Special Radiant Testing of Hydroweave™ Material to Determine Potential for Steam Release

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Introduction and Background

Aquatex Industries has developed a new patented material product for use in garments to aid in relieving the heat stress associated with heavy work or work in hot environments. The new product, Hydroweave™, employs a multi-layer construction consisting of an outer woven fabric shell, a fibrous batt containing a water-absorbent polymer, and a conductive, microporous film on a light fabric substrate. The water-absorbent polymer is distributed evenly throughout the material batt and has a finite water absorption capacity. To activate a garment made of Hydroweave for cooling, the garment is soaked, wrung out, and wiped clear of excess water. This process results in a fabric that is cool on the inner surface (due to the innermost film layer), but damp in the batting and shell outside the film. When in contact with the wearer's skin, heat is transferred to the Hydroweave material and is released to the outside environment by evaporation of the water in the garment. Because of the even distribution of water-absorbent polymer throughout the material batting, cooling is provided evenly for the entire garment and can continue for several hours depending on the degree of garment contact, environmental conditions, wearer physical activity, and type of outer clothing worn.

In addition to its cooling function, Hydroweave provides a secondary benefit of insulating the wearer from heat. When configured with flame-resistant materials, test results show Hydroweave to meet performance criteria established by the National Fire Protection Association for structural fire fighting protective materials (per NFPA 1971). Additional testing has shown activated Hydroweave composites to have thermal protective performance (TPP) and radiant heat resistance test results well in excess of minimum requirement for thermal insulation. For example, the TPP of Hydroweave composites in an activated condition is well in excess of 100, the maximum reportable TPP permitted by the test equipment [1]. A comparable composite of similar weight and thickness would provide a TPP rating of approximately 40. Similar results for activated Hydroweave composite specimens tested against 0.5 cal/cm^2s radiant heat exposure showed a two-fold improvement in the time to a second-degree burn when compared to standard fire fighting clothing composites.

Despite the potential benefits in both heat-stress reduction and improved thermal insulation, some concerns have been raised about the potential for steam generation or scalding temperatures due to water held in the Hydroweave material. This study was undertaken to investigate this phenomenon and determine both the heat and mass transfer aspects of Hydroweave material performance in a series of specialized radiant heat tests.

Approach

Test Method. Bench scale testing using the Radiant Protective Performance (RPP) test apparatus was conducted to measure the temperature rise and moisture transfer in the clothing. This testing was accomplished using a modified form of ASTM F 1939, *Standard Test Method for Radiant Protective Performance of Flame Resistant Clothing Materials* (1999), involving a radiant heat exposure of 0.1 cal/cm^{2}s. This level of radiant heat is considered "routine" in fire fighting and is representative of hot work at foundries where a worker might be expected to remain at these levels for 3 to 5 minutes [2,3]. Unprotected skin under these conditions would sustain a second-degree burn within 30 seconds [4].

Material Samples. Two different material combinations were evaluated.

1. The first combination was a Hydroweave composite using the Hydroweave material as a liner with the shell portion facing outward together with an exterior 6.0-oz/yd^2 60/40 Kevlar®/PBI® outer shell.

2. The second combination was a standard composite using the same outer shell but employing a liner consisting of Crosstech® laminated to a Nomex® E89 substrate and an innermost layer of aramid batt with woven aramid facecloth thermal barrier.

All materials were subjected to 5 cycles of laundering per AATCC 135 using a normal machine setting, wash temperature of 140^{o}C, and tumble-drying.

Wet Pretreatments. The materials were tested both wet and dry. Dry tests were performed on each combination without any further treatment of the material. In the case of the Hydroweave combination, the wet testing was accomplished by activating the Hydroweave liner. The standard composite was evaluated using two wet pretreatments (in addition to the dry test). These pretreatments were performed using the following procedures:

– *Hydroweave activation* – Activation was accomplished by putting the Hydroweave liner only through rinse and spin cycles of a washing machine (without detergent). Excess water was blotted from the film side of the material specimens.

– *Wet condition 1* - The first wet test was accomplished by using the same procedure above that was employed for activating the Hydroweave material, but for the thermal barrier portion of the standard composite only.

– *Wet condition 2* - A different wet condition was used to condition the thermal barrier composite to a moisture level more representative of wearing as would occur from sweating. The procedures specified in paragraph 6-1.8 of NFPA 1971 (1997 edition) were used. These procedures involved immersing the specimens in room temperature water for 2 minutes, allowing the specimens to hang dry for 5 minutes, and placing the specimens between AATCC blotting paper for a period of 10 minutes under a pressure of 0.5 psi. The resulting moisture condition provide an average of 2 grams of water in the specimens, consistent with industry reported moisture levels for thermal barriers after clothing wearing [5].

Sample Preparation and Measurements. All tests were conducted using a 100% cotton material between the sensor and the specimen. This material was be used to measure the amount of moisture transfer from the innermost layer of the specimen that occurred as the result of the radiant heat exposure. (The cotton layer was weighed before and after each test.)

Prior to each test, the weight and thickness of each composite specimen was measured (dry). For those specimens that were activated or wetted, the wet specimen weight was also measured prior to the test. Following each test, the weight of each specimen was recorded.

Test Measurements. The copper calorimeter was used as the principal measurement device in this test. However, instead of measuring time-to-pain and time-to-burn as dictated in ASTM F 1939, two different temperature rises were examined – the time to 19^{o}C rise and the time to 30^{o}C rise. For multi-layer composites, these temperatures roughly correlate to the time-to-pain and time-to-burn, respectively [6].

In addition to calorimeter measurements, two thermocouples were used for measuring heat exposures. The first thermocouple was placed on the outside of the specimen in direct contact with the outer surface of the shell material. The second thermocouple was placed on top of the cotton material layer. Both thermocouples were placed on the specimen in a manner as to not interfere with the calorimeter (see Figure 1).

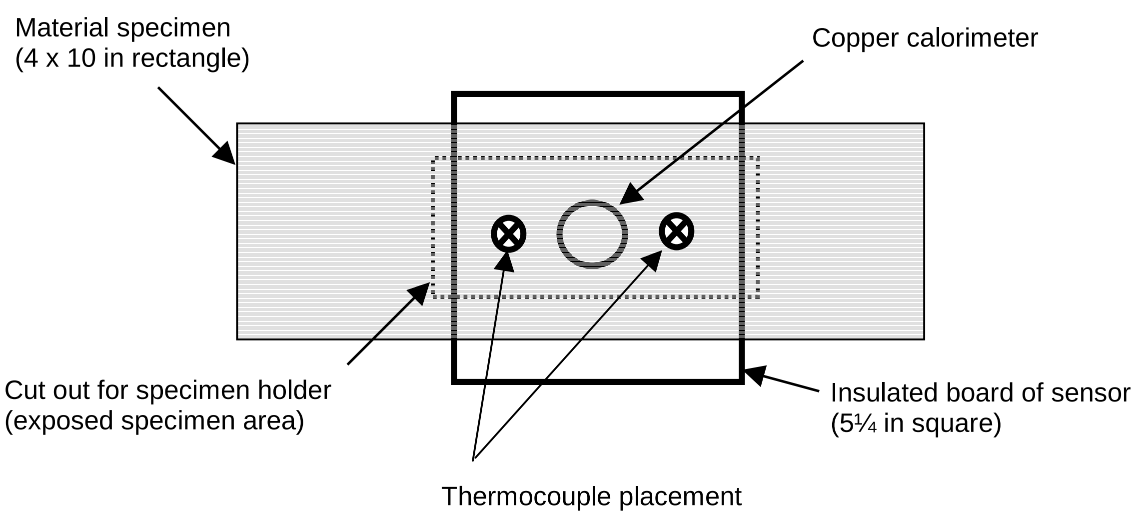

Figure 1- Orientation of Thermocouples in Testing

Test Conduct and Procedures. Each test was conducted for a length of approximately 7 minutes. This exposure period was established to ensure that mass transfer measurements were on the same basis. Following each test, each specimen was examined for any damage. (A series of codes were provided for rating the specimen during the test and following the exposure.) Table 1 provides a summary of test parameters and procedures.

Table 1 - Summary of Test Parameters

Test Methodology	ASTM F1939, *Standard Test Method for Radiant Protective Performance of Flame Resistant Clothing Materials*, 1999
Test Conditions	1. Exposure energy level – 0.1 cal/cm^{2}s 2. Exposure duration – 7 minutes
Measurements	• Thickness each specimen • Pretest dry weight cotton lining material for each specimen • Pretest dry weight each specimen • Pretest wet weight each specimen (for wet tests) • Post-test weight cotton lining material for each specimen • Post-test weight each specimen • Calorimeter response (temperature rise) • Thermocouple temperature measurement – externally placed on outer shell material surface • Thermocouple temperature measurement – placed on interior surface (between cotton lining material and innermost surface of specimen) • Visual observations of specimen condition following exposure
Test Materials	1. Hydroweave composite, dry 2. Hydroweave composite, activated 3. Standard composite, dry 4. Standard composite, liner wet (condition 1) 5. Standard composite, liner wet (condition 2)
Test approach	1. Calibrate the radiant test apparatus at 0.1 cal/cm^{2}s exposure. 2. Conduct preliminary tests without composite specimens. Test with cotton lining material and thermocouple placed on outside of cotton lining material. Conduct three replicates. 3. Test each dry composite in triplicate. Measure the pretest weights before exposure. Place a cotton lining material between each specimen and the sensor. Make the measurements described above. 4. Test the Hydroweave composite activated. To activate, take the Hydroweave portion of the composite and place in a washing machine. Subject to the rinse and spin cycle without any detergent. Concurrently, condition the liner portion of the standard composite in the same manner. Measure wet weight of specimens before testing. 5. For wet condition 2, subject liner portion of standard composite to immersion in room temperature water for 2 minutes, hang drying for 5 minutes, and blotting between AATCC paper for 10 minutes under 0.5 psi pressure. Measure wet weight of specimens before testing. 6. Following all tests, measure moisture transfer to cotton lining material without heat (as controls).

Results

Test results for all specimens tested are provided Appendix A. Thermocouple data were recorded by a datalogger and were saved as Excel files for each test (provided as plots for each group of experiments). Material condition observations were unremarkable. During the individual exposures, no specimen ignition occurred. Following the exposure, there were no reports of specimen break-open, melting, dripping, charring, embrittlement, or shrinkage.

Calorimeter Temperature Rise Data. Table 2 summarizes the times reported for calorimeter temperature rises of 19^{o}C and 30^{o}C, respectively, for each of the material composites and test conditions. The same data are shown graphically in Figure 2.

Table 2 – Summary of Calorimeter Temperature Rise Data

Material Composite	Wetness Condition	Avg. Thickness (mil)	Avg. Weight (g)		Time to 19^{o}C	Time to 30^{o}C
			Dry	Wet		
Cotton lining only	Dry	13	2.41	N/A	73.7	107.4
Hydroweave	Dry	140	21.70	N/A	225.4	355.4
Standard	Dry	138	17.60	N/A	202.9	332.2
Hydroweave	Activated	147	21.85	45.08	182.7	366.4
Standard	Condition 1	138	17.68	28.70	138.6	193.6
Standard	Condition 2	137	17.34	19.15	123.2	317.7

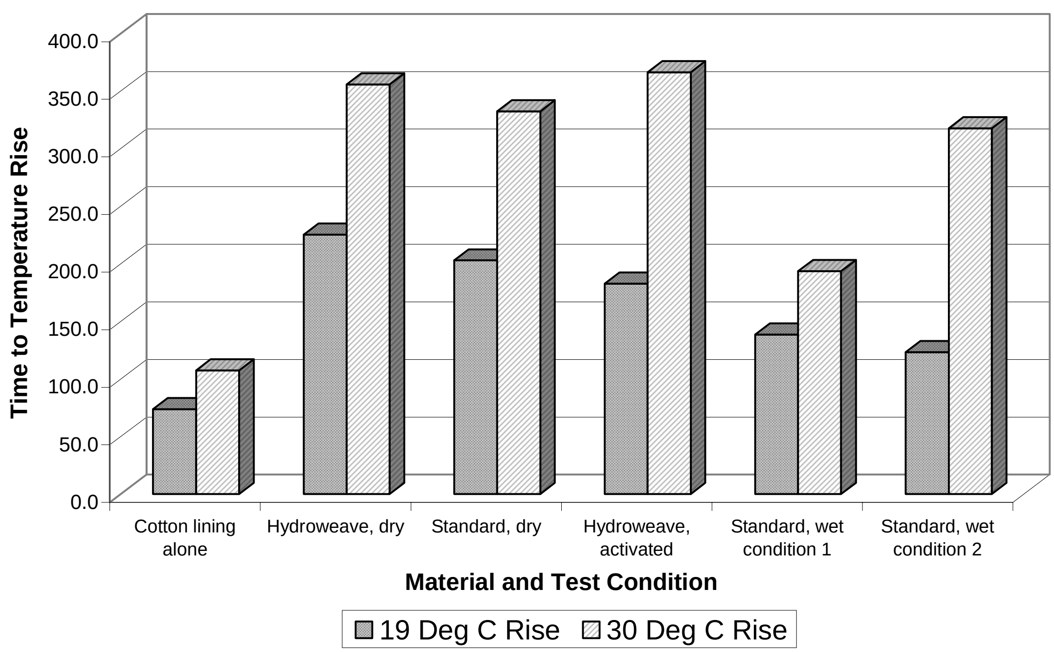

Figure 2 - Comparison of Calorimeter Temperature Rise Data

For the radiant heat flux used in this study, the longest time to a 30-degree temperature rise was achieved by the activated Hydroweave composite; however, there was a small decrease in the time for the 19-degree temperature rise between dry and activated composites. In comparison, the standard composite provided slightly lower temperature rise times compared to Hydroweave under wet conditions. Nevertheless, these decreases were more significant for comparing activated Hydroweave versus the standard composite under both wet conditions. Of interest was the fact that the lower level of moisture in the standard composite gave longer temperature rise times than the wet condition (2) that was associated with a more saturated liner.

Weight Change Data. Specimens were weighed before testing, after being wetted (for wet tests), and following testing. The cotton lining material was also weighed before and after testing to indicate moisture mass transfer through the material system. A summary of these data is provided in Table 3.

Table 3 – Summary of Material Specimen Weight Changes

Material Composite	Wetness Condition	Radiant Exposure	Avg. Initial Weight (g)	Weight Change (g)		
				Wet	Final	Cotton Lining
Hydroweave	Dry	Yes	21.70	N/A	-0.29	-0.03
	Activated	Yes	21.85	19.90	9.95	2.26
		No	22.46	20.22	18.43	1.42
Standard	Dry	Yes	17.60	N/A	-0.17	-0.02
	Condition 1	Yes	17.68	11.02	3.28	1.78
		No	17.47	10.86	8.09	2.22
	Condition 2	Yes	17.34	1.81	0.17	0.16
		No	17.25	1.79	1.34	0.25

These weight data provide useful information about the condition of the specimen. For example, the weight losses observed for the dry tests are most likely attributable to loss of intrinsic moisture in the material systems. For the tested composites, this represents approximately 1% of the total specimen weight.

Weight change information also demonstrates the amount of water weight gain for each type of composite and where the water goes after the radiant exposure. Corresponding “control” tests were conducted for each wet test where a composite specimen was set in the testing apparatus for the same 7-minute period but without radiant heat. The resulting weight gain by the cotton lining and loss of weight in the test composite specimen represent moisture transfer through absorption and evaporation. The evaporation of moisture from the entire test system (composite specimen plus cotton lining) was determined using a mass balance. Using the initial weight gain of the composite specimen after wetting, any mass not accounted for in either the composite specimen or the cotton lining was attributed to evaporation.

Figure 3 shows the overall weight gain due to wetting and disposition of moisture following the exposure period. The height of the bar indicates the total average moisture weight gain for the composite specimens for a given set of conditions. Each bar is then broken down into:

- Water retained in the composite
- Water absorbed by the cotton lining
- Water that evaporated from the system

The comparison of Hydroweave and the standard composite under wet condition 1 shows the relatively higher water absorption capacity of the Hydroweave material when both materials are subjected to similar wetting conditions. (Hydroweave demonstrated almost twice the absorption capacity.)

As would be expected, the water retained in the composite specimens is significant greater in ambient (pristine) exposures versus radiant heat exposures. During radiant exposures, there was also considerably more evaporation loss from the material system (composite plus cotton lining).

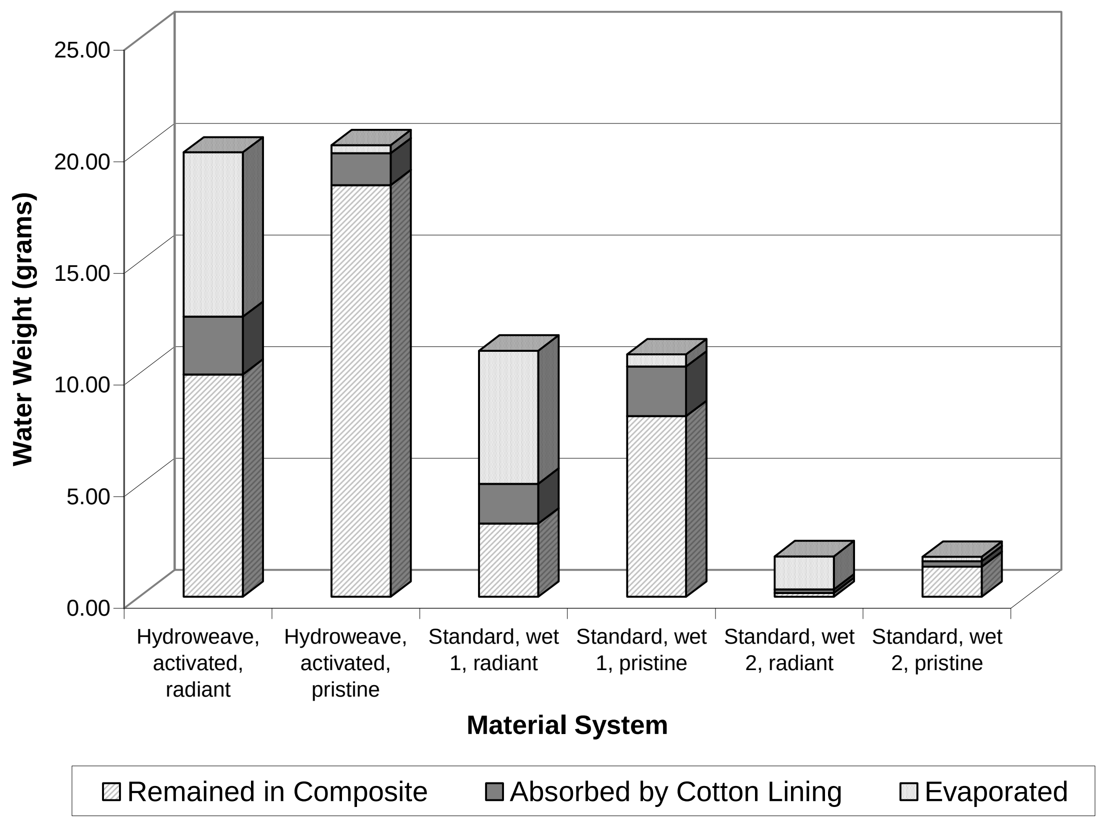

Figure 3 - Mass Balance of Moisture in Composite Specimens

The relative amount of evaporation was not consistent between composites or conditions. The Hydroweave composite showed less percent evaporation than the standard composite under both conditions. This may also be related to the even distribution of water absorptive polymer in the Hydroweave structure.

The results of interest are the respective weight gains for the cotton lining. The placement of a dry cotton lining next to the composite was expected to cause moisture transfer from the composite to the lining. With the application of heat, it was further expected that the rate of moisture transfer would increase with the increased energy of water molecules as heat is absorbed. The data show that the amount of water absorbed by the lining for the Hydroweave tests is greater for the radiant exposure as compared to the ambient test. However, the opposite trend is noted for the standard composite for both wet conditions.

Mass (moisture) transfer occurs because of differences in concentration. Moisture flows from high concentration areas into low concentration areas. Given that the cotton lining is initially dry and the composite is wet, moisture will flow from wet to dry. The same is true for the exterior air space, which is relatively drier than the composite. The differences between the two sets of results are likely explained by the difference in the configuration of the materials. Whereas the breathable film is adjacent to cotton lining for the Hydroweave composite (with the wetted batting on the exterior side of the film), the opposite orientation exists for the standard composite (cotton lining, wetted batting, and film). These configurations are illustrated in Figure 4. The respective heating of both composites created different moisture concentration gradients that affected the amount of moisture absorption by the cotton lining.

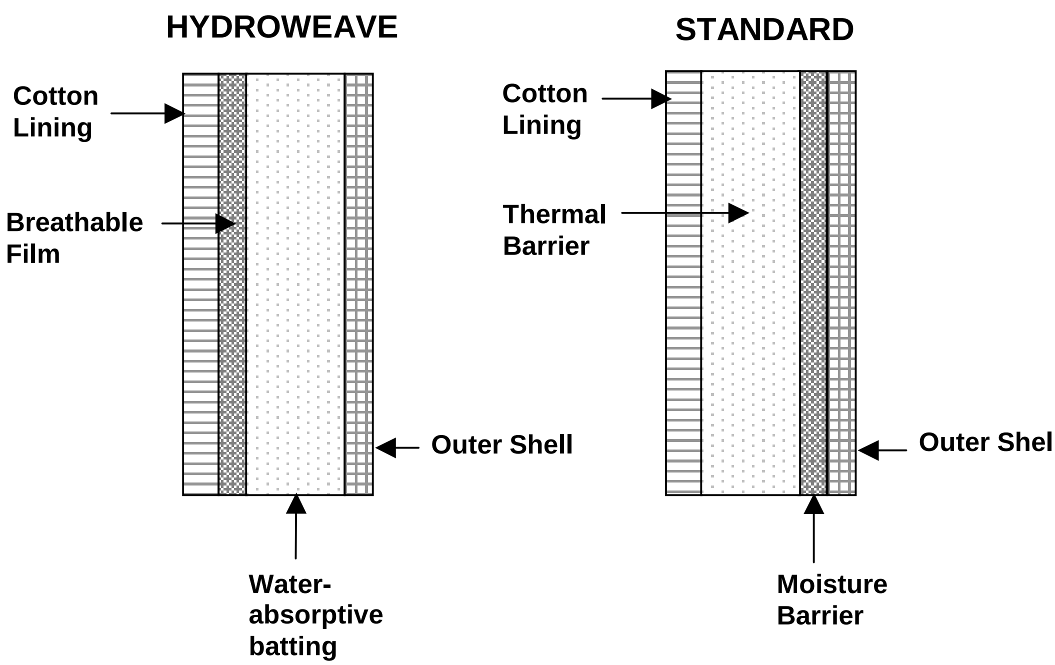

Figure 4 – Composite Configurations

Thermocouple Temperature Data. Other temperature data were acquired using thermocouples placed on the outer surface of the composite specimen and against the inner surface of the composite (between the innermost layer of the composite specimen and the cotton lining). Unlike calorimeter temperature data that provide the temperature of a copper slug that absorbs transferred heat, thermocouples provide nearly instantaneous temperature measurements. These measurements are provided in Figures 5 and 6.

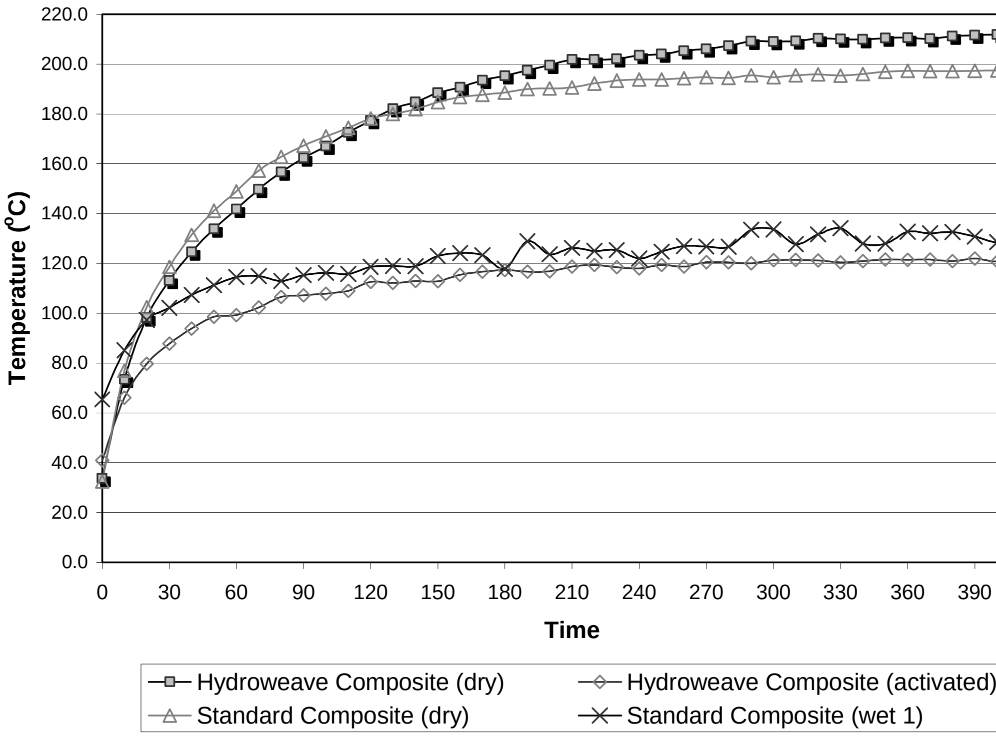

Figure 5 - Thermocouple Data for Outer Surface of Composite

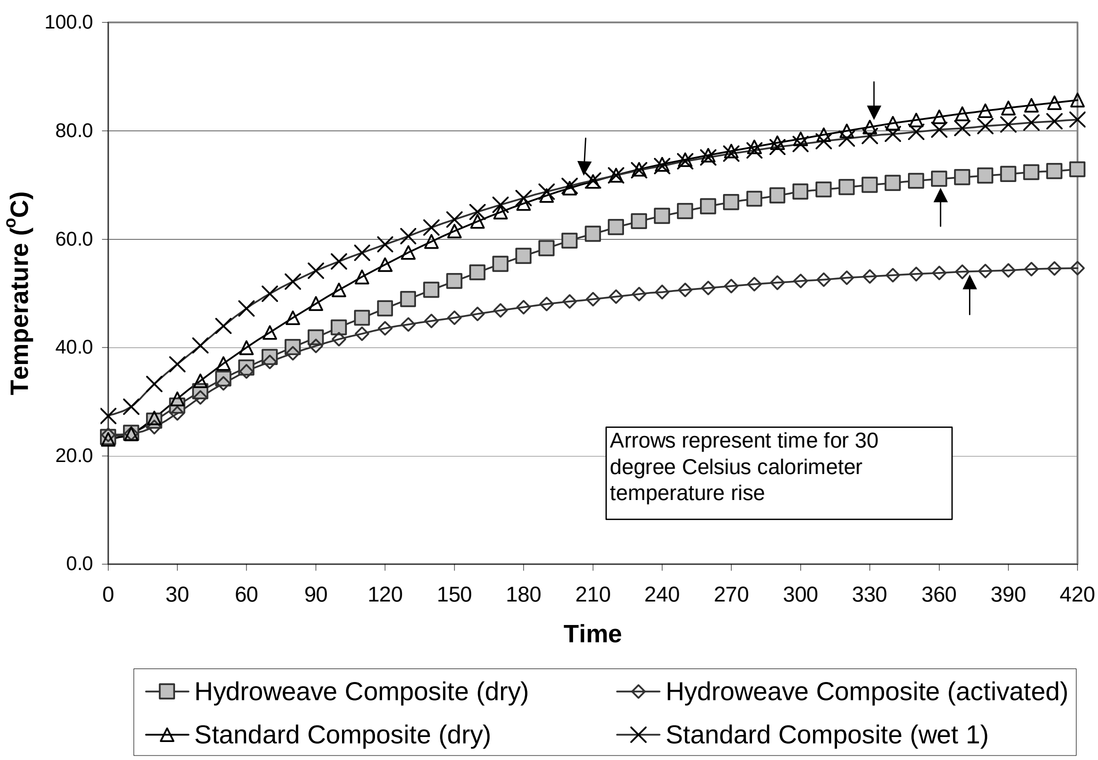

Figure 6 - Thermocouple Data for Inner Surface of Composite

Figure 5 shows the outside surface temperatures for two composites under both dry and wet conditions. Lower temperatures were observed for the activated Hydroweave and wet standard composites due to the moisture evaporation from shell fabric of each composite. These effects were significant in reducing the outside surface by 80^{o}C.

The plots of average inner surface temperatures of each composite are provided in Figure 6. The temperature plots for the standard composite are very similar under both dry and wet conditions. However, much lower inner surface temperatures were observed with the Hydroweave composite, particularly for the activated composite samples. Thermocouple temperatures are reported at selected times in Table 5.

Table 5 – Temperature of the Composite Inner Surface at Selected Times

Composite	**Wetness Condition**	**Average Temperature (^{o}C)**							**Temp. at 30^{o}C Rise***
		60	**120**	**180**	**240**	**300**	**360**	**420**	
Hydroweave	Dry	36.3	47.2	56.9	64.3	68.8	71.1	72.9	70.9
Standard	Dry	39.2	53.2	64.4	71.9	76.8	80.9	84.0	80.8
Hydroweave	Activated	35.6	43.5	47.4	50.2	52.3	53.8	54.7	53.9
Standard	Condition 1	47.2	59.0	67.6	73.5	77.6	80.2	82.1	69.3
Standard	Condition 2	Data not available							

* Thermocouple temperature at time when calorimeter shows 30^{o}C temperature rise

A comparison of calorimeter data and the thermocouple response is provided in the last column. The temperature measured by the thermocouple corresponding to the time for which the calorimeter measured a 30^{o}C temperature rise shows large differences in the results between composites and test conditions. These data suggest a difference in heat transfer mechanisms. The relatively higher temperatures for the standard composite can be explained by faster rates of heat transmission. The difference between activated or wet and a dry condition is due to the heat carried by moisture itself that is absorbed in the cotton lining. Nevertheless, the data show the moisture for the activated Hydroweave composite carries less heat.

Discussion

There are competing heat transfer mechanisms at the level of radiant heat exposure used in this study (0.1 cal/cm^{2}s). The presence of water in the material system fills air voids and provides conductive pathways through the individual material layers. On the other hand, the extra mass of water in the material will provide additional heat absorption capacity. In the case of Hydroweave, the material is able to provide a relatively high level of evenly distributed water absorption capacity and thus allows for greater heat absorption. The liner of the standard composite has a lower water absorption capacity and retains water differently that the batting in the Hydroweave composite.

Prior testing has shown that the contribution of moisture in materials provides a varied effects on thermal insulation depending on the material characteristics and type and duration of heat exposure (among other factors) [7]. For example, thermal protective performance (TPP) testing of the Hydroweave composite yields a TPP rating of 47 when dry and a TPP rating >100 when activated. The comparable standard composite (as used in this study) provides a TPP of approximately 40 dry and a TPP of 27 when the liner alone had been wetted using procedures analogous to Wet Condition 2. The TPP exposure represents a relatively severe (2.0 cal/cm^2s), but short-term exposure.

At the longer, but lower radiant heat exposure used in this study, less dramatic changes in thermal insulation were observed for the Hydroweave system. However, the same trend of lower insulation for a wet liner in the standard composite was demonstrated. Even in the circumstance where a lesser amount of water is introduced into the standard composite, the Hydroweave composite provides longer insulation.

Results for measuring moisture transfer through the system are consistent with the expectations given the differences in composite configuration and exposure conditions. While the cotton lining provided a convenient means for measuring moisture, it may have provided an effective environment for mass transfer. Typically, the microenvironment under clothing could be humid and under clothing may contain levels of moisture due to sweating [8,9].

The comparison of calorimeter and thermocouple responses points out the differences between methods for measuring heat transfer in material, but did yield important clues to composite differences. Calorimeters are intended to simulate body skin response to heat by providing a mass for absorbing thermal energy. In contrast, thermocouples provide rapid response and do not correlate with burn injuries. While calorimeters are more representative of skin responses, calorimeters do not accurately model all body mechanisms for dissipating heat (such as by increased blood flow through the skin) [10]. In this study, lower thermocouple temperatures were reported for Hydroweave tests at times when the calorimeter registered a 30^oC temperature rise. This difference indicates lower overall heat transfer rates for the Hydroweave composite. It also demonstrates that the moisture transfer from the standard composite to the cotton lining has more associated heat than Hydroweave.

Temperature by itself is not an indication of burn time, but data have been established for skin tolerance in contact with surfaces at specific temperatures [4]:

- At 60^oC (140^oF), pain is felt and initial tissue damage occurs.
- At 72^oC (160^oF), a second-degree burn will occur on 60 seconds of contact time.
- At 83^oC (180^oF), a second-degree burn will occur on 30 seconds of contact time.
- At 100^oC (212^oF), a second-degree burn will occur on 15 seconds of contact time.

Using the information provided by the thermocouple measurements at the inner surface of the tested composites, the activated Hydroweave composite never reaches 60^oC within the 7-minute exposure period. The inner surface of the dry Hydroweave composite rises to 73^oC only at the end of the exposure time but this temperature occurs nearly one-minute after sufficient heat energy is transferred through the composite to cause a second-degree burn injury. For the standard composite, higher temperatures are sustained earlier and consequently closer in time to the calorimeter measurement of burn injury (as measured by the 30^oC temperature rise.)

Conclusions

Under the conditions that have been used in this study, no detrimental effects have been observed for an activated Hydroweave composite as would be represented in a clothing system. In fact, the addition of moisture provides a slight enhancement of thermal protection under a relatively moderate radiant heat exposure. In comparison, a composite representing conventional material technology shows decreases in thermal insulation when moisture is added.

Based on the measurement of moisture transfer, calorimeter temperature response, and thermocouple temperature response, there is no evidence of excessive heat transfer through the Hydroweave composite resulting from elevated temperature water vapor or steam. The relatively high and evenly distributed water-absorbing capacity of Hydroweave prevents rapid temperature rises in the material and contributes to longer protection times.

The testing in this study represents only one set of conditions. As with all laboratory work, caution should be exercises in generalizing these test results for all exposure conditions. Supervisors and other persons responsible for employee safety should take into account the specific hazards and circumstances of their own situation in applying these results.

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