 Thermal Properties Used in the Skin Heat Transfer Model

<table>
<thead>
<tr>
<th>Human Skin/Thermal Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Epidermis</strong></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (W/m°C)</td>
<td>0.255</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1200</td>
</tr>
<tr>
<td>Specific heat (J/kg.°C)</td>
<td>3598</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>8.0×10⁻⁵</td>
</tr>
<tr>
<td><strong>Dermis</strong></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (W/m°C)</td>
<td>0.523</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1200</td>
</tr>
<tr>
<td>Specific heat (J/kg.°C)</td>
<td>3222</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>2.0×10⁻³</td>
</tr>
<tr>
<td><strong>Sub-cutaneous</strong></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (W/m°C)</td>
<td>0.167</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1000</td>
</tr>
<tr>
<td>Specific heat (J/kg.°C)</td>
<td>2760</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>1.0×10⁻²</td>
</tr>
</tbody>
</table>
D. Sensor and Heat Source Calibration

Figure 9.3 Medtherm Radiant Black Body Heat Source Calibration

Figure 9.4 TPP Sensor Radiant Black Body Heat Source Calibration
Figure 9.5 Medtherm Radiant Black Body Heat Source Calibration
E. Test Data Flux Change

### Mid Thermal Liner (High THL) Thermal Conditions at 0.50 Cal/cm².sec

![Graph](image)

**Figure 9.6** Mid Thermal liner, High THL system Dry, Wet, Dry Trim, & Wet Trim Conditions at 0.50 Cal/cm².sec MET Approach

### Mid Thermal Liner (Low THL) Thermal Conditions at 0.50 Cal/cm².sec

![Graph](image)

**Figure 9.7** Mid Thermal liner, Low THL system, under Dry, Wet, Dry Trim, and Wet Trim Conditions at 0.50 Cal/cm².sec MET Approach
Figure 9.8 Mid Thermal liner, High THL system, under Dry, Wet, Dry Trim, and Wet Trim Conditions at 0.25 Cal/cm² sec MET Approach

Figure 9.9 Mid Thermal liner, Low THL system, under Dry, Wet, Dry Trim, and Wet Trim Conditions at 0.25 Cal/cm² sec MET Approach
Figure 9.10 Mid Thermal liner, High THL system, under Dry, Wet, Dry Trim, and Wet Trim Conditions at 0.06 Cal/cm²/sec MET Approach

Figure 9.11 Mid Thermal liner, Low THL system, under Dry, Wet, Dry Trim, and Wet Trim Conditions at 0.06 Cal/cm²/sec MET Approach
F. MET Test Data

Table 9.2 MET Results for Thick, Thin, and Mid Thermal liners, Dry Condition

<table>
<thead>
<tr>
<th>Flux Level</th>
<th>Minimum Exposure Time Dry Results With High THL Moisture Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Thin)</td>
</tr>
<tr>
<td>0.50 Cal/cm(^2).sec</td>
<td>48</td>
</tr>
<tr>
<td>0.25 Cal/cm(^2).sec</td>
<td>98</td>
</tr>
<tr>
<td>0.06 Cal/cm(^2).sec</td>
<td>380</td>
</tr>
</tbody>
</table>

Table 9.3 MET Results for Thick, Thin, and Mid Thermal liners, Wet Condition

<table>
<thead>
<tr>
<th>Flux Level</th>
<th>Minimum Exposure Time Wet Results With High THL Moisture Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Thin)</td>
</tr>
<tr>
<td>0.50 Cal/cm(^2).sec</td>
<td>45</td>
</tr>
<tr>
<td>0.25 Cal/cm(^2).sec</td>
<td>88</td>
</tr>
<tr>
<td>0.06 Cal/cm(^2).sec</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 9.4 MET Results for Thick, Thin, and Mid Thermal liners, Dry Trim Condition

<table>
<thead>
<tr>
<th>Flux Level</th>
<th>Minimum Exposure Time Dry Trim Results With High THL Moisture Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Thin)</td>
</tr>
<tr>
<td>0.50 Cal/cm(^2).sec</td>
<td>55</td>
</tr>
<tr>
<td>0.25 Cal/cm(^2).sec</td>
<td>100</td>
</tr>
<tr>
<td>0.06 Cal/cm(^2).sec</td>
<td>540</td>
</tr>
</tbody>
</table>

Table 9.5 MET Results for Thick, Thin, and Mid Thermal liners, Wet Trim Condition

<table>
<thead>
<tr>
<th>Flux Level</th>
<th>Minimum Exposure Time Wet Trim Results With High THL Moisture Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Thin)</td>
</tr>
<tr>
<td>0.50 Cal/cm(^2).sec</td>
<td>35</td>
</tr>
<tr>
<td>0.25 Cal/cm(^2).sec</td>
<td>64</td>
</tr>
<tr>
<td>0.06 Cal/cm(^2).sec</td>
<td>340</td>
</tr>
</tbody>
</table>
Table 9.6 MET Results for Mid Thermal liner, Dry Condition

<table>
<thead>
<tr>
<th>Flux Level</th>
<th>(Mid) Low THL</th>
<th>(Mid) High THL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50 Cal/cm²·sec</td>
<td>53</td>
<td>54</td>
</tr>
<tr>
<td>0.25 Cal/cm²·sec</td>
<td>102</td>
<td>110</td>
</tr>
<tr>
<td>0.06 Cal/cm²·sec</td>
<td>465</td>
<td>545</td>
</tr>
</tbody>
</table>

Table 9.7 MET Results for Mid Thermal liner, Wet Condition

<table>
<thead>
<tr>
<th>Flux Level</th>
<th>(Mid) Low THL</th>
<th>(Mid) High THL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50 Cal/cm²·sec</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>0.25 Cal/cm²·sec</td>
<td>98</td>
<td>103</td>
</tr>
<tr>
<td>0.06 Cal/cm²·sec</td>
<td>430</td>
<td>420</td>
</tr>
</tbody>
</table>

Table 9.8 MET Results for Mid Thermal liner, Dry Trim Condition

<table>
<thead>
<tr>
<th>Flux Level</th>
<th>(Mid) Low THL</th>
<th>(Mid) High THL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50 Cal/cm²·sec</td>
<td>74</td>
<td>63</td>
</tr>
<tr>
<td>0.25 Cal/cm²·sec</td>
<td>129</td>
<td>111</td>
</tr>
<tr>
<td>0.06 Cal/cm²·sec</td>
<td>945</td>
<td>780</td>
</tr>
</tbody>
</table>

Table 9.9 MET Results for Mid Thermal liner, Wet Trim Condition

<table>
<thead>
<tr>
<th>Flux Level</th>
<th>(Mid) Low THL</th>
<th>(Mid) High THL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50 Cal/cm²·sec</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>0.25 Cal/cm²·sec</td>
<td>90</td>
<td>62</td>
</tr>
<tr>
<td>0.06 Cal/cm²·sec</td>
<td>505</td>
<td>295</td>
</tr>
</tbody>
</table>