Thermal Capacity of Fire Fighter Protective Clothing

Final Report

Prepared by:

National Institute for Occupational Safety and Health,
The National Personnel Protective Technology Laboratory
and
National Institute of Standards and Technology
and
North Carolina State University

A DHS/Assistance to Firefighter Grants (AFG) Funded Study

The Fire Protection Research Foundation
One Batterymarch Park
Quincy, MA, USA 02169-7471
Email: foundation@nfpa.org
http://www.nfpa.org/foundation

FOREWORD

Thousands of fire fighters sustain burn injuries every year. Line of duty injuries to fire fighters have been estimated to cost between 2.8 to 7.8 billion dollars a year. The most devastating off all injuries by every measure of pain, suffering, and cost is the burn injury. Significant numbers of these injuries occur when energy stored within the layers of the protective equipment are suddenly transferred to the fire fighter, resulting in burn injuries.

Protective equipment including turnout coats and pants are designed to insulate a fire fighter from the thermal environment. A series of protective layers and air gaps prevent the energy of the fire environment from being transferred to the fire fighter. However, if the protective layers are compressed, the energy stored within the material can suddenly be transferred to the user and cause burns.

Current product standards and testing protocols do not adequately evaluate the risk caused by this stored energy. Better understanding of the risk and the underlying physics will allow better designs for protective gear to prevent this type of burn injury. A performance metric addressing the amount of stored energy that accumulates in protective clothing under low heat flux conditions characterizing stored energy will lead to the development of more advanced materials.

This project provides helpful information for manufacturers to determine if the choice of materials for a particular design of protective clothing increases or decreases the potential for a low heat flux burn injury. This information supports current standards development activities underway at NFPA and ASTM based on the implementation of a stored energy test apparatus developed at North Carolina State University.

The goal of the project is to understand the thermal performance of fire fighters' protective clothing over a range of fire fighting exposures. This is accomplished by developing new information on the impact of stored energy on the thermal response of fire fighters' protective clothing, and improve test methods to measure this property so that this may be integrated into national consensus standards and training materials. This should ultimately translate into a reduction in the number of fire service burn injuries.

The Research Foundation expresses gratitude to the report authors and the primary team that has prepared this report, including Angie Shepherd and Bill Haskell of NIOSH NPPTL, Roger Barker, Shawn Deaton and Kevin Ross of NCSU, Nelson Bryner and Jeff Taylor of NIST, the Project Technical Panelists, and all others who contributed to this research effort. Special thanks are expressed to the U.S. Department of Homeland Security for providing the funding for this project.

The content, opinions and conclusions contained in this report are solely those of the author.

PROJECT TECHNICAL PANEL

Jason Allen, Intertek, Cortland NY

Steven Corrado, Underwriters Laboratories Inc, Research Triangle Park NC

Dean Cox, Fairfax County Fire & Rescue Department, Fairfax VA

Doug Dale, University of Alberta, Edmonton, AB Canada (ASTM F23.80 Subcommittee Liaison)

Rich Duffy, International Association of Fire Fighters

Pat Freeman, Globe Manufacturing, Pittsfield NH

Wei Gao, Director, Science & Technology Division, Ministry of Public Security of P.R. China
and Director of China Fire Protection Association

Bill Grilliot, Morning Pride Manufacturing, Dayton OH

Allen Hay, FDNY, New York City NY

Karen Lehtonen, Lion Apparel, Dayton OH

Mike McKenna, Sacramento Metro Fire District, Sacramento CA

Bruce Teele, NFPA, Quincy MA

Bruce Varner, Santa Rosa Fire Department, CA (IAFC Rep)

PROJECT SPONSOR

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Thermal Capacity of Fire Fighting Protective Clothing

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Fire Protection Research Foundation
1 Batterymarch Park
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Submitted by:

Center for Research on Textile Protection & Comfort
College of Textiles
North Carolina State University

In Collaboration with the

NIOSH National Personal Protective Technology Laboratory (NPPTL)

and the

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CAVEAT

This report describes the results of a limited laboratory study designed to provide a scientific basis for the evaluation of a laboratory testing apparatus and procedures useful in the evaluation of the thermal energy transmitted and stored in firefighter turnout materials when exposed to sub-flashover thermal environments. Care must be taken in drawing conclusions about the safety benefits from these data. The data describe the properties of selected fabrics in response to the controlled laboratory exposures and conditions that are specified. Study results must be weighed in light of the fact that no laboratory analysis can completely qualify complex fire fighting events, which can be physically complicated and unqualified. This study was not intended to recommend or exclude any materials from any particular application.

This report describes research to develop and demonstrate a viable laboratory testing procedure for measuring transmitted and stored thermal energy in materials used in the construction of firefighter turnout clothing. It recognizes the continuing need for ongoing research to establish a technical basis for any specific exposure conditions that may be the basis of evaluating performance in this test. It further recognizes that input from firefighters and consideration by the NFPA Technical Committee will be required to ultimately establish performance criteria for use with the technical data produced by the testing methodology described in this report.

SUMMARY

A laboratory testing procedure has been demonstrated for measuring the transmitted and stored thermal energy in moisture preconditioned turnout systems exposed to sub-flashover level radiant heat (0.2 cal/cm^{2}sec). Figure 1 shows the range of performance for twenty-eight different turnout materials configurations tested using this stored energy test (SET) method.

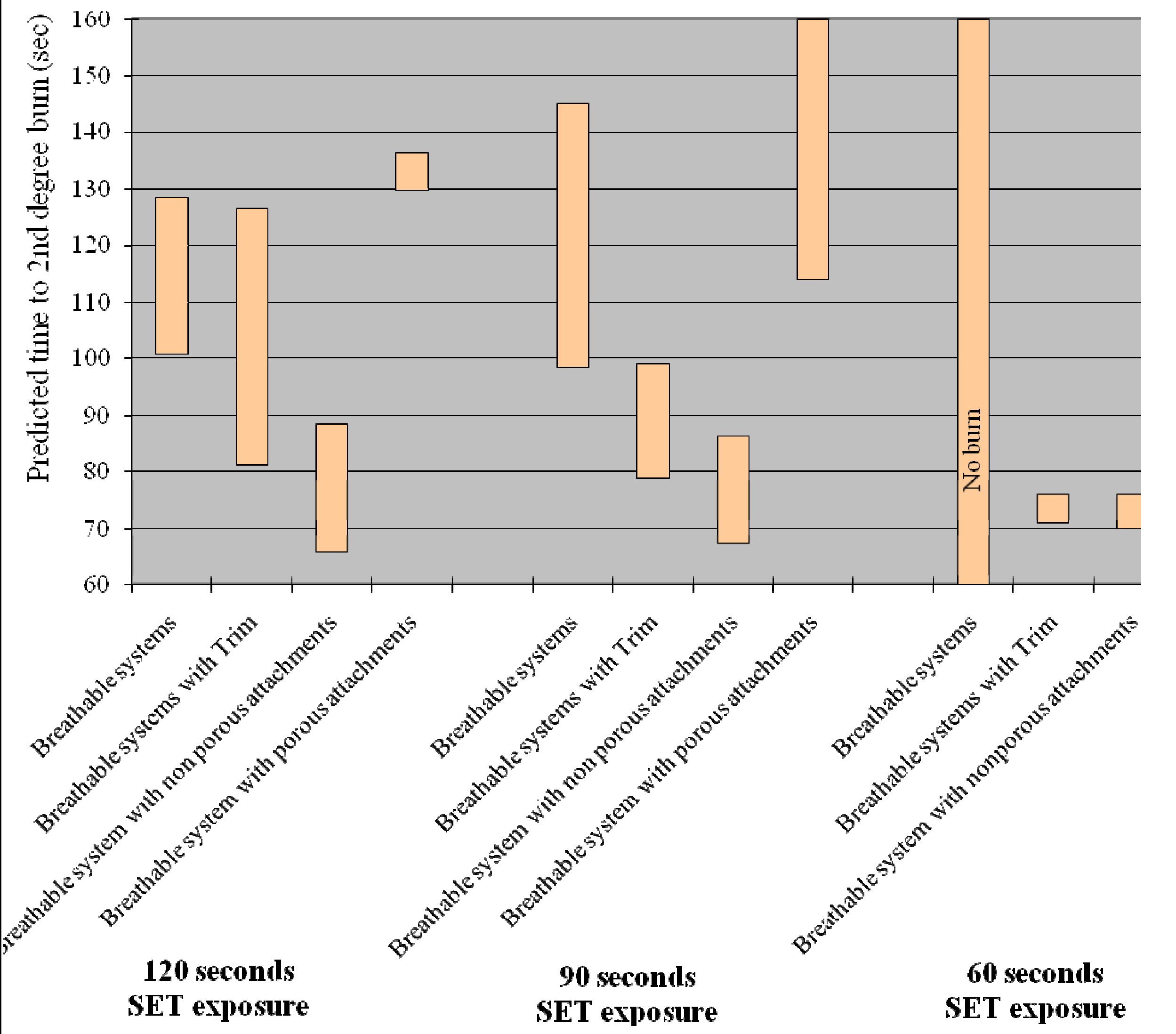

Figure 1. SET performance measured in 60, 90, and 120 seconds thermal exposures

These data show that, in turnout systems incorporating vapor permeable moisture barriers, the presence of non porous reflective trim or non porous reinforcing generally degrades SET performance. In systems with non porous outer shell attachments, reduction in test performance can be associated with increased moisture barrier moisture vapor transmission rate (MVTR).

Differences in thermal liners or outer shell fabrics have less pronounced effect compared to differences in moisture barrier permeability and trim porosity.

This laboratory based study shows that the Stored Energy Test (SET) method provides information not provided by any other protective performance test method currently incorporated in NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting. It supports a hypothesis that sub-flashover burn injuries may occur as the result of two different heat transmission mechanisms, or combination of two thermal phenomena. Tests conducted on moisture preconditioned materials exposed for 1.5 and 2.0 minutes to 0.2 cal/cm^2sec radiant heat, predict burns mainly from transmitted thermal energy. For these conditions, the SET functions essentially as a Radiant Protective Performance (RPP) test for moist samples with attached trim or reinforcements. For 1.0 minute radiant heat exposure followed by contact compression, SET performance is more noticeably influenced by thermal energy discharged from the heated turnout materials. Both phenomena could contribute to the burn hazard, depending on the specifics of the heat exposure and other conditions of use. In both scenarios, the presence of non porous reflective trim or non porous reinforcements reduces test performance when these materials are attached to the outer surface of a turnout composites consisting of a thermal liner, outer shell and a breathable moisture barrier.

Technical information has been provided that should be useful to the NFPA 1971 committee currently considering the establishment of performance criteria based on the results of this test method. By helping to identify material factors associated with SET performance, this study also provides insights into how turnouts may be designed to improve thermal protection in sub-flashover thermal exposures. In this regard, this research was limited to investigating a relatively small group of turnout materials and features used in turnout constructions. There is a need for tests on a wider range of configurations, including constructions that could mitigate SET degrading effects in breathable turnouts.

More tests are needed to more fully qualify all the observed materials effects, and to better understand these complex interactions. There is particular need for more tests at the 60 seconds thermal exposure condition.

This study indicates that the same turnout materials properties associated with higher levels of total heat loss (THL) can degrade performance in the SET. It would be useful, therefore, to generate THL data on turnout samples also tested in the SET. Data on thermal protective performance (TPP) would also be of value in demonstrating how the SET differentiates from this established test method.

INTRODUCTION

This report describes research conducted to develop a better understanding of the effects of turnout materials on heat transmission and thermal energy storage in moisture preconditioned samples exposed to low level radiant heat. It utilized a newly developed laboratory apparatus and testing procedures to generate data on a range of materials used in the construction of fire fighter turnouts. This project sought to produce a data base that would be useful to the committee currently considering stored energy testing and performance requirements for inclusion in the NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting. Performance criteria do not currently exist for evaluating the thermal protective performance of fire fighting garments with respect to the discharge of the stored thermal energy, or from heat transmitted by moist turnout materials exposed to sub flashover thermal conditions. There is an urgent need, therefore, to establish these performance criteria using a testing apparatus capable of predicting burn injuries associated with stored thermal energy or steam burns.

This project involved the combined efforts of the Fire Protection Research Foundation (FPRF), the National Institute of Standards and Technology (NIST), North Carolina State University (NCSU), and the National Institute for Occupational Safety and Health National Personal Protective Technology Laboratory (NIOSH/NPPTL). The primary technical aspects of the research were conducted at NCSU in coordination with NIOSH/NPPTL. NIST participated with NCSU in a study designed to assess the inter-laboratory reproducibility of the stored energy test method and procedures. The two stored energy test apparatuses and the burn prediction software used in this project were developed under NIOSH Contract No. 200-2005-12411 with North Carolina State University (NCSU). NIOSH/NPPTL made these test apparatuses available for the inter-laboratory testing conducted under the NFPA Fire Protection Research Foundation project. FPRF provided overall project team management and coordination and facilitated communications with user groups interested in the outcome of the research. This included formation of a Project Technical Panel (PTP) to function as an advisory group to the project. The PTP was established from the community of directly affected parties, including members of the fire service, clothing manufacturers, members of the relevant NFPA and ASTM Technical Committees, and technical experts on the subject of thermal measurements. The PTP provided invaluable guidance to the research team throughout every phase of the project.

BACKGROUND

Skin burn injuries associated with exposures to fire fighting conditions characterized by thermal energies below flashover have been long identified as a concern to firefighters. These below-flashover exposures are usually several minutes in duration and are generally not sufficient to produce significant thermal degradation to the outer shell fabric of the turnout suit. Burns are thought to occur as a result of thermal energy transmitted to the garment from the heated fire fighting environment. Subsequent compression of the heated turnout ensemble onto the body due to firefighter movement or external pressure is thought to exacerbate burns due to the discharge of thermal energy stored in the materials used in the construction of the turnout suit. Some of these burns have been associated with reflective trim, or reinforcement materials, attached to the outer shell of the turnout. The presence of moisture in the turnout materials, accumulated from sweat and water spray has also been associated with stored energy or steam burn phenomena.

Development of a qualified understanding of conditions that produce stored energy burns presents a significant challenge. This is because of the physical complexity inherent in actual fire fighting operations and the complicated interactions of many variables of use or exposure that may cause stored energy burns. Technically qualified characterization of these conditions, including specifics of the thermal exposure scenario or the moisture present in the turnout suit, often rely on anecdotal description of these events.

To facilitate development of a rationally based laboratory test method and performance criteria, it was important to obtain as much information as possible about the nature of fire fighting events that may be associated with stored energy burns. Information was gathered during firefighter stakeholder meetings held in conjunction with meetings of the NFPA 1971 Committee on Standards for Structural Firefighting Clothing and Equipment. In addition, a survey of several fire departments was conducted to obtain information about sub-flashover skin burn incidents, some of which may be associated with stored energy burns [1]. While this information cannot be characterized as definitive or exhaustive in nature, it did provide useful insights about the severity and location of burn injuries, as well as the thermal exposure scenarios and conditions of moisture and clothing configurations that may be associated with stored energy burns. The major observations garnered from this review of twenty-four firefighter burn incidents, assumed not to be associated with exposure to emergency or flashover events, can be summarized as follows:

Thermal Exposures

A wide range of thermal exposures and fire ground conditions can cause burn injuries in sub-flashover fire fighting operations. Although specific patterns or overall trends that associate with these burn injuries cannot be observed, many of these burn incidents may be associated with the effects of stored thermal energy.

Thermal Degradation in Turnout Materials

Significant thermal degradation to the turnout materials are not always observed in sub-flashover incidents. Visually observable thermal degradation to moisture barrier and thermal liner components can occur with no visual degradation to the outer shell of the turnout. Heat degradation and melting are most often observed in reflective trim components attached to the outer shell.

Location of Burn Injuries

Figure 2 illustrates the location and frequency of burn injuries, observed in the limited survey of sub-flashover burn incidents,that may be associated with stored thermal energy. These data indicate that most of the reported burns occur on the shoulders and arms. Some of the burns occur in areas where the turnout is compressed, such as the shoulder area by the weight of the SCBA, or in the elbow and/or knee areas where clothing compression occurs as a result of bending of the arms and/or legs.

A number of the burns occur in areas where reflective trim or reinforcements are attached to the outer shell of the turnout. A few of the burns occurred around the knees in cases where the firefighter was in a crouched position. Some burns even appear to occur where patches or logos are attached to garments worn underneath the turnout suit.

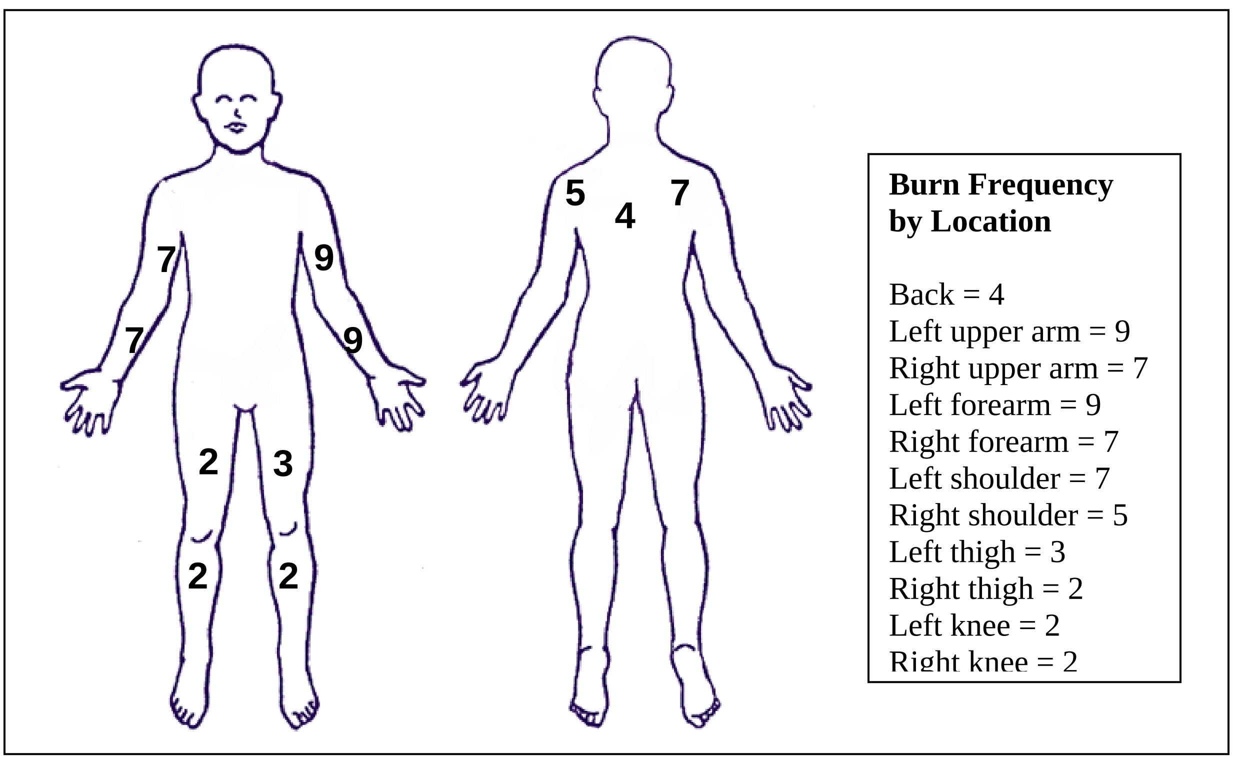

Figure 2. Distribution of burn injuries observed in twenty-four incidents assumed to be sub-flashover thermal exposures [1].

Moisture Conditions

Although not always reported, moisture due to sweating was most likely present in the turnout in most of these incidents. Some burns were observed in cases where external sources of water were present such as hose spray and rain; however, many burns occurred without external sources of moisture. This survey provided no basis for quantifying the amount or location of moisture present in the turnout systems.

Another separate case study reference has associated the presence of reflective trim, attached to turnout, with burn injuries [2]. An example of a burn behind trim found in Reference 2 is shown Figure 3. These burns apparently occur without significant degradation to the trim or to the outer shell fabric. They appear to align with the trim. No skin burn injury is indicated in the area of the arm immediately adjacent to the trim.

Figure 3. Burn Injury observed behind reflective trim attached to sleeve of a turnout coat and reported in reference [2]

STORED ENERGY TESTING CONCEPT

The collected burn injury information was useful in defining and validating the concept for a laboratory basis for evaluating the effects of turnout materials on burns that may be associated with stored thermal energy. The following criteria were used to develop the test method and procedures:

- The test method should be designed to measure both transmitted thermal energy and the heat discharged in compression of heated turnout materials. The intensity of the thermal exposure should be in the range classified as ordinary thermal conditions faced by firefighters (< 0.3 cal/cm^2sec incident heat flux) [3]. The results of the heat exposure should not produce visible thermal degradation to NFPA 1971 compliant outer shell fabrics.

- Test samples should consist of all layers, including the thermal liner, moisture barrier, and outer shell. Reinforcements and reflective trim could also be used in the construction of the composite test samples.

- Samples should be tested following a laboratory preconditioning protocol that exposes test materials to moisture in a consistent manner.

- Testing instrumentation and procedures of analysis should yield a report that permits evaluation of test samples in terms of thermal protective performance, as referenced by model predictions of time to expected second degree skin burn injury.

- Testing apparatus and procedures should generate reproducible results. They should yield demonstrably different results when tests are conducted on a range of turnout composites with known differences in layered compositions and reinforcements.

The test procedures developed in these performance requirements are conceptually illustrated in Figure 4.

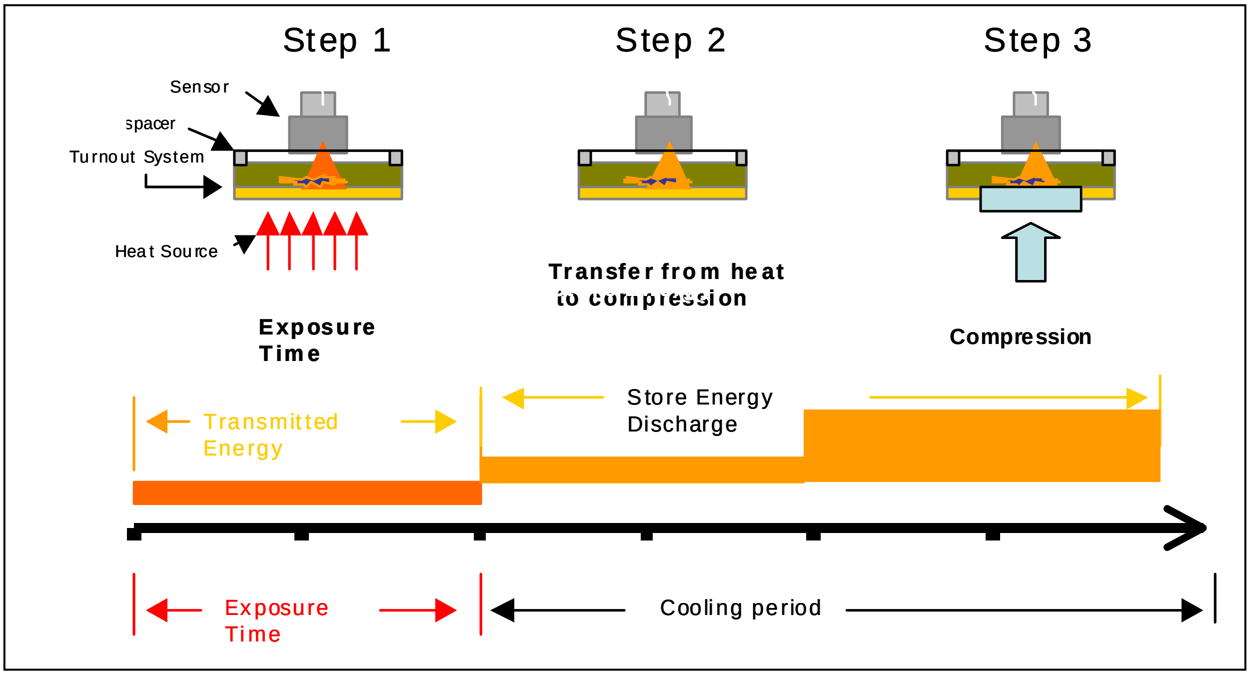

Figure 4. Illustration of sequential testing concept used to measure stored and transmitted thermal energy

The testing concept can be summarized as follows:

- Swatch sized samples of turnout materials are cut and assembled into composite specimens for testing.

- Test composites are preconditioned using a procedure developed to allow test turnout materials to absorb moisture in all layers of the composite and provides moisture levels that may represent the worst case scenario in terms of heat transfer [4].

- Test samples are exposed to sub-flashover conditions (0.2 cal/cm^{2}sec of predominately radiant heat) for a prescribed length of time. Transmitted thermal energy is measured by a heat sensor positioned 0.25 inches behind the test composite to represent the air gap found between the skin and fabric.

- Heated test samples are transferred to a compression device that causes the thermal sensor to compress against the back side of the turnout composite. The thermal energy discharged from the test sample is recorded.

- Total heat measured in the transmitted and compression stages of the test procedure is analyzed using a skin burn translation model to predict the onset of second degree burn injury.

STORED THERMAL ENERGY TEST APPARATUS

The stored and transmitted energy testing apparatus consists of a specimen holder, sensor assembly, transfer tray, data collection sensor, compressor assembly, heating source, and a data acquisition/controls/burn damage analysis system. The stored energy test apparatus is shown in Figures 5 and 6.

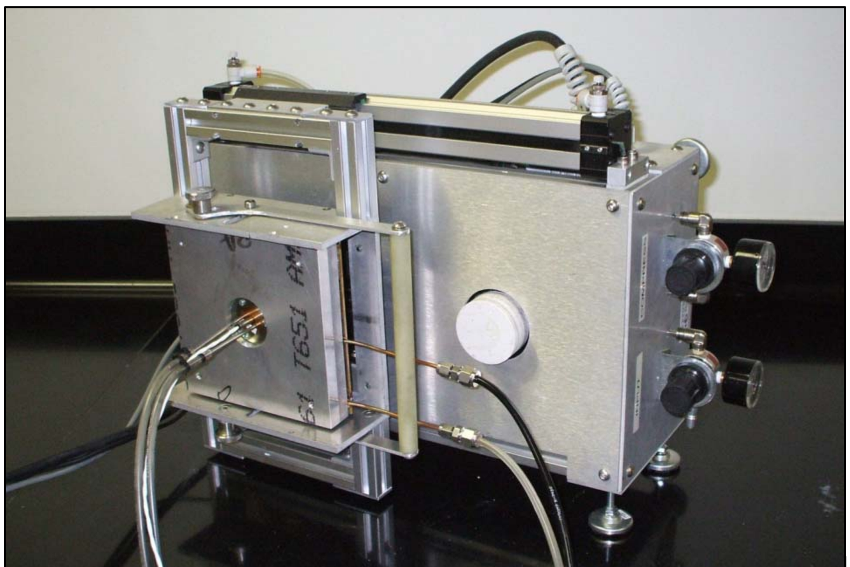

Figure 5. Photograph of stored thermal energy test apparatus developed by NCSU under NIOSH-NPPTL contract.

The sensor assembly consists of a water cooled Schmidt-Boelter thermopile type thermal sensor installed in a 6.5 x 6.5 inch water-cooled housing (Figure 7). The housing consists of a copper plate soldered with water fed copper tubes. This arrangement prevents sensor measurement errors that may be introduced by the effect of assembly heating during exposures.

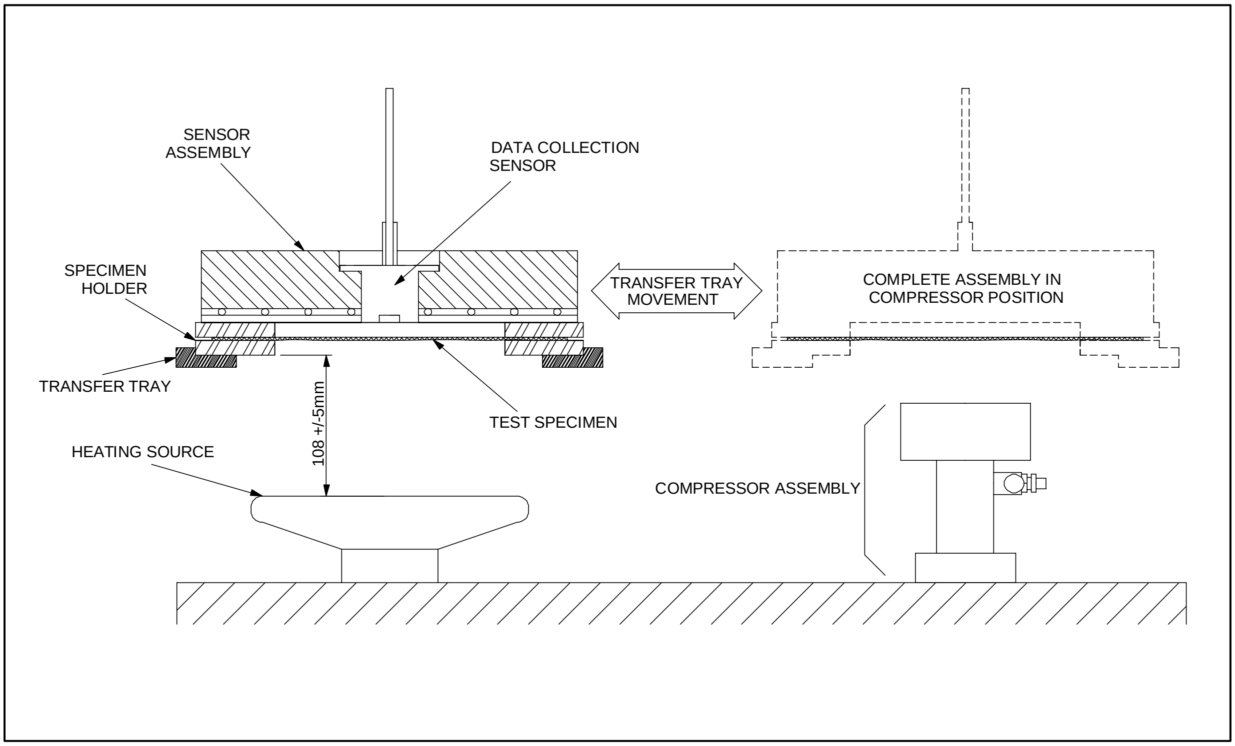

Figure 6. Stored thermal energy test apparatus (top view)

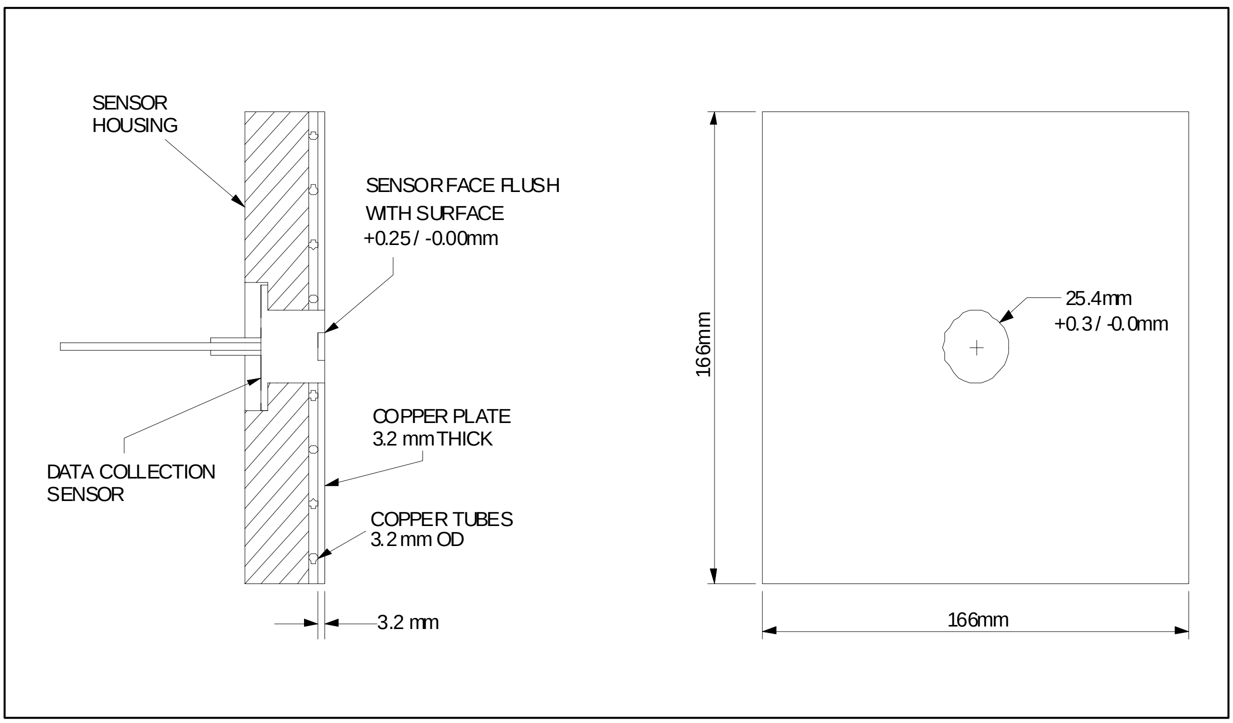

Figure 7. Thermal sensor assembly

Turnout composite test samples are held in a holder assembly consisting of two, upper and lower, 6.7 x 6.7 inch mounting plates (Figure 8).

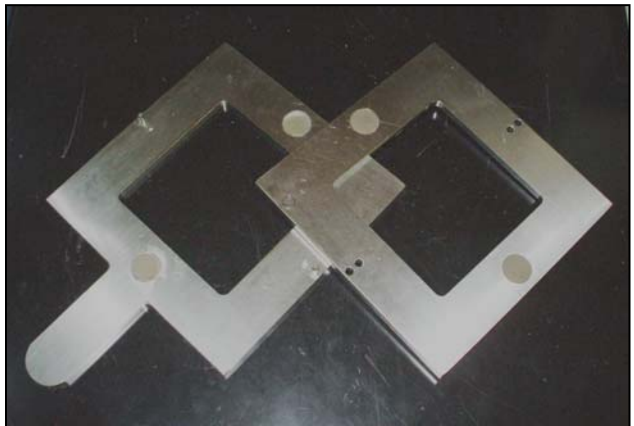
Figure 8. Sample holder

Test samples are exposed to heat produced by a ceramic heating source. During the initial phase of testing, heat transmitted through the test specimen is measured. In this phase, the thermal sensor assembly is positioned on top of the specimen holder forming a 0.25 inch (6.4 mm) air gap between the test specimen and the thermal sensor. The specimen assembly is placed in a transfer tray and moved between the heat source and compressor unit to effect the measurement of transmitted and stored thermal energy.

The compressor assembly consists of a compressor block, air cylinder, air regulator and framework for holding the system in place. Compressed air activates a piston that forces a circular heat resistant block to contacts and pushes the specimen against the thermal sensor assembly at a pressure of 13.8 ± 0.7 kPa (2.0 ± 0.1 psi). The compressor assembly is illustrated in Figure 9.

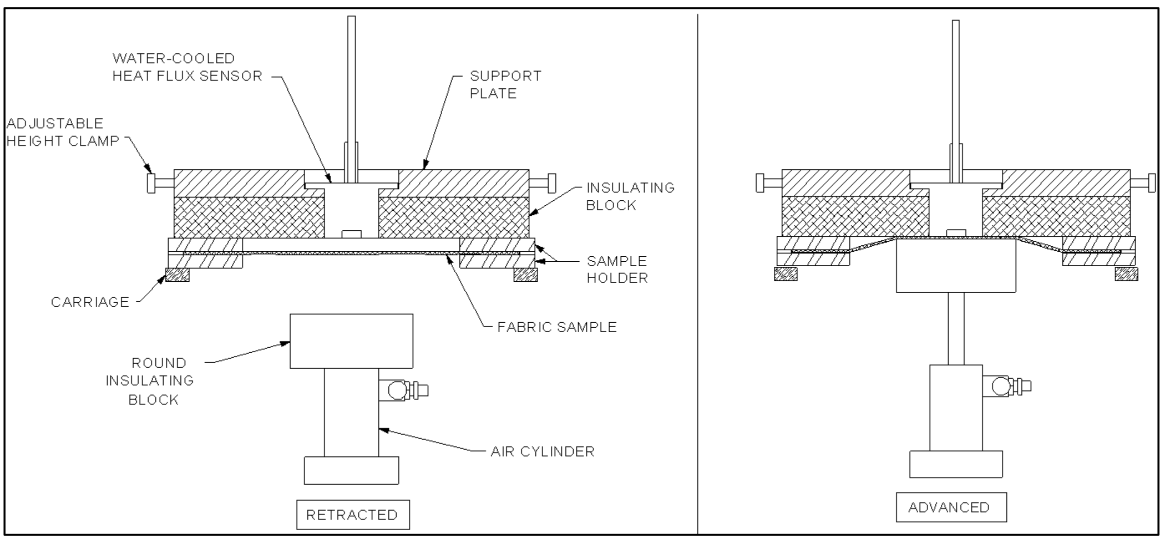

Figure 9. Compressor assembly

STORED THERMAL ENERGY TEST PROCEDURES

Moisture Preconditioning Procedures

The moisture preconditioning protocol that was developed can be summarized as follows:

- The thermal liner component of turnout test composite is placed between two sheets of wetted blotter paper. The amount of moisture in the blotter paper sheets is carefully controlled using specific water emersion steps coupled with a standardized wringing pressure.

- The thermal liner and blotter paper layers are assembled with the moisture barrier and outer shell layers used in the make-up of the turnout composite. This assembly is allowed to equilibrate for at least twelve hours in a sealed plastic bag. The wetted blotter paper is removed from the composite.

- The stored thermal energy test is performed within 15 minutes from the time test specimens are removed from the sealed plastic bag.

Thermal Exposure Procedures

Moisture preconditioned turnout samples were exposed to 0.2 cal/cm^2sec heat flux for two minutes. Following exposure, the apparatus transferred the test sample to the compression stage and heat discharged by contact with the back side of the turnout specimen was measured by the thermal sensor. Typical output from this test sequence is shown in Figure 10.

A burn model was applied to translate heat flux readings of stored and transmitted thermal energy into predicted time to second degree burn injury.

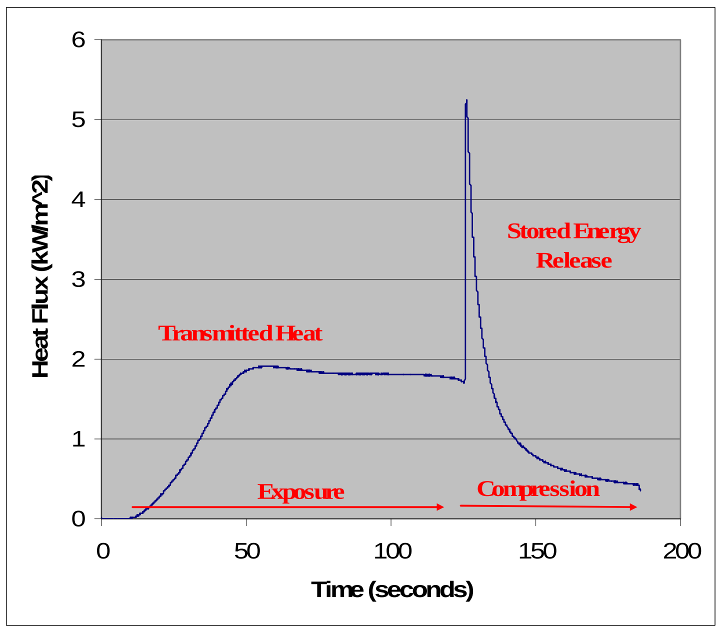

Figure 10. Typical heat flux profile showing transmitted and compression phases

EXPERIMENTAL RESULTS

Experiments were conducted on a variety of turnout materials configurations using the stored thermal energy apparatus and procedures. One series of experiments was designed to determine inter-laboratory precision of the test method. The results of the inter-lab study are summarized in Appendix A of this report. Another series was designed to generate data on a range of materials used in the construction of fire fighter turnouts. Detailed data from these tests are summarized in Appendix B.

Effect of Turnout Material Differences on SET Performance

A series of tests was conducted on a variety of materials used in the construction of firefighter turnout clothing selected with input from the Project Technical Panel. These experiments investigated effects associated with thermal liner, moisture barrier, outer shell, as well as the effect of reflective trim and reinforcement materials attached to the outer shell of the turnout composite. Table 1 describes the systems tested by this project. Table 2 lists the trim and reinforcement materials tested.

Table 1. Turnout test systems tested by this project

ID	**Thermal liner** (batt/facecloth)	**Moisture Barrier** (membrane/laminated to woven or spunlaced cloth)	**Outer shell** (woven fabric)
A	Needle punched para- & meta-aramid/ spun yarn meta-aramid (control)	5.0 oz/yd^2 enhanced bi-component ePTFE/ meta-aramid	7.5 oz/yd^2 para-aramid/PBI
B	Reprocessed aramid fiber / spun meta-aramid	5.0 oz/yd^2 enhanced bi-component ePTFE/ meta-aramid	7.5 oz/yd^2 para-aramid/PBI
C	Needle punched para- & meta-aramid/ filament & spun yarn meta-aramid	5.0 oz/yd^2 enhanced bi-component ePTFE/ meta-aramid woven cloth	7.5 oz/yd^2 para-aramid/PBI
D	2 layer para- & meta-blend spunlace waffle design/ meta-aramid blend of filament & spun yarn	5.0 oz/yd^2 enhanced bi-component ePTFE/ meta-aramid	7.5 oz/yd^2 para-aramid/PBI
E	2 layer of para- & meta-blend spunlace/ spun yarn meta-aramid	5.0 oz/yd^2 enhanced bi-component ePTFE/ meta-aramid	7.5 oz/yd^2 para-aramid/PBI
F	Needle punched para- & meta-aramid/ spun yarn meta-aramid	9.0 oz/yd^2 Neoprene/ FR cloth	7.5 oz/yd^2 para-aramid/PBI
G	Needle punched para- & meta-aramid/ spun yarn meta-aramid	5.2 oz/yd^2 Polyurethane bi-component film/ spunlaced	7.5 oz/yd^2 para-aramid/PBI
H	Needle punched para- & meta-aramid/ spun yarn meta-aramid	4.0 oz/yd^2 bi-component ePTFE/ meta-aramid spunlaced	7.5 oz/yd^2 para-aramid/PBI
I	Needle punched para- & meta-aramid/ spun yarn meta-aramid	5.3 oz/yd^2 bi-component PTFE film/ meta-aramid spunlaced	7.5 oz/yd^2 para-aramid/PBI
J	Needle punched para- & meta-aramid/ spun yarn meta-aramid	7.0 oz^2 enhanced bi-compoonent ePTFE/ meta-aramid on both sides	7.5 oz/yd^2 para-aramid/PBI
K	Needle punched para- & meta-aramid/ spun yarn meta-aramid	5.0 oz/yd^2 enhanced bi-component ePTFE/ meta-aramid	7.7 oz/yd^2 para-aramid/ PBO
L	Needle punched para- & meta-aramid/ spun yarn meta-aramid	5.0 oz/yd^2 enhanced bi-component ePTFE/ meta-aramid	7.5 oz/yd^2 meta-aramid/ para-aramid
M	Needle punched para- & meta-aramid/ spun yarn meta-aramid	5.0 oz/yd^2 enhanced bi-component ePTFE/ meta-aramid	7.5 oz/yd^2 para-aramid/PBI, dyed black

Table 2. Trim and Reinforcements tested by this project

ID	Trim and Reinforcements[1]	Description
T1	Trim 1	Yellow Trim 1 (glass beads)
T2	Trim 2	Yellow Trim 2 (cube-corner microprism)
Neo	Neoprene	9.0 oz/yd^2 Neoprene fabric
NPF	Non-Porous coated fabric	Polymer-coated para-armaid woven fabric
L	Leather	Leather
PF	Porous Fabric	7.5 oz/yd^2 para-armaid/PBI woven fabric

[1] Trim or reinforcements attached to outer surface of outershell.

The following sections discuss data produced in 120 seconds thermal exposures in the SET. This exposure duration was found to produce the greatest difference in test response for the turnout materials selected for this study.

Effects of Reflective Trim and Outer Shell Reinforcements

Data showing the effect of reflective trim and attached reinforcement layers are shown in Table 3 and in Figure 11. For this test series, the control turnout composite incorporated NFPA 1971 compliant materials in a system that used a vapor permeable moisture barrier. The base composite was combined with non-porous reflective trim, or with porous or non-porous reinforcement layers. All tests followed moisture preconditioning of the turnout test samples.

Table 3. Effect of trim or reinforcing layer on SET performance in breathable turnout systems

System[2]	Description	Predicted time to 2nd degree burn[1] (seconds)
A	Base Composite (BC)	112
A-T1	BC with yellow trim (glass beads)	89
A-T2	BC with yellow trim (microspheres)	74
A-NEO	BC with neoprene reinforcement	66
A-NPF	BC with non porous fabric	83
A-L	BC with leather	136
A-PF	BC with porous fabric	130

[1] Average of five replicate samples.
[2] Turnout samples used the same outer shell (7.5 oz/yd^2 para-armaid /PBI fabric), moisture barrier (5.0 oz/yd^2 enhanced bi-component ePTFE membrane laminated to meta-aramid woven cloth) components, and thermal liner components (7.2 oz/yd^2 needle punched para- and meta-aramid batt quilted to a spun yarn aramid face cloth)

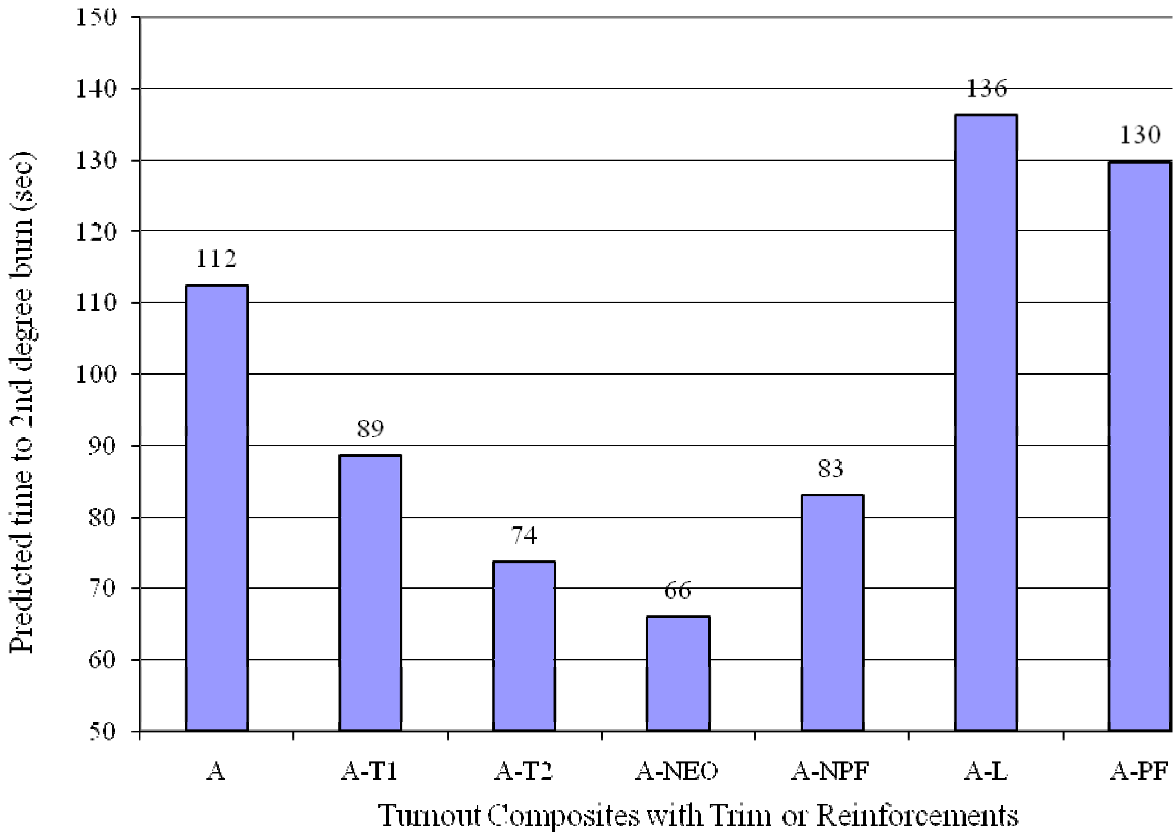

Figure 11. Effect of trim and reinforcement on SET performance for breathable base composite (System A)

These data show that SET results are influenced by differences in the moisture vapor porosity of the attached reinforcement: leather or a porous coated fabric attached to the outer shell increases SET performance in comparison to the base composite. Reflective trim and non-porous reinforcement material attached to the outer shell significantly reduces test performance compared to the base turnout composite.

Effect of Moisture Barrier Breathability

The results of tests conducted to determine the effect of moisture barrier vapor permeability on transmitted and stored thermal energy are shown in Table 4 and in Figure 13. Tests were conducted on turnout composites containing moisture barriers selected to have differing levels of moisture vapor permeability as indicated by measured moisture vapor transmission rate (MVTR). Moisture barrier components were combined with the same NFPA 1971 compliant outer shell fabric and thermal liner components to make up test samples. They were tested with and without non-permeable reflective trim attached to the outer shell.

Moisture vapor transmission rate (MVTR), measured following procedures similar to ASTM E96 [6], ranged from 13 to 584 g/m^2/ -24 hours. Two of the turnout composites tested (samples F and G) do not pass the THL performance requirements of NFPA 1971. The other turnout composites in the test group are certified to exceed the 205 w/m^2 THL requirement of NFPA 1971.

These experiments demonstrate that SET results are strongly correlated with moisture barrier MVTR (Figure 12). When tested with non-porous trim attached, turnout composites with the highest level of breathability (MVTR) gave the lowest predicted second degree burn time in the SET. Turnout samples, tested with attached trim, transmit heat sufficient to predict second degree burn injury during the two minute heating phase of the SET. Differences in moisture barrier MVTR appears to have little effect on SET outcome in turnout systems tested without attached trim.

Table 4. Effect of Moisture Barrier MVTR on Stored Energy Test Results.[1]

System [2]	MVTR[3] (g/m^2 -24 hrs)	Weight [4] (oz/yd^2)	Predicted time to 2nd degree burn (seconds)	
			without trim	with trim
F	13	9.0	117	147
G	294	5.2	119	126
H	392	4.0	129	105
I	445	5.3	125	107
J	515	7.0	121	92
A	584	5.0	112	89

[1] Average of five replicate measurements
[2] All turnout samples incorporated same outer shell (7.5 oz/yd^2 para-armaid /PBI fabric) and thermal liner components (7.2 oz/yd^2 Needle punched para- and meta-aramid batt quilted to a spun yarn aramid face cloth)
[3] Moisture vapor transfer rate of membrane (g/m2/24hrs.)
[4] Weight of moisture barrier component

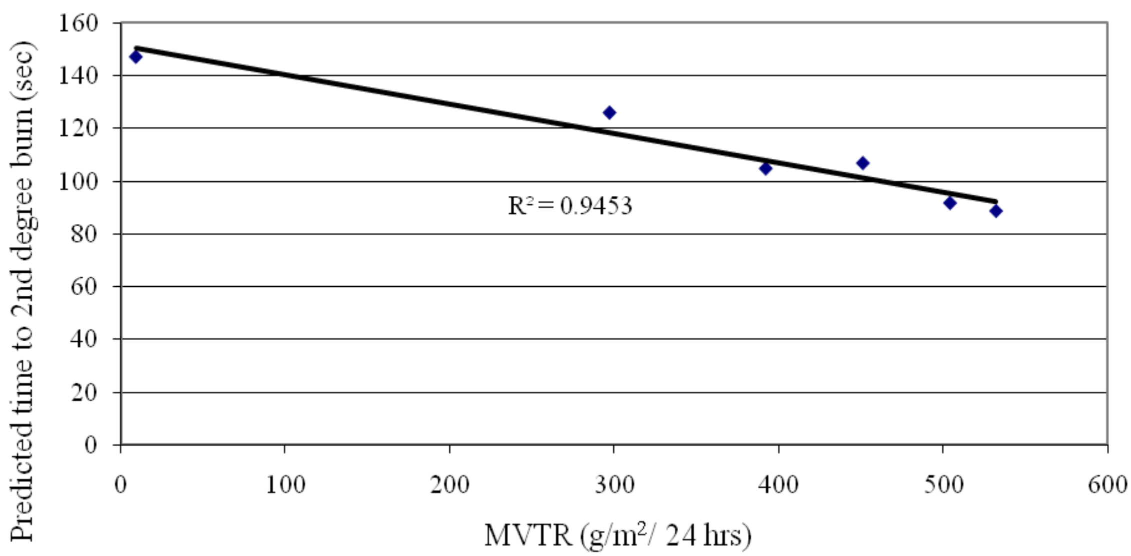

Figure 12. Correlation between moisture barrier MVTR and SET performance in turnout composites with reflective trim

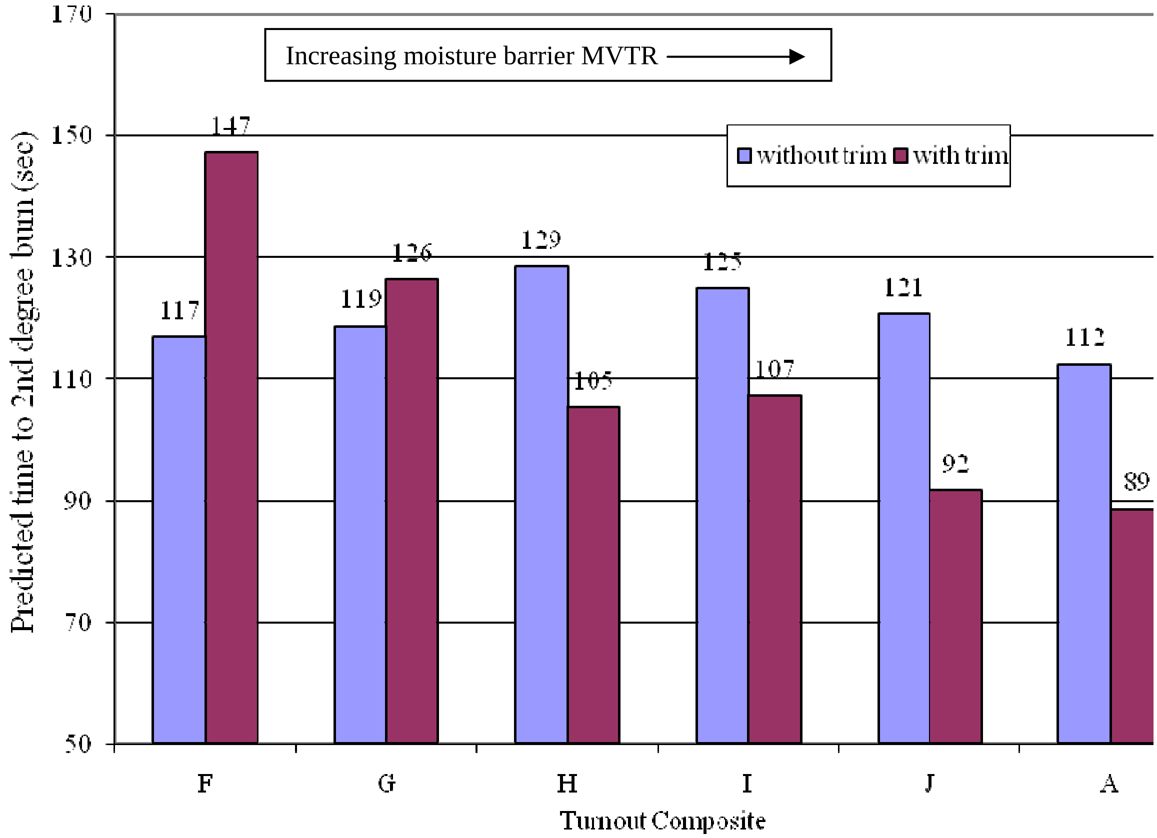

Figure 13. Effect of moisture barrier MVTR on stored energy test results in turnout systems tested with and without reflective trim.

Effect of Thermal Liner Thickness

Stored energy tests were conducted on five turnout composite samples made up with thermal liner components selected to have different constructions. Thermal liner components were combined with the same NFPA 1971 compliant outer shell fabric and moisture barrier to make up the turnout test composite. The thickness of the thermal liners ranged from 2.0 to 3.8 millimeters. TPP values were reported to range from 38.9 to 58.7 cal/cm^2.

Data from these tests (Table 5, Figure 14) show that the lowest predicted second degree burn time in the SET is produced by the turnout composite having the thinnest thermal liner (sample E). Although the translation is not proportional, the observed differences in SET results generally correlate with the TPP of the turnout sample. We observe that the higher TPP of the thickest composite (sample B) does not produce a proportionate increase in burn protection measured in the stored energy test.

These tests indicate that constructional differences in the thermal liner have less impact on SET results than differences related to moisture barrier vapor permeability. They show the effect that nonporous reflective trim has on reduced SET performance. For all composites tested, sufficient heat is transferred to predict second degree burn in less than the two minute heating phase of the test.

Table 5. Effect of thermal liner on predicted burn time in SET [1]

System [2]	Thickness [4] (mm)	Weight [3] (oz/yd^2)	TPP [5] (cal/cm^2)	Predicted time to 2nd degree burn (seconds)	
				without trim	with trim
B	3.8	9.0	58.7	111	92
C	3.1	7.6	41.2	111	88
A	3.1	7.2	40.8	112	89
D	2.9	7.7	39.9	107	87
E	2.0	7.2	38.9	101	86

[1] Average of five replicate samples
[2] Turnout samples used the same outer shell (7.5 oz/yd^2 para-armaid /PBI fabric) and moisture barrier (5.0 oz/yd^2 enhanced bi-component ePTFE membrane laminated to meta-aramid woven cloth) components
[3] Weight of thermal liner component
[4] Thickness of thermal liner component
[5] TPP of turnout composite without trim (TPP values supplied to project)

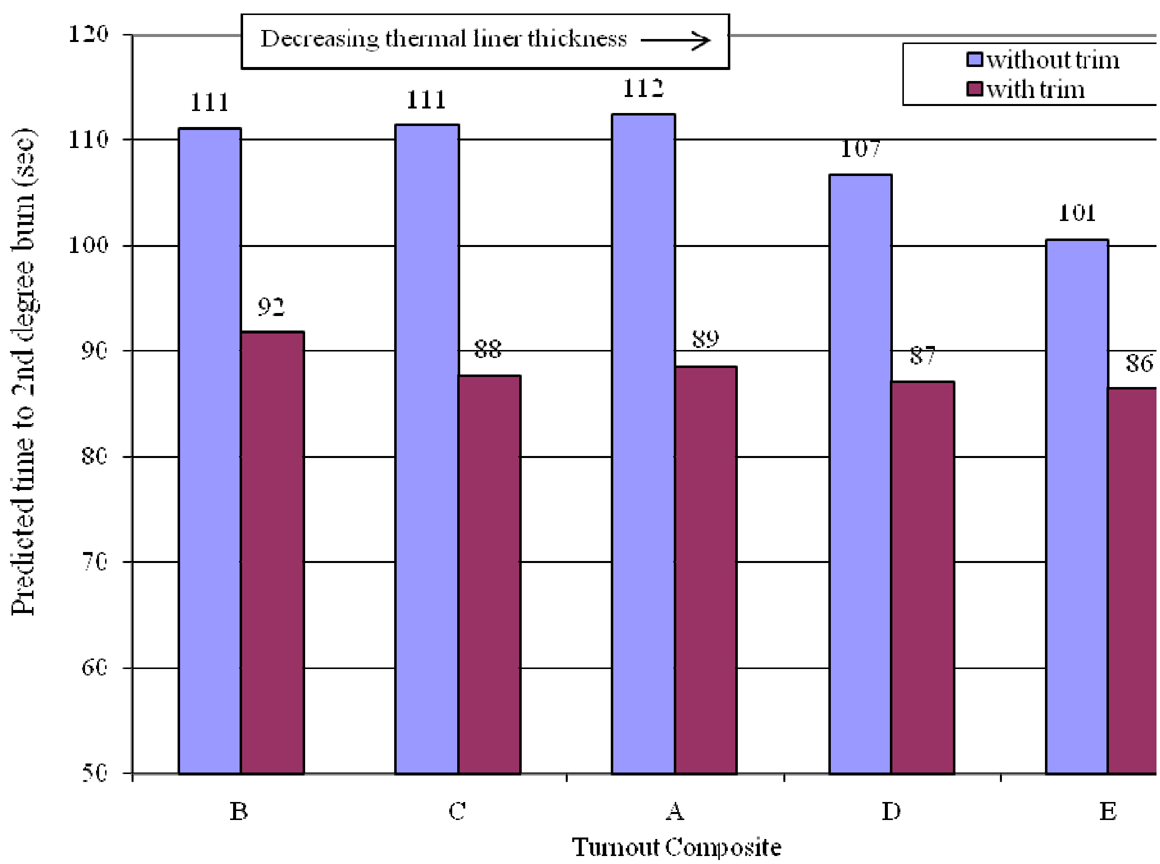

Figure 14. Effect of thermal liner thickness on SET performance in breathable turnout composite with and without reflective trim

Effect of Outer Shell Material

An experimental series was conducted to determine the effect of the outer shell component on SET performance. The results of the tests are shown in Table 6 and in Figure 15.

These data show that, while different outer shell fabrics can influence SET performance, effects are not as pronounced as can be associated with differences in the moisture barrier or thermal liner components. They suggest that SET outcomes may be influenced by many factors of outer shell construction, including its color. However, these limited data are insufficient to permit a definitive analysis of any possible correlations.

Table 6. Effect of outer shell on predicted burn time from stored energy[1]

System [2]	Outer Shell	Thickness[3] (mm)	Weight [4] (oz/yd^2)	Predicted time to 2nd degree burn (seconds)	
				without trim	with trim
A	7.5 osy Para-aramid/PBI	0.73	7.8	112	89
K	7.7 osy Para-aramid/PBO	0.86	8.0	122	81
L	7.5 osy Meta-aramid	0.80	7.9	119	80
M	7.5 osy Para-aramid/PBI, dyed black	0.75	8.1	120	91

[1] Average of five replicate measurements
[2] All turnout samples incorporated the same moisture barrier (5.0 oz/yd^2 enhanced bi-component ePTFE membrane laminated to meta-aramid woven cloth) and thermal liner components (7.2 oz/yd^2 needle punched para- and meta-aramid batt quilted to a spun yarn aramid face cloth)
[3]Measured thickness of outershell fabric
[4] Measured weight of outer shell

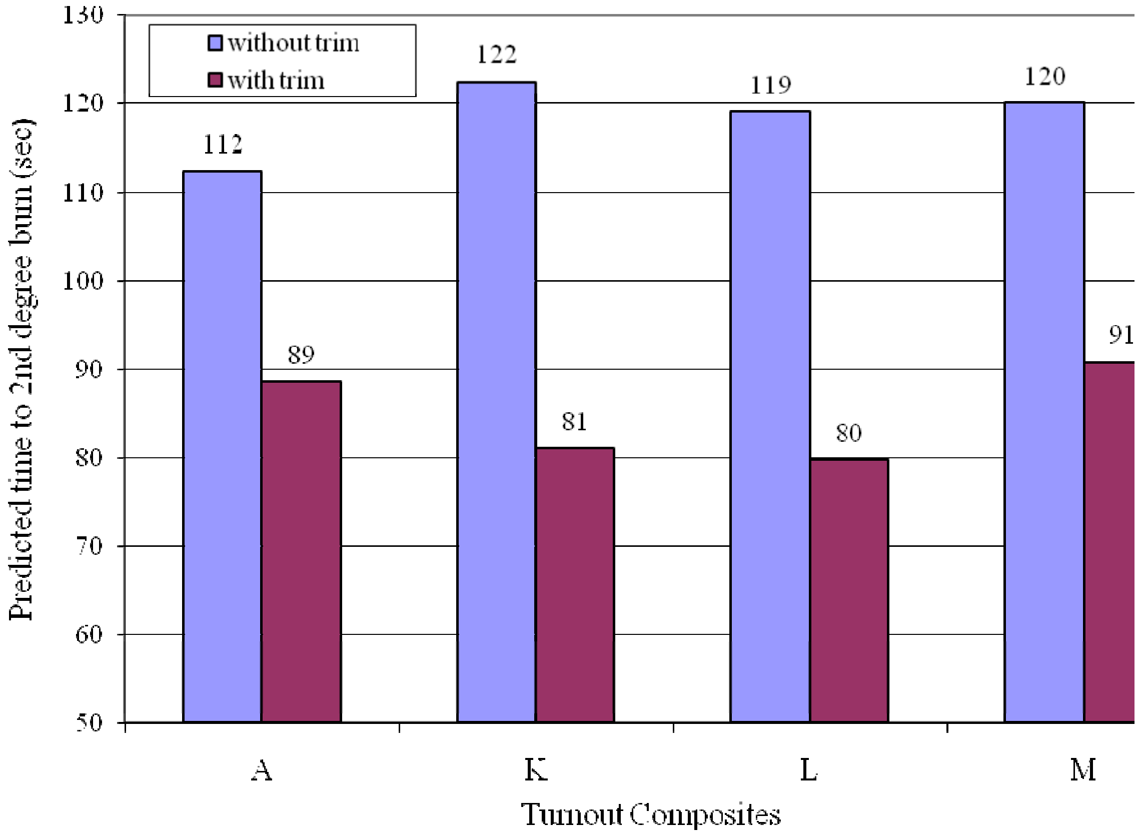

Figure 15. Effect of outer shell on predicted burn time from stored energy

Additional Studies on Moisture Barrier and Reinforcement Permeability

A series of experiments was conducted to further study effects of moisture barrier and outer shell attachment porosity on SET performance. The first series used turnout composite constructions in which the physical integrity of the moisture barrier component had been deliberately breached to create pathways for vapor transmission. This was accomplished by cutting slits into the moisture barrier materials (Figure 16).

Figure 16. Moisture barrier sample with cuts to increase moisture vapor permeability

Table 7 shows the effect of breaching the integrity of the moisture barrier on SET results. These data show effects for moisture barriers having different vapor permeability when tested in a turnout system that incorporates nonporous reflective trim.

Table 7. Effect of moisture barrier integrity on SET results[1]

Systen[2]	MVTR of moisture barrier (g/m^2 -24 hrs)[3]	Predicted time to 2nd degree burn (seconds)	
		Intact MB	Slit MB
F	13	147	99
G	294	126	93
H	392	105	86
I	445	107	91
A	584	89	85

[1] Average of five replicate measurements
[2] All turnout samples incorporated same outer shell (7.5 oz/yd^2 para-armaid /PBI fabric) with a non porous trim (Yellow Trim 1 (glass beads) attached and thermal liner components (7.2 oz/yd^2 Needle punched para- and meta-aramid batt quilted to a spun yarn aramid face cloth)
[3] MVTR of intact barrier component

They show that the effect of physical openings is related to the vapor permeability of the intact moisture barrier: the largest reduction in SET performance is observed in the least moisture permeable moisture barriers. This finding is consistent with observations that breathable moisture barriers generally reduce SET performance in turnout systems with non porous trim.

A second experimental series investigated the effect of slitting outer shell attachments on SET results (Table 8).

Table 8. Effect of trim and reinforcement integrity on SET results in a breathable turnout system[1]

System [2]	Attachment	Predicted time to 2nd degree burn (seconds)	
		Intact Attachment	Slit
A	Base control (no trim)	112	NA
A-T1	Yellow Trim 1 (glass beads)	89	99
A-T2	Yellow Trim 2 (cube-corner microprism)	74	81[3]
A-Neo	Neoprene	66	93
A-NPF	non-porous coated fabric	83	100

[1] Average of five replicate measurements
[2] All turnout samples incorporated the same outer shell (7.5 oz/yd^2 para-armaid /PBI fabric), moisture barrier (5.0 oz/yd^2 enhanced bi-component e PTFE membrane laminated to meta-aramid woven cloth) and thermal liner components (7.2 oz/yd^2 Needle punched para- and meta-aramid batt quilted to a spun yarn aramid face cloth)

These data show that artificial modifications to increase vapor permeability of nonporous shell attachments significantly improves SET performance. However, these modifications do not restore the level of performance afforded by the base turnout composite without attached trim.

These findings corroborate observations indicating the reductive impact of nonporous trim or impermeable outer shell reinforcements on SET performance, in turnout systems with vapor permeable moisture barriers.

Effect of Exposure Time in the SET

Figure 17 shows the effect of the thermal exposure time in the SET. It should be noted that contact with the heated test sample occurs five seconds following the radiant heating phase of the test. Therefore, before compression, the test measures transmitted thermal energy in the same manner as a RPP type test method. After the thermal sensor contacts the test sample, the SET registers the discharge of stored thermal energy.

For radiant heat exposures 90 and 120 seconds in duration, burns are predicted to occur mainly as a result of transmitted thermal energy. In these exposures, the discharge of stored thermal energy from heated composites can accelerate the onset of test predicted burn. However, transmitted thermal energy remains the main contributor to the thermal hazard. In one minute exposures, discharged thermal energy contributes a larger fraction to the predicted burn potential. In turnout test systems incorporating a moisture permeable barrier, nonporous trim consistently reduces protective performance in each of the three thermal exposure durations examined by this research.

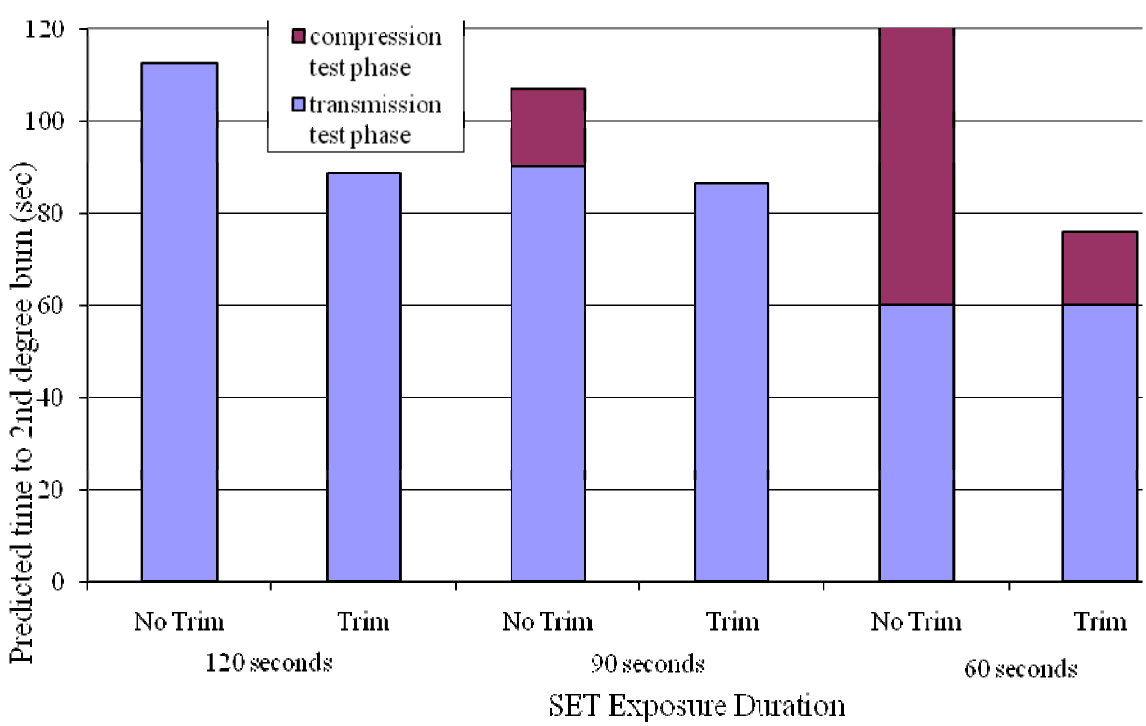

Figure 17. Effect of SET heat exposure duration on predicted SET burn time for breathable turnout system with and without attached reflective trim

AUTHOR'S NOTE

This research was preceded by a project that developed the stored energy test apparatus and testing procedures described in this report. Some portions of the final report for that project have been included in the present report [1]. This was done to provide background and clarity for a reader of this report

REFERENCES

1. Development of a Test Method for Measuring Transmitted Heat and Stored Thermal Energy in Firefighter Turnouts, final report presented to National Institute for Occupational Safety and Health (NIOSH) National Personal Protective Technology Laboratory (NPPTL) under Contract No. 200-2005-12411, April 29, 2008

2. Borkowski, B., Collection of burn injuries case studies found behind reinforcements. barryb@totalfiregroup.com

3. Abbot, N.J. and Schulman, S., "Protection from Fire: Nonflammable Fabrics and Coatings," *J. Coated Fabrics*, Vol. 6, July 1976, pp.48-62

4. Barker, R.L., Guerth-Schacher, C., Grimes, R.V., and Hamouda, H., "Effects of Moisture on the Thermal Protective Performance of Firefighter Protective Clothing in Low Level Radiant Heat Exposures," Textile Research Journal, January 2006.

5. ASTM E 96/E 96M Standard Test Methods for Water Vapor Transmission of Materials

APPENDICES

Appendix A: Inter-laboratory Differences of Procedure for Measuring Transmitted Heat and Stored Thermal Energy in Firefighter Turnouts

Appendix B: SET Data

Appendix A: Inter-laboratory Differences of Procedure for Measuring Transmitted Heat and Stored Thermal Energy in Firefighter Turnouts

Turnout composites were tested at NCSU and NIST using the developed SET procedure to determine lab to lab variability. The difference in predicted burn times between these two labs averaged 4.7% over 36 composites indicating good inter-lab agreement. Figure A1 shows a comparison of the SET results from these two test sites. This comparison indicates a greater average percent difference (5.6%) occurred in tested base composites without trim and reinforcements. Sample A (control) with attached trim and various reinforcements have an average difference of 3.9% between laboratory test sites.

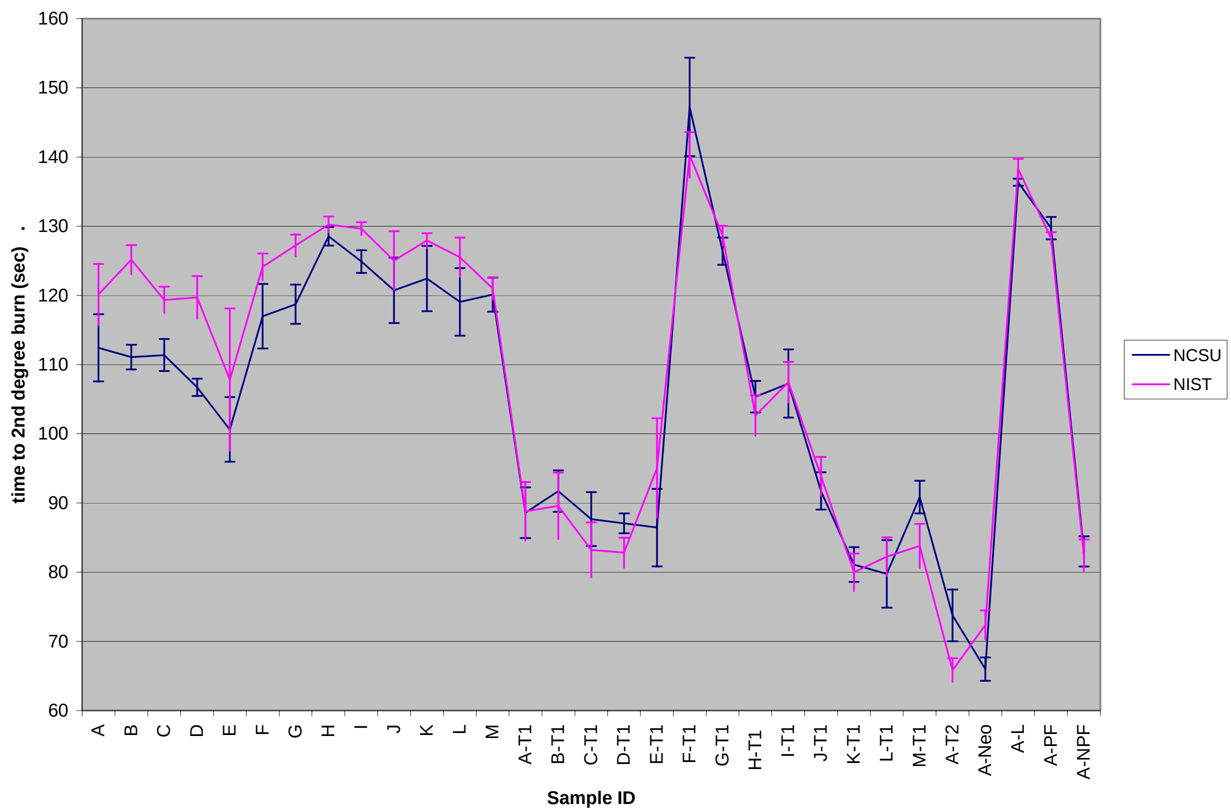

Figure A1. Comparison of SET results at NCSU and NIST

Data produced at both laboratory sites are included in Table A1.

Table A1. SET results from NCSU and NIST

	NCSU				NIST			
	90 Seconds		120 Seconds		90 Seconds		120 Seconds	
Sample	No Trim	With T1	No Trim	With T1	No Trim	With T1	No Trim	With T1
A	107	86	112	89	105	85	120	89
B	103	86	111	92	106	91	125	91
C	104	86	111	88	107	82	119	82
D	103	86	107	87	103	81	120	81
E	98	82	101	86	NA	NA	108	95
F	102	NPB	117	147	104	NPB	124	NPB
G	105	109	119	126	106	109	127	109
H	145	99	129	105	NPB	98	130	98
I	115	99	125	107	NPB	98	130	98
J	106	90	121	92	NA	NA	125	94
K	114	82	122	81	116	78	116	78
L	107	79	119	80	112	78	112	78
M	106	87	120	91	116	84	116	84
A-T2	71		74		66		66	
A-Neo	67		66		72		72	
A-NPF	82		83		NA		82	
A-L	NPB		136		NPB		138	
A-PF	114		130		112		128	

NA=Test were not conducted on sample due to lack of materials
NPB=No predicted time to second degree burn

Appendix B: SET Data

Test Duration: 120 seconds

System ID	Replicate	SET Value	System ID	Replicate	SET Value
A	1	117.88	**G**	1	116.28
	2	106.91		2	120.59
	3	111.24		3	117.75
	4	117.01		4	122.69
	5	109.03		5	116.32
	Average	112.41		Average	118.73
B	1	112.16	**H**	1	128.61
	2	113.01		2	130.13
	3	111.81		3	127.35
	4	109.62		4	129.57
	5	108.81		5	127.07
	Average	111.08		Average	128.55
C	1	113.10	**I**	1	123.35
	2	113.64		2	126.03
	3	112.35		3	127.09
	4	109.15		4	123.40
	5	108.67		5	124.56
	Average	111.38		Average	124.89
D	1	106.63	**J**	1	124.10
	2	105.76		2	122.36
	3	106.36		3	114.90
	4	105.96		4	116.58
	5	108.85		5	125.69
	Average	106.71		Average	120.73
E	1	100.48	**K**	1	114.74
	2	99.03		2	126.05
	3	108.63		3	121.33
	4	98.22		4	126.04
	5	96.77		5	124.11
	Average	100.63		Average	122.45
F	1	119.30	**L**	1	124.97
	2	119.49		2	118.87
	3	117.96		3	122.86
	4	108.74		4	114.51
	5	119.45		5	114.08
	Average	116.99		Average	119.06
			M	1	116.35
				2	123.13
				3	119.93
				4	120.05
				5	121.08

				Average	120.11

Test Duration: 120 seconds (continued)

System ID	Replicate	SET Value	System ID	Replicate	SET Value
A - T1	1	83.33	**G - T1**	1	122.97
	2	92.19		2	127.21
	3	87.53		3	126.75
	4	87.93		4	128.06
	5	92.00		5	126.91
	Average	88.60		Average	126.38
B - T1	1	89.81	**H - T1**	1	103.58
	2	93.21		2	102.95
	3	94.24		3	108.73
	4	93.98		4	106.01
	5	87.39		5	105.49
	Average	91.73		Average	105.35
C - T1	1	85.37	**I - T1**	1	104.06
	2	94.38		2	113.83
	3	86.70		3	107.36
	4	84.71		4	109.91
	5	87.15		5	101.19
	Average	87.66		Average	107.27
D - T1	1	86.98	**J - T1**	1	91.65
	2	87.19		2	92.69
	3	85.32		3	93.16
	4	89.30		4	87.14
	5	86.52		5	94.01
	Average	87.06		Average	91.73
E - T1	1	78.22	**K - T1**	1	79.39
	2	87.19		2	78.61
	3	90.16		3	84.97
	4	92.58		4	81.94
	5	84.05		5	80.59
	Average	86.44		Average	81.10
F - T1	1	148.95	**L - T1**	1	80.48
	2	142.35		2	81.41
	3	138.55		3	76.93
	4	149.35		4	86.48
	5	157.02		5	73.51
	Average	147.24		Average	79.76
			M - T1	1	91.50
				2	92.32
				3	86.86
				4	92.83
				5	90.73
				Average	90.85

Test Duration: 120 seconds (continued)

System ID	Replicate	SET Value	System ID	Replicate	SET Value
A - T2	1	68.37	**A - Moisture Barrier Slit**	1	111.69
	2	73.00		2	115.12
	3	76.17		3	116.42
	4	78.18		4	115.41
	5	73.03		5	111.70
	Average	73.75		Average	114.07
A - Neo	1	66.67	**F - Moisture Barrier Slit**	1	129.69
	2	66.65		2	130.71
	3	65.22		3	128.59
	4	67.93		4	129.18
	5	63.49		5	130.17
	Average	65.99		Average	129.67
A - NPF	1	83.20	**G - Moisture Barrier Slit**	1	128.15
	2	84.87		2	126.38
	3	79.25		3	129.60
	4	84.12		4	130.44
	5	83.56		5	125.93
	Average	83.00		Average	128.10
A - L	1	136.34	**H - Moisture Barrier Slit**	1	128.96
	2	136.25		2	130.42
	3	135.88		3	130.81
	4	137.21		4	129.31
	5	136.05		5	125.32
	Average	136.35		Average	128.96
A - PF	1	129.82	**I - Moisture Barrier Slit**	1	129.61
	2	130.62		2	129.31
	3	130.41		3	129.28
	4	126.91		4	128.55
	5	130.86		5	127.96
	Average	129.72		Average	128.94
E - NPF	1	81.41	**A - T1 Moisture Barrier Slit**	1	86.48
	2	77.05		2	84.01
	3	78.90		3	81.22
	4	80.12		4	83.33
	5	80.55		5	87.90
	Average	79.61		Average	84.59
J - NPF	1	83.22	**F - T1 Moisture Barrier Slit**	1	93.02
	2	86.78		2	107.09
	3	82.88		3	98.02
	4	87.08		4	99.48
	5	83.23		5	98.80
	Average	84.64		Average	99.28

Test Duration: 120 seconds (continued)

System ID	Replicate	SET Value	System ID	Replicate	SET Value
G - T1 Moisture Barrier Slit	1	97.76	**A - T1 Reinforcement Slit**	1	95.65
	2	96.20		2	100.42
	3	90.42		3	97.73
	4	93.49		4	101.92
	5	88.76		5	103.25
	Average	93.33		Average	99.79
H - T1 Moisture Barrier Slit	1	84.80	**A - T2 Reinforcement Slit**	1	86.78
	2	88.76		2	79.27
	3	86.28		3	76.42
	4	84.85		4	-
	5	84.64		5	-
	Average	85.87		Average	80.82
I - T1 Moisture Barrier Slit	1	88.49	**A - Neo Reinforcement Slit**	1	99.40
	2	92.47		2	94.95
	3	92.51		3	108.08
	4	95.02		4	81.17
	5	86.90		5	80.81
	Average	91.08		Average	92.88
			A - NPF Reinforcement Slit	1	127.92
				2	91.17
				3	85.65
				4	104.63
				5	92.61
				Average	100.40

Test Duration: 90 seconds

System ID	Replicate	SET Value	System ID	Replicate	SET Value
A	1	110.50	**H**	1	No Burn
	2	109.54		2	No Burn
	3	104.25		3	No Burn
	4	105.20		4	136.48
	5	105.65		5	153.85
	Average	107.03		Average	N/A
B	1	103.57	**I**	1	114.90
	2	101.95		2	120.15
	3	103.11		3	108.35
	4	104.76		4	110.16
	5	99.40		5	121.50
	Average	102.56		Average	115.01
C	1	108.85	**J**	1	107.59
	2	102.27		2	104.55
	3	102.80		3	103.70
	4	105.11		4	109.85
	5	102.30		5	107.07
	Average	104.27		Average	106.55
D	1	102.19	**K**	1	103.27
	2	102.38		2	120.25
	3	103.29		3	109.20
	4	101.61		4	115.14
	5	104.37		5	121.06
	Average	102.77		Average	113.78
E	1	98.17	**L**	1	103.60
	2	96.23		2	113.85
	3	99.66		3	104.71
	4	96.70		4	105.46
	5	100.95		5	105.32
	Average	98.34		Average	106.59
F	1	102.35	**M**	1	104.37
	2	101.36		2	109.04
	3	101.57		3	108.67
	4	102.26		4	105.69
	5	101.22		5	103.40
	Average	101.75		Average	106.23
G	1	105.28			
	2	105.87			
	3	104.07			
	4	102.56			
	5	106.31			
	Average	104.82			

Test Duration: 90 seconds (continued)

System ID	Replicate	SET Value	System ID	Replicate	SET Value
A - T1	1	86.93	**H - T1**	1	98.04
	2	85.07		2	99.39
	3	86.40		3	99.85
	4	87.38		4	99.50
	5	85.75		5	98.25
	Average	86.31		Average	99.01
B - T1	1	92.29	**I - T1**	1	97.65
	2	91.93		2	99.49
	3	96.35		3	99.88
	4	95.67		4	98.06
	5	93.80		5	98.34
	Average	94.01		Average	98.68
C - T1	1	87.02	**J - T1**	1	88.31
	2	87.07		2	89.95
	3	86.06		3	90.96
	4	81.04		4	89.63
	5	89.64		5	90.34
	Average	86.17		Average	89.84
D - T1	1	86.22	**K - T1**	1	82.60
	2	88.27		2	81.67
	3	82.44		3	80.63
	4	86.74		4	82.24
	5	88.41		5	81.47
	Average	86.42		Average	81.72
E - T1	1	81.01	**L - T1**	1	82.91
	2	79.10		2	79.53
	3	79.17		3	80.48
	4	89.54		4	76.98
	5	82.08		5	74.32
	Average	82.18		Average	78.84
F - T1	1	No Burn	**M - T1**	1	85.95
	2	No Burn		2	85.50
	3	No Burn		3	89.12
	4	No Burn		4	88.29
	5	No Burn		5	87.69
	Average	N/A		Average	87.31
G - T1	1	112.73			
	2	107.19			
	3	106.72			
	4	108.13			
	5	109.31			
	Average	108.82			

Test Duration: 90 seconds (continued)

System ID	Replicate	SET Value	System ID	Replicate	SET Value
A - T2	1	73.75	**A - PF**	1	108.56
	2	71.77		2	111.47
	3	72.25		3	112.31
	4	67.57		4	110.50
	5	71.86		5	128.56
	Average	71.44		Average	114.28
A - Neo	1	66.88	**E - NPF**	1	78.34
	2	71.47		2	78.27
	3	68.43		3	83.06
	4	65.12		4	77.68
	5	64.71		5	79.06
	Average	67.32		Average	79.28
A - NPF	1	79.66	**J - NPF**	1	86.84
	2	84.09		2	85.86
	3	81.94		3	82.98
	4	80.56		4	88.05
	5	83.02		5	85.44
	Average	81.85		Average	85.83
A - L	1	No Burn		1	
	2	No Burn		2	
	3	No Burn		3	
	4	No Burn		4	
	5	No Burn		5	
	Average	N/A		Average	

Test Duration: 60 seconds

System ID	Replicate	SET Value	System ID	Replicate	SET Value
A	1	No Burn	**E - T1**	1	71.44
	2	No Burn		2	71.91
	3	No Burn		3	69.69
	4	No Burn		4	71.41
	5	No Burn		5	70.95
	Average	N/A		Average	71.08
E	1	No Burn	**J - T1**	1	77.23
	2	No Burn		2	75.47
	3	No Burn		3	77.46
	4	No Burn		4	76.57
	5	No Burn		5	79.52
	Average	N/A		Average	77.25
J	1	No Burn	**A - NPF**	1	70.55
	2	No Burn		2	70.16
	3	No Burn		3	70.34
	4	No Burn		4	70.96
	5	No Burn		5	70.22
	Average	N/A		Average	70.45
A - T1	1	75.75	**E - NPF**	1	69.15
	2	76.26		2	70.62
	3	76.00		3	69.32
	4	76.84		4	70.90
	5	74.00		5	70.11
	Average	75.77		Average	70.02
			J - NPF	1	72.28
				2	73.56
				3	71.73
				4	72.57
				5	72.82
				Average	72.59