ABSTRACT

GUERTH-SCHACHER, CORDULA CHRISTINA. Evaluation of the Effects of Moisture on the Thermal Protective Performance of Fire Protective Clothing in Low Level Heat Exposures. (Under the direction of Roger L. Barker.)

This research sought to develop a better understanding of the effects of moisture on the mechanisms that contribute to heat transfer throughout turnout clothing materials in prolonged exposure to radiant thermal energy. It investigated the role of critical material variables, including the moisture vapor permeability and insulation properties of turnout composite ensembles. The scientific insights gained are expected to ultimately contribute to the development of laboratory test procedures for evaluating the thermal protective performance of turnout materials exposed to subflashover radiant heat conditions.

EVALUATION OF THE EFFECTS OF MOISTURE ON THE THERMAL PROTECTIVE PERFORMANCE OF FIRE PROTECTIVE CLOTHING IN LOW LEVEL HEAT EXPOSURES

by
CORDULA CHRISTINA GUERTH-SCHACHER

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APPROVED BY:

Michael Boles	Jeffrey Joines
Roger L. Barker Chair of Advisory Committee	Hechmi Hamouda

BIOGRAPHY

The author, Cordula Guerth-Schacher was born on September 11, 1970 in Wuerzburg, Germany. After her secondary education in Germany she studied at the Fachhochschule Coburg, Abt. Muenchberg and received her Diplom Ingenieur Degree, which is equivalent of the Bachelor of Science degree, in Textile Chemistry/ Textile Finishing. Her thesis for the Bachelor degree investigated if high strength fibers are required to produce a high strength needle-bonded nonwoven batting.

In 1993 she was admitted to North Carolina State University and received her Masters of Science Degree in Textile Chemistry in 1996. Her Masters thesis was titled "Chemomechanical Softening of Nonwovens". In 1996 she was admitted to the doctoral program in Fiber and Polymer Science at North Carolina State University. In addition to finishing her dissertation she has continued to work part time in the area of fire protective clothing at the Thermal Protection and Comfort Center at North Carolina State University.

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1.0 INTRODUCTION

Structural firefighters often work in environmental conditions that can produce profuse sweating. The moisture that is produced by sweating may accumulate in the turnout clothing that is used to protect firefighters from skin burn injury resulting from the transmission of an intense heat event. The goal of this research is to investigate the effects of sweat generated moisture on capacity of materials used in turnout clothing to provide protective insulation in thermal exposures encountered in firefighting events that have not reached flashover conditions. Such exposures are usually several minutes in duration and the exposure levels are generally not sufficient to produce visual degradation in the outer shell fabric of the turnout clothing. This research will seek to develop a better understanding of the effects of moisture on the mechanisms that contribute to heat transfer throughout turnout clothing materials in prolonged exposure to radiant thermal energy. It will investigate the role of critical material variables, including the moisture vapor permeability and insulation properties of turnout composite ensembles. The scientific insights gained are expected to contribute to the development of laboratory test procedures for evaluating the thermal protective performance of turnout materials exposed to subflashover radiant heat conditions.

2.0 BACKGROUND

The objectives of this research must be considered in light of thermal environments that are encountered by firefighters and the materials that are used in the construction of their protective clothing.

2.1 Thermal Firefighting Environment

Table 2.1 shows how firefighting thermal environments that have been classified into categories based on routine, hazardous and emergency conditions of heat flux intensity and the duration of the exposure [12].

Table 2-1. Firefighter Thermal Environments

Exposure	Air Temperature (°F/°C)	Radiant Flux ($cal/cm^2/sec$)	Exposure Duration
Coletta [1]			
Routine	140°F (60°C)	0.03	5 - 60 minutes
Hazardous	572°F (300°C)	0.20	5 - 20 minutes
Emergency	1832°F (1000°C)	2.50	5 - 20 seconds
Abbott [2]			
Routine	20 – 70°C	< 0.04	10 - 20 minutes
Hazardous	70 - 300°C	0.04 - 0.30	1 - 5 minutes
Emergency	300 – 1200°C	0.30 - 5.0	15 - 20 seconds
Foster & Roberts [3]			
Routine	100°C	0.02	25 minutes
Hazardous	120°C	0.07	10 minutes
	160°C	0.10	1 minute
Emergency	160 - 235°C	0.23	< 1 minute

This laboratory based research focused on investigated conditions simulating firefighting environments in the hazardous and emergency exposure.

Hazardous conditions are typically considered as thermal events that would be encountered outside a burning building or a small building fire. Coletta describes the thermal exposures as lasting 5 – 20 minutes with an air temperature of 300 °C and a thermal radiation of 0.20 cal/cm^2/sec (8.37 kW/m^2). Abbot *et. al.*, who call hazardous conditions ordinary conditions, set the range to be 1 – 5 minutes at a range of air temperatures of 70 – 300 °C and a thermal radiation between 0.04 – 0.30 cal/cm^2/sec (1.67 kW/ m^2 – 12.56 kW/ m^2). The range set by Foster *et. al.* [3] has been taken to be at least 1 minute at 160 ºC and a thermal radiation of 0.096 cal/cm^2/sec (4 kW/ m^2) and can be tolerated up to 10 minutes.

The different classifications, summarized in Table 2-1, show that the definition of emergency exposure conditions vary widely. Emergency conditions, which are typically encountered in flashover conditions, have been taken to be above the range of "hazardous" conditions and ranging to beyond 235 ºC and 0.23 cal/cm^2/sec (10 kW/ m^2) by Foster *et. al.* [3]. Abbot *et. al.* [2] describe these conditions as having temperatures of 300 ºC – 1200 ºC and 0.30 cal/cm^2/sec to 5.0 cal/cm^2/sec (12.56 kW/ m^2 – 209.34 kW/ m^2). Coletta defines emergency conditions as ranging from 5 – 20 seconds with air temperatures of 1000 ºC and a thermal radiation of 2.50 cal/cm^2/sec. Severe thermal problems and life threatening injuries are associated with these conditions.

2.2 Firefighter Turnout Clothing

Firefighter turnout garments consist of three functional layers: an outer shell fabric, a moisture barrier, and a thermal liner component. Figure 2-1 illustrates a typical three-layer turnout fabric system. Each layer in the system performs a specific contribution to maximize the functional performance of the turnout composite. The outer shell fabric provides protection against radiant heat and flame contact. It typically consists of inherently flame resistant fabric material, such as fabrics containing Kevlar® or Nomex® fibers. The shell fabric must have high strength to resist ripping and abrasion. It must protect the inner layers and possess a level of moisture repellency to effectively resist water penetration from fire ground sources, such as rain or spray from a hose.

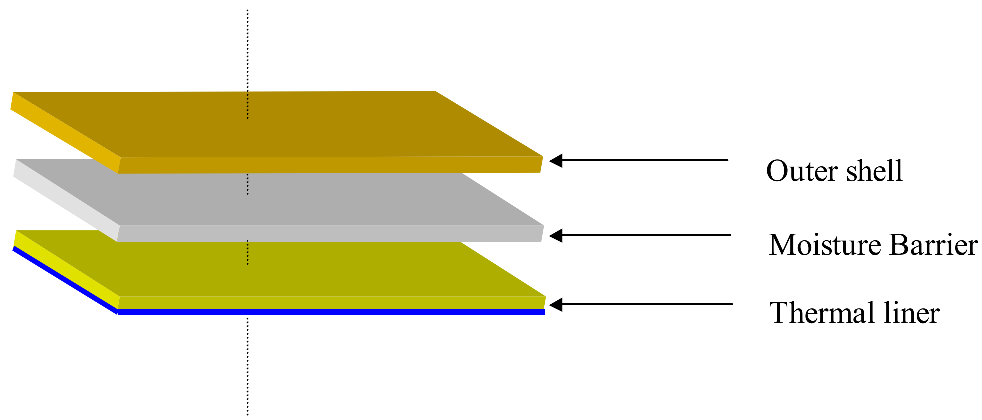


Figure 2-1 Sketch of a Three Layered Turnout System

Moisture barriers, positioned behind the outer shell fabric in the ensemble, function to prevent liquid water from external fire ground sources from penetrating through to the inner layers of the clothing system or to the firefighter. Moisture barriers have different degrees of moisture vapor permeability, or breathability. A permeable moisture barrier allows penetration of moisture vapor while preventing penetration of external liquid water. Permeable barriers allow for the exchange of moisture and heat between the skin of the wearer and the outside environment.

Thermal liners typically consist of a woven facecloth and a nonwoven batting material. The purpose of the batting material is to provide additional thermal protective insulation. This may be accomplished by an open batting structure that incorporates air spaces to inhibit heat transfer. The facecloth provides the thermal liner with strength, and in some cases, promotes wicking to remove sweat from the skin.

In addition to these three layers, firefighter turnout garments incorporate a reflective trim. The trim is attached to the outer shell fabric to aid visibility in smoke engulfed areas. Trim fabric has to be both fluorescent and retro-reflective, i.e. reflecting light back to the viewer. Trim fluorescence is produced using fluorescent dyes or pigments. Other types of

Trim products produce retro- reflectivity using microspheres to reflect light directly back towards the light source. These fluorescent materials may be coated onto a backing material or Neoprene substrate.

2.3 Effect of Moisture on Heat Transfer Through Fabrics

Heat transfer through fabrics is governed by their structural characteristics. Textile materials are three-dimensional fiber networks with enclosed air pockets. Heat is conducted through the fibers but is inhibited by trapped air, due to the low thermal conductivity of air. Small air pockets allow radiation to be transferred through fabrics; however, radiation transfer is not only hindered by large air pockets, but is also absorbed very quickly by fibers. Convective heat transfer occurs through large air spaces where air movement is possible [4, 5]. Air spaces within fibers are typically not large enough to allow convection to be a main contributor to heat transfer. Therefore, heat is transferred in fabrics mainly by conduction, with the main contributing factor being the low conductivity of air [4].

In order to understand moisture effects on thermal protective performance, one must understand its effects on the mechanisms of heat transfer through fibrous materials. This is because moisture can dramatically effect fabric heat capacity and thermal conductivity. Furthermore, with sufficient heat, liquid moisture present in fabrics can undergo an endothermic phase change vaporizing as steam, and contribute to the heat transfer [6].

Figure 2-2 provides a conceptual illustration of the influence of moisture on heat transfer in clothing materials. Adding moisture dissipates the air present in dry fabrics, increasing the heat capacity (c_p) of the fabric material [6]. With increased heat capacity, more heat is absorbed by wetted materials than dry materials, thus potentially limiting the amount of heat transmitted to the skin. Competing with the effect that moisture has on increasing heat capacity is the effect moisture has on thermal conductivity (k). Increased thermal conductivity promotes higher rates of heat transfer through fabrics, thus increasing the likelihood of burn injuries. Finally, moisture in fabrics can be heated above its vaporization point, generating steam. Steam moves to cooler parts of the system, closer to the skin. Once it condenses, it releases large amounts of heat. This heat locally increases the temperature leading to a faster heat transfer to the skin, ultimately leading to a burn injury.

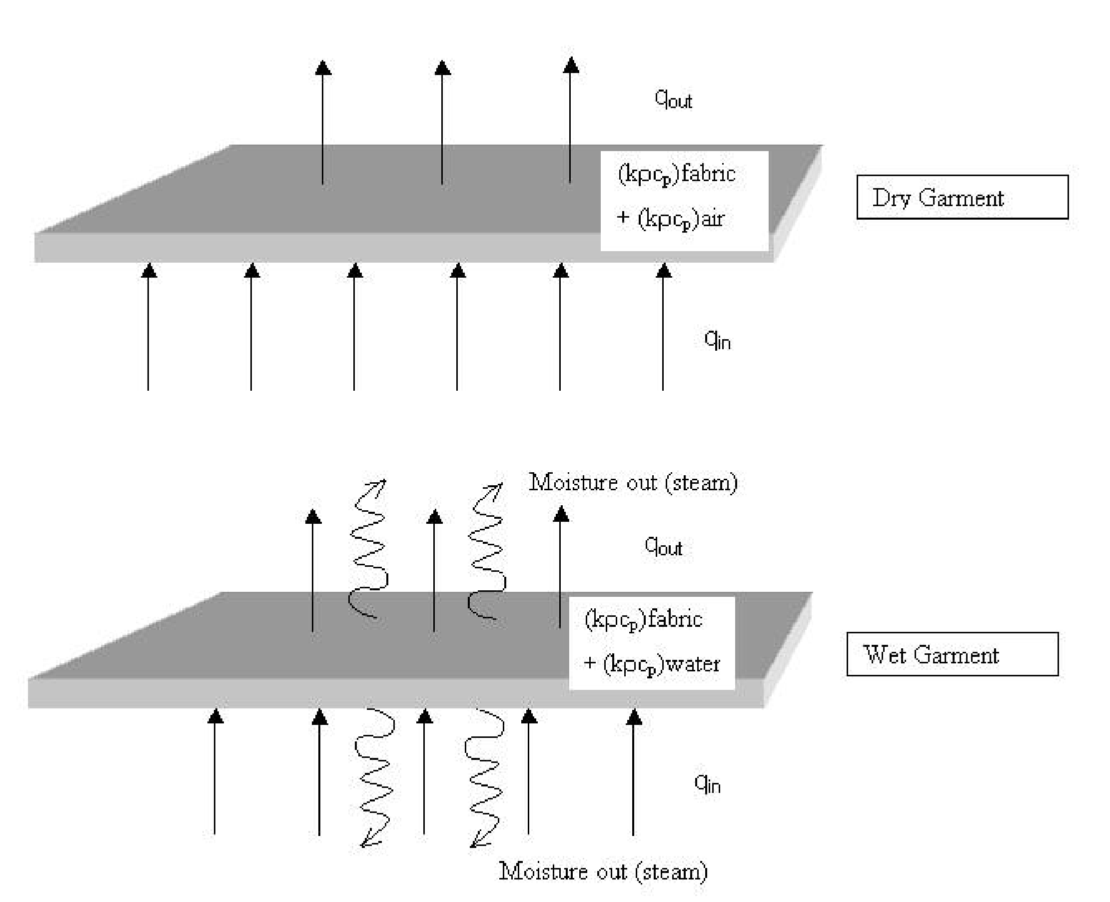


Figure 2-2 Effects of Moisture on Heat Transfer

Moisture effect on heat transfer through single layer fabrics has been studied by Chen [7]. Chen investigated simultaneous heat and moisture transfer through single layer cotton fabrics at different moisture conditions (dry, conditioned and moist) and for varying heat flux intensities (0.5 – 4.5 cal/cm^2/sec). Results of this study are illustrated in Figure 2-3. At high heat exposures and for short test durations, moisture detrimentally effects thermal protection. For longer exposures, moisture can actually increase thermal protection. Chen found that in intense exposures moisture present in fabrics vaporizes and recondenses at the surface of the thermal sensor, thus increasing the rate of heat transfer. In other instances moisture can act as a heat sink to dissipate incident radiant heat. For these conditions vaporization and recondensation of moisture decrease, leading to a gradual reduction in heat transfer through moist fabrics. Therefore, Chen [7] shows that heat transfer through moist fabrics depends on the intensity of the incident heat.

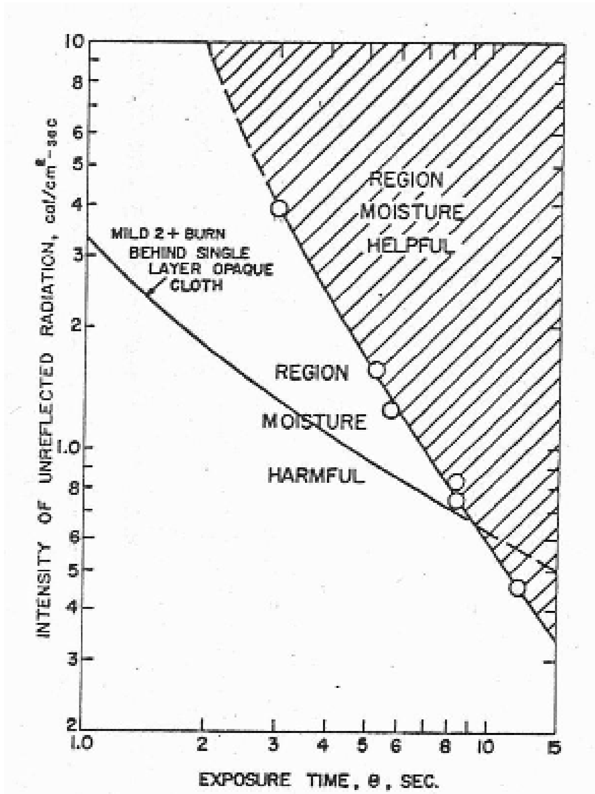


Figure 2-3 Results of research by Chen [7]

Lee and Barker [8] studied heat transfer through single layered protective fabrics in low and high radiant heat exposures. Three different moisture conditions were used in this study: dry, conditioned (65 %RH, 21ºC) and wet, at moisture loads ranging from 60 – 80 %. Radiant exposure ranged from 0.48 cal/cm^2/sec to 2 cal/cm^2/sec. These tests showed that, at high radiant exposure, the thermal protective performance of the fabric is reduced by up to 35 %. Two different phenomena were proposed to explain the observed effects. Moisture slows fabric heating by increasing the heat capacity of the fabric. Moisture vaporization, on the other hand, leads to a faster heat transfer to the sensor, where the steam recondenses. The latter phenomenon is overriding at high radiant heat flux levels. Moisture affected thermal protection differently at lower incident heat flux levels; the thermal protection of both the conditioned and wet samples increases. In this case, the higher heat capacity of wet samples plays a greater role than vapor transport to the sensor.

These studies suggest that moisture plays a complex role in high intensity thermal transfer: it can inhibit or increase heat transfer through thermal protective material depending upon the specific conditions.

2.4 Modeling Heat Transfer in Moist Turnout Materials

As described in reference [9], a basic heat transfer model has been constructed to estimate the effect of added moisture on turnout systems. This model envisioned a turnout system consisting of an outer shell, moisture barrier and thermal liner as illustrated in Figure 2-4. The heat flux boundary condition modeled are illustrated in Figure 2-4.

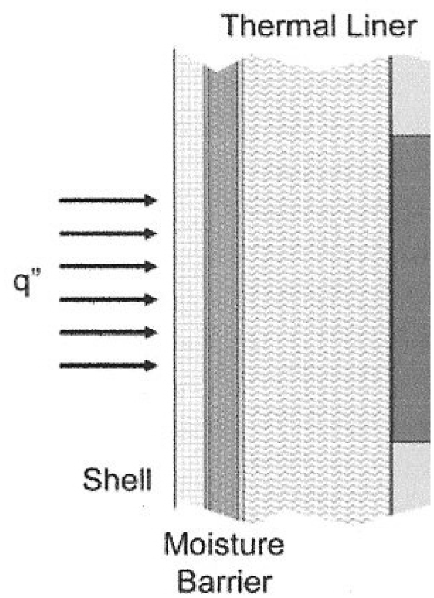


Figure 2-4 Heat Transfer Model through Fire Fighter Turnout System [9]

To simplify the model and yet obtain usable results, the thermal properties of the turnout composite were assumed to be homogeneous and isentropic. The thermophysical properties of the system were then modified by incorporating the physical and thermal properties of water using a weighting method. To obtain a rough estimate of the time to second-degree burn, the turnout system is assumed to be a semi-infinite body. The solution to the heat transfer problem then reduced to the solution for a semi-infinite body exposed to a constant heat flux boundary condition. The solution equation for this problem was directly taken from the literature [10] as:

$$T_{(x,t)} - T_i = \frac{2q}{k}\left(\frac{\alpha t}{\Pi}\right)^{\frac{1}{2}} \exp\left(-\frac{x^2}{4\alpha t}\right) - \frac{q}{k} x\, erfc\left[\frac{x}{2(\alpha t)^{\frac{1}{2}}}\right]$$

Where $T_{(x,t)}$ is the temperature distribution in the system, T_i is the initial temperature, q'' is the incident heat flux, k is the isentropic thermal conductivity in and α is the isentropic thermal diffusivity. Dry material values for the systems under study were taken to be approximately k = 0.05 W/m^2°C, ρ = 250 Kg/m^3 (measured), and C_p = 1150 W s/Kg °C. Modifying the dry material values to account for the addition of water into the systems, the resulting material values can be seen in Table 2-2.

Table 2-2. Estimated Effect of Water on Thermophysical Properties [9]

	k	ρ	C_p	α
Water	w/m °C	kg/m^3	W s/kg °C	m^2/s
0%	0.050	250.00	1150.00	1.74E-07
5^0/0	0.077	285.47	1294.01	2.09E-07
10%	0.102	317.72	1424.93	2.26E-07
20%	0.146	374.15	1654.04	2.35E-07
30%	0.182	421.89	1847.90	2.34E-07
50%	0.241	498.29	2158.08	2.24E-07
70%	0.286	556.71	2395.28	2.14E-07
100%	0.337	622.44	2662.12	2.03E-07

As described in reference [9], the heat transfer problem was solved and second-degree burn times were calculated for moisture add-on values of 0 (dry), 5,10,20,50 and 100%. The graph showing the effect of added moisture on the estimated time to second degree burn for a turnout composite exposed to an incident heat flux of 6.3 KW/m^2 (0.15 cal/cm^{2}sec) is shown in Figure 2-5.

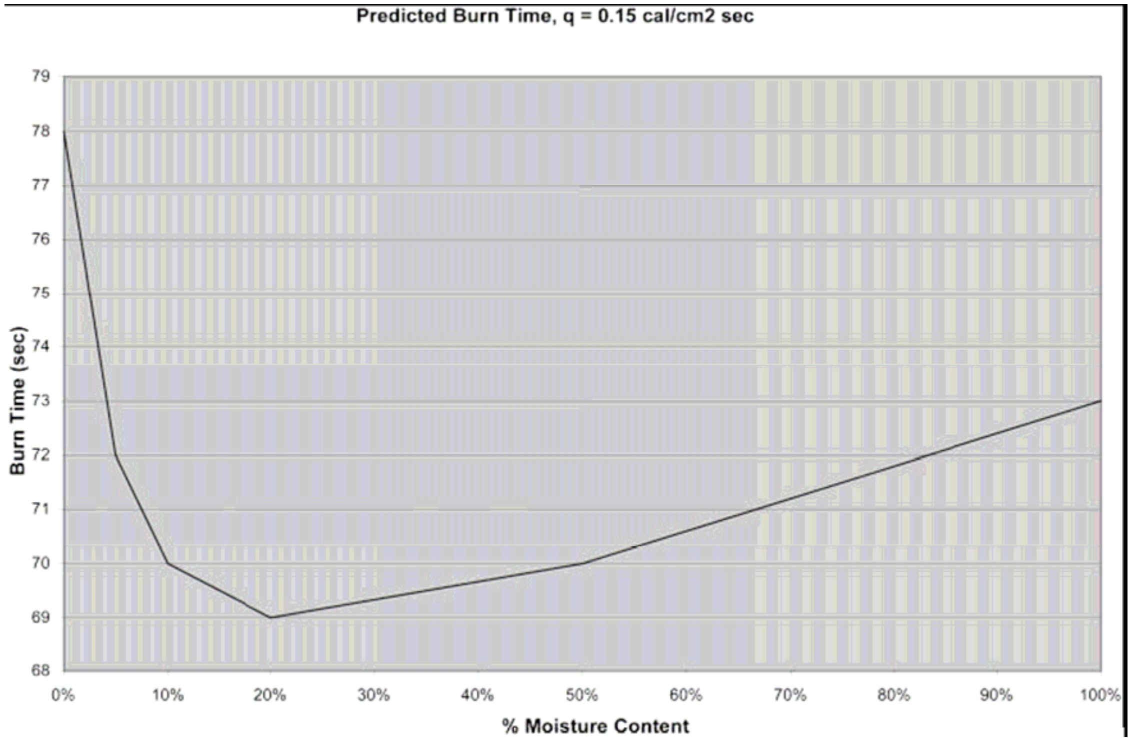


Figure 2-5. Relationship between second-degree burn time and turnout moisture content predicted by model for 6.3 kW/m^2 (0.15 cal/cm^2/sec) exposure [9].

Figure 2-5 indicates that the predicted second-degree bum time drops significantly with the introduction of moisture. This precipitous drop was attributed to the large difference in thermal conductivity between the turnout systems and water. At a moisture level of 20%, burn times reach a minimum and values begin to increase as additional moisture is added to the system. This can be attributed to the large difference in specific heat between the turnout systems and water. At 100% moisture add-on, the time to achieve a second-degree bum recovers to a point close to that of a dry system.

2.5 Laboratory Measurement of Thermal Protective Performance

2.5.1 Test Platforms

Various methods of supplying incident heat onto the fabrics have been employed for prolonged exposures of radiant energy. The most common testing methods utilize electrically heated quartz tubes, that provide a measurable heat flux output. These test platforms include the Radiant Protective Performance (RPP) test instrument [11], and the Stored Energy Test (SET) type instrument [12]. The later modeled after the radiant component of the Thermal Protective Performance (TPP) test platform. Another test, the Standard Test Method for Surface Flammability of Materials using a Radiant Heat Energy Source (ASTM E162) [13], utilizes a gas heated vertical plate as a heat source. All test platforms are capable of emitting heat flux levels between 0.1 and 2.0 cal/cm^2/sec (4 – 84 kW/m^2).

RPP test instrument consists of a radiant panel utilizing 5 quartz tubes, that are configured vertically. A schematic drawing can be seen in Figure 2-6. Test specimens, measuring 3” x 10”, are placed onto a sample holder that is positioned vertically from the quartz tubes. The sample holder is slid into a groove so that the distance between the sample and the quartz tubes is approximately 1”. A shutter plate is placed between the quartz tubes and the sample holder, and the test instrument is turned on for 60 seconds to heat up and reach the desired heat flux. After the 60 seconds heating period the shutter is removed and the test is started. A TPP type sensor consisting of a copper disk with 4 type J-thermocouples soldered to the backside measures the temperature rise at the inner most layer of the fire fighter turnout assembly to be tested. A computer data acquisition program compares the measured test data to the Stoll data curve for second degree burn and pain time.

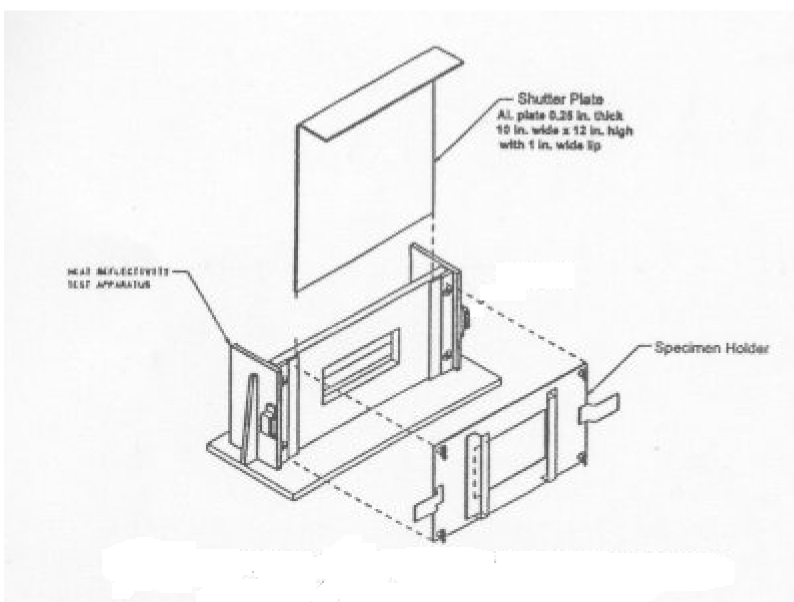


Figure 2-6. Drawing of RPP Tester [13]

The SET instrument, developed by NCSU, differs from the RPP instrument by using nine quartz tubes that can be adjusted to the selected heat flux and by utilizing a horizontal instead of a vertical sample set-up. Further, the SET instrument is water cooled and can therefore keep the selected heat flux even after prolonged exposures without being turned off after each test. The apparatus used to perform the radiant tests is shown in Figure 2-7. The sample, measuring 6” x 6”, rests in a sample holder and is placed above the quartz tubes at the start of the test [12]. A sensor block which holds the TPP type test sensor is positioned on top of the sample. Data acquisition is performed through a computer program, which is used to compare the measured temperature rise of the test senor to the Stoll data curve. One limitation of this Stored Energy apparatus is that the quartz tubes are further removed from the sample. This spacing configuration can lead to losses that would not be present in the RPP tester, where the fabric test sample is positioned close to the heat source.

Figure 2-7. Photograph of the Stored Energy Test (SET) apparatus [12]

A third method of testing the performance of fire protective clothing to prolonged radiant heat exposures utilizes the instrument described by the ASTM E162 Standard method [13]. The test instrument consists of a sample holder that is mounted on a trolley, to be positioned at different distances from a gas fired radiant panel. The different positions of the trolley allow for a range of heat exposures between 1.0 and more than 50 kW/m^2. A radiant shield is placed between the sample holder and the radiant panel prior to testing and removed upon the start of the test. Testing can be conducted for up to 30min, and a temperature profile is measured by thermocouples and registered by the data acquisition instrument. Figure 2-8 shows a drawing of the test instrument.

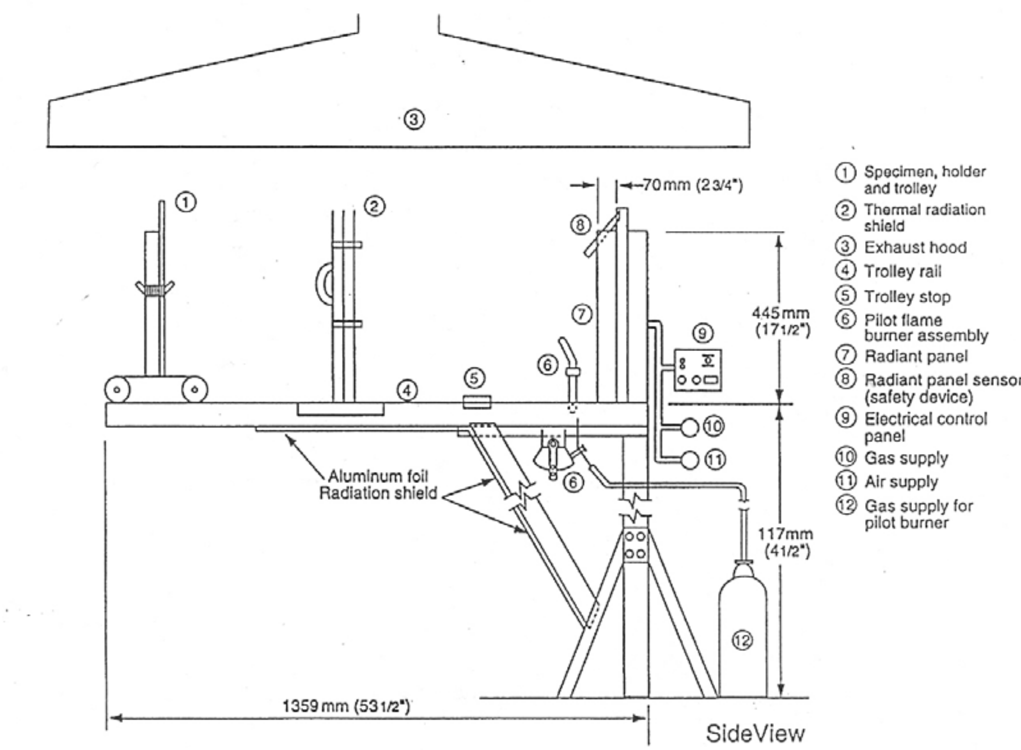


Figure 2-8. Drawing of Testing Instrument detailed in ASTM E 162 [14]

2.5.2 Heat Sensors

Several different heat sensors can be considered for the use in heat transfer measurements through fabrics exposed to intense thermal energy. The most well known type is the heat sensor used with the Thermal Protective Performance (TPP) Test [15]. A sketch of a TPP sensor is shown in Figure 2-9. The TPP sensor utilizes a copper disk. On the back of the copper disk, four (4) type J thermocouples are soldered. The sensor is housed in an insulating block. A drawback of this type of heat sensor is that in long-term exposures it heats up and loses its sensitivity [12, 23]. This raises the question of whether TPP sensors allow for accurate measurements in the long-term exposures used in this study.

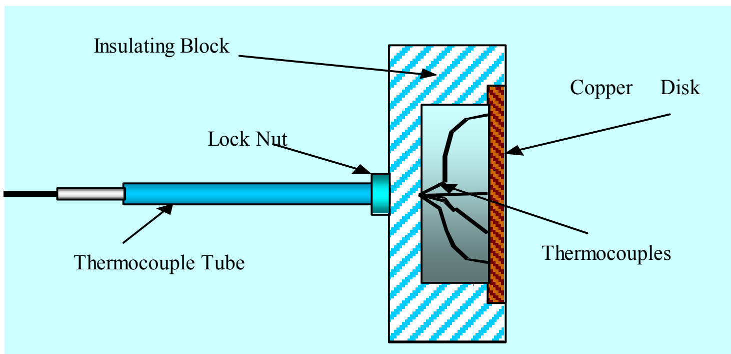


Figure 2-9 Sketch of a TPP Sensor [30]

It is therefore necessary to investigate other thermal sensors available. A newer type of copper slug calorimeter, the Pyrocal sensor (see Figure 2-10) [16], can be used in these tests. This sensor consists of a copper disk with a type T thermocouple attached to the back. An insulating guard ring surrounds the copper disk thereby inhibiting radial heat losses to the housing. Both the copper disk and the guard ring are surrounded by an insulated housing. The insulating capabilities of the guard ring lead to a slower rise in temperature of the copper disk, thus allowing a more accurate heat flux measurement over longer time periods than the typically used TPP sensor.

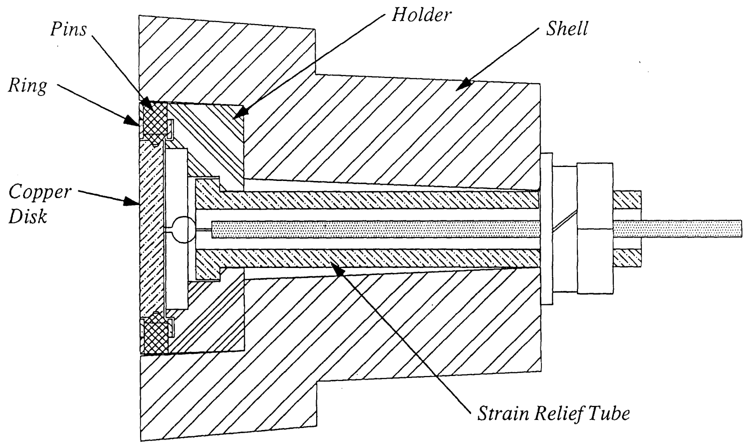


Figure 2-10. Sketch of a Pyrocal Sensor [16]

A third method of measuring thermal transfer through fabrics is to attach a thermocouple onto the fabric, and measure the temperature continuously during testing [17]. It is important to understand that thermocouples measure the temperature of the fabric surface, whereas a calorimeter type thermal sensor measures heat flux transferred through the systems. Therefore, selection of a thermal sensor plays an important role in the test results. Temperature measurements using a thermocouple are dependent on the way a thermocouple is attached to the fabric whose temperature it needs to measure. Several methods of attaching a thermocouple were investigated for this research. It was found that the best way was to fix the thermocouple with tape to the fabric and additionally attach the thermocouple wires to the sample holder. Thermocouples have a very fast response time due to temperature differences, therefore differences in the temperature in laboratories or of the materials may impact the temperature measurement of the thermocouple.

A fourth sensor utilizes material that simulates the properties of human skin. A type T thermocouple is either imbedded into the material or attached to the surface of the senor. This type of sensor is mainly used in instrumented manikin tests. Advantages of these sensors can be attributed to their properties resembling human skin, and therefore giving a similar temperature profile. Disadvantages have been noted to be a long cooling period of up to 30 minutes. Further these sensors are not as rugged a copper calorimeter are. Therefore these sensors mostly have not been used in benchtop tests [4].

2.5.3 Skin Burn Models

Accurate burn predictions do not depend on the choice of thermal sensor alone. It is also important to choose the appropriate burn prediction method. Three different types of burn prediction methods are commonly used in bench top tests. These are based on Stoll [18], Henriques Integral [19], and the 55 º criteria [17].

The Stoll criteria is commonly used with the TPP and Pyrocal sensor and is applied to the heat flux read by the sensor to predict time to second degree burn [18]. Data are only available for 30 seconds, therefore for prolonged exposures an exponential decay extrapolation of the Stoll data is used. The second degree burn time is estimated by the intersection between the extrapolated Stoll curve and the data generated by the sensor. The Stoll criterion is used with sensors which act as heat sinks, therefore dissipating heat like skin. This may lead to an underestimate of the burn potential to the skin.

A second method, the Henriques integral utilizes an Arrhenius equation to estimate time to second and third degree burn.

$$\Omega = \int_0^t P * \exp^{\frac{\Delta E}{RT}}$$

Where Ω= Burn

P = System Constant

T = Temperature (ºC)

t = Time (s)

R = Gas constant

ΔE = Activation Energy

Heat flux measurements of the sensor are converted to skin temperature measurements at approximately 80 μm and at 200 μm. The interface from surface skin tissue to deeper skin tissue can be found at a skin depth of approximately 80 μm. Second degree burns are burn injuries where the burn damage exceeds the basal layer. Henriques *et al*. [19] found in tests that a burn injury occurs when the skin temperature exceeds 44 ºC. Therefore, the Henriques integral will only be executed when the calculated temperature at the basal layer reaches 44º C. At a skin depth of about 200 μm, fatty tissues that lay underneath the deeper skin tissue can be damaged, leading to a third degree burn. The advantage of using the Henriques integral is that first, second and third degree burn times can be estimated and it is used in mannequin tests. Further, no extrapolation has to be made, and therefore this method of determining second degree burn times is more likely to lead to realistic results. Iterative numerical methods are necessary to evaluate the Henriques integral making it somewhat more complicated to evaluate than the Stoll data curve.

A third method has been proposed, where the time when the thermal liner reaches 55º C indicates potential burn hazard [17]. Thermocouples, which have an extremely fast response time to temperature changes, are attached to the fabric surface and measure its temperature. Due to the extremely fast response of the thermocouples and the method of attachment to the fabric surface, this method may over predict the burn potential. Differences in the starting temperature will lead to variability in the time it takes a thermocouple to reach a temperature of 55º C, and consequently lead to a high variability in the estimate of a second degree burn time using the 55º C criteria.

3.0 RESEARCH ON MOISTURE EFFECTS IN FIREFIGHTER TURNOUT SYSTEMS

Tables 3-1 and 3-2 summarize material configurations and test conditions that have been used in studies of moisture effects on the thermal protective performance of firefighter turnout materials. Table 3-1 describes the different fabric systems used in these studies. Table 3-2 shows the range of heat exposures and water application methods and add-ons. Relevant findings from these studies can be summarized as follows:

Table 3-1. Test Materials Used in Research Studies on Firefighter Systems

Research Study	Shell Fabric	Moisture Barrier	Thermal Liner	Comments
Gohlke [20]	Nomex®	Neoprene Gore-Tex	Nomex®	Standard Materials used
Mäkinen *et. al*. [21]	FR Viscose/ Aramid	None	Cotton Twill	Underwear was used (Cotton, Wool, and Aramid)
Rossi *et. al.* [22]	Aramid, FR Cotton	PTFE, PU PES, PVC	Aramid	Partially non-standard US firefighter assemblies
Stull [23]	Nomex® III PBI/Kevlar®	Neoprene Crosstech®	Caldura SL Aralite® Q9	Combinations for theses different materials
Rossi [24]	Aramid	PTFE PES, PU	Aramid Wool	Partially non-standard US firefighter assemblies
Jensen [17]	Kevlar®/PBI	Neoprene Crosstech®	Aralite®	Standard Materials used
Barker and Guerth [12]	Kevlar®/PBI	Neoprene Crosstech®	Aralite®	Standard Materials used

Table 3-2. Test Variables Used in Research Studies on Firefighter Systems

Research Study	Moisture Application Method	Moisture Added	Test Method	Thermal Exposure ($cal/cm^2/sec$)
Gohlke (1980)	N/A	225 – 250 g/m^2	Radiant Panel (like in TPP)	0.47
Mäkinen et. al. (1988)	N/A	0 – 80 %	ISO 6942	0.48
Rossi et. al. (1996)	Immersion in water for 1h20min then spin-dried	inner layers: 20% - 54 % outer layers: 4 % - 18 %	ISO 6942	1.90 and 0.11
Stull (1996)	Application of 1 g water to middle of thermal liner, or Immersion in water for 2 min then condition for 15 min under 34.5 kPa pressure	0 – 30 % of dry composite weight	RPP	1 – 2.5
Rossi (1997)	sweating torso	N/A	Radiant Panel (No Standard given)	0.11
Jensen (1997)	Spray on or immersion, rolling with rubber roll and wringing	total of 15 g	ASTM E162	0.06 – 1
Barker and Guerth (1999)	Spray on application	6 g of water	Proposed Stored Energy Test Set-Up	0.14 – 0.5

Gohlke [20] investigated the effects of moisture on two firefighter systems (permeable, and impermeable). Four moisture conditions were tested: shell and liner dry, shell dry and liner wet, shell wet and liner dry, and shell wet and liner wet. He found that the permeable barrier shows slightly better thermal performance when the shell fabric is dry, and the impermeable system shows slightly higher thermal protection when the outer shell fabric is wet. Gohlke`s research provides a first insight into the complex, and often conflicting effects of moisture on thermal protection. However, a drawback of this study is the manner in which burn and warning times were determined. Gohlke`s procedure called for the removal of the test sample from the radiant panel when a second-degree burn could still be avoided. The warning time was calculated as the time between the onset of pain time and the removal of the sample from the heat source. Most test protocols, however, propose that testing continues until a second degree burn time can be predicted. Comparisons between Gohlke's and other studies are therefore complicated.

Mäkinen et al. [21] studied the effect of moisture content in underwear on thermal protection. She found that humidity in underwear decreased time to pain and time to burn, with the shortest burn time occurring at a moisture content of 30 – 40%. At higher moisture levels the drop in thermal protection actually may slightly increase. These data were gathered on systems without a moisture barrier. Therefore moisture vapor transfer may occur freely within the system, allowing heated moisture vapor to reach the skin faster. The moisture vapor recondenses on the skin, leading to a faster burn time. This may explain why moisture content in underwear leads to a drastic drop in thermal protection.

Stull [23] compared the conductive heat resistance and the RPP tests. In the conductive heat resistance tests moisture was added to two different systems (permeable and impermeable). He found that thermal protection was diminished only in saturated systems. Furthermore, the permeable systems provided lower thermal protection than the impermeable system. The results in the RPP test showed that thermal protection decreases as heat flux intensity increases. It is unfortunate that the moisture tests were only performed in the conductive heat resistance test, because different test methods do not necessarily lead to comparable results. It would have been helpful to see how the wet systems would have performed on the RPP test platform.

Rossi and Zimmerli [22] investigated the influence of humidity on the radiant heat transmission through protective clothing. They found that at low radiant heat flux exposures, humidity in the inner clothing layers decreases the time to pain and the time to burn.

Moisture present in the outer shell layers also decreases thermal protection. They suggest that this is due to the increased heat conduction in the system. Both the measured times to pain and burn seem longer than expected. This may be due to the use of the standard TPP sensor, which is known to heat up in prolonged thermal exposures. This heating process leads to a decreased sensitivity of the senor, and ultimately to an overestimation of the predicted pain time and burn time.

Rossi [24] investigated the effects of moisture on firefighter turnout systems using a novel sweating torso. He found that thermal protection was higher for wet permeable systems than for dry permeable systems. For an impermeable system, thermal protection was higher in the dry system then in the wet system. Water was lost to the outside of the shell fabric during the tests with a permeable system. Rossi suggests that water vapor may flow during low level heat exposures from the thermal liner to the outside of the shell fabric, if the partial water pressure is lower on the inside than on the outside of the firefighter turnout system. The sweating torso used provides a continuous supply of moisture during low radiant heat exposures, whereas most test systems use a prescribed preconditioning protocol to apply moisture prior to testing. A dynamic system, such as the one described by Rossi, may lead to different results in thermal protection than the normal test set-up because fabrics cannot dry out in a dynamic system.

Jensen [17] investigated the effects of moisture on thermal protection in the presence of reflective trim material. Jenson used the RPP test and the Standard Test Method for Surface Flammability of Materials using a Radiant Heat Energy Source (ASTM E162) [13] to measure thermal protection. Results for the RPP test showed a slight decrease in thermal protection for the permeable system when moisture is added. The trim did not add thermal protection to the permeable system. The impermeable, on the other hand, shows an increase in protection when water is added; trim also increases the thermal protection. The test with the ASTM E162 [13] apparatus used thermocouples to measure the temperature rise behind the shell fabric and the thermal liner. In the permeable system, moisture leads to a faster initial temperature rise on the thermal liner behind the reflective trim. When no trim is present the temperature rise on the thermal liner is slower. In the impermeable system, however, a more gradual temperature rise is observed on the thermal liner, especially behind the reflective trim. The two tests performed used different methods to estimate thermal protection. Therefore, the results of the two tests can not be directly compared, but both tests show similar trends in thermal protection.

Barker and Guerth [12] studied the effect of moisture on the thermal energy stored in firefighter protective clothing using two firefighter systems (permeable and impermeable). They found that increases in the intensity of heat exposures lead to a decrease in protection time. Permeable systems provide a better thermal protection in a low intensity heat flux then impermeable systems. The difference in thermal protection between permeable and impermeable systems decreases for higher heat flux intensities. Overall moisture reduces thermal protection in the systems but to a higher degree in the permeable system. Thermal protection afforded in separate wetted t-shirt layers placed onto the thermal liner depends on the intensity of the heat flux. At high intensities thermal protection is diminished, whereas at low intensities thermal protection may be increased. These tests used a weighted sensor to compress the tested sample and a preheating period; therefore the results cannot be directly compared to TPP or RPP type tests. Still these tests show the complex effects of moisture conditioning on thermal protection.

4.0 GAPS IN RESEARCH

Although many studies have been made into the effects of moisture on the thermal protective performance of firefighter protective materials in low-level heat exposures, several questions remain unanswered. The following demonstrates that additional knowledge and improved testing approaches are needed:

1. Preconditioning procedure – Moisture has been applied in various ways but seldom have data from physiological studies or field data been related to moisture accumulation in firefighter garments. It is important to understand moisture distribution as well as amounts of moisture stored in firefighter garment assemblies and their effect on heat transfer. A precisely conditioned sample will lead to better reproducibility in tests of thermal protective performance, and aid in understanding the role of absorbed moisture in heat transfer that may contribute to burn injuries in firefighters.
2. Heat and Moisture Transfer Mechanisms – A more fundamental understanding of the underlying effects of absorbed moisture on heat and moisture transfer in firefighter turnout clothing is needed. A successful model will assist development of test methods, and in designing firefighter garment assemblies that can reduce the amount of heat transferred to cause burn injuries.
3. Contribution of Clothing Materials to Heat and Moisture Transfer – It is important to understand the contributions of different fabric layers in the turnout assembly on heat and moisture transfer. There is a particular need for more insights into the role of moisture barrier permeability to moisture regain and the effects of the insulation provided by the thermal liner component of the turnout ensemble. There is an additional need to investigate how impermeable reflective trim fabric affects the overall thermal protective performance of the turnout composite. An investigation of the trim component is important, since reports are available of firefighters receiving second degree burns underneath reflective trim [25]. Currently investigations intothese phenomena where trim is attached to the fabric have not led to satisfactory explanations.

The intention of this research is to conduct investigations and analysis that will advance the state of understanding in critical areas related to these phenomena.

5.0 DEVELOPMENT OF A MOISTURE PRECONDITIONING PROTOCOL

Studies have shown that moisture present in firefighter turnout systems has a complex influence on heat transmission and potential for skin burn injuries [12, 17, 23]. At the same time, there is significant current interest in developing laboratory thermal protective performance testing protocols that incorporate reliable and realistic moisture preconditioning procedures. A major obstacle in developing these testing methodologies is the lack of basic understanding of how moisture is absorbed in turnout systems when exposed to perspiration for a sweating firefighter.

The present research sought to develop an understanding of moisture absorption from perspiration in turnout systems during wear, and from laboratory devices that simulate perspiration from firefighters. This facet of this investigation, as reiterated in the sections below, has been described in reference [26].

5.1 Sweat Absorption in Firefighter Turnouts

The optimum moisture preconditioning protocol should simulate both the amount and distribution of moisture absorbed by turnout clothing worn by firefighters. Figure 5-1 shows how moisture accumulates in different components of firefighters' clothing system in wear. These data, extracted from physiological studies on the effects of turnout breathability on firefighter heat stress and comfort [27 – 29], show that the highest percentage of moisture accumulates in absorbent clothing or layers in closest contact with sweat-wetted skin. An absorbent T-shirt material absorbs moisture levels that approach saturation (>90%). In comparison, turnout garments, worn over a T-shirt and station uniform, absorb moisture in amounts that are significantly below saturation levels (1.5 – 15%). Within individual fabric layers of the turnout composite, moisture is absorbed primarily by the thermal liner component (Figure 5-2). Moisture absorption, and distribution within the turnout, are determined by the moisture absorption capacity of the thermal liner, by the breathabiltiy of the moisture barrier, and by the sweat output in wear. Sweat output in wear can range from 0.5 l/hr up to 3 l/hr depending on environment, amount, and duration of physical exertion. More moisture is absorbed by turnout liners that incorporate thicker thermal liners, principally because thicker thermal liners have greater capacity to contain moisture than thinner liner components.

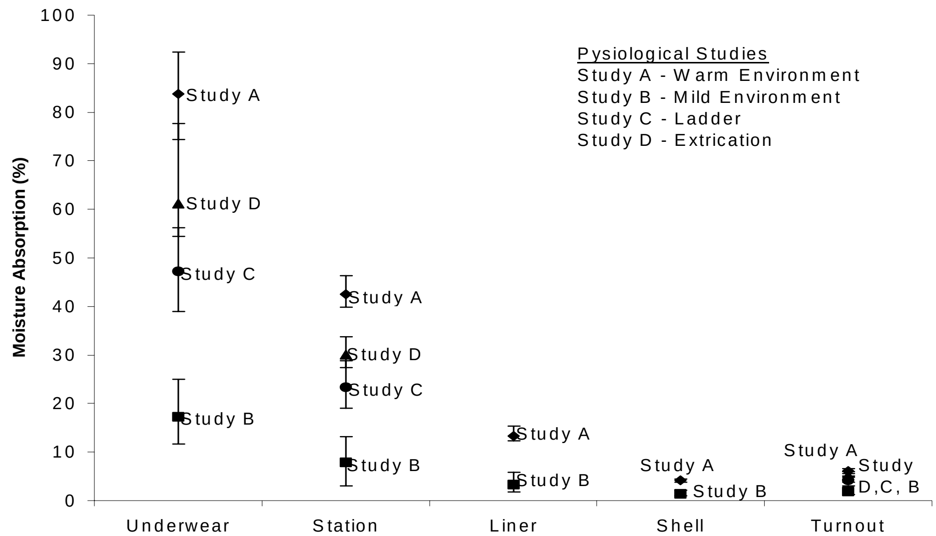


Figure 5-1: Percent Moisture Absorption of Fire Fighter Turnout Garments in Wear Trials [26]

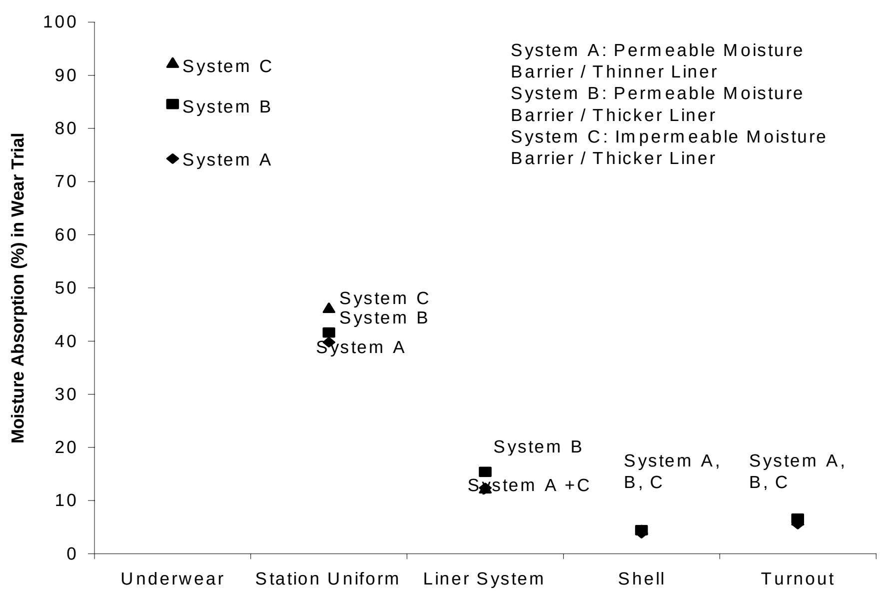


Figure 5-2: Effect of Moisture Barrier Permeability and Thermal Liner on Sweat Accumulation in Fire Fighter Clothing (Warm Environment Study) [26]

Turnout systems which utilize vapor impermeable moisture barriers generally produce more moisture in inner (T-shirt) clothing layers, because there is no opportunity for moisture to escape by evaporation.

Examination of data from physiological studies provides a first estimate of the amounts and distribution in firefighter turnouts. This information also provides useful insights into mechanisms of moisture transport in firefighter turnout systems.

5.2 Moisture Transport Mechanisms in Turnouts

Barker and Guerth [26] performed a study that used sophisticated laboratory moisture delivery systems to study ways in which moisture is absorbed and transported in turnout composites. Moisture is transferred in turnout materials by two basic mechanisms: by wicking of liquid moisture into clothing materials through direct contact with sweat wetted skin, or by condensation of moisture vapor from evaporated sweat.

5.2.1 Liquid Sweat Uptake

A modified Gravimetric Absorbency Testing System (GATS) was used to measure the moisture accumulation in turnout composites, simulating wicking of liquid moisture from direct contact with sweating skin. The GATS procedure measures demand wettability. The test indicates the lateral wicking ability of the fabric, or the ability of the material to take up liquid in a direction perpendicular to the fabric surface. The NCSU GATS apparatus was modified to incorporate a special test cell and cover to assess absorption behavior in the presence of evaporation see Figure 5-3. In this arrangement, liquid is drawn from a fluid reservoir by the capillary action of the fabric. The hydrostatic pressure of the fluid delivery system is adjusted by controlling the position of the simple platform (the test is nominally operational with a zero hydrostatic head). Liquid is delivered to the test material placed on a porous plate. Fifty-four pens, distributed over the area of the test surface, uniformly restrain the test fabric. The amount (grams) of liquid siphoned from the reservoir is recorded as a function of time. This data is used to calculate absorption rates, absorption capacities, evaporation capacities, and the percentage of moisture evaporated by the fabric. The GATS was used to measure the uptake of liquid moisture by four different firefighter turnout systems (each liner system was layered with a 7.5 oz/yd2 Kevlar®/PBI shell fabric). Results of these experiments are presented in Figures 5-4 – 5-6.

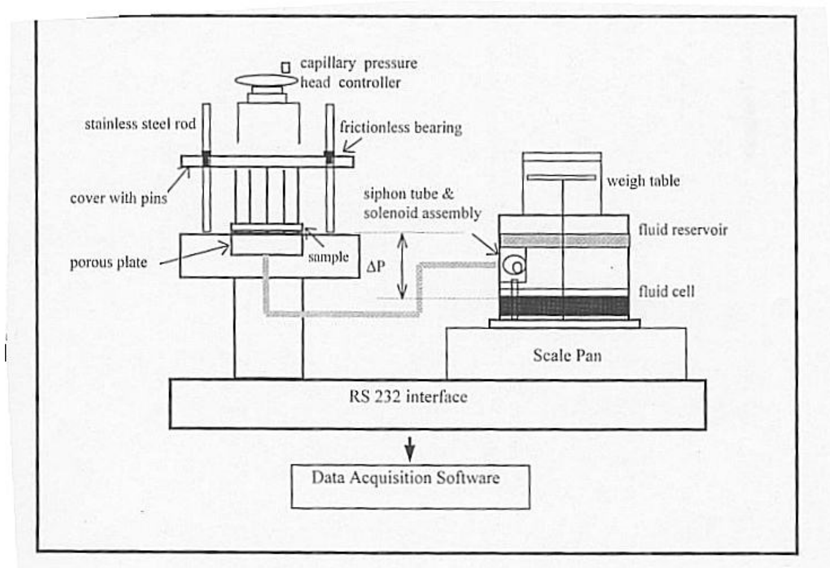


Figure 5-3. GATS Apparatus [26]

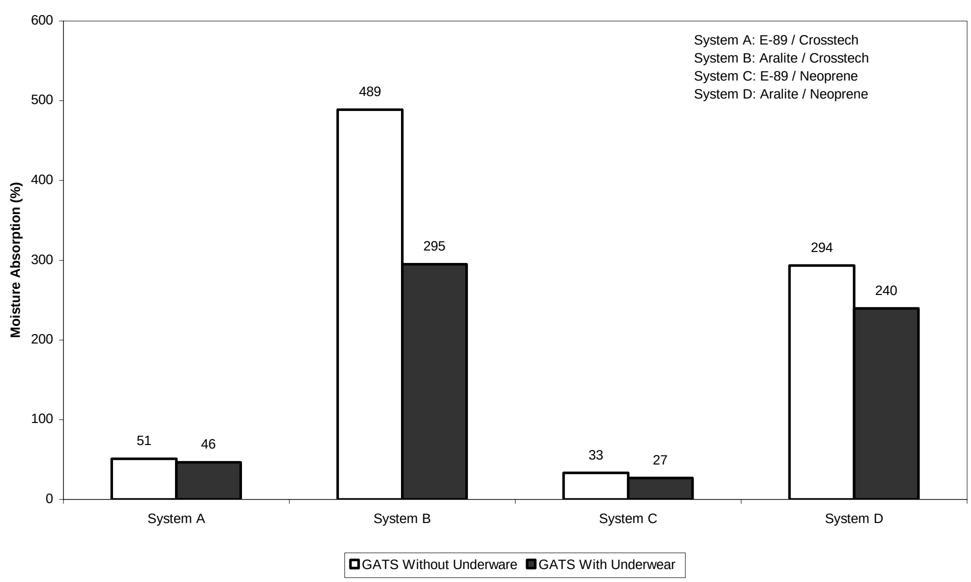


Figure 5-4. Moisture Absorbed by Turnout Liner Systems (Moisture Barrier/Thermal Liner) in GATS [26]

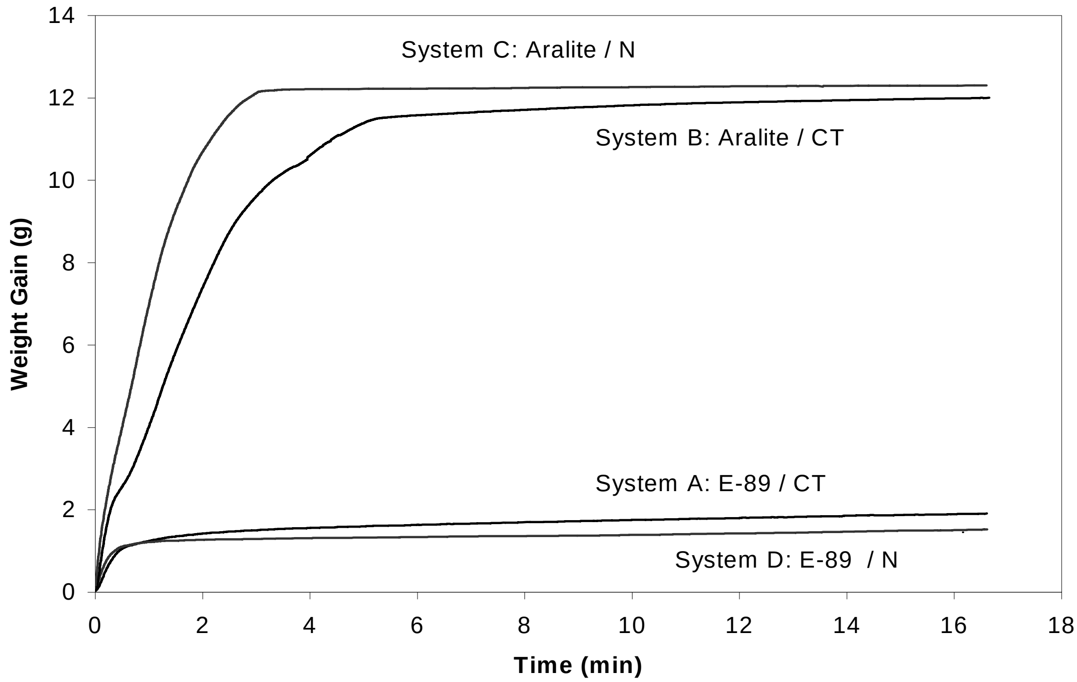


Figure 5-5. Moisture Transport (Absorbed and Evaporated) by Clothing Systems, Without Inner Clothing Layers, in GATS as Function of Time. [26]

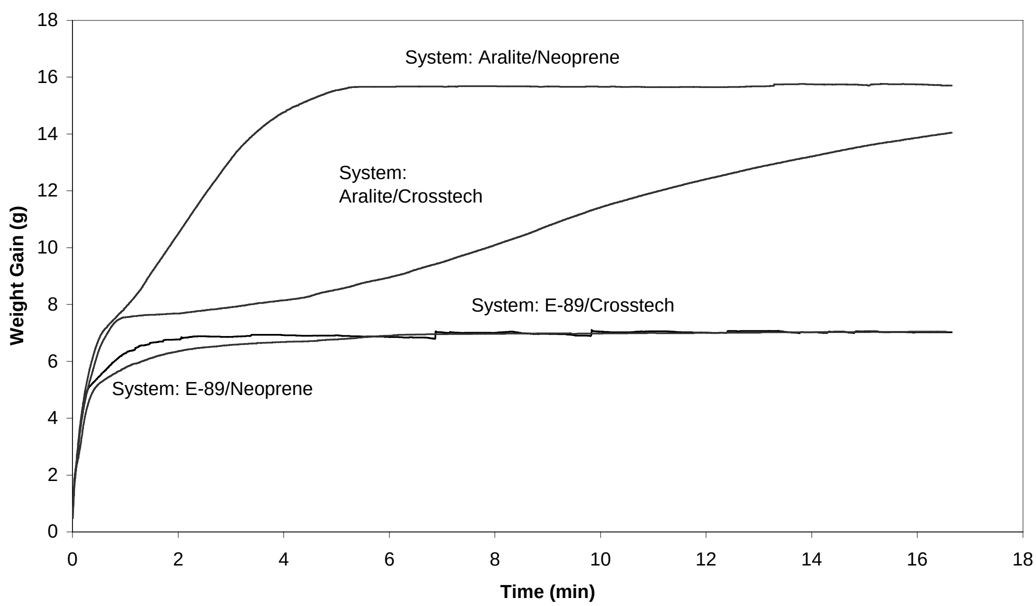


Figure 5-6. Moisture Transport (Absorbed and Evaporated) by Clothing Systems and Inner Clothing Layers (Underwear and Station Uniform) in GATS as Function of Time [26]

Data from these tests showed that the absorption capacity of the thermal liner component is the dominating factor controlling moisture uptake by wicking into the layered turnout composite. Liquid moisture uptake by wicking into Aralite® is almost ten times greater than in the E-89® thermal liner. In contrast, since it controls moisture loss by evaporation mechanisms, which is a small fraction of the moisture movement in comparison to wicking, the vapor permeability of the moisture barrier component has much less effect on the liquid pick-up. Breathable moisture barriers (Crosstech®) contribute to less build up moisture in the thermal liner than the impermeable moisture barrier (neoprene). The effect of moisture barrier permeability is evident in systems that incorporate Aralite® thermal liners. However, while the amount of moisture absorbed and retained in the liner is greatest for nonbreathable composites, permeable Crosstech® barriers approach over time the total amount of moisture absorbed by impermeable neoprene systems. These results demonstrate that moisture is also transmitted by evaporation, in breathable turnout systems. Most significantly, it shows that exposure to an unlimited supply of liquid moisture can produce moisture pick-up levels exceeding several times saturation in some liners (e.g. Aralite® thermal liners).

Experiments were conducted to simulate two types of clothing configurations: one arrangement simulated the thermal liner being placed in direct contact with the wetted surface of the GATS, and the other simulated an absorbent T-shirt and station uniform clothing layer being placed between the wetted surface and the thermal liner component. Tests show that absorbent clothing inner layers reduce the amount of moisture absorption into the liner system. However, moisture pick-up continues to exceed saturation levels in Aralite® liner systems. These findings suggest that moisture is transported by wicking mechanisms that occur as the intervening absorbent inner layers exceed their saturation capacity.

5.2.2 Moisture Condensation by Sweat Evaporation

As noted in reference [26], a source of moisture accumulation in turnout systems is the condensation of vapor produced by sweat evaporation. Moisture condensation in turnouts is related to the moisture vapor permeability of the turnout and to the transmission of thermal energy. The guarded sweating hotplate (skin model) apparatus, available at NCSU, was used to study these phenomena in firefighter turnout systems. The main component of the skin model is a perforated plate of sintered metal (stainless steel) sized 20 x 20 inches (Figure 5-7). The plate is electrically heated to skin temperature (35º C) and covered by the test fabric. A guard ring heated to the same temperature as the metal plate prevents lateral heat loss. Water is fed from the surface of the test apparatus onto which a cellophane sheet is placed, shielding the fabric from liquid water. The entire assembly is based in a housed controlled environmental chamber to provide control of ambient conditions (temperature, humidity) and air flow.

Figure 5-7. NCSU Sweating Hot Plate Apparatus [26]

The guarded sweating hot plate apparatus is routinely used to measure heat transfer through clothing materials associated with thermal comfort or heat stress. In this research, it was employed as a controlled moisture delivery system to simulate the process of moisture accumulation in turnouts resulting from vapor condensation. Accumulation from simulated sweat evaporation was determined for four different turnout composite systems. Turnout systems were selected to study the effects associated with differences in thermal liners and moisture barriers. The results of these experiments as seen in Figure 5-8 indicate that the moisture barrier component is the primary source of differences in moisture uptake; for permeable systems (Crosstech®), equivalent amounts of moisture accumulates in the E-89® (System A) liner and in the Aralite® (System B) liner. On the other hand, because moisture loss by evaporation is prevented in impermeable systems, more moisture builds up in the Aralite® liner than in the E-89® system (Systems C and D).

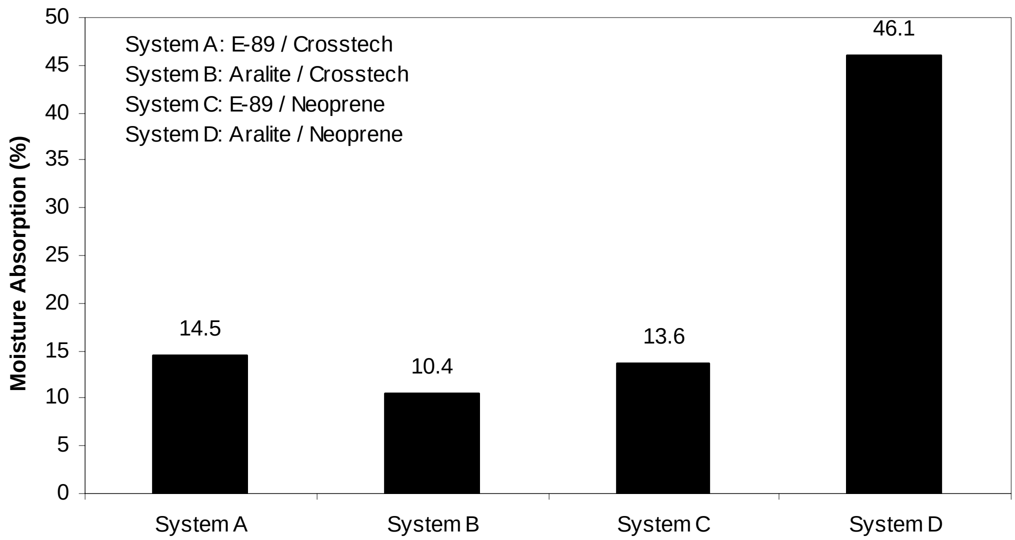


Figure 5-8. Moisture Absorbed in Turnout Liner (Moisture Barrier / Thermal Liner) Systems in Sweating Hot plate (1/2 hour preconditioning at 25 deg C, 65 % RH ambient condition) [26]

5.2.3 Correlations with Sweat Absorption

Comparisons of sweat pick up between turnout systems in actual firefighter wear (Figures 5-1 and 5-2), and laboratory experiments that simulate moisture delivery, either by a sweat wicking mechanism or by condensation of evaporative moisture, indicate that moisture levels are most closely approximated by laboratory preconditioning with the guarded sweating hot plate. Sweating plate preconditioning, using absorbent inner layers, can be expected to produce closer correlation with moisture levels observed in wear. These results suggest that when thermal liners do not directly contact liquid sweat, and the level of moisture in inner clothing layers is less than saturation level, moisture accumulates by condensation of evaporated moisture vapor. Moisture build up by processes involving the wicking of liquid sweat can be expected in cases where the thermal liner is in intimate contact with sweat wet skin, as simulated by the GATS procedure.

5.2.4 Developing a Practical Preconditioning Procedure

The aforementioned studies provided valuable insights into the mechanisms of moisture transport in firefighter turnout systems. They showed that moisture can accumulate in turnouts, both by wicking of liquid moisture, and by condensation of evaporated sweat. They demonstrate that the level and distribution of absorbed moisture varies, depending on the type of thermal liner, on the breathability of the moisture barrier component, and on the presence of underlying absorbent clothing layers. This knowledge was applied to develop rational preconditioning protocols for evaluating the effects of moisture on thermal protective performance in prolonged exposure to radiant heat. In this regard, our experiments suggest that the sweating guarded hot plate may be a means of preconditioning turnouts to realistic levels of moisture content prior to thermal testing. However, the sweating plate procedure involves the use of elaborate and costly laboratory equipment and therefore may not be ideal as a practical preconditioning method. Consequently, the following simpler procedure was adopted: the turnout test specimen is precisely weighed and sufficient water is then sprayed onto the facecloth side of the thermal liner to increase the weight of the turnout composite (thermal liner, moisture barrier, shell fabric) by approximately 15 percent. This amount of add-on was chosen to reasonably approximate the level of moisture actually absorbed by turnout liners, as observed in wear trials. The turnout composite is sealed in a plastic bag and allowed to condition for a period of at least twelve hours; specimens are subsequently removed from the sealed bag and precisely weighed.

Table 5-1 shows the results of triplicate measurements for four different turnout materials. These data confirm that the above described moisture preconditioning protocol produces consistent amounts of moisture add-ons, with little variability in repeated tests. The demonstrated consistency of the protocol is a significant development, since it has been shown that reproducibility of moisture effects on thermal tests is critically controlled by the ability to consistently load moisture into the specimen [12].

Table 5-1. Moisture Pick-up in Turnout materials Using Preconditioning Method [26]

System -Replicate	Moisture Pick-up (%)
A: Crosstech/E89	
-1	17.7
-2	18.5
-3	18.1
Average	***18.1***
% CV	***2.3***
B: Crosstech/Aralite	
-1	17.4
-2	18.1
-3	18.3
Average	***18.0***
% CV	***2.7***
C: Neoprene/E89	
-1	19.3
-2	18.1
-3	19.1
Average	***18.8***
% CV	***3.6***
D: Neoprene/Aralite	
-1	18.3
-2	18.7
-3	18.1
Average	***18.4***
% CV	***1.7***

An additional characteristic of the moisture preconditioning protocol is illustrated in Figure 5-9. These results demonstrate that the procedure produces the highest accumulation in the thermal liner, the innermost component of the turnout system. Significantly, less moisture accumulates in the moisture barrier and shell fabric. Therefore, the moisture gradient observed mimics the gradient that occurs in actual wear, where clothing layers closest to the sweat wetted skin retain the highest percentage of moisture (see Figure 5-2). The observed consistency of the preconditioning procedure, as well as the moisture gradient produced in different layers of the turnouts, are undoubtedly facilitated by the step in the protocol that calls for a lengthy conditioning period in a sealed plastic bag. This step allows moisture distribution to occur within the layers of the turnout specimen.

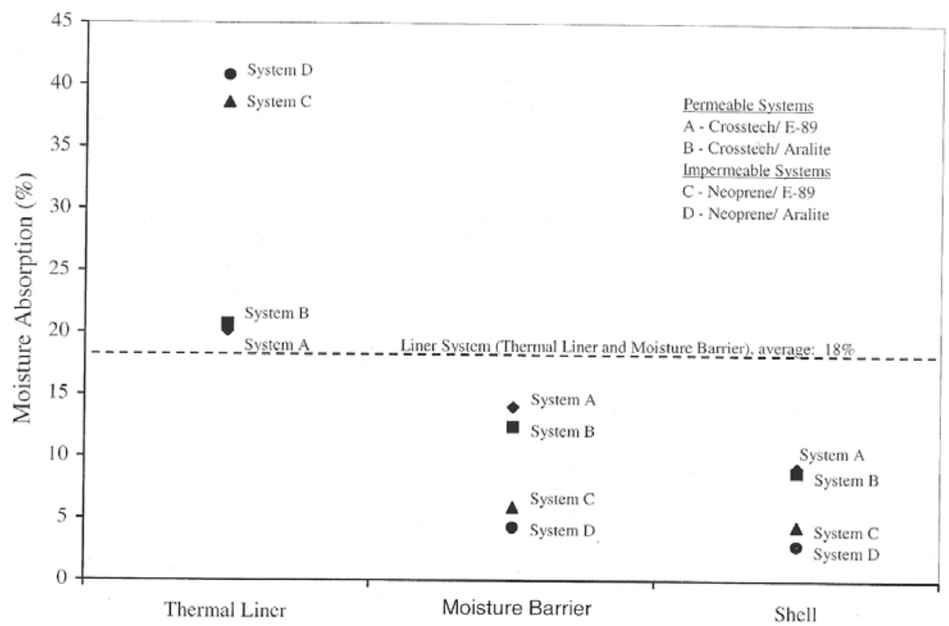


Figure 5.9 Distribution of Moisture in Turnout Layers Using Laboratory Protocol [26]

Valuable insights into the mechanisms of moisture transport in firefighter turnout systems were found. It shows that moisture can accumulate in turnouts, by both wicking of liquid moisture and condensation of evaporated sweat. It demonstrates that the level and distribution of absorbed moisture varies, depending on the type of thermal liner, on the breathability of the moisture barrier component, and on the presence of underlying absorbent clothing layers. This knowledge was applied to develop a rational preconditioning protocol for evaluating the effects of moisture on thermal protective performance in prolonged exposure to radiant heat.

6.0 EXPERIMENTAL APPROACH

An experimental approach was selected that enabled a study of the effects of moisture on the thermal protective performance exposed to radiant thermal energy in the subflashover thermal environment.

6.1 Test Materials

Three turnout systems were selected on the basis of differences in their moisture vapor permeability. Details of the test turnout systems are shown in Table 6-1.

Table 6-1. Turnout Systems Tested

System	Shell Fabric	Moisture Barrier	Thermal Liner	Weight (g/m2)	Total Heat Loss (THL)
Highly Permeable	Kevlar/PBI	PTFE Membrane	Aramid Needle-bond	685	207
Moderately Permeable	Kevlar/PBI	PU Membrane	Aramid Needle-bond	681	130
Impermeable	Kevlar/PBI	Neoprene Membrane	Aramid Needle-bond	863	93

Since the focus of this investigation was to study the effect of moisture on thermal protective performance, a single type of outer shell fabric and thermal liner were chosen and used with the three turnout systems tested. Thus, the material variables investigated were moisture vapor permeability and the effect reflective trim has on thermal protective performance.

6.1.1. Properties of Test Materials

A single type of shell fabric and thermal liner component were used in each of the three turnout systems tested. The shell fabric used in this study is a 7.5 oz/yd^2 Kevlar®/PBI material. It is a commonly used shell fabric for firefighter turnout gear, and was selected for it’s heat stability as well as the fact that it is a state of the art material.The thermal liner consisted of a dyed aramid facecloth that is quilted to a Kevlar® needle-bonded batting. The single layer nonwoven batting used in the thermal liner has a relatively open structure. This open structure creates air pockets within the liner and therefore provides a relatively high insulative value. It is a firefighter turnout material commonly used in the construction of firefighter turnout suits.

Three moisture barriers encompassing a range of moisture vapor permeability were chosen. These moisture barriers are identified as impermeable, moderately permeable and highly permeable. The ability to allow moisture vapor to permeate through the moisture barrier depends on the microstructure of the moisture barrier.

The impermeable moisture barrier consists of a monolithic polymer film coated onto a substrate fabric. This film does not allow moisture transport through the moisture barrier, and moisture can collect at the polymer film. Therefore, it served as a bench mark to assess the effect moisture transport has on the thermal protective performance of systems utilizing more permeable moisture barriers.

The moderately permeable moisture barrier contains a bicomponent film. In this case, moisture transfer through the barrier can occur both through the micropores, and by interactions between the molecular structure of the system and the moisture barrier.

The highly permeable system includes a microporous film, which allows moisture vapor to pass through microscopic pores within the barrier, and does block liquid water from penetrating the moisture barrier.

The reflective trim used in this study was a material commonly used in firefighter turnout ensembles. It consisted of a 3’’ wide yellow reflective layer coated onto a neoprene substrate. An one inch wide reflective silver layer was coated onto the center of the yellow reflective coating.

6.1.2 Comfort Properties of Test Materials

Moisture vapor permeability is an important determinant of the comfort and heat stress of a firefighter turnout material. Impermeable garment materials tend to be rated lower in their comfort properties than moisture vapor permeable materials.

Comfort properties are here measured as thermal resistance and evaporative resistance of a material with the guarded sweating hot plate. Thermal resistance is the amount of heat that can be transferred through a turnout system, and is measured dry, whereas evaporative resistance measures the amount of moisture that can be transferred through the garment system. These two measurements are combined using an equation to calculate the total heat loss. Total heat loss of the systems used in this study can be found in table 6-1. It can be seen that moisture vapor impermeable systems have a low total heat loss, and therefore do not allow heat and moisture exchange with the environment readily. This can lead to the problem of heat stress in a firefighter. As permeability is increased it can be seen that total heat loss increases decreasing the heat stress a firefighter would be exposed to when wearing the garment. Data, shown in Table 6-1, indicate a direct correlation between the breathability (moisture vapor permeability) and total heat loss of a firefighter turnout system. Impermeable systems have the lowest total heat loss, and as moisture vapor permeability increases total heat loss increases also.

6.2 Apparatus and Test Conditions

The test apparatus illustrated in Figure 6-1 was used to measure the thermal protective properties. To deliver a constant heat flux to the turnout system under test, a horizontally positioned and electronically regulated radiant quartz tube source was used. This configuration is similar to the RPP Test (ASTM F1939 [11]) heat flux source, and was located approximately 1.5 inches below the test samples. A water-cooled chamber located around the perimeter of the test samples was utilized to reduce heat losses during testing. A Pyrocal Calorimeter [16] was selected to measure heat flux through the turnout systems. The Pyrocal calorimeter was secured in an insulating block, fabricated from a machineable ceramic, and attached to the sample holder with the calorimeter located in a central position adjacent to the thermal layer the turnout systems. The heat flux levels generated from the quartz tubes were calibrated using the standard TPP copper disk calorimeter exposed to the heat source for 10 seconds.

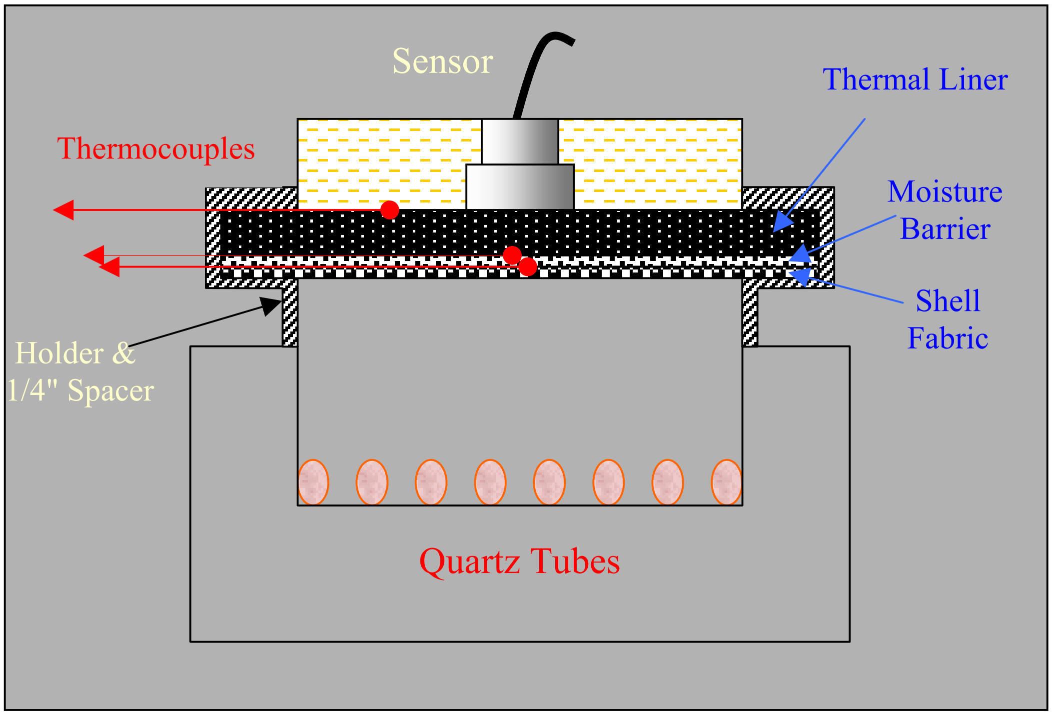


Figure 6-1. Sketch and Photograph of test setup used to measure thermal protective performance in low-level thermal exposures.

Three type K thermocouples were attached between different layers in the turnout system, as illustrated in Figure 6-1. The thermocouples were positioned between the shell fabric and the moisture barrier, between the moisture barrier, and the thermal liner and on top of the thermal liner. Thermocouples were attached to the shell fabric, moisture barrier and thermal liner using a small amount of adhesive.

Skin burn estimate was made using the Henriques burn integral [19]. Henriques integral calculations were performed after testing, therefore preliminary tests were utilized to set the time of exposure that should give a second degree burn prediction. Exposure times between 100 sec for a heat flux of 0.5 cal/cm^2/sec up to 225 for a heat flux of 0.15 cal/cm^2/sec were chosen. Calculations were performed using a Fortran program as discussed in reference [16]. This program utilizes time and heat flux data to calculate estimated burn time.

Experiments were performed at three different heat flux intensities: 0.15 cal/cm^2/sec, 0.25 cal/cm^2/sec, and 0.50 cal/cm^2/sec (6.3 to 21 kW/m^2)

As shown in table 2.1, these heat flux exposures are within the range that firefighters may encounter below the flashover intensity. These heat flux conditions were predominantly radiant. They are sufficient low in thermal energy so that degradation of the turnout system is minimum.

6.3 Moisture Preconditioning Procedure

Physiological studies of sweat generated in wearing fire fighter suits demonstrated that the amount and distribution of absorbed moisture, varies depending on the type of thermal liner, the breathability of the moisture barrier component, and on the presence of underlying absorbent clothing layers [27-29]. This knowledge was applied to develop a preconditioning protocol. The following simple procedure was adopted: The turnout test specimen was precisely weighed. Sufficient water was then sprayed onto the facecloth side of the thermal liner to increase the weight of the turnout composite (thermal liner, moisture barrier, shell fabric) by the desired amount. The moistened turnout composite sample was sealed in a plastic bag and allowed to condition for a period of at least twelve hours.

Specimens were subsequently removed from the sealed bag and precisely weighed.

Four moisture add-on levels were examined. The first moisture level selected was the dry condition. The second level selected was 2.5 grams of water per 6 in. x 6 in. sample of the system under test, or approximately 15% by turnout system weight, which corresponds to moisture levels observed in turnout systems worn by firefighters exercising in a warm environment. This moisture level is also the point where significant reductions in protective performance were predicted by the heat transfer analysis [9]. The third level selected was 8 grams, or 50% by weight. This moisture conditions corresponds to a firefighter sweating at a rate of 1.5 liters/ hr. The final level selected was a moisture saturated condition, of an add-on level equal to 100% by weight (16 grams of water per 6 in. x 6 in. sample). This moisture level was selected to represent a condition corresponding to the moisture present in a turnout system that had been exposed to the maximum rate of human sweat output and corresponds to approximately 3 liters of sweat per hour.

1.

6.4 Summary of Experimental Plan

Table 6-2 provides a summary of the material variables, heat exposures, and moisture preconditioning levels examined in this study.

Table 6-2. Experimental Variables

Material Variables		
Common outer shell:	7.5 oz/yd2 Kevlar/PBI	
Common Thermal Liner	7.2 oz/yd2 Aramid Needle-punched Nonwoven	
Moisture Barrier component	System 1	Highest Vapor Permeability (PTFE material / 210 THL) Light Weight system (685 g/m2)
	System 2	Medium Range Vapor Permeability (PU material / 130 THL) Light Weight system (681 g/m2)
	System 3	Vapor Impermeable (Neoprene material / 93 THL) Heavy Weight system (863 g/m2)
Trim component	3 inch Triple Trim attached to outer shell No Trim	
Heat Exposures	0.15, 0.25, and 0.5 cal/cm^2/sec (subflashover)	
Moisture Preconditioning	Dry	No moisture added
	Moist	12 - 15 % (2.5 g) Add-on
		40 - 50 % (8 g) Add-on
	Saturated	80 – 100 % (16 g) Add-on

The results from these experiments permit determination of the conditions where moisture in a firefighter system has a harmful or helpful effect on thermal protection. Analysis was conducted to compare material ensembles with and without trim at the different heat flux and moisture levels to investigate the effect on thermal protection. Both heat flux data and thermocouple measurements of temperature rise in the turnout layers were used to study these phenomena. Three replicate measurements of all turnout systems were tested. Detailed data and statistical analysis are provided in Appendix A and B.

7.0. RESULTS AND DISCUSSION

The effects of moisture on heat transmission and the thermal protective performance were investigated for selected turnout materials, over a range of incident heat flux and moisture conditions. The most important observations and insights drawn from these data are discussed in the following sections.

7.1 Effects of Moisture on Thermal Protection

Figure 7-1 provides a graphical comparison of the effects of moisture on the thermal protective insulation of the turnout system for the highest moisture vapor permeability turnout system included in this study (System 1). Burn times have been estimated using the Henriques integral method for these thermal exposure intensities of 0.15, 0.25, and 0.50 $cal/cm^2/sec$. Systems are compared at four different moisture add on levels ranging from dry to moist and moisture saturated conditions. Results are given for turnout systems with and without an attached reflective trim component.

Figures 7-2 and 7-3 show similar comparisons for a breathable turnout system with somewhat lower moisture vapor permeability (System 2) and for a moisture impermeable system examined by this research (System 3). Burn time indexes are given in seconds form the onset of the thermal exposure until sufficient heat is transferred to predict a second degree burn using the Henriques burn model. Heat transfer data were collected for timed interval ranging from 100 sec at the 0.5 $cal/cm^2/sec$ exposure level to 225 sec at the 0.15 $cal/cm^2/sec$ exposure level. Test systems that did not transmit sufficient heat to predict a second degree burn using the protocol adapted by this research are represented as having zero burn times.

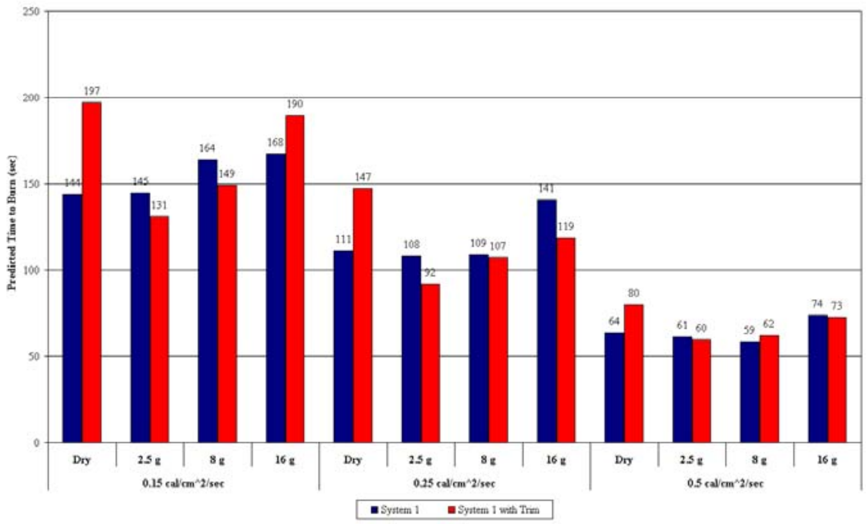


Figure 7-1. Effect of moisture on predicted 2nd degree burn time for high vapor permeable turnout system, with and without attached trim.

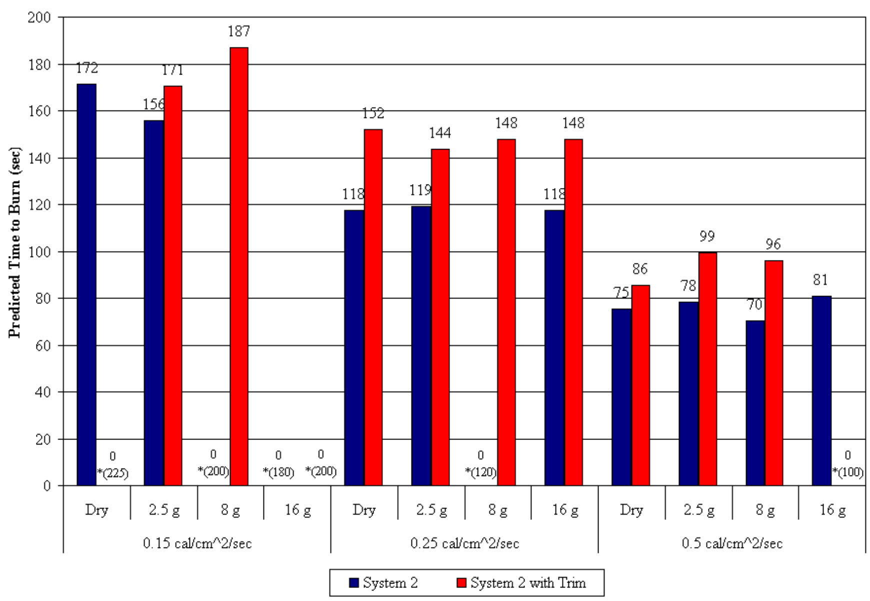


Figure 7-2. Effect of moisture on predicted 2nd degree burn time for moderately vapor permeable turnout system with and without attached trim.

*(225) Indicates exposure conditions insufficient to predict second degree burn time within 225 seconds of exposure condition.

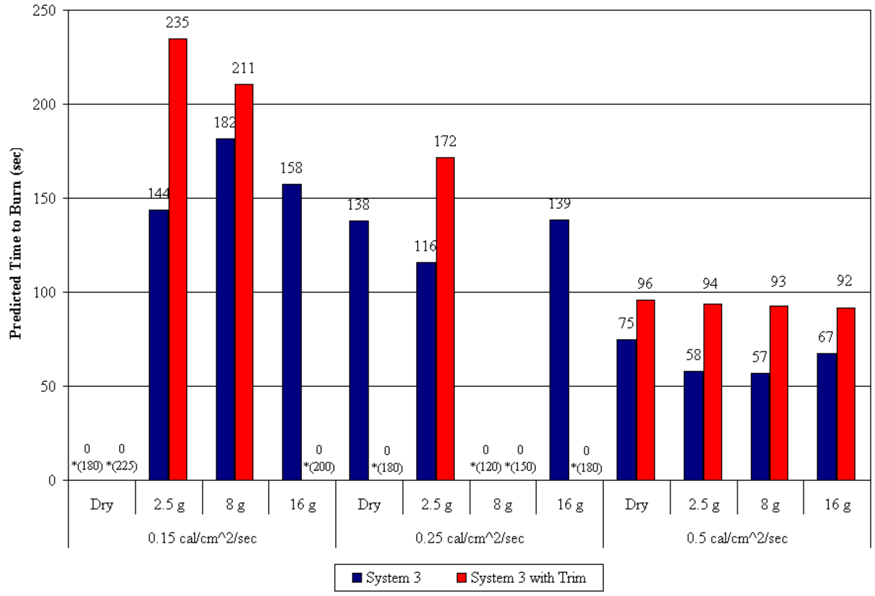


Figure 7-3. Effect of moisture on predicted 2nd degree burn time for vapor impermeable turnout system with and without attached trim.

*(180) Indicates exposure conditions insufficient to predict second degree burn time within 180 seconds of exposure condition.

For turnout systems, with and without attached trim, moisture at lower levels of add on (12-50 %) causes a decrease in the thermal protective insulation in comparison to a dry system. When moisture is added at saturation levels in the turnout (80 – 100 %) the thermal insulation recovers to levels comparable to the insulating levels observed in dry material systems. The observed trends are more pronounced for turnout systems having the highest level of moisture vapor permeability or breathability (System 1 and 2) than with the moisture vapor impermeable turnout (System 3). The effects of moisture on thermal protective insulation are most pronounced when reflective trim is attached to the test composites. These trends are similar for the thermal exposure intensities investigated (0.15 – 0.5 cal/cm^2/sec).

These findings show that the thermal insulation in these exposures is affected by system basis weight and vapor permeability. In the material composites investigated, system weight and moisture vapor permeability was contributed by the moisture barrier component.

Thermal protective insulation in exposures utilizing the moisture vapor impermeable turnout (System 3), exhibiting a higher weight, are higher than for a lighter weight turnout (System 1) with high moisture vapor permeability. The moisture barrier used in the impermeable system had the highest heat capacity of all turnout components, which undoutably accounts for the increased thermal protective insulation in system 3.

7.2 Effects of Moisture on Turnout Systems without Attached Trim

Figures 7-4 – 7-6 show the results of experiments conducted to enable a more detailed analysis of the heat transfer through the three turnout systems. These finding show the effects of the added moisture on the predicted second degree burn times for the three turnout systems tested. Predicted burn times were based on the average of three replicate tests for each system tested.

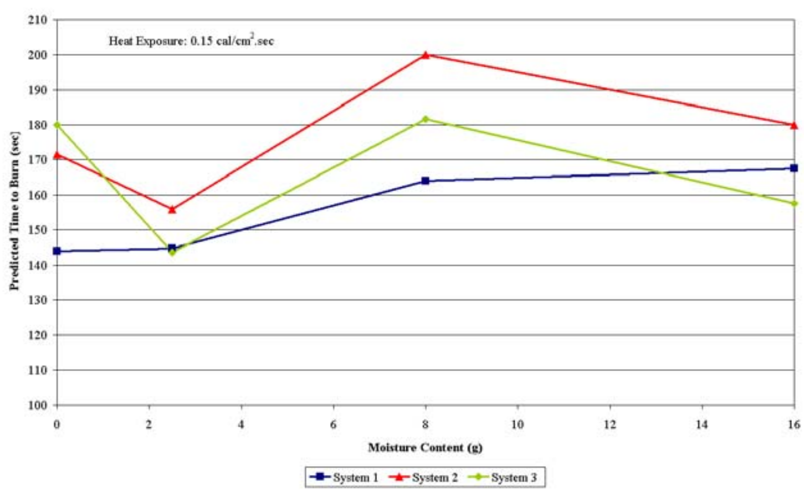


Figure 7-4 Effect of moisture for vapor permeable and impermeable turnout systems (0.15 cal/cm^2/sec heat flux exposure)

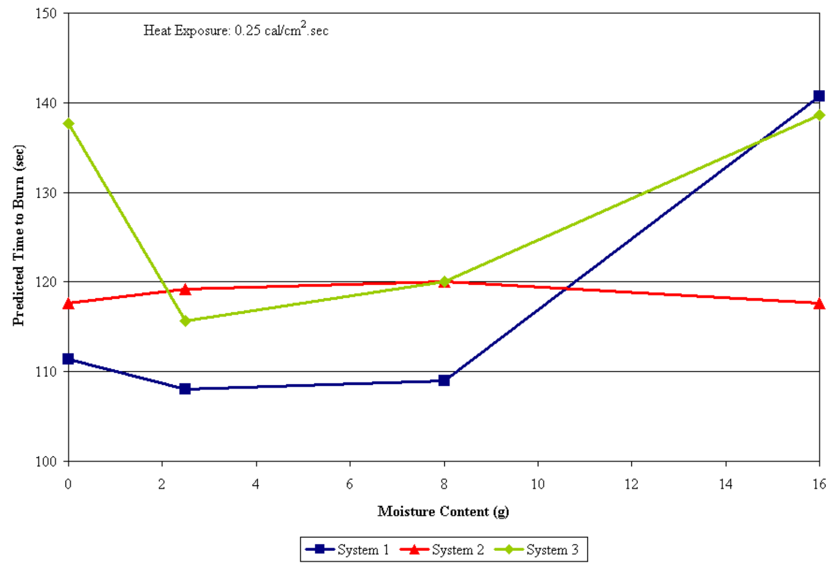


Figure 7-5 Effect of moisture vapor permeable and impermeable turnout systems (0.25 cal/cm^2/sec heat flux exposure)

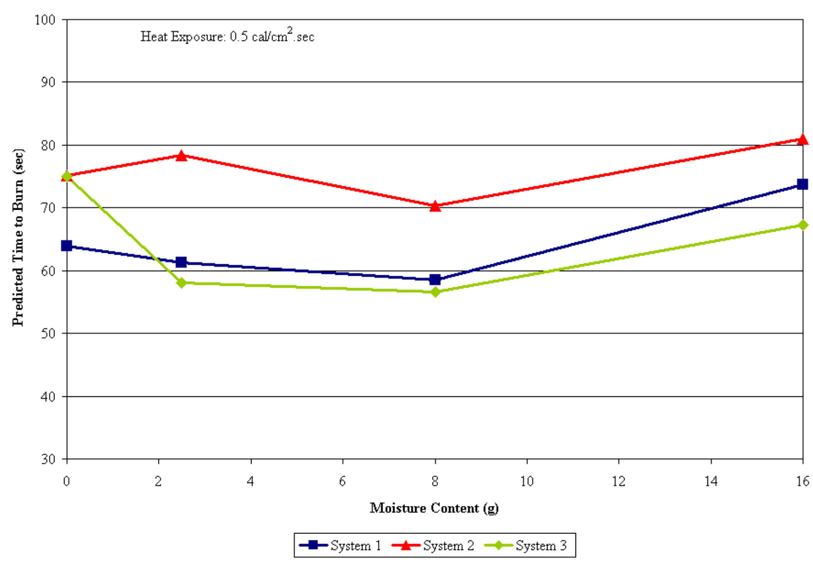


Figure 7-6 Effect of moisture on vapor permeable and impermeable turnout systems (0.5 cal/cm^2/sec exposure)

These findings show that added moisture effects the predicted thermal insulation in a complex manner: It is dependent upon the specific amount of moisture applied to the preconditioned system and the make of material systems and the intensity of the heat exposure. As previously noted, for a moist system total moisture added at levels of 12 to 50 %, produce a decrease in thermal insulation in comparison to dry systems, followed by a recovery in insulation at moisture saturated levels. Predicted thermal insulation appears to be lowest for highest vapor permeable system. These observations indicate that thermal insulation of the moderate vapor permeable system appears to be generally higher than for the vapor impermeable system tested by this study. Increases in heat flux show the same trend with system with highest moisture vapor permeability showing the lowest thermal insulation, and a system with moderate moisture vapor permeability showing the highest thermal insulation.

As predicted by the simple theoretical model, discussed in reference [9], these findings reflect the competing effects that added moisture has on altering both the heat capacity and conductivity of the turnout fabric system. Figures 7-4 – 7-6 show that, for impermeable turnout systems, a reduction in thermal protection is observed, similar to the effect predicted by the simple model. As indicated by the model, the effect of moisture in reducing insulation is greatest for smaller amounts of added moisture. The predicted recovery of thermal insulation as moisture levels approach saturated levels is also seen in these data.

It can be observed that highest vapor permeable systems do not show the expected decrease in thermal protection seen in the model. The heat capacity and conductivity assumed in the model were closely related to ones expected for the impermeable system. It is possible that a more accurate heat capacity and conductivity assumption might lead to a better fit of the model to the impermeable system.

7.3 Heat Transfer in Turnout Systems without Attached Trim

Figures 7.7 - 7.9 show the effects of added moisture on the measured heat transfer through turnout systems made up using different types of moisture barriers. These graphs show measurements made on systems without attached trim.

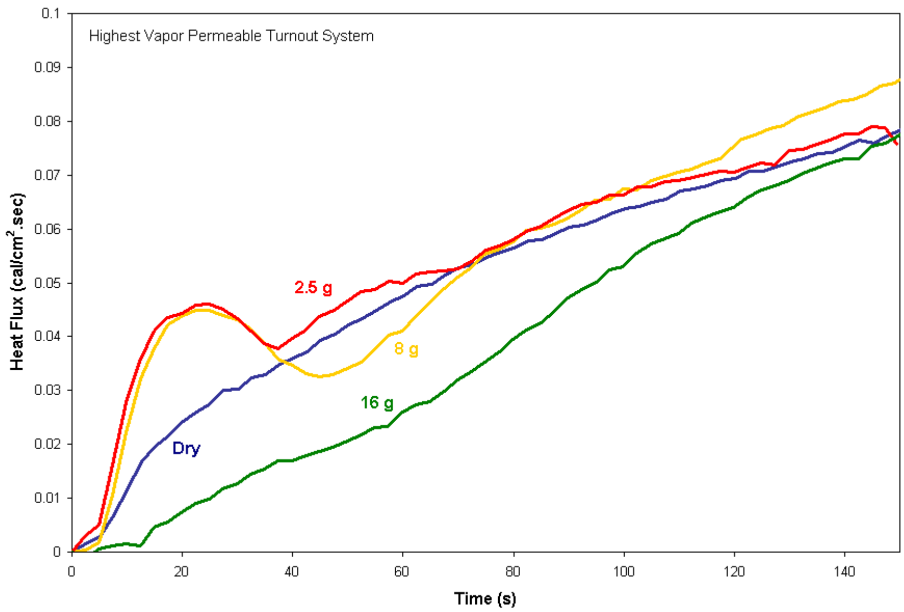


Figure 7.7: Moisture Effect on heat flux through highest vapor permeable system (0.15 cal/cm^2/sec exposure)

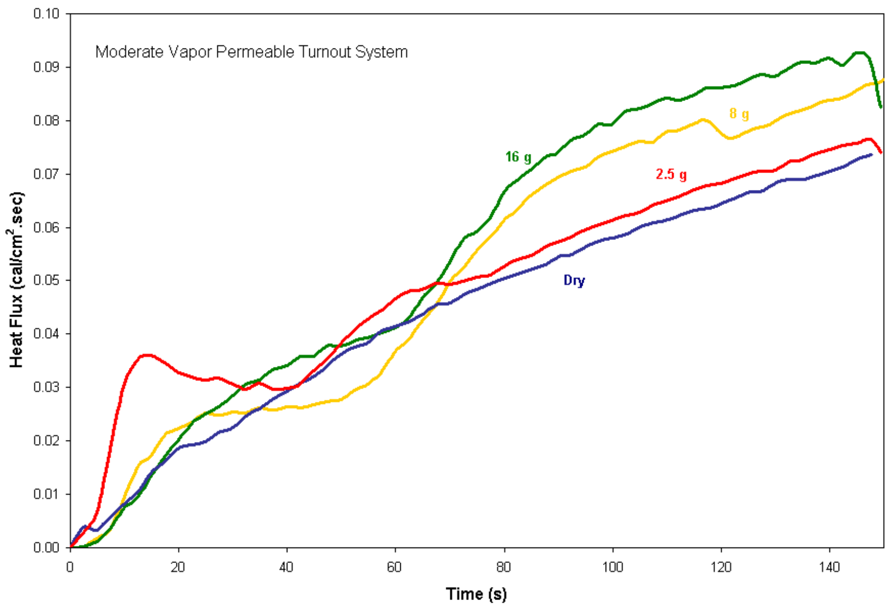


Figure 7.8. Moisture Effect on heat flux through moderate vapor permeable system (0.25 cal/cm^2/sec exposure)

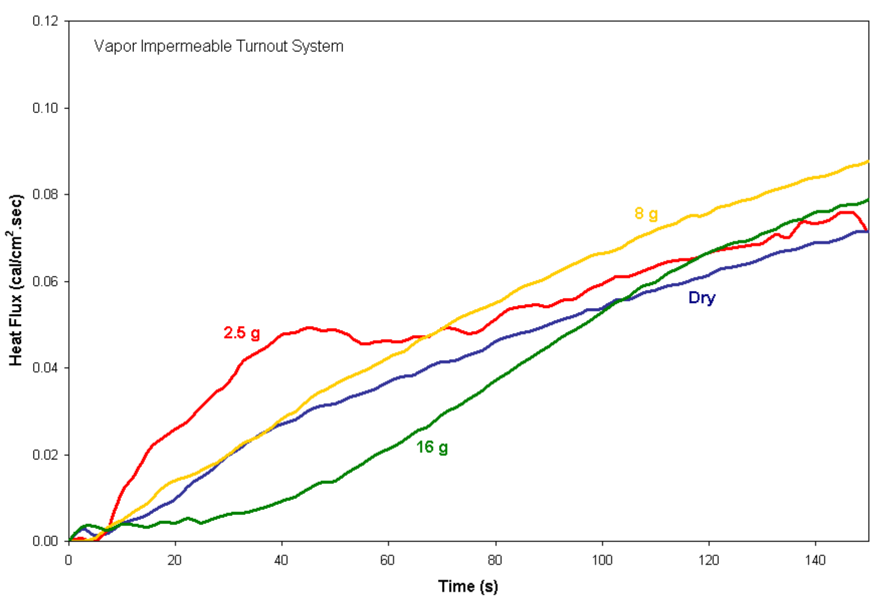


Figure 7.9: Moisture Effect on heat flux through vapor impermeable system (0.25 cal/cm^2/sec exposure)

These data continue to indicate the complex effects of moisture on heat transfer through turnout systems. They show that the effect of moisture on heat transfer rate varies throughout the duration of the heat assault. Therefore, in the initial phases of the exposure, moisture causes a rapid increase in the rate of heat transfer curves. This phenomenon is most pronounced for vapor permeable systems (System 1 and 2) with 2.5g and 8g of added moisture (15 – 50%). It is not as pronounced in the vapor impermeable trim.

7.4 Analysis of Temperature Distribution in Turnout System

Thermocouples attached to the inside of the thermal liner component and between the moisture barrier and outer shell fabric, provided information on the temperature distribution across the turnout composite throughout the duration of the heat exposures. Figures 7-10 and 7-11 show an example of the temperature profiles measured in turnout system 1.

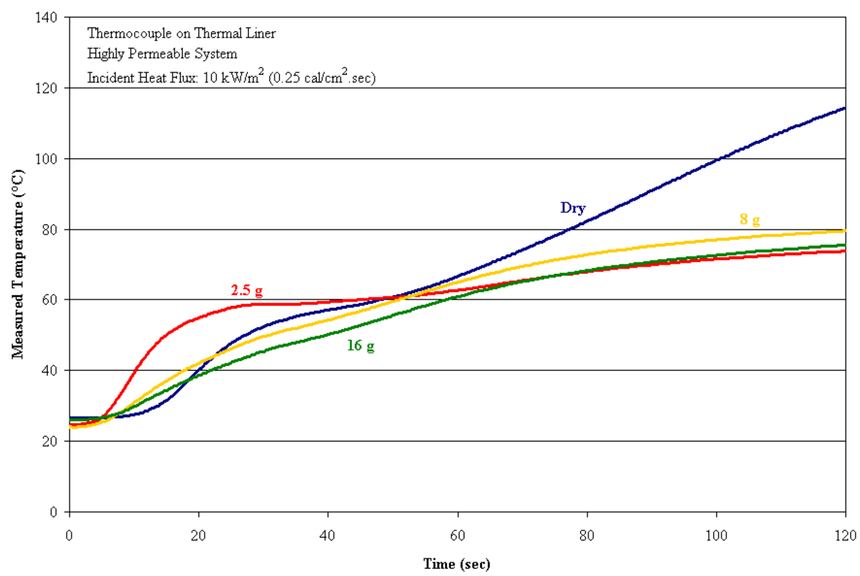
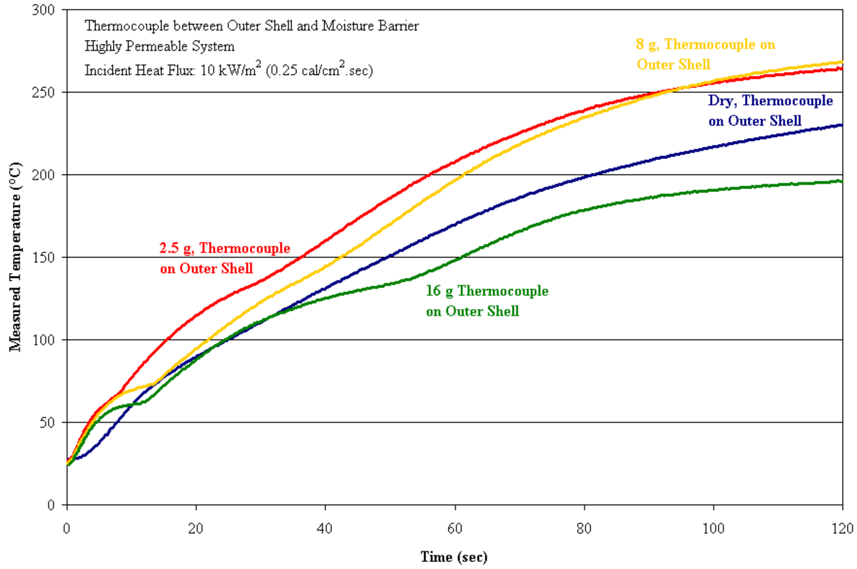


Figure 7-10: Temperature measurement on top of thermal liner in highly permeable system (System 1) for four different moisture conditions (0.25 cal/cm^2/sec heat exposure).



7.11 Temperature measurement between Outer Shell and Moisture Barrier in high permeable system (System 1) for four different moisture conditions (0.25 cal/cm^2/sec heat exposure)

The data shows that the effect of moisture on rate of heating varies during the exposure duration. At low levels of moisture add-on (15 – 50%), moisture initially accelerates the rate of heating compared to a dry system. The accumulation in heat transferred is most pronounced for turnout systems 1 and 2. For saturated turnout systems moisture slows the rate of heating over the duration of the test. As shown in Figure 7-10 the temperature on the inside of the thermal liner never reaches the level needed to produce steam (100° C).

Figure 7-11 illustrates the effect of moisture on the rate of heating on the interface between the outer shell and the moisture barrier. Low levels of moisture lead to an increased rate of heating over the duration of the test as compared to a dry system. For a saturated system moisture also slows the rate of heating when compared to a dry system. Temperatures in the outer shell do reach temperature levels that produce steam. These data show, for turnout systems without trim attached, no indication that any steam that may be generated does contribute to heat transfer to the inner layers of the system.

7.5 Effects of Moisture on Turnout Systems with Attached Trim

Figures 7-12 – 7-14 show the results of experiments conducted to enable a more detailed analysis of the heat transfer through the three turnout systems with attached trim. The finding show the effects of the added moisture on the predicted second degree burn times for the three turnout systems tested. Predicted burn times were based on the average of three replicate tests for each system.

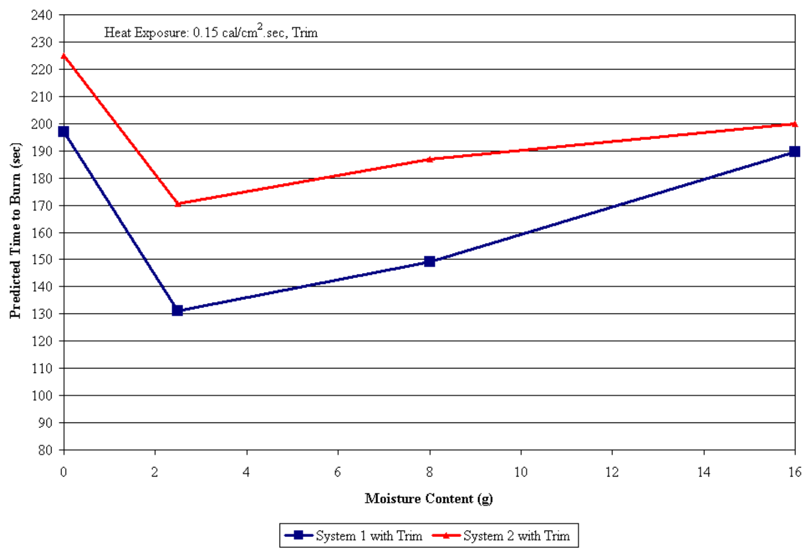


Figure 7-12 Effect of moisture for vapor permeable and impermeable turnout systems with attached trim (0.15 cal/cm^2/sec exposure)

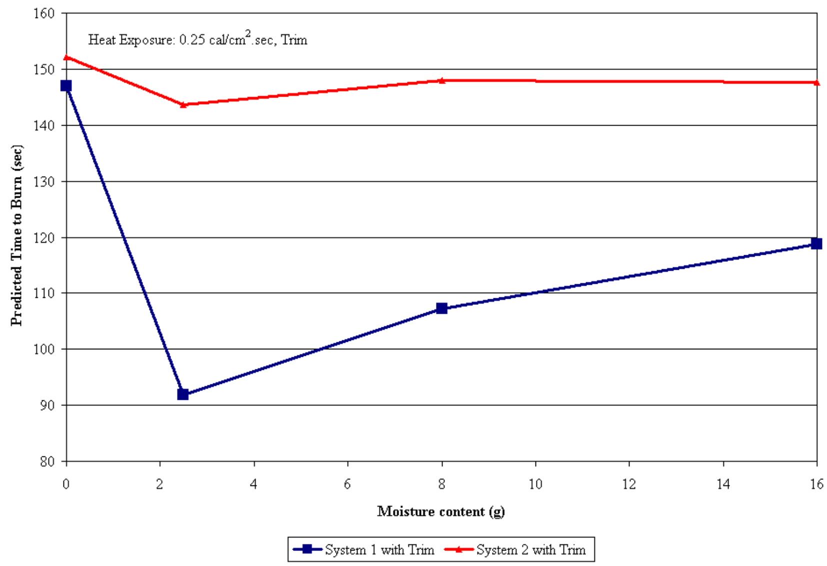


Figure 7-13 Effect of moisture for vapor permeable and impermeable turnout systems with attached trim (0.25 cal/cm^2/sec exposure)

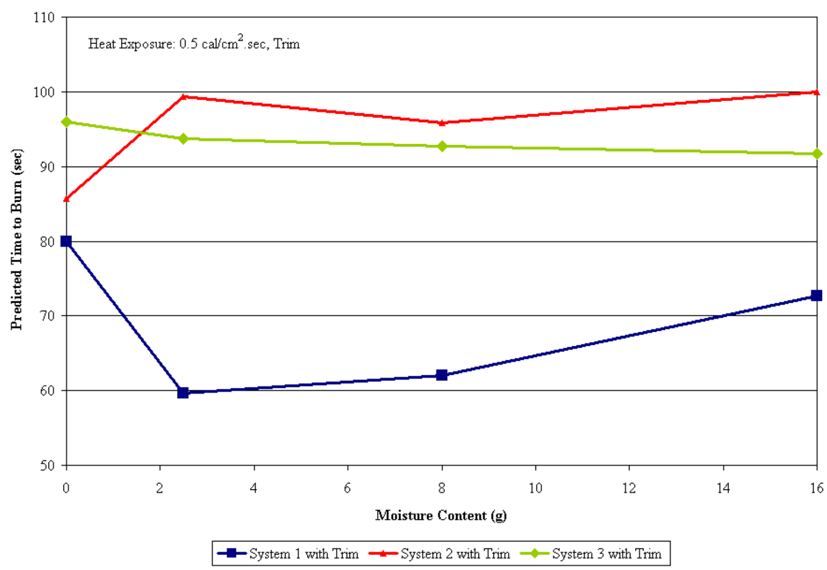


Figure 7-14 Effect of moisture for vapor permeable and impermeable turnout systems with trim (0.5 cal/cm^2/sec exposure)

These finding shows that added moisture effects the predicted thermal insulation in a complex manner: It is dependent upon the specific amount of moisture applied to the preconditioned system and the make of material systems and the intensity of the heat exposure.

As previously noted, for a moist system total moisture added at levels of 12 to 50%), produce a decrease in thermal insulation in comparison to dry systems, followed by a recovery in insulation at moisture saturated levels. Predicted thermal insulation appears to be lowest for highest vapor permeable system. These observations show that in general thermal insulation of the moderate vapor permeable system appears to be higher. Increases in heat flux show the same trend with system with highest moisture vapor permeability showing the lowest thermal insulation, and a system with moderate moisture vapor permeability showing the highest thermal insulation.

As predicted by the simple theoretical model, discussed in Reference [9], these findings reflect the competing effects that added moisture has on altering both the heat capacity and conductivity of the turnout. Figures 7-12 – 7-14 show that, for high vapor permeable turnout systems, a reduction in thermal protection is observed, similar to the effect predicted by the simple model. As indicated by the model, the effect of moisture in reducing insulation is greatest for smaller amounts of added moisture. The predicted recovery of thermal insulation as moisture levels approach saturated levels is also seen in these data. It can be observed that as vapor permeability increases the reduction in thermal protective insulation is not as pronounced. Increases in the intensity of the heat exposure tend to lead to reductions in thermal insulation.

7.6 Effect of Reflective Trim on Heat Transfer

Figures 7.15 - 7.17 show the effects of added moisture on the measured heat transfer through turnout systems made up using different types of moisture barriers. These graphs show measurements made on systems with attached trim..

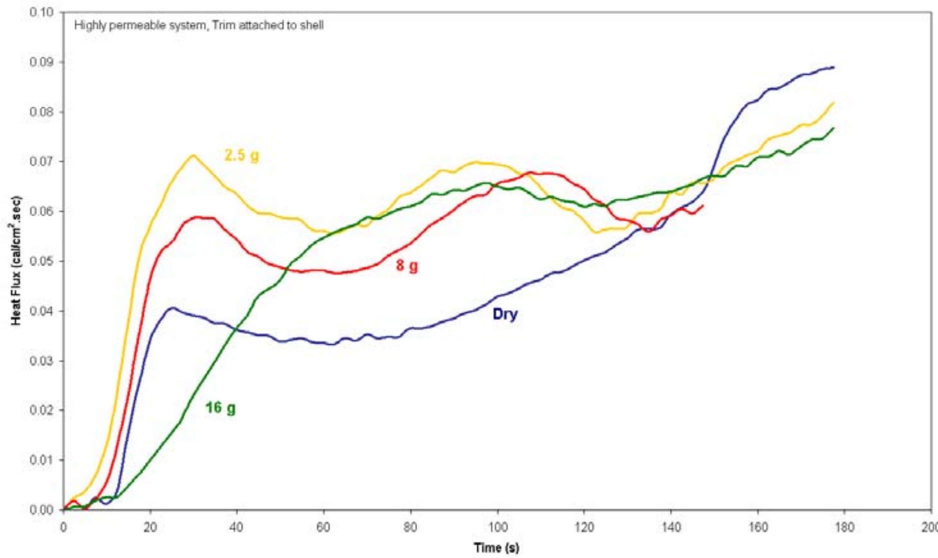


Figure 7-15: Moisture Effect on Heat flux through highest permeable system with trim (0.25 cal/cm^2/sec exposure)

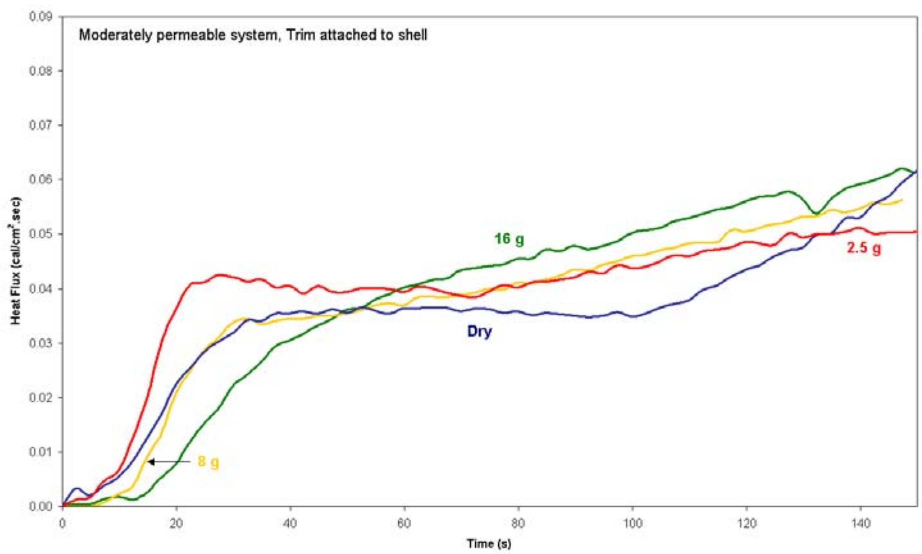


Figure 7-16. Moisture Effect on Heat flux through moderate permeable system with trim (0.25 cal/cm^2/sec exposure)

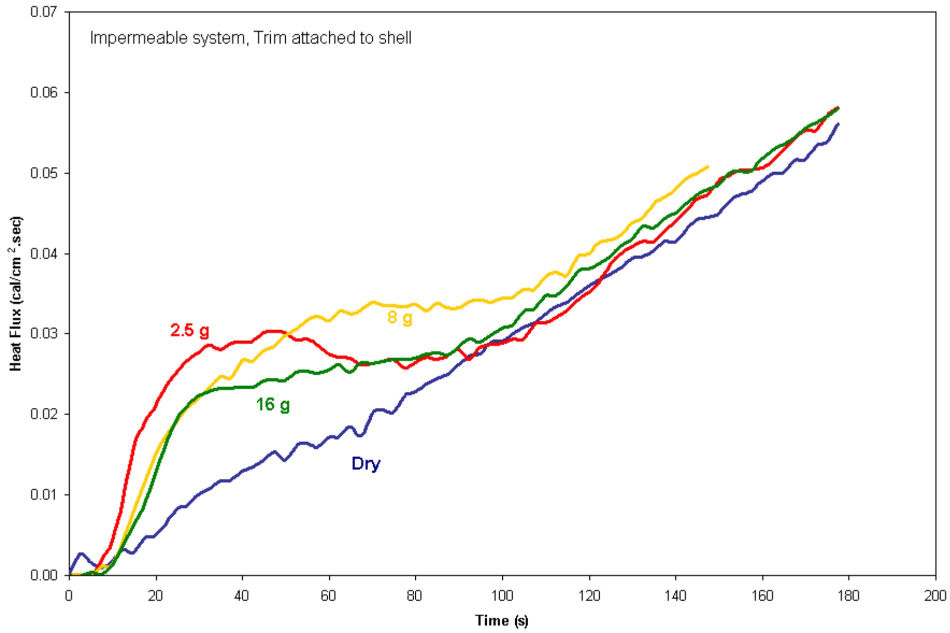


Figure 7-17: Moisture Effect on Heat flux through vapor impermeable system with trim (0.25 cal/cm^2/sec exposure)

These data indicate moisture has a complex effect on heat transfer. They show that the effect of moisture on heat transfer rate varies throughout the duration of the heat assault. Therefore, in the initial phases of the exposure, moisture causes a rapid increase in the rate of heat transfer curves. This phenomenon is most pronounced for vapor permeable systems (System 1 and 2) with 2.5g and 8g of added moisture (15 – 50%). It is not as pronounced in the vapor impermeable turnout.

7.7 Analysis of Temperature Distribution in Turnout System with Trim

Thermocouples attached to the inside of the thermal liner component and between the moisture barrier and outer shell fabric, provided information on the temperature distribution across the turnout composite throughout the duration of the heat exposures. Figures 7-18 and 7-19 show an example of the temperature profiles measured in System 1 with attached reflective trim.

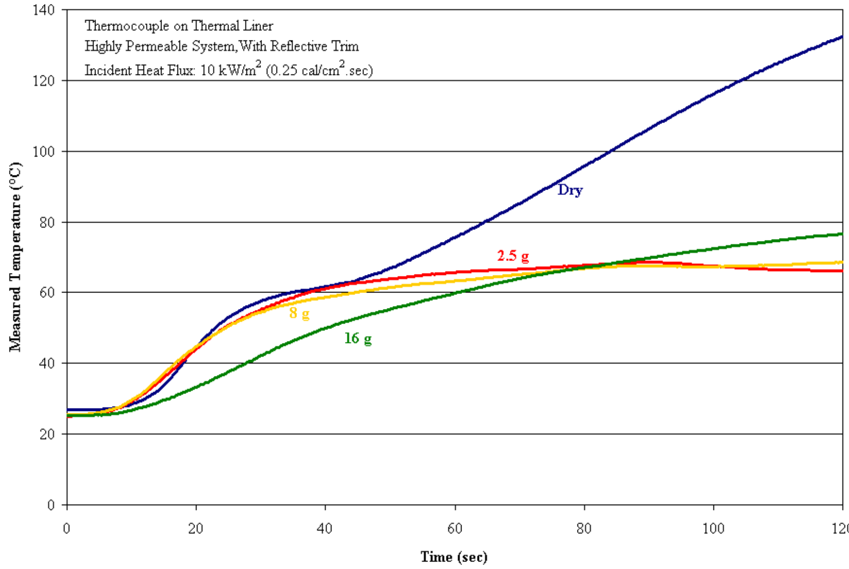


Figure 7-18: Temperature measurement on top of thermal liner in highly permeable system with trim attached (System 1) for four different moisture conditions (0.25 cal/cm^2/sec heat exposure).

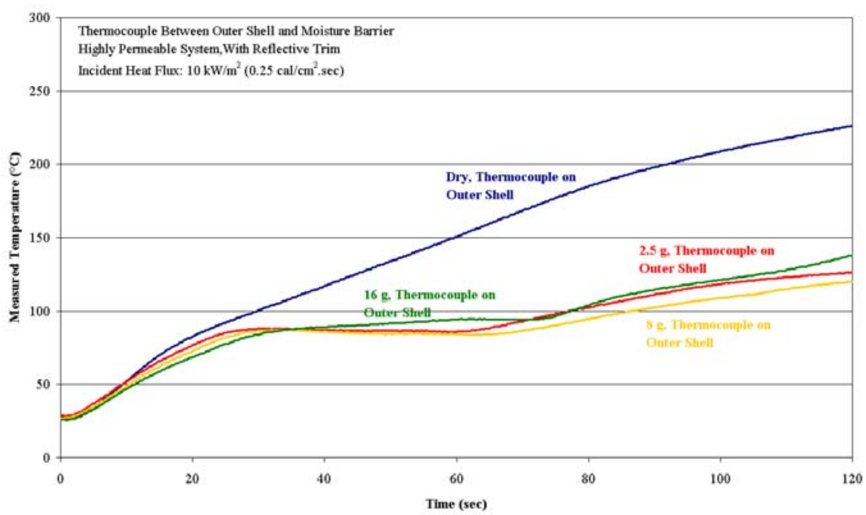


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Figure 7-19 Temperature measurement between Outer Shell and Moisture Barrier in high permeable system (System 1) with trim attached for four different moisture conditions (0.25 cal/cm^2/sec heat exposure)

The data shows that the effect of moisture on rate of heating varies during the exposure duration. At low levels of moisture add-on (15 – 50%), moisture initially accelerates the rate of heating compared to a dry system. This is most pronounced for systems 1 and 2. For saturated systems moisture slows the rate of heating over the duration of the test. As illustrated in Figure 7-18 the temperature on the inside of the thermal liner never reaches 100 degree C, thereby inhibiting the formation of steam.

Figure 7-19 illustrates the effect of moisture on the rate of heating on the interface between the outer shell and the moisture barrier. Moisture slows the rate of heating when compared to a dry system. Temperatures in the outer shell do reach temperature levels where steam can be formed, however it appears that steam formation in the outer layers occurs to late in the test to have an effect on the heating rate on the inside of the thermal liner.

8.0 CONCLUSIONS

This study has advanced understanding about how moisture distributes in firefighter turnout materials. It has shown that moisture from sweating accumulates mainly in the layers of the turnout that are closest to the skin, in next to the skin garments and in the thermal liner component of the turnout system. Laboratory preconditioning experiments confirm that moisture, added to the facecloth side of a layered system, accumulates predominantly in the thermal liner layer. Any distribution of the moisture to the outer layers of the systems depends on the permeability of the moisture barrier component: In a system with an impermeable moisture barrier the added moisture concentrates in the thermal liner as well as on the surface of the impermeable moisture barrier. In a system with an vapor permeable barrier a small fraction of moisture redistributed to the outer shell fabric, if the moisture is added using a protocol that permits equilibration with time.

This research has shown that moisture can act to increase or decrease the thermal insulation of turnout materials. It has shown that the magnitude and direction of moisture effects depend on the specific conditions of the thermal exposure, and on turnout material variables. The presence of an impermeable reflective trim layer attached to the outer shell significantly influences moisture effects on thermal transmission in radiant heat exposures.

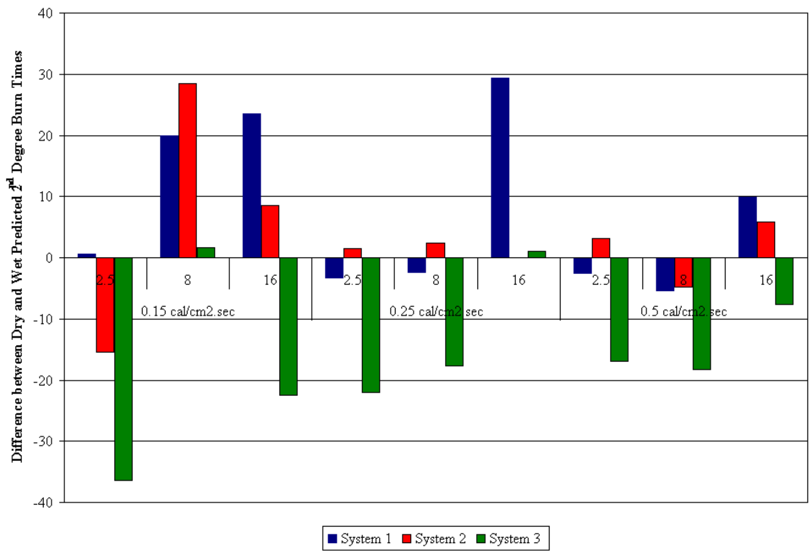


Figure 8-1 Difference in Protective Insulation between Wet and Dry Systems without Trim.

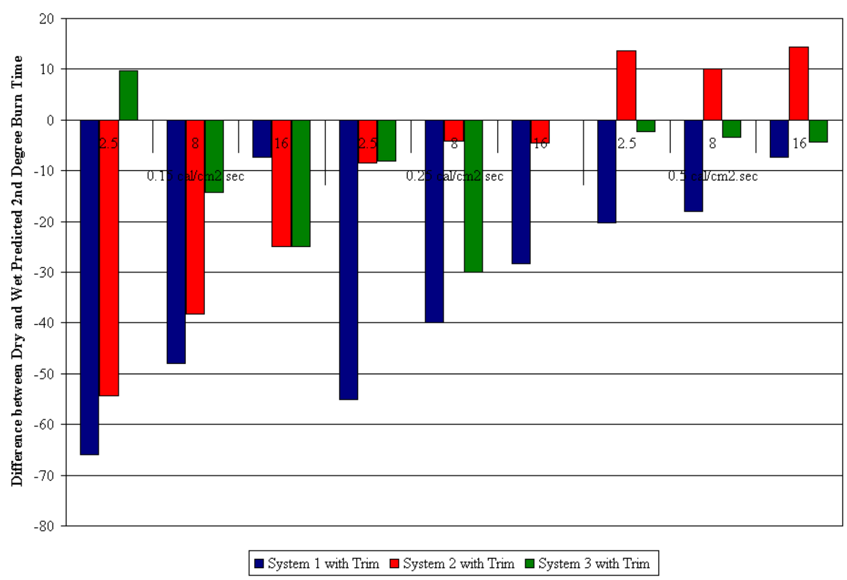


Figure 8-2 Difference in Protective Insulation between Wet and Dry Turnout Systems with Trim

As shown in Figures 8-1 and 8-2, moisture increases the thermal insulation in vapor permeable turnout systems examined by this study. However, when reflective trim is added to the composite, moisture causes a decrease in the measured thermal insulation. In the vapor impermeable system studied, moisture produces a decrease in thermal insulation when no reflective trim is attached to the system. The effects of moisture on systems with added trim are less pronounced in the system that incorporate an impermeable moisture barrier. It must be noted that the overall effect of added trim is to increase the thermal insulation of the turnout composite. The differences noted refer to a comparison between dry and wet system with and without trim.

Consistent with predictions of a simple thermal model, added moisture increases the rate of heat transfer in the initial phase of the thermal exposure, because of the effects of moisture on increasing the thermal conductivity. After the initial phase of the heat exposure, moisture slows the rate of heat transfer, as it increases the heat capacity of the turnout materials. .

This research has confirmed the complexity of the heat transfer mechanisms operating in moist turnout materials. It provides a basis for further studies that will continue to explore these phenomena. These studies should lead to the development and qualification of optimum laboratory moisture preconditioning protocol and thermal testing procedures for evaluating the thermal protective insulation of turnout materials in these radiant heat exposures.

9.0 RECOMMENDATIONS

This research investigated the effects of moisture on heat transfer in radiant heat exposures. More research is needed to study the effects of stored energy, or energy that may be discharged when heated turnout materials contact the skin in compression.

This research used test instruments and sample configurations that provided specific information. They embodied limitation with respect to interpreting these data for other types of thermal exposures and conditions. This study used a slug type calorimeter to acquire heat flux data. Future experiments should consider thermal sensor technologies that account for heat build up in prolonged exposure. Additional experiments should also investigate the effect of sample orientation in testing. Differences in heat transfer produced in exposures where test samples are positioned in vertical and horizontal configurations, may explain differences in thermal performance observed in this and other studies [14, 17].

The moisture preconditioning protocol used assumed a prescribed level of moisture add-on from simulated sweating. Other preconditioning protocols may be considered that account for differences in the intrinsic moisture absorption capacity of different types of turnout composite materials.

A very limited number of turnout materials and trim configurations were investigated by this research. Future research should include a wide range of material variables. There is a particular need for more study on the role of reflective trim on thermal transmission in radiant heat exposures.

Finally, no single series of laboratory experiments can qualify all the factors that contribute to the protective performance of firefighter clothing. These exposures are extremely complicated in actual firefighting activities.

10.0 REFERENCES

[1] Coletta, G.C., Arons, I.J., Ashley, L.E., and Drenman, A.P., "The Development of Criteria for Firefighter's Gloves, Volume II: Glove Criteria and Test Methods," Arthur D. Little, Inc., Cambridge, MA 02140

[2] Abbott, N.J., and Schulman, S., "Protection from Fire: Nonflammable Fabrics and Coatings," J. Coated Fabrics, Vol. 6, July 1976, pp. 48-62

[3] Foster, J.A., and Roberts, G.V., "Measurements of the Firefighter Environment – Summary Report," Fire Engineers Journal, Vol. 55 No. 178, September 1995, pp. 30 – 34

[4] Dent, R.W., Donvan, J. G., and Skelton, J., "Development of Synthetic Down-Alternatives", Albany International Research Co., Research Report, US Army Contract No. DAAK60-83-C-0022, 1984

[5] Torvi, D.A., "Heat Transfer in Thin Fibrous Materials Under High Heat Flux Conditions," Doctoral Dissertation, University of Alberta, Calgary, Alberta, 1997

[6] Lee, Young M., "Analysis of Thrmal Protective Performance of Heat Resistant Polymeric Fabrics," Ph.D. Dissertation, North Carolina State University, Raleigh, NC, 1985

[7] Chen N.Y., "Transient Heat and Moisture Transfer to Skin Through Thermally Irradiated Cloth," Doctoral Dissertation, Massachusetts Institute of Technology, Boston, 1959

[8] Lee, Y.M., and Barker, R.L., "Effect of Moisture on the Thermal Properties of Heat-Resistant Fabrics," Journal of Fire Sciences, Vol.4, September/October 1986, pp. 315 – 331

[9] 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 Res. J., 76(1), pp 27-31 (2006)

[10] Bejan, A., "Heat Transfer", pp. 148-151, 1993

[11] American Society for Testing and Standards, ASTM F 1939-99a, "Standard Test Method for Radiant Protective Performance of Flame Resistant Clothing Materials"

[12] Barker, R.L., Guerth, C., Behnke, W.P., and Bender, M., "Measuring the Thermal Energy Stored in Firefighter Protective Clothing," *Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume, ASTM STP 1386*, C. N. Nelson and N. W. Henry, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2000

[13] American Society for Testing and Standards, ASTM E 162-06, "Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source."

[14] Mell, W. E., and Lawson, J.R., "A Heat Transfer Model for Fire Fighter's Protective Clothing," NIST IR 6299, National Institute of Standard and Technology, Gaithersburg, MD, 1999

[15] Behnke, W.P., "Thermal Protective Performance Test for Clothing," Fire Technology, Vol. 13(1), February 1977

[16] Grimes, R., Mulligan, J.C, Hamouda, H., Barker, R. "The Design of a Surface Heat Flux Transducer for Use in Fabric Thermal Protection Testing," *Performance of Protective Clothing: Fifth Volume, ASTM STP 1237*, James S. Johnson and S.Z. Mansdorf, Eds., American Society for Testing and Materials. West Conshohocken, PA. 1996, pp. 607 – 624.

[17] Stoll, A.M., and Chianta, M.A., "Method and Rating Systems for Evaluation of Thermal Protection," *Aerospace Medicine*, Volume 40 (1969)

[18] Henriques, F.C., Jr. and Moritz, A.R., "Studies of Thermal Injuries II. The Relative Importance of Time and Surface Temperature in the Causation of Cutaneous Burns," The American Journal of Pathology, Vol 23, 1947, pp 695-720

[19] Jensen, R.L. Jr., "Thermal Performance of Firefighters' Protective Clothing," Paper provided to industry, 3M, Minneapolis, 1998

[20] Gohlke, D.J., "GORE-TEX Barriers and Steam," Product Brochure, W. L. Gore & Associates, Inc. May 1980

[21] Mäkinen, H., Smolander, J., and Vuorinen, H., "Simulation of the Effect of Moisture Content in Underwear and on the Skin Surface on Steam Burns of Firefighters," *Performance of Protective Clothing: Second Symposium, ASTM STP 989*, S. Z. Mansdorf, R. Sager, and A. P. Nielsen, Eds., American Society for Testing and Materials, Philadelphia, 1988, pp. 415 – 421

[22] Rossi, R.M., and Zimmerli, T., "Influence of Humidity on the Radiant, Convective and Contact Heat Transmission Through Protective Clothing Materials," *Performance of Protective Clothing: Fifth Volume, ASTM STP 1237*, James S. Johnson and S. Z. Mansdorf, Des., American Society for Testing and Materials, 1996

[23] Stull, J.O., "Comparison of Conductive Heat Resistance and Radiant Heat Resistance with Thermal Protective Performance of Firefighter Protective Clothing," *Performance of Protective Clothing: Sixth Volume, ASTM STP 1273*, Jeffrey O. Stull and Arthur D. Schwope, Eds., American Society for Testing and Materials, Philadelphia, 1997, pp. 248 - 168

[24] Rossi, R.M, "Breathability of Heat Protective Clothing – Water Vapour Transmission at High Temperatures ",*Proceedings: Fifth Scandinavian Symposium on Protective Clothing*, Ruth Nielsen and Carsten Borg, Eds. Elsinore, Denmark, May 5 – 8, 1997

[25] Taylor, F.P., "Report on Fire Fighter Burn Incident Investigation/Study," Lion Apparel, Inc., Protective Systems Group, Clemson University's Protective Clothing Conference, April 29-30, 1997

[26] Barker, R.L., and Guerth, C., "Moisture Absorption in Advanced Heat Resistant Protective Clothing Systems," Proceedings of 2nd World Textile Conference, Brussels, Belgium, July 1-3, 2002, pp 439 – 450.

[27] Myhre, L.G., Barker, R.L., Scruggs, B.J., Shalev, I., Prahsarn, C., and Miszko, T., "Effect of Measured Heat Loss Through Turnout Materials of Firefighter Comfort and Heat Stress. Part II: Performance in a Warm Environment," *Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume ASTM STP 1386,* C.N. Nelson and N.W. Henry, Eds., American Society for Testing and Materials, West Conshohocken, PA 2000.

[28] Barker, R.L., Myhre, L.G., Scruggs, B.J., Shalev, I., Prahsarn, C., and Miszko, T., "Effect of Measured Heat Loss Through Turnout Materials of Firefighter Comfort and Heat Stress. Part I: Performance in a Mild Environment," *Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume ASTM STP 1386,* C.N. Nelson and N.W. Henry, Eds., American Society for Testing and Materials, West Conshohocken, PA 2000.

[29] Stull, J.O., Duffy, R.M., "Field Evaluation of Protective Clothing Effects on Fire Fighter Physiology: Predictive Capability of Total Heat Loss Test," *Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume ASTM STP 1386,* C.N. Nelson and N.W. Henry, Eds., American Society for Testing and Materials, West Conshohocken, PA 2000.

[30] Barker, R., Hamouda, H., Shalev, I., and Johnson, J., “Review and Evaluation of Thermal Sensors for use in Testing Firefighters Protective Clothing,” NIST GCR 99-772, National Institute of Standard and Technology, Gaithersburg, MD, 1999

APPENDICES

Appendix A
Detailed Estimated Second Degree Burn Data

Second degree burn data was calculated using a FORTRAN program. This program estimated for each time step the Ω value. Four data points were gathered per second during testing. Burn injury prediction is typically just an estimate and is mainly used in comparing thermal insulation of different materials. Estimated second degree burn times were therefore estimated to the nearest half second, which still allowed for comparisons of different material variables.

The following tables show the raw data, estimated to the nearest half second and the averaged value of three replicates.

Henriques Integral Burn Time Estimate

Incident Heat Flux: 0.15 cal/cm^2/sec

	System 1			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	168.0	147.0	162.0	168.0
Run 2	133.0	144.0	162.0	172.0
Run 3	131.0	143.0	168.0	162.5
Average	144.0	144.7	164.0	167.5

	System 1 with Trim			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	198.0	133.0	141.0	190.0
Run 2	201.0	131.0	153.0	191.0
Run 3	192.0	129.0	153.0	188.0
Average	197.0	131.0	149.0	189.7

Henriques Integral Burn Time Estimate

Incident Heat Flux: 0.15 cal/cm^2/sec

	System 2			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	171.50	149.00	<200	<180
Run 2	172.00	162.00	<200	<180
Run 3	171.00	157.00	195.0	<180
Average	171.50	156.00	195.0	#DIV/0!
<200 no Burn time estimated after 200 sec exposure				

	System 2 with Trim			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	<225	179.0	188.0	<200
Run 2	<225	169.0	188.0	<200
Run 3	<225	164.0	184.5	<200
Average	#DIV/0!	170.7	186.8	#DIV/0!
<200 no Burn time estimated after 200 sec exposure				

	System 3			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	<180	128.0	171.0	157.0
Run 2	<180	140.0	193.0	< 180
Run 3	<180	163.0	181.0	158.0
Average	#DIV/0!	143.7	181.7	157.5
<180 no Burn time estimated after 180 sec exposure				

	System 3 with Trim			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	<225	222.0	212.0	196.0
Run 2	<225	246.0	209.0	<200
Run 3	<225	236.0	211.0	<200
Average	#DIV/0!	234.7	210.7	196.0
<200 no Burn time estimated after 200 sec exposure				

Henriques Integral Burn Time Estimate

Incident Heat Flux: 0.25 cal/cm^2/sec

	System 1			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	114.0	104.0	108.0	138.0
Run 2	114.0	114.0	111.0	148.0
Run 3	106.0	106.0	108.0	136.0
Average	111.3	108.0	109.0	140.7

	System 1 with Trim			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	146.0	88.5	106.0	112.0
Run 2	148.0	93.5	106.5	122.0
Run 3	147.0	93.5	109.0	122.0
Average	147.0	91.8	107.2	118.7

	System 2			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	113.5	123.5	111.0	106.0
Run 2	113.5	116.0	<120	121.0
Run 3	126.0	118.0	<120	126.0
Average	117.7	119.2	111.0	117.7
<120 no Burn time estimated after 120 sec exposure				

	System 2 with Trim			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	147.0	136.0	150.0	154.0
Run 2	156.0	144.0	<150	141.0
Run 3	153.5	151.0	146.0	148.0
Average	152.2	143.7	148.0	147.7
<150 no Burn time estimated after 150 sec exposure				

Henriques Integral Burn Time Estimate

Incident Heat Flux: 0.25 cal/cm^2/sec

	System 3			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	134.0	117.0	117.0	149.0
Run 2	141.0	116.0	<120	141.0
Run 3	138.0	114.0	<120	126.0
Average	137.7	115.7	117.0	138.7
<120 no Burn time estimated after 120 sec exposure				

	System 3 with Trim			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	< 180	178.50	<150	< 180
Run 2	< 180	164.00	<150	< 180
Run 3	< 180	173.00	<150	168.00
Average	#DIV/0!	171.83	#DIV/0!	168.00
<180 no Burn time estimated after 180 sec exposure				

Incident Heat Flux: 0.5 cal/cm^2/sec

	System 1			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	65.5	54.0	58.5	76.5
Run 2	63.0	69.0	59.0	73.5
Run 3	63.0	61.0	58.0	71.0
Average	63.8	61.3	58.5	73.7

	System 1 with Trim			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	78.0	64.0	64.0	76.0
Run 2	81.0	58.0	59.0	73.5
Run 3	81.0	57.0	63.0	68.5
Average	80.0	59.7	62.0	72.7

Henriques Integral Burn Time Estimate

Incident Heat Flux: 0.5 $cal/cm^2/sec$

	System 2			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	78.5	67.0	68.0	<90
Run 2	71.0	84.0	74.0	84.0
Run 3	76.0	84.0	69.0	78.0
Average	75.2	78.3	70.3	81.0
<90 no Burn time estimated after 90 sec exposure				

	System 2 with Trim			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	81.0	97.0	98.0	<100
Run 2	88.0	99.0	96.0	<100
Run 3	88.0	102.0	93.5	<100
Average	85.7	99.3	95.8	#DIV/0!
<100 no Burn time estimated after 100 sec exposure				

	System 3			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	71.0	63.0	58.0	68.0
Run 2	83.0	54.0	61.0	68.0
Run 3	71.0	57.0	51.0	66.0
Average	75.0	58.0	56.7	67.3

	System 3 with Trim			
Moisture Content	Dry	2.5 g	8 g	16 g
Run 1	96.0	96.0	98.0	91.0
Run 2	96.0	98.0	91.0	96.0
Run 3	96.0	87.0	89.0	88.0
Average	96.0	93.7	92.7	91.7

Appendix B
Statistical Analysis

Statistical analysis was performed to gauge how moisture content and moisture vapor permeability affect the thermal protective insulation of the firefighter turnout materials tested in this study. This analysis was accomplished by utilizing the data for each heat flux separately. Due to heat flux being the dominant factor it was necessary to keep it constant to be able to estimate the differences between different moisture barriers and moisture content.

Reflective trim has to be seen as an additional layer on the system and could confound the analysis on how moisture content and moisture vapor permeability might affect the thermal insulation, therefore data for systems with and without trim were analyzed separately.

Analysis performed was ANOVA, and a student t-test to gauge if the data gathered for the different moisture content and moisture vapor permeable systems are statistically different. Analysis contains first the three systems without trim at each heat flux level, then the same systems with trim at all three heat flux levels, and lastly the comparison of the three systems at all heat flux levels, with and without trim.

In general these statistical analysis show that for systems without reflective trim, differences in moisture content are not as pronounced as for systems with reflective trim attached to the systems. Further it can be seen that the statistical analysis conforms that addition of reflective trim to high moisture vapor permeable system has a pronounced effect in thermal insulation especially as low amounts of moisture are added to the system. Statistically, the effect of moisture vapor permeability on thermal insulation is most pronounced for system 1 which generally shows statistically significant lower thermal insulation than the other two systems. The difference between the other two systems appears, generally, to be not statistically significant.

The following pages show a summary of the statistical results for each test material and test condition, and the detailed statistical analysis obtained using a statistical software program. In the summary of the statistical analysis differences that are statistically significant are denoted with an S, and differences that are not statistically significant noted as NS.

Summary of Statistical Analysis
0.15 cal/cm^2/sec

System 1	Dry	2.5 g	8 g	16 g
Dry	-	NS	NS	S
2.5 g	NS	-	NS	S
8 g	NS	NS	-	NS
16 g	S	S	NS	-

System 2	Dry	2.5 g	8 g	16 g
Dry	-	S	S	-
2.5 g	S	-	S	-
8 g	S	S	-	-
16 g	-	-	-	-

System 3	Dry	2.5 g	8 g	16 g
Dry	-	-	-	-
2.5 g	-	-	S	NS
8 g	-	S	-	NS
16 g	-	NS	NS	-

0.25 cal/cm^2/sec

System 1	Dry	2.5 g	8 g	16 g
Dry	-	NS	NS	S
2.5 g	NS	-	NS	S
8 g	NS	NS	-	S
16 g	S	S	S	-

System 2	Dry	2.5 g	8 g	16 g
Dry	-	NS	NS	NS
2.5 g	NS	-	NS	NS
8 g	NS	NS	-	NS
16 g	NS	NS	NS	-

System 3	Dry	2.5 g	8 g	16 g
Dry	-	S	S	NS
2.5 g	S	-	NS	S
8 g	S	NS	-	S
16 g	NS	NS	NS	-

0.50 $cal/cm^2/sec$

System 1	Dry	2.5 g	8 g	16 g
Dry	-	NS	NS	S
2.5 g	NS	-	NS	S
8 g	NS	NS	-	S
16 g	S	S	S	-

System 2	Dry	2.5 g	8 g	16 g
Dry	-	NS	NS	NS
2.5 g	NS	-	NS	NS
8 g	NS	NS	-	NS
16 g	NS	NS	NS	-

System 3	Dry	2.5 g	8 g	16 g
Dry	-	S	S	NS
2.5 g	S	-	NS	S
8 g	S	NS	-	S
16 g	NS	S	S	-

0.15 $cal/cm^2/sec$, Trim

System 1	Dry	2.5 g	8 g	16 g
Dry	-	S	S	NS
2.5 g	S	-	S	S
8 g	S	S	-	S
16 g	NS	S	S	-

System 2	Dry	2.5 g	8 g	16 g
Dry	-	-	-	-
2.5 g	-	-	S	-
8 g	-	S	-	-
16 g	-	-	-	-

System 3	Dry	2.5 g	8 g	16 g
Dry	-	-	-	-
2.5 g	-	-	S	S
8 g	-	S	-	NS
16 g	-	S	NS	-

0.25 cal/cm^2/sec, Trim

System 1	Dry	2.5 g	8 g	16 g
Dry	-	S	S	S
2.5 g	S	-	S	S
8 g	S	S	-	S
16 g	S	S	S	-

System 2	Dry	2.5 g	8 g	16 g
Dry	-	NS	NS	NS
2.5 g	NS	-	NS	NS
8 g	NS	NS	-	NS
16 g	NS	NS	NS	-

0.50 cal/cm^2/sec, Trim

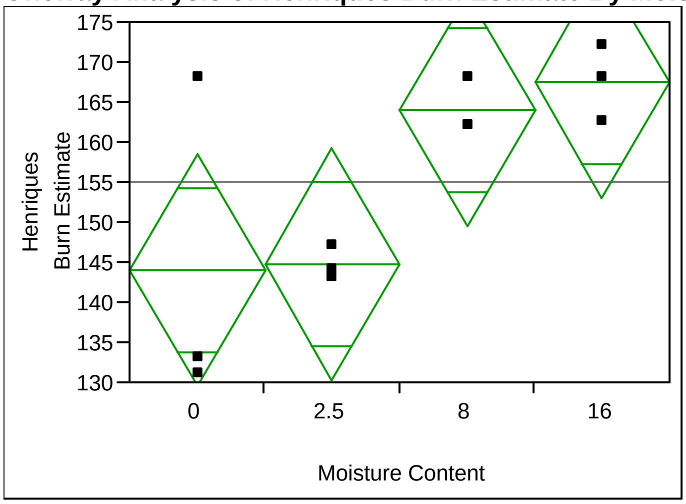
System 1	Dry	2.5 g	8 g	16 g
Dry	-	S	S	S
2.5 g	S	-	NS	S
8 g	S	NS	-	S
16 g	S	S	S	-

System 2	Dry	2.5 g	8 g	16 g
Dry	-	S	S	-
2.5 g	S	-	NS	-
8 g	S	NS	-	-
16 g	-	-	-	-

System 3	Dry	2.5 g	8 g	16 g
Dry	-	NS	NS	NS
2.5 g	NS	-	NS	NS
8 g	NS	NS	-	NS
16 g	NS	NS	NS	-

System 1, Heat Flux 0.15 cal/cm^2/sec

Oneway Analysis of Henriques Burn Estimate By Moisture Content



Oneway Anova

Summary of Fit

Rsquare	0.596377
Adj Rsquare	0.445018
Root Mean Square Error	10.86374
Mean of Response	155.0417
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	1395.0625	465.021	3.9402	0.0537
Error	8	944.1667	118.021		
C. Total	11	2339.2292			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	144.000	6.2722	129.54	158.46
2.5	3	144.667	6.2722	130.20	159.13
8	3	164.000	6.2722	149.54	178.46
16	3	167.500	6.2722	153.04	181.96

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for each pair using Student's t

t	Alpha
2.30600	0.05

Abs(Dif)-LSD	16	8	2.5	0
16	-20.455	-16.955	2.379	3.045
8	-16.955	-20.455	-1.121	-0.455
2.5	2.379	-1.121	-20.455	-19.788
0	3.045	-0.455	-19.788	-20.455

Positive values show pairs of means that are significantly different.

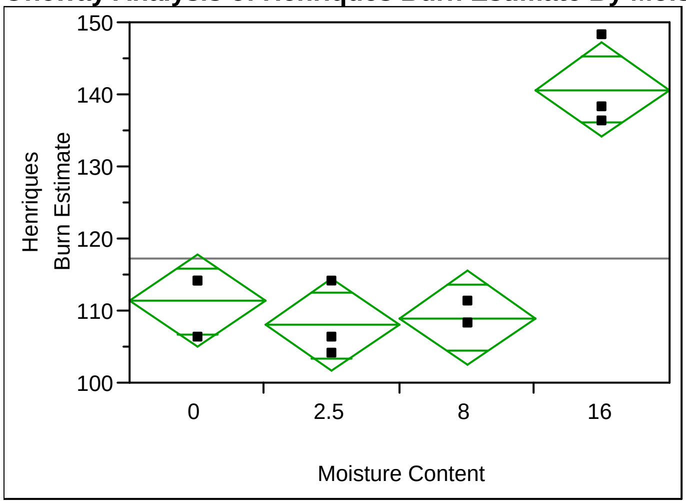
Level			Mean
16	A		167.50000
8	A	B	164.00000
2.5		B	144.66667
0		B	144.00000

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
16	0	23.50000	3.0453	43.95473	0.0293	
16	2.5	22.83333	2.3786	43.28807	0.0329	
8	0	20.00000	-0.4547	40.45473	0.0542	
8	2.5	19.33333	-1.1214	39.78807	0.0609	
16	8	3.50000	-16.9547	23.95473	0.7035	
2.5	0	0.66667	-19.7881	21.12140	0.9419	

System 1, Heat Flux 0.25 cal/cm^2/sec

Oneway Analysis of Henriques Burn Estimate By Moisture Content



Oneway Anova
Summary of Fit

Rsquare	0.921887
Adj Rsquare	0.892595
Root Mean Square Error	4.839077
Mean of Response	117.25
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	2210.9167	736.972	31.4721	<.0001
Error	8	187.3333	23.417		
C. Total	11	2398.2500			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	111.333	2.7938	104.89	117.78
2.5	3	108.000	2.7938	101.56	114.44
8	3	109.000	2.7938	102.56	115.44
16	3	140.667	2.7938	134.22	147.11

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.30600	0.05

Abs(Dif)-LSD	16	0	8	2.5
16	-9.111	20.222	22.555	23.555
0	20.222	-9.111	-6.778	-5.778
8	22.555	-6.778	-9.111	-8.111
2.5	23.555	-5.778	-8.111	-9.111

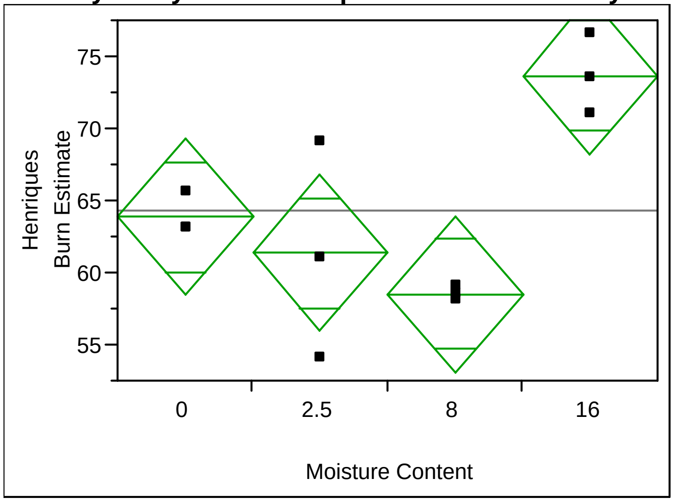
Positive values show pairs of means that are significantly different.

Level			Mean
16	A		140.66667
0		B	111.33333
8		B	109.00000
2.5		B	108.00000

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
16	2.5	32.66667	23.5554	41.77790	<.0001	
16	8	31.66667	22.5554	40.77790	<.0001	
16	0	29.33333	20.2221	38.44456	<.0001	
0	2.5	3.33333	-5.7779	12.44456	0.4234	
0	8	2.33333	-6.7779	11.44456	0.5711	
8	2.5	1.00000	-8.1112	10.11123	0.8066	

System 1, Heat Flux 0.5 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Oneway Anova
Summary of Fit

Rsquare	0.746976
Adj Rsquare	0.652093
Root Mean Square Error	4.069705
Mean of Response	64.33333
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	391.16667	130.389	7.8725	0.0090
Error	8	132.50000	16.562		
C. Total	11	523.66667			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	63.8333	2.3496	58.415	69.252
2.5	3	61.3333	2.3496	55.915	66.752
8	3	58.5000	2.3496	53.082	63.918
16	3	73.6667	2.3496	68.248	79.085

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.30600	0.05

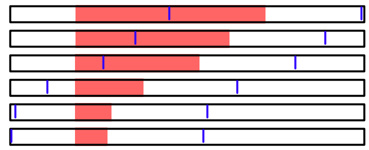
Abs(Dif)-LSD	16	0	2.5	8
16	-7.6626	2.1707	4.6707	7.5040
0	2.1707	-7.6626	-5.1626	-2.3293
2.5	4.6707	-5.1626	-7.6626	-4.8293
8	7.5040	-2.3293	-4.8293	-7.6626

Positive values show pairs of means that are significantly different.

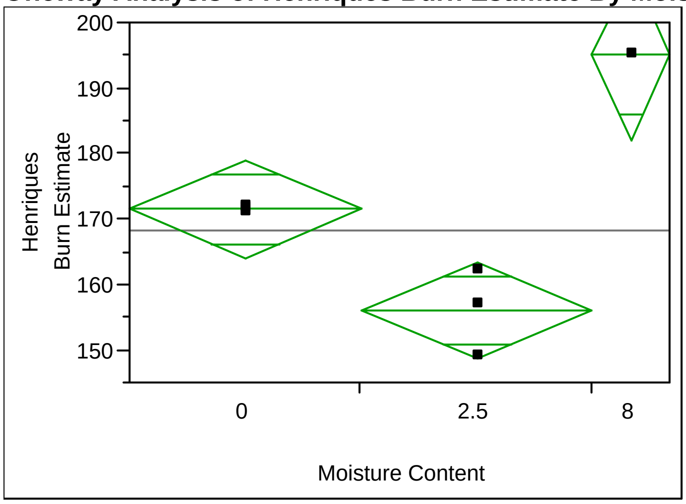
Level			Mean
16	A		73.666667
0		B	63.833333
2.5		B	61.333333
8		B	58.500000

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
16	8	15.16667	7.50404	22.82929	0.0018	
16	2.5	12.33333	4.67071	19.99596	0.0059	
16	0	9.83333	2.17071	17.49596	0.0182	
0	8	5.33333	-2.32929	12.99596	0.1472	
2.5	8	2.83333	-4.82929	10.49596	0.4186	
0	2.5	2.50000	-5.16262	10.16262	0.4734	



System 2, Heat Flux 0.15 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Oneway Anova
Summary of Fit

Rsquare	0.932629
Adj Rsquare	0.898943
Root Mean Square Error	4.650269
Mean of Response	168.2143
Observations (or Sum Wgts)	7

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	2	1197.4286	598.714	27.6862	0.0045
Error	4	86.5000	21.625		
C. Total	6	1283.9286			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	171.500	2.6848	164.05	178.95
2.5	3	156.000	2.6848	148.55	163.45
8	1	195.000	4.6503	182.09	207.91

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.77645	0.05

Abs(Dif)-LSD	8	0	2.5
8	-18.259	8.591	24.091
0	8.591	-10.542	4.958
2.5	24.091	4.958	-10.542

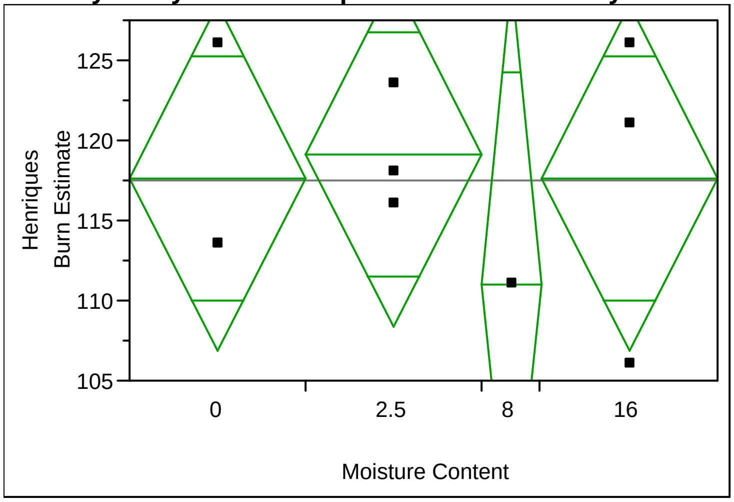
Positive values show pairs of means that are significantly different.

Level		Mean
8	A	195.00000
0	B	171.50000
2.5	C	156.00000

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
8	2.5	39.00000	24.09141	53.90859	0.0019	
8	0	23.50000	8.59141	38.40859	0.0119	
0	2.5	15.50000	4.95804	26.04196	0.0151	

System 2, Heat Flux 0.25 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Missing Rows
2Excluded Rows
204

Oneway Anova
Summary of Fit

Rsquare	0.126268
Adj Rsquare	-0.3106
Root Mean Square Error	7.648529
Mean of Response	117.45
Observations (or Sum Wgts)	10

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	50.72500	16.9083	0.2890	0.8321
Error	6	351.00000	58.5000		
C. Total	9	401.72500			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	117.667	4.4159	106.86	128.47
2.5	3	119.167	4.4159	108.36	129.97
8	1	111.000	7.6485	92.28	129.72
16	3	117.667	4.4159	106.86	128.47

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.44691	0.05

Abs(Dif)-LSD	2.5	0	16	8
2.5	-15.281	-13.781	-13.781	-13.444
0	-13.781	-15.281	-15.281	-14.944
16	-13.781	-15.281	-15.281	-14.944
8	-13.444	-14.944	-14.944	-26.467

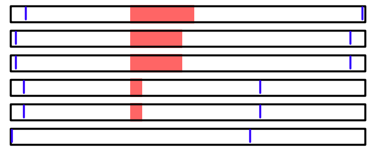
Positive values show pairs of means that are significantly different.

Level		Mean
2.5	A	119.16667
0	A	117.66667
16	A	117.66667
8	A	111.00000

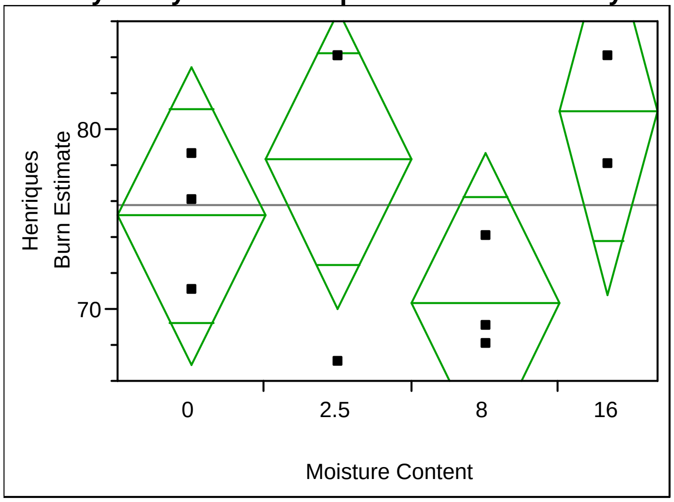
Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value
2.5	8	8.166667	-13.4439	29.77721	0.3908
0	8	6.666667	-14.9439	28.27721	0.4789
16	8	6.666667	-14.9439	28.27721	0.4789
2.5	0	1.500000	-13.7810	16.78096	0.8182
2.5	16	1.500000	-13.7810	16.78096	0.8182
16	0	0.000000	-15.2810	15.28096	1.0000

Difference



System 2, Heat Flux 0.5 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Oneway Anova
Summary of Fit

Rsquare	0.3866
Adj Rsquare	0.123714
Root Mean Square Error	6.100351
Mean of Response	75.77273
Observations (or Sum Wgts)	11

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	164.18182	54.7273	1.4706	0.3028
Error	7	260.50000	37.2143		
C. Total	10	424.68182			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	75.1667	3.5220	66.838	83.495
2.5	3	78.3333	3.5220	70.005	86.662
8	3	70.3333	3.5220	62.005	78.662
16	2	81.0000	4.3136	70.800	91.200

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.36462	0.05

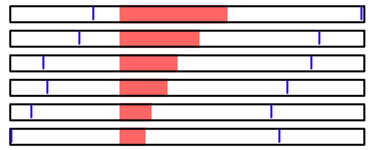
Abs(Dif)-LSD	16	2.5	0	8
16	-14.425	-10.502	-7.335	-2.502
2.5	-10.502	-11.778	-8.611	-3.778
0	-7.335	-8.611	-11.778	-6.945
8	-2.502	-3.778	-6.945	-11.778

Positive values show pairs of means that are significantly different.

Level		Mean
16	A	81.000000
2.5	A	78.333333
0	A	75.166667
8	A	70.333333

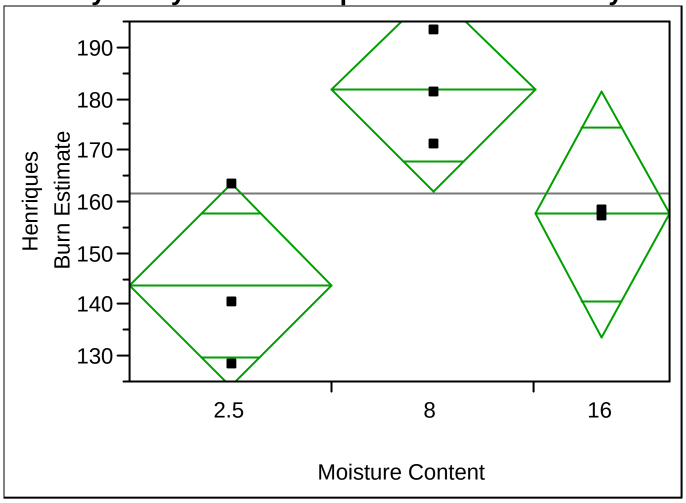
Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
16	8	10.66667	-2.5015	23.83487	0.0970	
2.5	8	8.00000	-3.7780	19.77799	0.1523	
16	0	5.83333	-7.3349	19.00153	0.3297	
0	8	4.83333	-6.9447	16.61133	0.3642	
2.5	0	3.16667	-8.6113	14.94466	0.5451	
16	2.5	2.66667	-10.5015	15.83487	0.6466	



System 3, Heat Flux 0.15 cal/cm^2/sec

Oneway Analysis of Henriques Burn Estimate By Moisture Content



Oneway Anova
Summary of Fit

Rsquare	0.715812
Adj Rsquare	0.602136
Root Mean Square Error	13.23505
Mean of Response	161.375
Observations (or Sum Wgts)	8

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	2	2206.0417	1103.02	6.2970	0.0431
Error	5	875.8333	175.17		
C. Total	7	3081.8750			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
2.5	3	143.667	7.6413	124.02	163.31
8	3	181.667	7.6413	162.02	201.31
16	2	157.500	9.3586	133.44	181.56

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.57058	0.05

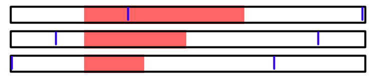
Abs(Dif)-LSD	8	16	2.5
8	-27.779	-6.891	10.221
16	-6.891	-34.022	-17.224
2.5	10.221	-17.224	-27.779

Positive values show pairs of means that are significantly different.

Level			Mean
8	A		181.66667
16	A	B	157.50000
2.5		B	143.66667

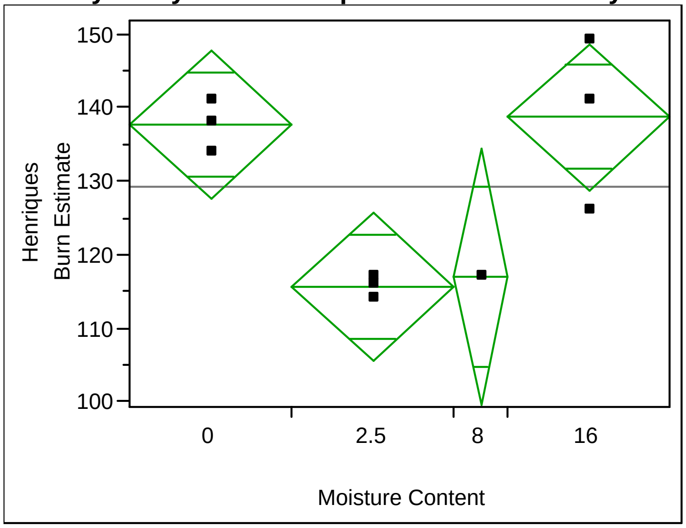
Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
8	2.5	38.00000	10.2213	65.77868	0.0170	
8	16	24.16667	-6.8908	55.22417	0.1019	
16	2.5	13.83333	-17.2242	44.89084	0.3041	



System 3, Heat Flux 0.25 cal/cm^2/sec

Oneway Analysis of Henriques Burn Estimate By Moisture Content



Missing Rows
2Excluded Rows
204

Oneway Anova
Summary of Fit

Rsquare	0.79651
Adj Rsquare	0.694765
Root Mean Square Error	7.094599
Mean of Response	129.3
Observations (or Sum Wgts)	10

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	1182.1000	394.033	7.8285	0.0170
Error	6	302.0000	50.333		
C. Total	9	1484.1000			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	137.667	4.0961	127.64	147.69
2.5	3	115.667	4.0961	105.64	125.69
8	1	117.000	7.0946	99.64	134.36
16	3	138.667	4.0961	128.64	148.69

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.44691	0.05

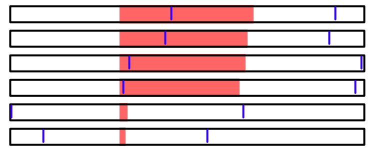
Abs(Dif)-LSD	16	0	8	2.5
16	-14.174	-13.174	1.621	8.826
0	-13.174	-14.174	0.621	7.826
8	1.621	0.621	-24.551	-18.712
2.5	8.826	7.826	-18.712	-14.174

Positive values show pairs of means that are significantly different.

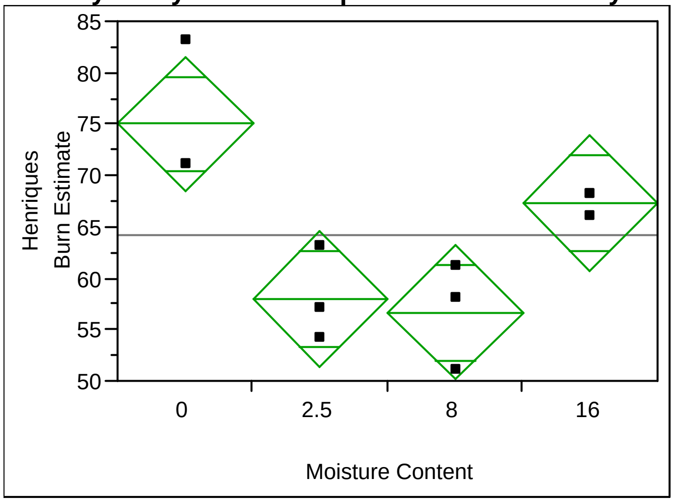
Level			Mean
16	A		138.66667
0	A		137.66667
8		B	117.00000
2.5		B	115.66667

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
16	2.5	23.00000	8.8257	37.17426	0.0074	
0	2.5	22.00000	7.8257	36.17426	0.0090	
16	8	21.66667	1.6212	41.71210	0.0383	
0	8	20.66667	0.6212	40.71210	0.0451	
8	2.5	1.33333	-18.7121	21.37877	0.8761	
16	0	1.00000	-13.1743	15.17426	0.8686	



System 3, Heat Flux 0.5 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Oneway Anova
Summary of Fit

Rsquare	0.774735
Adj Rsquare	0.690261
Root Mean Square Error	4.91596
Mean of Response	64.25
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	664.91667	221.639	9.1713	0.0057
Error	8	193.33333	24.167		
C. Total	11	858.25000			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	75.0000	2.8382	68.455	81.545
2.5	3	58.0000	2.8382	51.455	64.545
8	3	56.6667	2.8382	50.122	63.212
16	3	67.3333	2.8382	60.788	73.878

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.30600	0.05

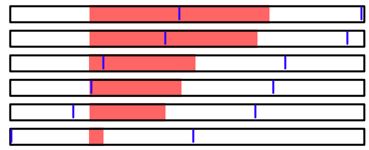
Abs(Dif)-LSD	0	16	2.5	8
0	-9.2560	-1.5893	7.7440	9.0773
16	-1.5893	-9.2560	0.0773	1.4107
2.5	7.7440	0.0773	-9.2560	-7.9227
8	9.0773	1.4107	-7.9227	-9.2560

Positive values show pairs of means that are significantly different.

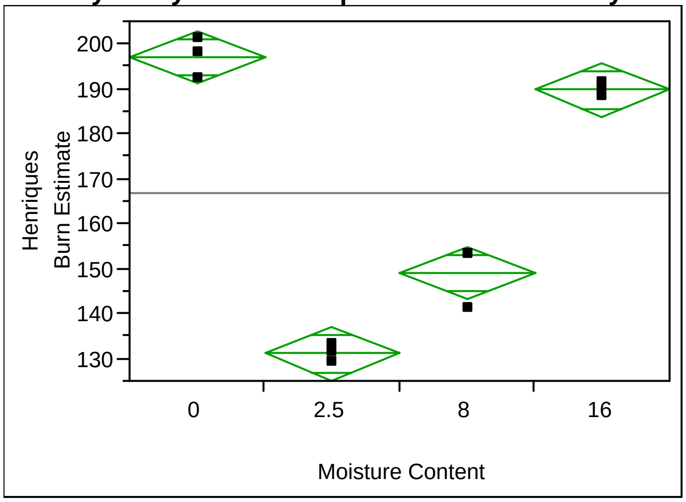
Level		Mean
0	A	75.000000
16	A	67.333333
2.5	B	58.000000
8	B	56.666667

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
0	8	18.33333	9.07734	27.58932	0.0018	
0	2.5	17.00000	7.74401	26.25599	0.0029	
16	8	10.66667	1.41068	19.92266	0.0289	
16	2.5	9.33333	0.07734	18.58932	0.0485	
0	16	7.66667	-1.58932	16.92266	0.0925	
2.5	8	1.33333	-7.92266	10.58932	0.7483	



System 1 with Trim, Heat Flux 0.15 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Oneway Anova
Summary of Fit

Rsquare	0.983713
Adj Rsquare	0.977605
Root Mean Square Error	4.339739
Mean of Response	166.6667
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	9100.0000	3033.33	161.0619	<.0001
Error	8	150.6667	18.83		
C. Total	11	9250.6667			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	197.000	2.5055	191.22	202.78
2.5	3	131.000	2.5055	125.22	136.78
8	3	149.000	2.5055	143.22	154.78
16	3	189.667	2.5055	183.89	195.44

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.30600	0.05

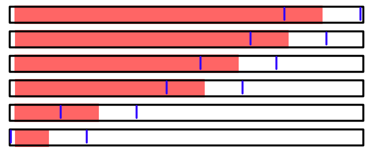
Abs(Dif)-LSD	0	16	8	2.5
0	-8.171	-0.838	39.829	57.829
16	-0.838	-8.171	32.496	50.496
8	39.829	32.496	-8.171	9.829
2.5	57.829	50.496	9.829	-8.171

Positive values show pairs of means that are significantly different.

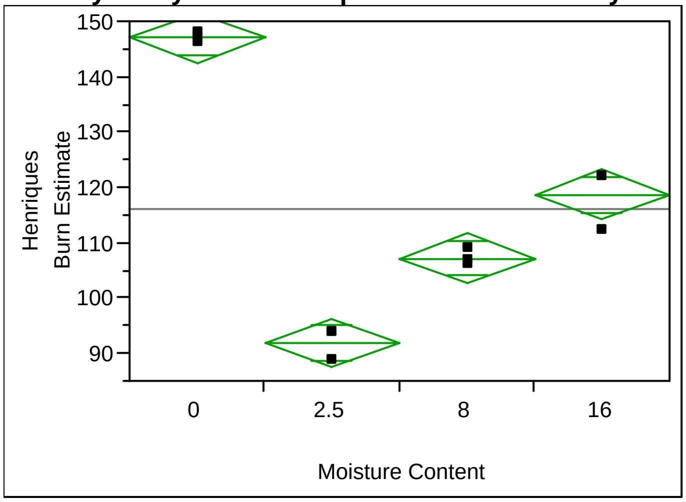
Level				Mean
0	A			197.00000
16	A			189.66667
8		B		149.00000
2.5			C	131.00000

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
0	2.5	66.00000	57.8289	74.17105	<.0001	
16	2.5	58.66667	50.4956	66.83772	<.0001	
0	8	48.00000	39.8289	56.17105	<.0001	
16	8	40.66667	32.4956	48.83772	<.0001	
8	2.5	18.00000	9.8289	26.17105	0.0010	
0	16	7.33333	-0.8377	15.50439	0.0723	



System 1 with Trim, Heat Flux 0.25 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Excluded Rows
204

Oneway Anova
Summary of Fit

Rsquare	0.98183
Adj Rsquare	0.975016
Root Mean Square Error	3.363406
Mean of Response	116.1667
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	4890.1667	1630.06	144.0933	<.0001
Error	8	90.5000	11.31		
C. Total	11	4980.6667			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	147.000	1.9419	142.52	151.48
2.5	3	91.833	1.9419	87.36	96.31
8	3	107.167	1.9419	102.69	111.64
16	3	118.667	1.9419	114.19	123.14

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.30600	0.05

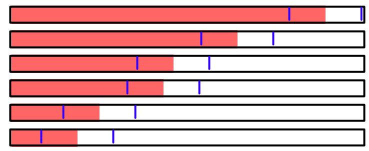
Abs(Dif)-LSD	0	16	8	2.5
0	-6.333	22.001	33.501	48.834
16	22.001	-6.333	5.167	20.501
8	33.501	5.167	-6.333	9.001
2.5	48.834	20.501	9.001	-6.333

Positive values show pairs of means that are significantly different.

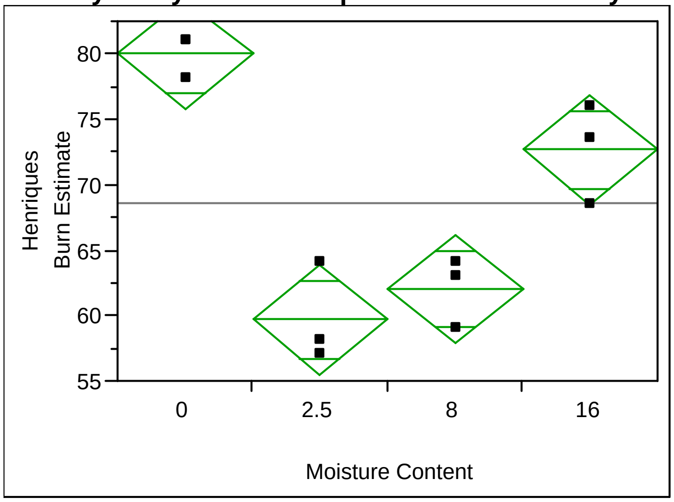
Level					Mean
0	A				147.00000
16		B			118.66667
8			C		107.16667
2.5				D	91.83333

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
0	2.5	55.16667	48.83390	61.49944	<.0001	
0	8	39.83333	33.50056	46.16610	<.0001	
0	16	28.33333	22.00056	34.66610	<.0001	
16	2.5	26.83333	20.50056	33.16610	<.0001	
8	2.5	15.33333	9.00056	21.66610	0.0005	
16	8	11.50000	5.16723	17.83277	0.0030	



System 1 with Trim, Heat Flux 0.5 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Oneway Anova
Summary of Fit

Rsquare	0.912292
Adj Rsquare	0.879402
Root Mean Square Error	3.119161
Mean of Response	68.58333
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	809.58333	269.861	27.7373	0.0001
Error	8	77.83333	9.729		
C. Total	11	887.41667			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	80.0000	1.8008	75.847	84.153
2.5	3	59.6667	1.8008	55.514	63.819
8	3	62.0000	1.8008	57.847	66.153
16	3	72.6667	1.8008	68.514	76.819

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.30600	0.05

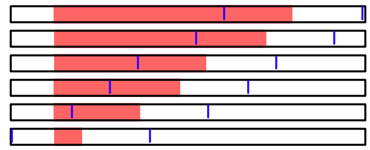
Abs(Dif)-LSD	0	16	8	2.5
0	-5.873	1.460	12.127	14.460
16	1.460	-5.873	4.794	7.127
8	12.127	4.794	-5.873	-3.540
2.5	14.460	7.127	-3.540	-5.873

Positive values show pairs of means that are significantly different.

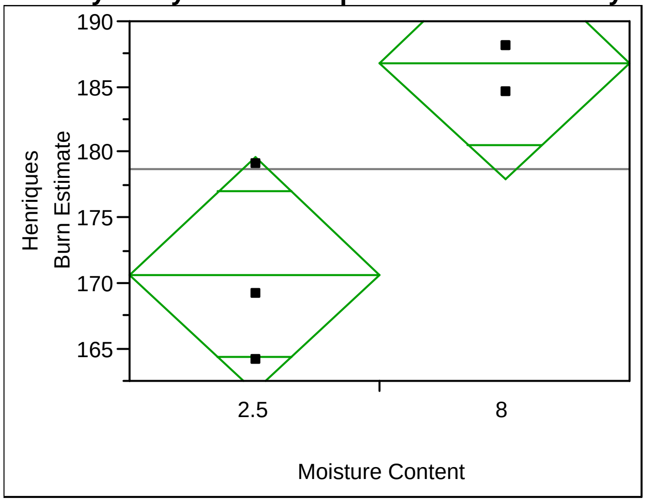
Level				Mean
0	A			80.000000
16		B		72.666667
8			C	62.000000
2.5			C	59.666667

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
0	2.5	20.33333	14.4604	26.20623	<.0001	
0	8	18.00000	12.1271	23.87290	0.0001	
16	2.5	13.00000	7.1271	18.87290	0.0009	
16	8	10.66667	4.7938	16.53956	0.0030	
0	16	7.33333	1.4604	13.20623	0.0205	
8	2.5	2.33333	-3.5396	8.20623	0.3864	



System 2 with Trim, Heat Flux 0.15 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content

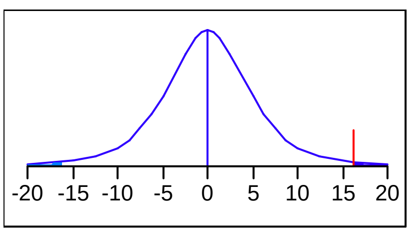


Oneway Anova
Summary of Fit

Rsquare	0.758484
Adj Rsquare	0.698106
Root Mean Square Error	5.586442
Mean of Response	178.75
Observations (or Sum Wgts)	6

t Test
8-2.5
Assuming equal variances

Difference	16.1667	t Ratio	3.544303
Std Err Dif	4.5613	DF	4
Upper CL Dif	28.8309	Prob > |t|	0.0239
Lower CL Dif	3.5024	Prob > t	0.0120
Confidence	0.95	Prob < t	0.9880



Analysis of Variance

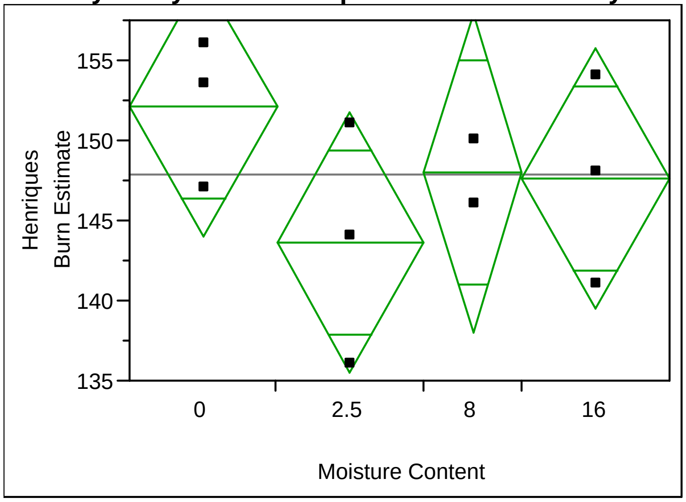
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	1	392.04167	392.042	12.5621	0.0239
Error	4	124.83333	31.208		
C. Total	5	516.87500			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
2.5	3	170.667	3.2253	161.71	179.62
8	3	186.833	3.2253	177.88	195.79

Std Error uses a pooled estimate of error variance

System 2 with Trim, Heat Flux 0.25 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Missing Rows
1Excluded Rows
204

Oneway Anova

Summary of Fit

Rsquare	0.30401
Adj Rsquare	0.005729
Root Mean Square Error	5.958188
Mean of Response	147.8636
Observations (or Sum Wgts)	11

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	108.54545	36.1818	1.0192	0.4398
Error	7	248.50000	35.5000		
C. Total	10	357.04545			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	152.167	3.4400	144.03	160.30
2.5	3	143.667	3.4400	135.53	151.80
8	2	148.000	4.2131	138.04	157.96
16	3	147.667	3.4400	139.53	155.80

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for each pair using Student's t

t	Alpha
2.36462	0.05

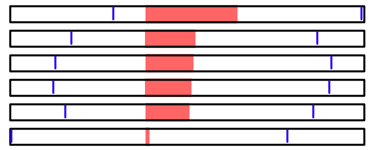
Abs(Dif)-LSD	0	8	16	2.5
0	-11.504	-8.695	-7.004	-3.004
8	-8.695	-14.089	-12.528	-8.528
16	-7.004	-12.528	-11.504	-7.504
2.5	-3.004	-8.528	-7.504	-11.504

Positive values show pairs of means that are significantly different.

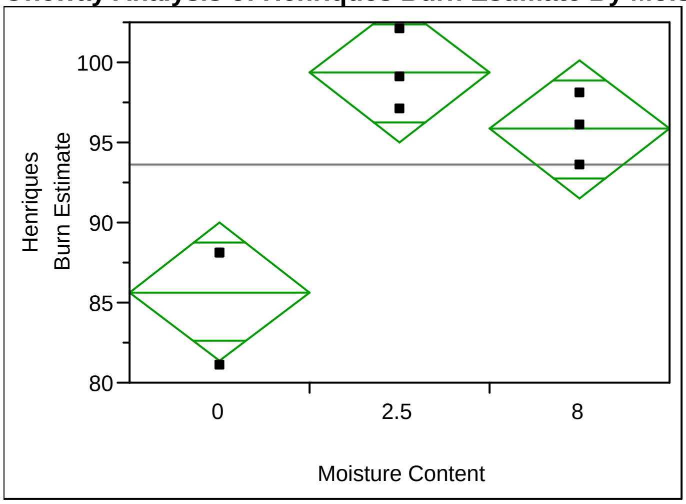
Level		Mean
0	A	152.16667
8	A	148.00000
16	A	147.66667
2.5	A	143.66667

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
0	2.5	8.500000	-3.0035	20.00352	0.1241	
0	16	4.500000	-7.0035	16.00352	0.3857	
8	2.5	4.333333	-8.5280	17.19466	0.4518	
0	8	4.166667	-8.6947	17.02799	0.4687	
16	2.5	4.000000	-7.5035	15.50352	0.4381	
8	16	0.333333	-12.5280	13.19466	0.9528	



System 2 with Trim, Heat Flux 0.5 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Missing Rows
3Excluded Rows
204

Oneway Anova
Summary of Fit

Rsquare	0.844924
Adj Rsquare	0.793232
Root Mean Square Error	3.041381
Mean of Response	93.61111
Observations (or Sum Wgts)	9

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	2	302.38889	151.194	16.3453	0.0037
Error	6	55.50000	9.250		
C. Total	8	357.88889			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	85.6667	1.7559	81.370	89.96
2.5	3	99.3333	1.7559	95.037	103.63
8	3	95.8333	1.7559	91.537	100.13

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.44691	0.05

Abs(Dif)-LSD	2.5	8	0
2.5	-6.0764	-2.5764	7.5903
8	-2.5764	-6.0764	4.0903
0	7.5903	4.0903	-6.0764

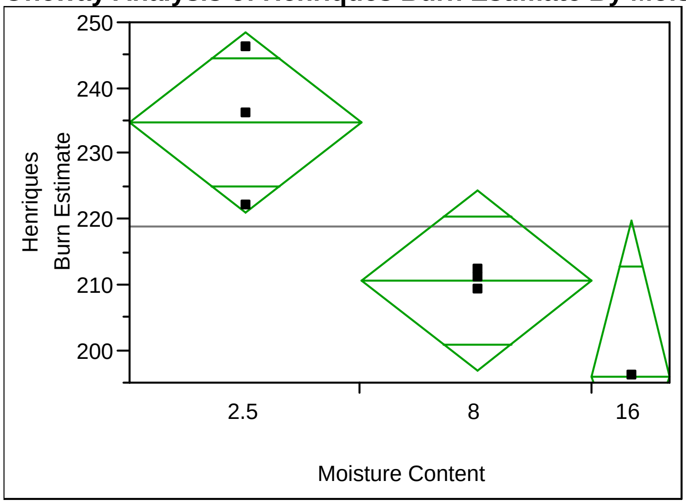
Positive values show pairs of means that are significantly different.

Level			Mean
2.5	A		99.333333
8	A		95.833333
0		B	85.666667

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
2.5	0	13.66667	7.59031	19.74303	0.0015	
8	0	10.16667	4.09031	16.24303	0.0064	
2.5	8	3.50000	-2.57636	9.57636	0.2084	

System 3 with Trim, Heat Flux 0.15 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Missing Rows
5Excluded Rows
204

Oneway Anova

Summary of Fit

Rsquare	0.833037
Adj Rsquare	0.749556
Root Mean Square Error	8.592633
Mean of Response	218.8571
Observations (or Sum Wgts)	7

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	2	1473.5238	736.762	9.9787	0.0279
Error	4	295.3333	73.833		
C. Total	6	1768.8571			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
2.5	3	234.667	4.9610	220.89	248.44
8	3	210.667	4.9610	196.89	224.44
16	1	196.000	8.5926	172.14	219.86

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for each pair using Student's t

t	Alpha
2.77645	0.05

Abs(Dif)-LSD	2.5	8	16
2.5	-19.479	4.521	11.119
8	4.521	-19.479	-12.881
16	11.119	-12.881	-33.739

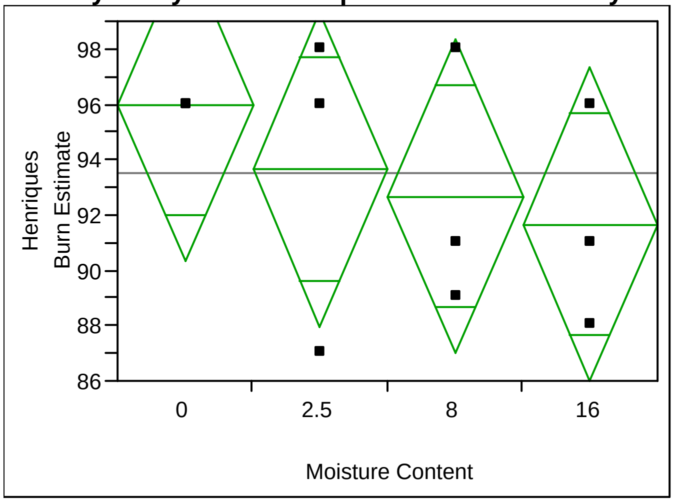
Positive values show pairs of means that are significantly different.

Level			Mean
2.5	A		234.66667
8		B	210.66667
16		B	196.00000

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
2.5	16	38.66667	11.1190	66.21433	0.0176	
2.5	8	24.00000	4.5209	43.47914	0.0268	
8	16	14.66667	-12.8810	42.21433	0.2134	

System 3 with Trim, Heat Flux 0.5 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By Moisture Content



Excluded Rows
204

Oneway Anova

Summary of Fit

Rsquare	0.175141
Adj Rsquare	-0.13418
Root Mean Square Error	4.272002
Mean of Response	93.5
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture Content	3	31.00000	10.3333	0.5662	0.6525
Error	8	146.00000	18.2500		
C. Total	11	177.00000			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	3	96.0000	2.4664	90.312	101.69
2.5	3	93.6667	2.4664	87.979	99.35
8	3	92.6667	2.4664	86.979	98.35
16	3	91.6667	2.4664	85.979	97.35

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for each pair using Student's t

t	Alpha
2.30600	0.05

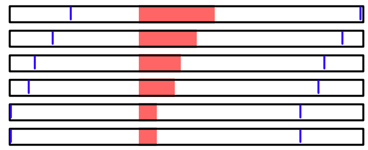
Abs(Dif)-LSD	0	2.5	8	16
0	-8.0435	-5.7102	-4.7102	-3.7102
2.5	-5.7102	-8.0435	-7.0435	-6.0435
8	-4.7102	-7.0435	-8.0435	-7.0435
16	-3.7102	-6.0435	-7.0435	-8.0435

Positive values show pairs of means that are significantly different.

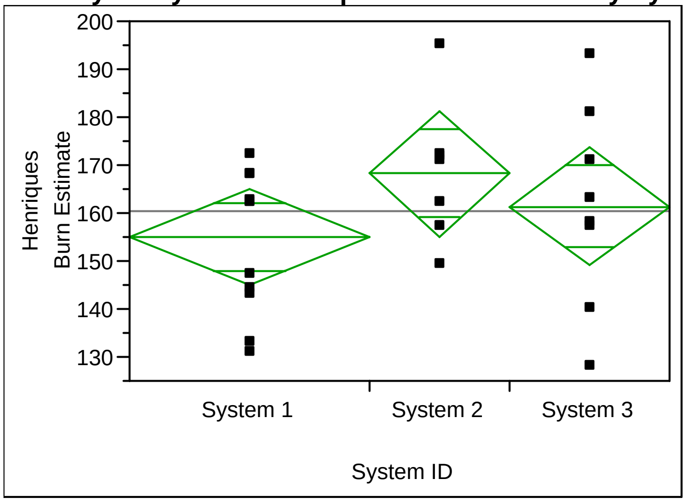
Level		Mean
0	A	96.000000
2.5	A	93.666667
8	A	92.666667
16	A	91.666667

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
0	16	4.333333	-3.71018	12.37685	0.2493	
0	8	3.333333	-4.71018	11.37685	0.3672	
0	2.5	2.333333	-5.71018	10.37685	0.5224	
2.5	16	2.000000	-6.04352	10.04352	0.5821	
2.5	8	1.000000	-7.04352	9.04352	0.7816	
8	16	1.000000	-7.04352	9.04352	0.7816	



Comparison of System 1-3, 0.15 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By System ID



Oneway Anova
Summary of Fit

Rsquare	0.104144
Adj Rsquare	0.02949
Root Mean Square Error	16.71456
Mean of Response	160.3333
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
System ID	2	779.4673	389.734	1.3950	0.2672
Error	24	6705.0327	279.376		
C. Total	26	7484.5000			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
System 1	12	155.042	4.8251	145.08	165.00
System 2	7	168.214	6.3175	155.18	181.25
System 3	8	161.375	5.9095	149.18	173.57

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.06390	0.05

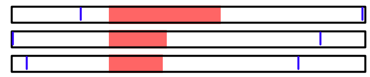
Abs(Dif)-LSD	System 2	System 3	System 1
System 2	-18.440	-11.015	-3.234
System 3	-11.015	-17.249	-9.412
System 1	-3.234	-9.412	-14.083

Positive values show pairs of means that are significantly different.

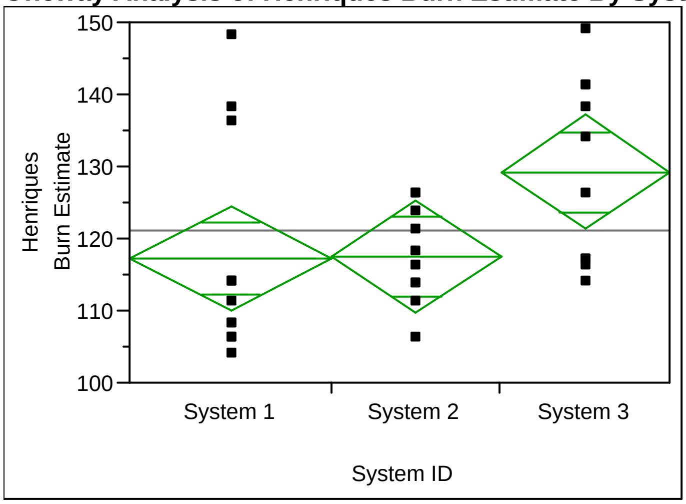
Level		Mean
System 2	A	168.21429
System 3	A	161.37500
System 1	A	155.04167

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
System 2	System 1	13.17262	-3.2340	29.57929	0.1105	
System 2	System 3	6.83929	-11.0147	24.69326	0.4369	
System 3	System 1	6.33333	-9.4124	22.07905	0.4146	



Comparision of System 1-3, 0.25 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By System ID



Missing Rows
4Excluded Rows
180

Oneway Anova
Summary of Fit

Rsquare	0.186705
Adj Rsquare	0.130616
Root Mean Square Error	12.15429
Mean of Response	121.0781
Observations (or Sum Wgts)	32

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
System ID	2	983.4797	491.740	3.3287	0.0500
Error	29	4284.0750	147.727		
C. Total	31	5267.5547			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
System 1	12	117.250	3.5086	110.07	124.43
System 2	10	117.450	3.8435	109.59	125.31
System 3	10	129.300	3.8435	121.44	137.16

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.04523	0.05

Abs(Dif)-LSD	System 3	System 2	System 1
System 3	-11.117	0.733	1.406
System 2	0.733	-11.117	-10.444
System 1	1.406	-10.444	-10.148

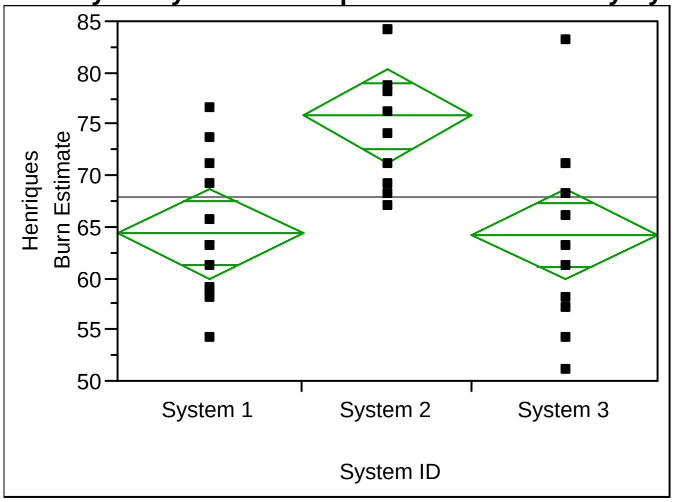
Positive values show pairs of means that are significantly different.

Level			Mean
System 3	A		129.30000
System 2		B	117.45000
System 1		B	117.25000

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
System 3	System 1	12.05000	1.4063	22.69369	0.0279	
System 3	System 2	11.85000	0.7330	22.96697	0.0375	
System 2	System 1	0.20000	-10.4437	10.84369	0.9696	

Comparision of System 1-3, 0.5 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By System ID



Missing Rows
1Excluded Rows
180

Oneway Anova
Summary of Fit

Rsquare	0.354994
Adj Rsquare	0.314681
Root Mean Square Error	7.513734
Mean of Response	67.9
Observations (or Sum Wgts)	35

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
System ID	2	994.3015	497.151	8.8060	0.0009
Error	32	1806.5985	56.456		
C. Total	34	2800.9000			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
System 1	12	64.3333	2.1690	59.915	68.751
System 2	11	75.7727	2.2655	71.158	80.387
System 3	12	64.2500	2.1690	59.832	68.668

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.03693	0.05

Abs(Dif)-LSD	System 2	System 1	System 3
System 2	-6.5261	5.0507	5.1341
System 1	5.0507	-6.2482	-6.1649
System 3	5.1341	-6.1649	-6.2482

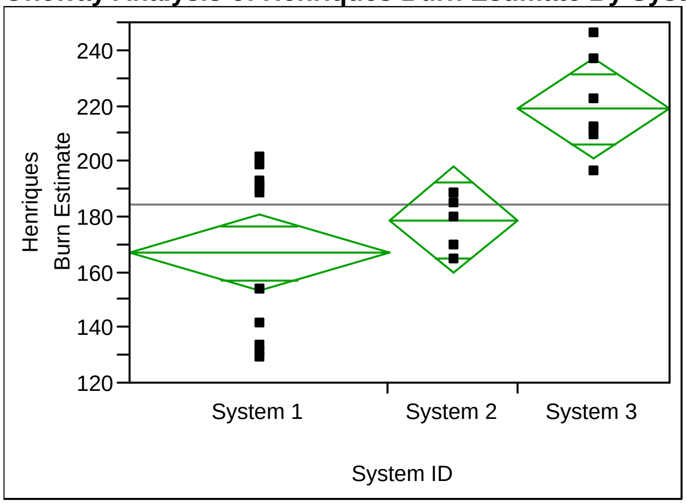
Positive values show pairs of means that are significantly different.

Level		Mean
System 2	A	75.772727
System 1	B	64.333333
System 3	B	64.250000

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
System 2	System 3	11.52273	5.13407	17.91138	0.0009	
System 2	System 1	11.43939	5.05074	17.82805	0.0009	
System 1	System 3	0.08333	-6.16490	6.33156	0.9785	

Comparision of System 1-3 with Trim, 0.15 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By System ID



Oneway Anova
Summary of Fit

Rsquare	0.51551
Adj Rsquare	0.471466
Root Mean Square Error	22.89938
Mean of Response	184.18
Observations (or Sum Wgts)	25

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
System ID	2	12275.041	6137.52	11.7043	0.0003
Error	22	11536.399	524.38		
C. Total	24	23811.440			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
System 1	12	166.667	6.6105	152.96	180.38
System 2	6	178.750	9.3486	159.36	198.14
System 3	7	218.857	8.6552	200.91	236.81

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.07387	0.05

Abs(Dif)-LSD	System 3	System 2	System 1
System 3	-25.385	13.686	29.604
System 2	13.686	-27.419	-11.662
System 1	29.604	-11.662	-19.388

Positive values show pairs of means that are significantly different.

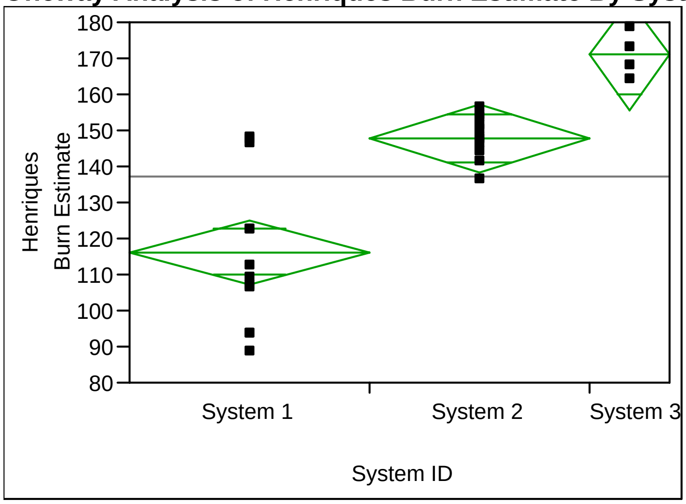
Level			Mean
System 3	A		218.85714
System 2		B	178.75000
System 1		B	166.66667

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
System 3	System 1	52.19048	29.6043	74.77667	<.0001	
System 3	System 2	40.10714	13.6859	66.52837	0.0047	
System 2	System 1	12.08333	-11.6619	35.82854	0.3027	

Comp System 1-3, 0.15 cal/cm^2.sec

Comparision of System 1-3 with Trim, 0.25 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By System ID



Oneway Anova
Summary of Fit

Rsquare	0.67037
Adj Rsquare	0.642901
Root Mean Square Error	15.07744
Mean of Response	137.1852
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
System ID	2	11095.674	5547.84	24.4044	<.0001
Error	24	5455.900	227.33		
C. Total	26	16551.574			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
System 1	12	116.167	4.3525	107.18	125.15
System 2	11	147.864	4.5460	138.48	157.25
System 3	4	170.875	7.5387	155.32	186.43

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.06390	0.05

Abs(Dif)-LSD	System 3	System 2	System 1
System 3	-22.004	4.842	36.742
System 2	4.842	-13.269	18.707
System 1	36.742	18.707	-12.704

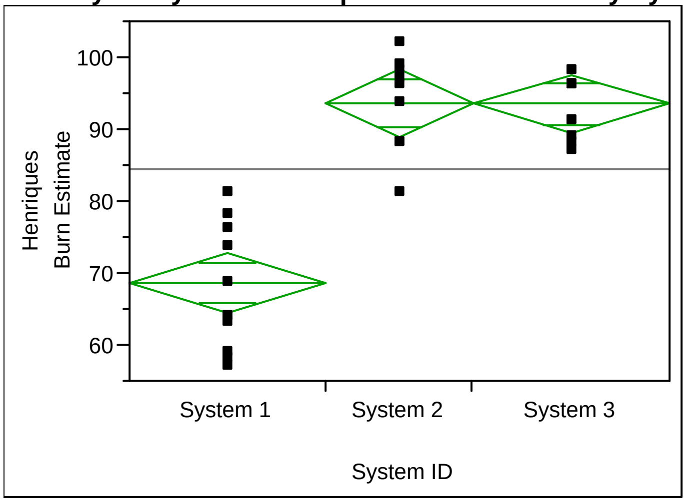
Positive values show pairs of means that are significantly different.

Level				Mean
System 3	A			170.87500
System 2		B		147.86364
System 1			C	116.16667

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
System 3	System 1	54.70833	36.74217	72.67449	<.0001	
System 2	System 1	31.69697	18.70746	44.68648	<.0001	
System 3	System 2	23.01136	4.84219	41.18054	0.0152	

Comparision of System 1-3 with Trim, 0.5 cal/cm^2/sec
Oneway Analysis of Henriques Burn Estimate By System ID



Oneway Anova
Summary of Fit

Rsquare	0.769908
Adj Rsquare	0.754569
Root Mean Square Error	6.885505
Mean of Response	84.4697
Observations (or Sum Wgts)	33

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
System ID	2	4759.1641	2379.58	50.1914	<.0001
Error	30	1422.3056	47.41		
C. Total	32	6181.4697			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
System 1	12	68.5833	1.9877	64.524	72.643
System 2	9	93.6111	2.2952	88.924	98.298
System 3	12	93.5000	1.9877	89.441	97.559

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t

t	Alpha
2.04227	0.05

Abs(Dif)-LSD	System 2	System 3	System 1
System 2	-6.629	-6.090	18.827
System 3	-6.090	-5.741	19.176
System 1	18.827	19.176	-5.741

Positive values show pairs of means that are significantly different.

Level			Mean
System 2	A		93.611111
System 3	A		93.500000
System 1		B	68.583333

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Lower CL	Upper CL	p-Value	Difference
System 2	System 1	25.02778	18.8270	31.22857	<.0001	
System 3	System 1	24.91667	19.1758	30.65749	<.0001	
System 2	System 3	0.11111	-6.0897	6.31190	0.9711	