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Investigation and Correlation of Manikin and Bench-Scale Fire Testing of Clothing Systems

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The US Army currently has five flame/thermal protective clothing systems to provide protection for soldiers against fire hazards. The protective performance of these clothing systems against burn injuries was investigated in full-scale manikin tests. The protective performance of fabric layers of these clothing systems was also examined in bench-scale tests. In addition, air gap thicknesses and distributions of the five clothing systems were determined by using a three-dimensional laser scanning technique. In this paper, test conditions of the manikin and bench-scale tests are compared, and the test results are correlated in light of the air gap measurements. The behavior of individual sensors on the manikin with similar test conditions to those of bench-scale tests are compared with the bench-scale tests. It is found that if the air gap distribution of a clothing system is known, bench-scale tests could provide useful information for full-scale performance, especially bench-scale tests with zero air gap measurements. Published in 2002 by John Wiley & Sons, Ltd.

INTRODUCTION

Flame/thermal threat is one of the hazards that the US soldiers are exposed to on the battlefield.[1,2] The heat flux level of the threat varies and depends on the type of weapon.[3] Threat analysis shows that the majority of battlefield fire hazards are in the vicinity of a fire-level heat flux of 2 Cal/cm^2-s; much higher heat flux levels are seldom directly encountered, and much more difficult and often impractical to provide protection against.[3] Therefore, 2 Cal/cm^2-s has been chosen as the threshold value protection for soldiers. Nomex fabric is used presently for military clothing systems to provide fire protection. The five current Nomex-based military protective clothing configurations are shown in Table 1. Single-layer systems 1 to 3 provide less fire protection than the multi-layer systems 4 and 5, which are used in confined, more hazardous environments, such as in a tank or a cockpit. The performance of the complete full-scale clothing systems of the five configurations was evaluated in terms of percentage body burn injuries using the ASTM Standard Manikin Test Method F 1930-99.[4,5] This Test Method is time consuming and expensive. A bench-scale test apparatus[6–9] was also used to investigate the skin burn injuries of the five clothing configurations. Bench-scale tests are simpler, quicker and less costly. However, currently there is a lack of understanding and correlation between full-scale and bench-scale fire protective clothing tests. The influence of air gaps on bench-scale tests,[10] and the air gap distribution and its effects on full-scale manikin tests are poorly understood. Because of the importance of the air gap effect on the heat transfer through clothing layers onto the skin, the size and distribution of the air gaps of the five clothing configurations were investigated using a three-dimensional (3-D) laser scanning facility.[11,12] This paper presents: (1) the results from the manikin fire tests, the bench-scale tests and the 3-D scanning, and (2) the correlation of the two scale test results in terms of the air gap measurements.

EXPERIMENTAL INVESTIGATION

Manikin tests

Details of the experimental setup and methods on the manikin flame resistant clothing tests, the 3-D scanning technique, and the bench-scale fire tests have been reported previously.[4,6,11] They will be only briefly described here. The ASTM Manikin Test[4] is commonly used to evaluate the skin burn injury protection provided by full-scale fire protective clothing systems. The physical size of the manikin is a man's 40 Regular. There are 124 skin simulant heat sensors evenly distributed on the surface of the manikin as shown in Plate 1. For convenience, the sensors are grouped into five regions as shown on the front and on the back of the manikin. Eight propane gas burners impinge gas flames on the manikin generating an average incident surface heat flux of 2 Cal/cm^2-s. Due to the initial transient gas flow, the minimum flame exposure time is 3 s. During a test, the full-scale clothing system is put on the manikin and the gas burners are turned on with the desired flame

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Table 1. Five configurations of current military fire protective clothing systems (A, aviators, B, tankers)

Configuration	1A	2A	3A	4A	5A
Underwear	T shirt/Briefs	Cotton	Nomex	Nomex	Nomex
Coat/Trousers	X	X	X	X	X
Bib overall					X
Jacket CW				X	X
Configuration	1B	2B	3B	4B	5B
Underwear	T shirt/Briefs	Cotton	Nomex	Nomex	Nomex
CVC coverall	X	X	X	X	X
Bib overall					X
Jacket CVC				X	X

exposure time. The heat sensor temperatures are used to calculate the skin burn injury at each sensor. These calculations are then used to predict the percentage of the body surface that has second- and third-degree burns. The test results of the manikin tests are typically percentage body burns.

Air gap measurements

As shown previously,[12] due to the unique human body shape and the drape of a clothing system, there is a general pattern of air gap distribution between the clothing system and the human body. The air gap distributions of clothing configurations 1, 3, 4 and 5 were investigated using the 3-D laser scanning technique.[11] A same size 40R manikin previously used for fire testing was used for the air gap investigation. The 3-D scanning gives the total distance between the surface of the manikin (body skin) and the outer surface of the clothing system. Subtracting the total thickness of the clothing layers from the measured total distance provides the true air gap thickness. For a single fabric layer above the underwear, such as configurations 1 and 3, this calculated air gap thickness is basically the total air layer thickness between the skin and the outer fabric. For multi-layer fabrics above the underwear, such as configurations 4 and 5, the calculated air gap thickness represents the air gaps within the fabric layers and the air gap next to the skin.

As mentioned earlier, there are 124 heat sensors on the manikin. Due to the flexible joints between the two arms and the torso (needed for easy donning of clothes), reliable air gap measurements were difficult to obtain on the two arms and hands, especially the areas around the armpit. Consequently, air gap measurements of the areas on approximately 75 heat sensors, excluding the arms and hands, were obtained.

Bench–scale tests

A bench-scale test apparatus was designed, constructed and used to investigate the skin burn injury protection of the five clothing configurations.[6–9] The apparatus consists of an infrared heater radiating high intensity heat vertically downward to a 12.7 cm × 17.8 cm fabric sample. The fabric sample is positioned horizontally on a 10.2 cm square × 2.54 cm thick skin simulant slab made from the same composite material as that of the manikin. The slab is supported by a metal frame which can move the slab vertically relative to the radiant heater for a desired heat flux level. At a distance of 9 cm from the radiant heater, 84 kW/m^2 (2.0 Cal/cm^2-s) is obtained. A skin simulant heat sensor is positioned at the center of the slab to measure first- and second-degree skin burn injuries. A metal spacer is used to position the fabric above the slab if an air gap is desired. Tests were conducted with zero and 6.35 mm air gaps. A water-cooled shutter is positioned between the radiant heater and the fabric to provide the desired heat exposure time on the fabric.

RESULTS AND DISCUSSION

Approach

Test results of the manikin tests, the bench-scale tests and the 3-D scanning have been reported separately.[5,6–9,11–12] Emphasis here will be mainly on the comparison between the manikin and bench-scale tests in light of the 3-D scanning air gaps measurements. A full-scale clothing system comprises a highly 3-D geometry and clothing details. Pocket flaps, collars and fabric edges are more susceptible to ignition than the other flat areas of the clothing system. The confined space between the legs enhances heat transfer on the fabric in that area. Fabric folds, seams and wrinkles affect fabric thicknesses. These full-scale clothing characteristics, along with the variable air gap thickness around the body, makes the heat transfer process highly complicated. In addition, the non-uniform incident heat flux distribution on the manikin due to the convective heat transfer from the eight gas burners further makes the one-dimensional (1-D) bench-scale test simulation difficult. In view of all these differences between the 3-D full-scale manikin tests and the 1-D bench-scale tests, comparing the latter to the overall test results of the former is almost impossible and has questionable meaning. Therefore, it is more meaningful first to examine the details of the temperature response and burn injury prediction of the heat sensors individually and as groups on the manikin, and see how they compare with those of the bench-scale tests.

Incident heat flux comparison

Before discussing the detailed results of the heat sensors, it is beneficial first to examine the incident heat flux distribution on the manikin. Plate 2 shows the 4 s heat flux calibration profiles from the eight gas burners on the 124 heat sensors of the nude manikin. The profiles are presented in four groups as shown in Plate 2 for the ten regions shown in Plate 1. It is seen that, due to the finite time for the gas flow, it takes longer than 1 s for the heat flux to become steady. During the initial transient, some heat flux values are higher than 4.0 Cal/cm^2-s, particularly on the top areas of the head and chest. Even during the steady time period, there is a deviation of about $\pm$ 0.5 Cal/cm^2-s from the average 2 Cal/cm^2-s value. After the gas turn-off at the end of the 4 s, heat flux values still persist for over 1 s due to the residue gas flow. Comparing these heat flux profiles to the well-defined steady 2 Cal/cm^2-s radiant heat flux in the bench-scale tests shows the challenge and difficulty in matching the incident heat flux values between the two scale tests. With the exception of a few heat sensors, the majority of the heat sensors are exposed to heat flux values either higher or lower than 2 Cal/cm^2-s as one will see later. Another difference in the test condition is the initial environmental temperature, about 23°C for the bench-scale tests and about 30°C for the manikin tests, higher than 23°C due to the residual heat from the previous test for repeated manikin tests. The higher initial temperature for the manikin tests is most likely due to the confined sealed chamber nature of the tests, and has an effect of enhancing skin burn injuries.

General heat sensor temperature comparison

As presented previously,[12] due to the unique body shape and draping of clothing systems, there is a general air gap distribution around the body, tight with small air gaps on the shoulders, large air gaps around the abdomen, and more randomly distributed small and large air gaps on the arms and legs. The overall air gap measurements for the chest, abdomen and leg areas (excluding arms and head, Plate 1) are shown in Fig. 1. Because of the evenly distributed heat sensor locations on the manikin, the percentage of total number of sensors also represents the percentage of body surface area (excluding head and arms). As expected, multi-layered clothing systems of configurations 4 and 5 trap more air than single-layered clothing systems of configurations 1 and 3. The commonly used air gap thickness of 6.35 mm (1/4 inch) in bench-scale tests covers about 30% of the body surface for configurations 1 and 3, 20% for configuration 4, and 5% for configuration 5. Zero air gap areas occupy less than 15% for all configurations. These are important information and useful guidelines for bench-scale tests as one will see later.

Plates 3, 4 and 5 show the comparison of the heat sensor temperature profiles between the manikin and bench-scale tests for clothing configurations 1A, 3A and 5A. Due to the nature of the air gap distributions, the comparison is made for the ten body regions shown in Plate 1. In all these figures, the initial environmental temperature difference at time zero mentioned earlier is clearly shown, especially in Plate 5. The slow temperature response due to the initial 1 s incident heat flux delay for the manikin tests is also evident. In contrast, the rapidly applied incident radiant heat flux in the bench-scale tests results in a fast temperature rise as shown in Plates 3 and 4. The thermal protection of slower temperature response provided by the 6.35 mm air gap in the bench-scale tests is also seen in these figures. The effect of the air gap distributions on the temperature response of the chest and abdomen areas can be seen in Plates 3 and 4. Due to the larger air gap thicknesses in the latter, their temperatures are practically all below those of the bench-scale tests (with zero and 6.35 mm air gaps), whereas the small air gap chest areas result in the overlap of the temperatures of the manikin and the bench-scale. More detailed temperature and burn injury comparisons for these two areas will be given later. For the leg areas with random air gap distributions, the bench-scale temperatures also fall within those of the manikin. For the head area, no protection was provided for the face (sensors 11 and 12), which results in their high temperature rises. For configuration 5A (Plate 5), since the fabric layers provide most of the fire retardancy, the behavior of the temperature difference for the manikin and bench-scale between the chest and abdomen areas is similar. For the manikin tests, temperatures still rise after the gas burners are turned off, except for the abdomen area where larger air gaps provide additional protection. This is most likely due to the slow heat loss to the environment because of the sealed room, a test condition that is quite different from the bench-scale tests.

Detailed heat sensor temperature and burn injury comparison

Further insight into the correlation between the manikin tests and the bench-scale tests is obtained by comparing the latter with those heat sensors (group 1) on the manikin that have similar test conditions, i.e. very small air gaps close to zero and incident heat flux close to 2 Cal/cm^2-s. In contrast, heat sensors (group 2) that have very large air gaps and incident heat flux close to 2 Cal/cm^2-s are also of interest for comparison. It is anticipated that group 1 sensors should show better agreement with the bench-scale tests than group 2 sensors. Based on the 3-D air gap measurements and the heat flux calibration (Plate 2), six heat sensors are found for each group and their locations are shown in Plate 1. The small air gap group is mainly located around the shoulder. The large air gap group is mainly on the front abdomen area. Details of the sensor numbers and their corresponding air gap thicknesses and incident heat flux levels are shown in Tables 2 and 3. Comparison of the temperature profiles of these sensors with those of the bench-scale tests are shown in Figs 2 and 3. In both figures, for the large air gaps sensors, their temperatures are lower than those of the bench-scale tests whereas the temperatures of the bench-scale tests are within the temperature range of the small air gap sensors. If one increases and matches the initial environmental temperature for the bench-scale tests to that of the manikin tests and assumes the temperature profiles would increase by the same amount, and also delays and

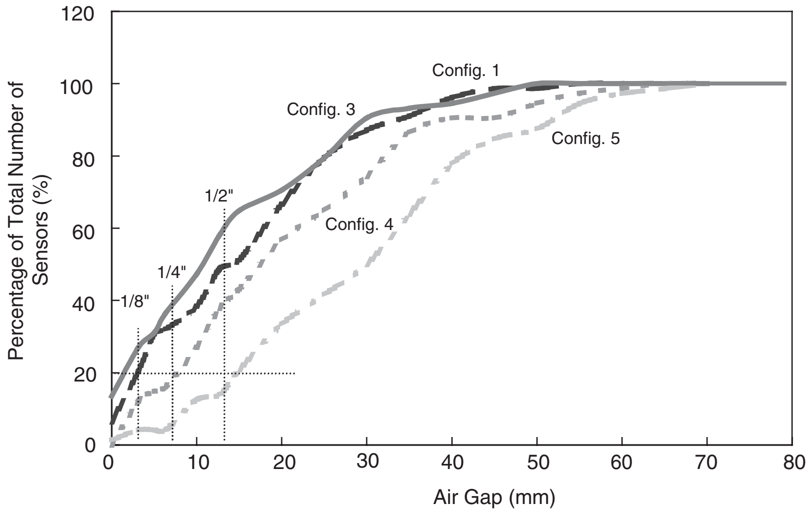

Figure 1. Air gap distribution as a function of percentage of total number of sensors for four clothing configurations.

Table 2. Comparison of burn injury prediction for clothing configuration 1A between manikin and bench-scale tests for heat sensors with small or large air gaps and approximately 2 Cal/cm^2-s incident heat flux

Test burn time (s)	Sensor number and location	Manikin data: Air gap thickness (mm)	Heat flux (cal/cm^2 s) max/min	Burn injury time (s)	Bench-scale data: Zero spacing burn injury time (s)	6.3 mm spacing burn injury time (s)
Small air gap						
3	61—front chest	0	2.62/2.18	No[a]	No	–
4				14.7, No / No / No	No	–
6				8.8, 9.6[b]	7.6, 8.2[b]	–
3	62—front chest	0	2.25/1.74	No	No	–
4				No	No	–
6				No	7.6, 8.2	–
3	63—front chest	1.7	1.98/1.92	No	No	–
4				No	No	–
6				10.1, 11.0	7.6, 8.2	–
3	74—front chest	3.5	2.15/1.88	No	No	–
4				No	No	–
6				No	7.6, 8.2	–
3	79—front abdomen	2.8	2.02/1.78	No	No	–
4				No	No	–
6				No	7.6, 8.2	–
3	98—rear chest	0	2.20/1.78	No	No	–
4				7.9, 10.9 / No / No	No	–
6				8.1, 8.8	7.6, 8.2	–
Large air gap						
3	71—front abdomen	17.2	2.03/1.78	No	–	–
4				No	–	–
6				No	–	No
3	76—front chest	30.2	1.90/1.75	No	–	–
4				No	–	–
6				No	–	No
3	77—front chest	35.4	2.20/2.02	No	–	–
4				No	–	–
6				No	–	No
3	78—front abdomen	21.4	2.15/1.78	No	–	–
4				No	–	–
6				No	–	No
3	89—front abdomen	18.7	1.95/1.70	No	–	–
4				No	–	–
6				No	–	No
3	120—rear right leg	39.6	2.10/1.94	No	–	–
4				No	–	–
6				No	–	No

[a]No burn injury.
[b]2nd degree burn, 3rd degree burn for manikin tests; 1st degree burn, 2nd degree burn for bench–scale tests.

Table 3. Comparison of burn injury prediction for clothing configuration 3A between manikin and bench-scale tests for heat sensors with small or large air gaps and approximately 2 Cal/cm^2-s incident heat flux

	Manikin data				Bench-scale data	
Test burn time (s)	Sensor number and location	Air gap thickness (mm)	Heat flux (cal/cm^2 s) max/min	Burn injury time (s)	Zero spacing burn injury time (s)	6.3 mm spacing burn injury time (s)
Small air gap						
3	61—front chest	0	2.62/2.18	No	No	–
4				No	No	–
6				9.4, 10.6 / 11.1, 13.4 / 13.1 , 16.3	No	–
3	62—front chest	2.1	2.25/1.74	No	No	–
4				No	No	–
6				30, No / No / 14.4, 24.9	No	–
3	63—front chest	0	1.98/1.92	No	No	–
4				No	No	–
6				13.7, 16.4 / No / No	No	–
3	74—front chest	0	2.15/1.88	No	No	–
4				No	No	–
6				22.9, No / 20.9, No / No	No	–
3	98—rear chest	0	2.20/1.78	No	No	–
4				21.1, No / No / No	No	–
6				10.4, 12.9 / 9.1, 10.4 / No	No	–
3	116—rear abdomen	1.0	2.25/1.96	No	No	–
4				No	No	–
6				No	No	–
Large air gap						
3	42—front left leg	46.3	2.30/1.85	No	–	–
4				No	–	–
6				No	–	No
3	51—front right leg	24.9	2.08/1.92	No	–	–
4				No	–	–
6				No	–	No
3	71—front abdomen	23.5	2.03/1.78	No	–	–
4				No	–	–
6				No	–	No
3	76—front chest	33.2	1.90/1.75	No	–	–
4				No	–	–
6				No	–	No
3	77—front chest	33.5	2.20/2.02	No	–	–
4				No	–	–
6				No	–	No
3	120—rear right leg	29.8	2.10/1.94	No	–	–
4				No	–	–
6				No	–	No

shifts the time zero by 1 s as the manikin temperature profiles do, the resulting temperature profiles will be those shown in Figs 4 and 5. It is seen that now the agreement for the small air gap tests is even better and the correlation for the large air gaps becomes worse. These findings and comparisons clearly show the importance of air gaps on skin temperature response and their influence on the bench-scale tests for correlation with manikin tests. Another observation from Figs 2 and 3 is that due to the confined non-ventilated environment of the manikin tests, temperatures keep on increasing for a certain time period after the gas burners are turned off and the subsequent temperature drops are much slower than those of the bench-scale tests. These differences result in a higher tendency for burn injuries in the manikin tests than the bench-scale tests.

From the temperature profiles in Figs 2 and 3 first- and second-degree burn injuries were calculated for the bench-scale tests, and second- and third-degree burn injuries for the manikin tests. For completeness, all four burn injury times are shown in Tables 2 and 3. For the manikin tests, three tests were conducted for the same test condition; all three test results are presented in the two tables. Due to the various characteristics pertaining to full-scale clothing systems in the manikin tests discussed earlier, and the different incident heat flux profiles between the manikin and bench-scale tests, exact correlation is not expected. Instead, qualitative comparison and correlation of the second-degree burn injury time in light of the air gaps are sought. For the small air gap tests of configuration 1A in Table 2, the zero air gap tests of the bench-scale correlate better with the manikin tests than the 6.3 mm air gap tests. In some tests, the second-degree burn injury times are quite close, i.e. the 6 s tests for sensors 61 and 98. On the other hand, for the large air gap tests, both the 6.3 mm bench-scale tests and the manikin tests show no burn injuries but the zero air gap tests show burn injuries for the 6 s tests. For configuration 3A in

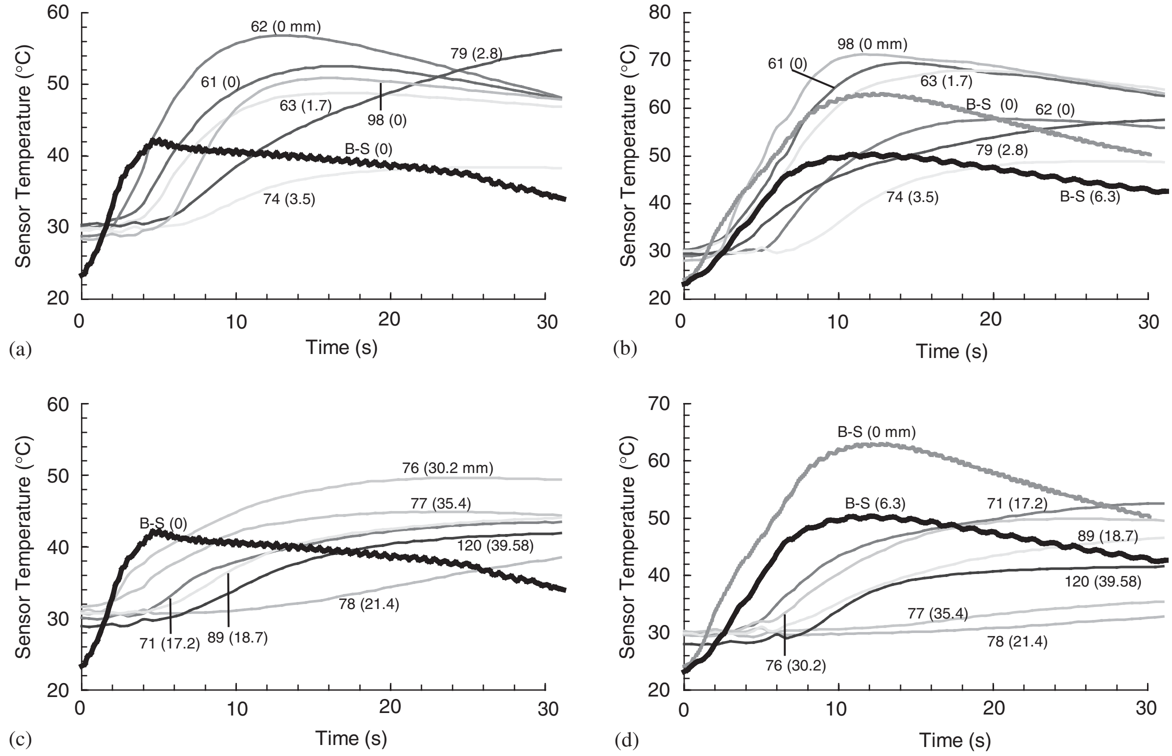

Figure 2. Heat sensor temperature comparison for clothing configuration 1A between manikin and bench-scale tests for heat sensors with approximately 2 Cal/cm^2-s initial incident heat flux: (a) 4 s tests, small air gaps; (b) 6 s tests, small air gaps; (c) 4 s tests with large air gaps; (d) 6 s tests with large air gaps; 62 (0 mm) = sensor 62 with zero air gap, etc; B-S = bench-scale.

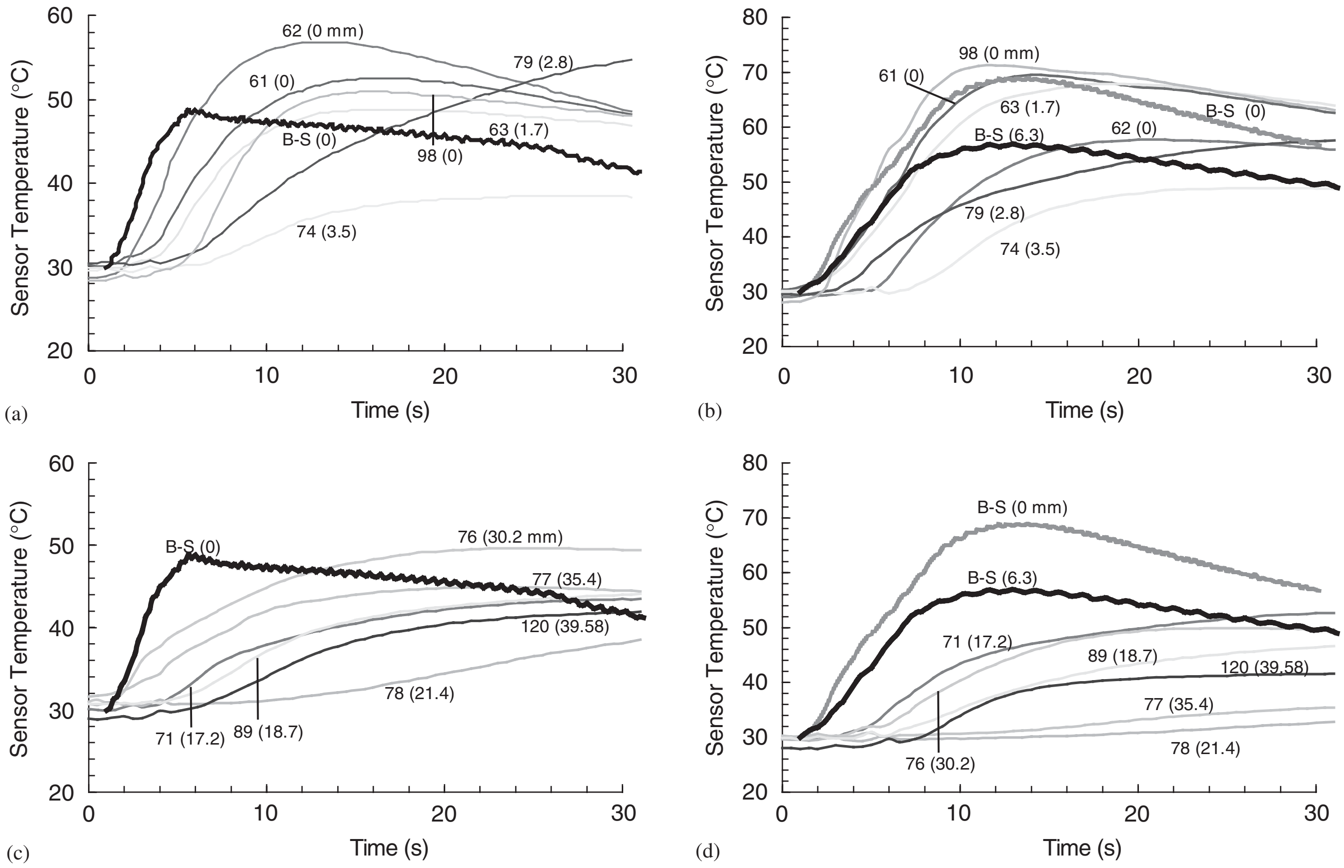

Figure 3. Heat sensor temperature comparison for clothing configuration 3A between manikin and bench-scale tests for heat sensors with approximately 2 Cal/cm^2-s: a–d; same as Fig. 2.

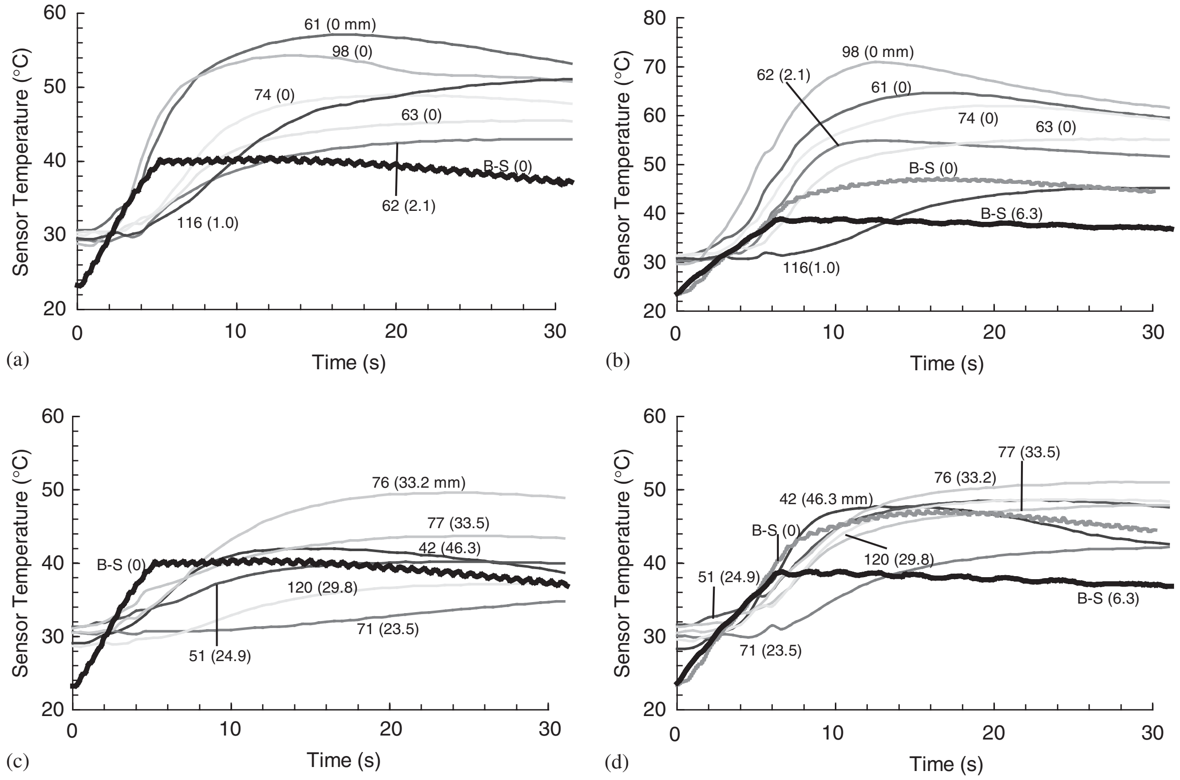

Figure 4. Same as Fig. 2 except time zero and initial sensor temperature of the bench-scale tests have been shifted to match those of the manikin tests.

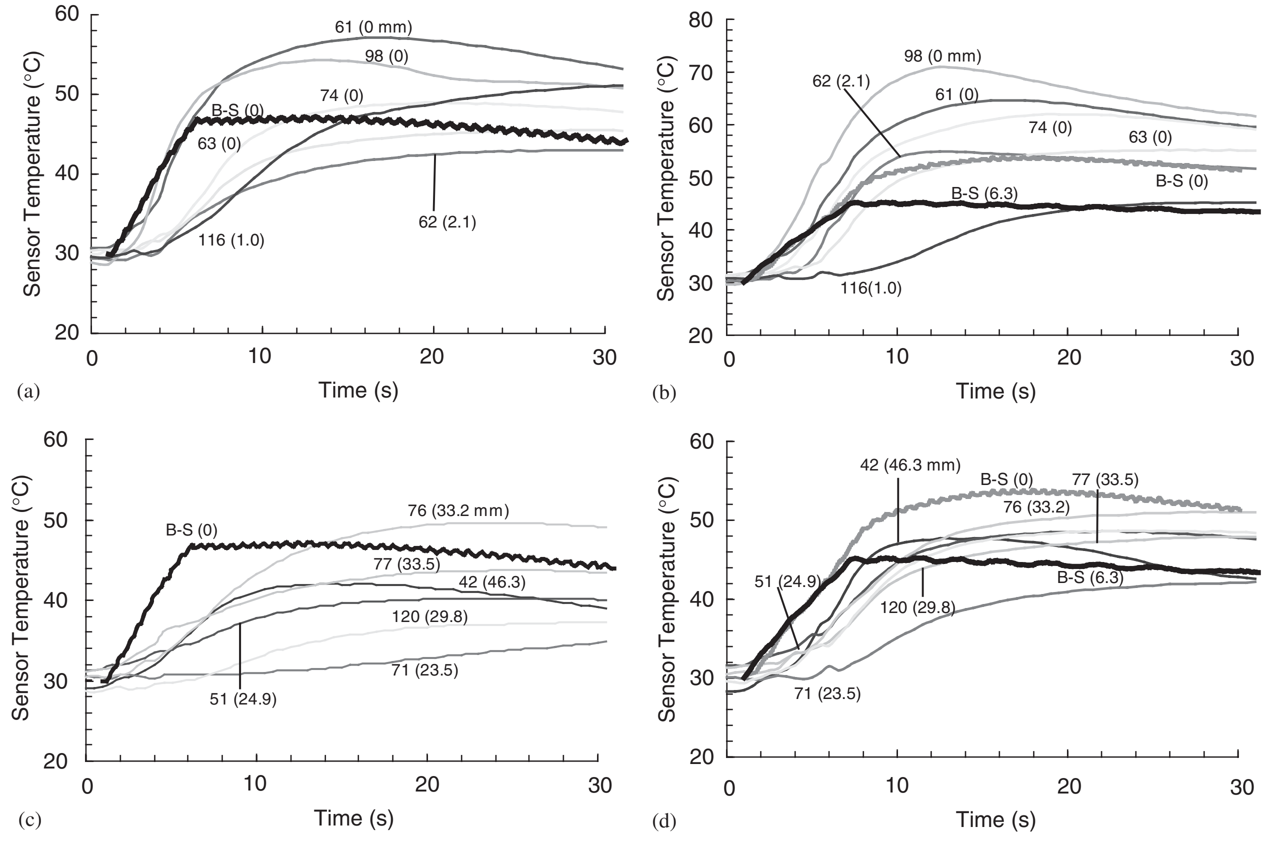

Figure 5. Same as Fig. 3 except time zero and initial sensor temperature of the bench-scale tests have been shifted to match those of the manikin tests.

Table 4. Comparison of burn injury prediction for clothing configuration 1A between manikin and bench-scale tests for heat sensors in the leg area

Test burn time (s)	Sensor number and location	Manikin data: Air gap thickness (mm)	Manikin data: Heat flux ($cal/cm^2 s$) max/min	Manikin data: Burn injury time (s)	Bench-scale data: Zero spacing burn injury time (s)	Bench-scale data: 6.3 mm spacing burn injury time (s)
Outside leg						
3	35—front left leg	27.8	2.32/1.92	No	No	–
4				6.9, 7.7	No	–
6				7.2, 7.4	7.6, 8.2	No
3	47—front right leg	9.3	2.29/1.68	No	No	–
4				No	No	–
6				9.6, 12.4	7.6, 8.2	No
3	51—front right leg	11.6	2.08/1.92	No	No	–
4				12.9, No	No	–
6				8.4, 9.1	7.6, 8.2	No
3	87—front left leg	14.2	2.08/1.48	No	No	–
4				No	No	–
6				No	7.6, 8.2	No
3	124—rear right leg	20.58	2.12/1.83	No	No	–
4				No	No	–
6				11.1, 15.0	7.6, 8.2	No
Middle leg						
3	120—rear right leg	39.58	2.10/1.94	No	No	–
4				No	No	–
6				No	7.6, 8.2	No
Inside leg						
3	29—rear left leg	23.48	2.03/1.92	8.4, 10.4	No	–
4				11.1, 13.9	No	–
6				4.9, 5.2	7.6, 8.2	No
3	33—front left leg	21.7	2.18/1.82	No	No	–
4				5.3, 5.8	No	–
6				4.3, 4.7	7.6, 8.2	No
3	37—rear left leg	0	2.28/1.97	No	No	–
4				6.7, 7.4	No	–
6				5.8, 6.8	7.6, 8.2	No
3	58—front right leg	16.3	2.20/1.90	No	No	–
4				8.7, 12.4	No	–
6				6.7, 7.0	7.6, 8.2	No
3	83—front right leg	15.7	2.39/1.82	No	No	–
4				3.8, 4.1	No	–
6				4.9, 5.3	7.6, 8.2	No
3	122—rear left leg	6.78	2.22/2.09	No	No	–
4				10.7, 11.9	No	–
6				5.9, 6.1	7.6, 8.2	No

Table 3, it is noted that for the small air gap manikin tests, the sensors show burn injuries after the gas burners were turned off. This could be due to the heat accumulation effect in the sealed test chamber mentioned earlier. Since this is not the case for the bench-scale tests, no burn injuries occur. This finding shows that one has to examine test conditions carefully before comparing test results.

It is important to examine the heat sensors in the leg area and compare them with the bench-scale tests. Twelve heat sensors with incident heat flux levels about 2 Cal/cm^2-s, as shown in Tables 4 and 5, are chosen. Four are located in the outside leg area, six in the inside leg area and one in between the two areas (see Plate 1). It is noted that their air gap thicknesses vary, but are generally moderately large. For configuration 1A in Table 4, the inside leg area shows much more severe burn injury than the outside leg area due to the enhanced heat transfer mentioned earlier. As expected, the bench-scale test results underestimate the manikin test results for the inside leg area even though air gap thicknesses of the former are smaller. For configuration 3A in Table 5, the Nomex underwear provides sufficient fire retardancy so that practically no burn injury occurs in either the manikin or the bench-scale tests.

Overall comparison

The test results in Figs 2 and 3 and Tables 2–5 show that bench-scale tests at zero air gap test conditions are capable of predicting burn injuries of the small air gap areas of manikin tests, which are the most vulnerable areas. If one knows the percentage of small air gap areas for a clothing system, which is probably a reasonably known value for a single-layer clothing system, then the bench-scale tests could be useful in predicting the protective performance of the clothing system. Simulating the large air gap areas

Table 5. Comparison of burn injury prediction for clothing configuration 3A between manikin and bench-scale tests for heat sensors in the leg area

Test burn time (s)	Sensor number and location	Manikin data: Air gap thickness (mm)	Manikin data: Heat flux (cal/cm^2 s) max/min	Manikin data: Burn injury time (s)	Bench-scale data: Zero spacing burn injury time (s)	Bench-scale data: 6.3 mm spacing burn injury time (s)
Outside leg						
3	35—front left leg	16.0	2.32/1.92	No	No	–
4				No	No	–
6				No	No	No
3	47—front right leg	9.5	2.29/1.68	No	No	–
4				No	No	–
6				No	No	No
3	51—front right leg	24.9	2.08/1.92	No	No	–
4				No	No	–
6				No	No	No
3	87—front left leg	12.7	2.08/1.48	No	No	–
4				No	No	–
6				No	No	No
3	124—rear right leg	6.0	2.12/1.83	No	No	–
4				No	No	–
6				No	No	No
Middle leg						
3	120—rear right leg	29.8	2.10/1.94	No	No	–
4				No	No	–
6				No	No	No
Inside leg						
3	29—rear left leg	19.1	2.03/1.92	No	No	–
4				No	No	–
6				12.2, 15.3	No	No
3	33—front left leg	26.1	2.18/1.82	No	No	–
4				No	No	–
6				9.3, 11.2	No	No
3	37—rear left leg	22.9	2.28/1.97	No	No	–
4				No	No	–
6				No	No	No
3	58—front right leg	14.8	2.20/1.90	No	No	–
4				No	No	–
6				No	No	No
3	83—front right leg	17.6	2.39/1.82	No	No	–
4				No	No	–
6				No	No	No
3	122—rear left leg	1.5	2.22/2.09	No	No	–
4				No	No	–
6				No	No	No

Table 6. Comparison of overall body burn (%) of manikin tests and burn injury of bench-scale tests.

Burn time	3 s		4 s		6 s	
Configuration	Manikin	Bench-scale	Manikin	Bench-scale	Manikin	Bench-scale
1A	18%	No	23%	No	25%	8.2s/No[a]
3A	0	No	2%	No	26%	No
5A	—	—	0	No	0	No

[a]8.2 s for second degree burn at zero air gap/no burn injury at 6.35 mm air gap.

of the manikin by setting a finite air gap value in the bench-scale tests is a difficult task because of the uncertainty in both values and distribution of the large air gaps. Therefore, the most valuable capability of bench-scale test is the zero air gap tests which are most severe and conservative but more applicable to full-scale tests.

As mentioned earlier, not all small air gaps areas on the manikin were exposed to an incident heat flux of 2 Cal/cm^2-s. In fact, some were exposed to much higher heat flux levels, such as sensors 64, 65, 67 and 72. That being the case, plus the conditions of enhanced heat flux levels between the legs, local ignition and combustion of fabric edges, and the sealed confined nature of the manikin test chamber, one could expect the overall manikin tests to be more severe in terms of measured burn injuries than the bench-scale tests. This is indeed what the comparison shows for the overall manikin tests as shown in Table 6. One can see that for configurations 1A and 3A, manikin tests show second degree burn on 18%, 23% and 26% of the manikin body whereas no burn injury occurs for the bench-scale tests.

CONCLUSION

An investigation and comparison of manikin and bench-scale thermal protective clothing tests were conducted. The comparison was performed based on the air gap measurements of the clothing systems from 3-D scanning. The comparison shows that areas on the manikin with zero and small air gaps show good correlation with the bench-scale tests conducted with zero air gap at similar incident heat flux levels. This finding shows that zero air gap tests are most useful for bench-scale tests. If the percentage area with small air gaps of a clothing system is known and if the local incident heat flux on the manikin is calibrated to be similar to that of the bench-scale tests, bench-scale tests can be used to provide useful information on full-scale performance. In view of the difficulty in obtaining a well-defined uniform incident heat flux on the manikin, and the various air gap thicknesses and construction details of a clothing system, using bench-scale tests to predict full-scale performance remains an extremely difficult task. Further investigation and correlation between manikin and bench-scale tests at similar finite air gaps and incident heat flux are warranted.

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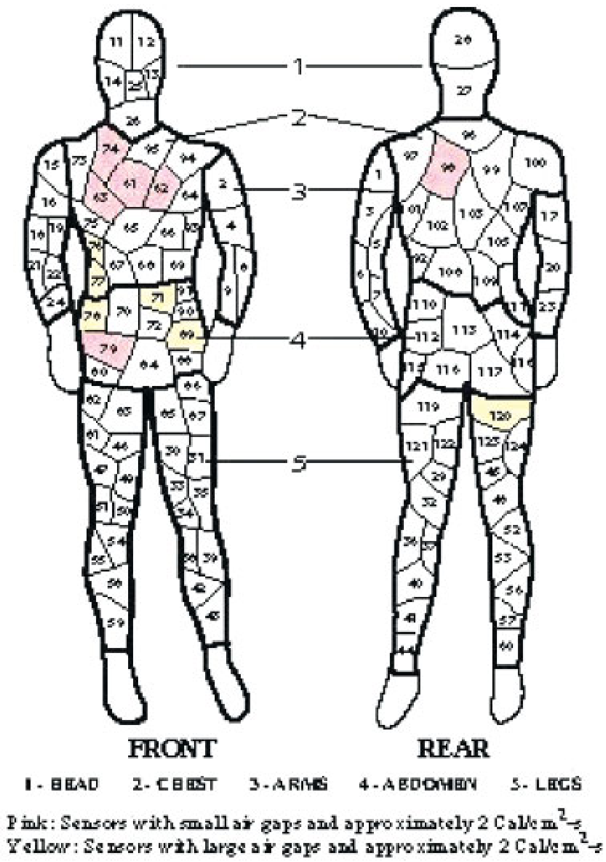

Plate 1. Schematics showing heat sensor locations and their ten regions on the manikin.

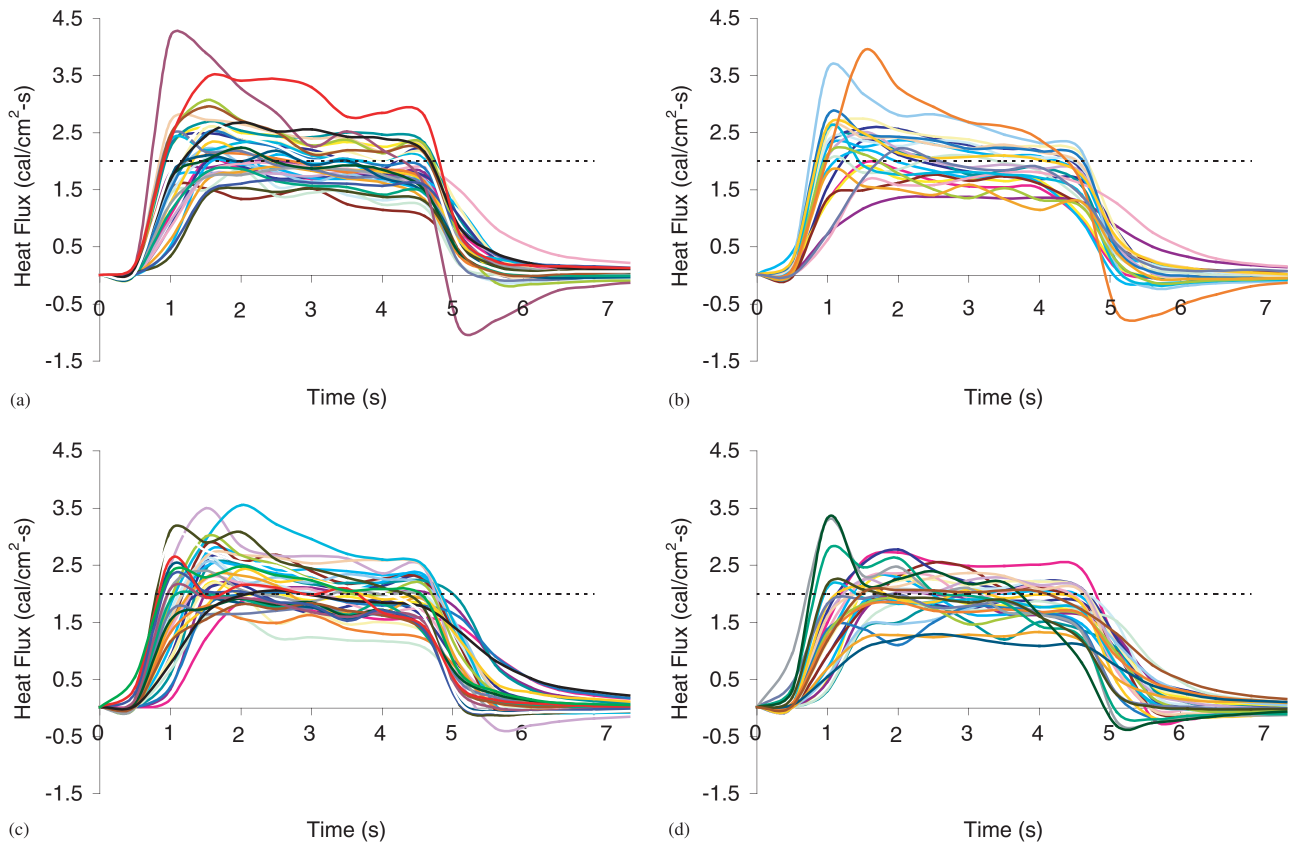

Plate 2. Calibration heat flux profiles of manikin (4s burn time) grouped into four regions. (a) front head, chest and abdomen; (b) rear head, chest and abdomen; (c) front arms and legs; (d) rear arms and legs.

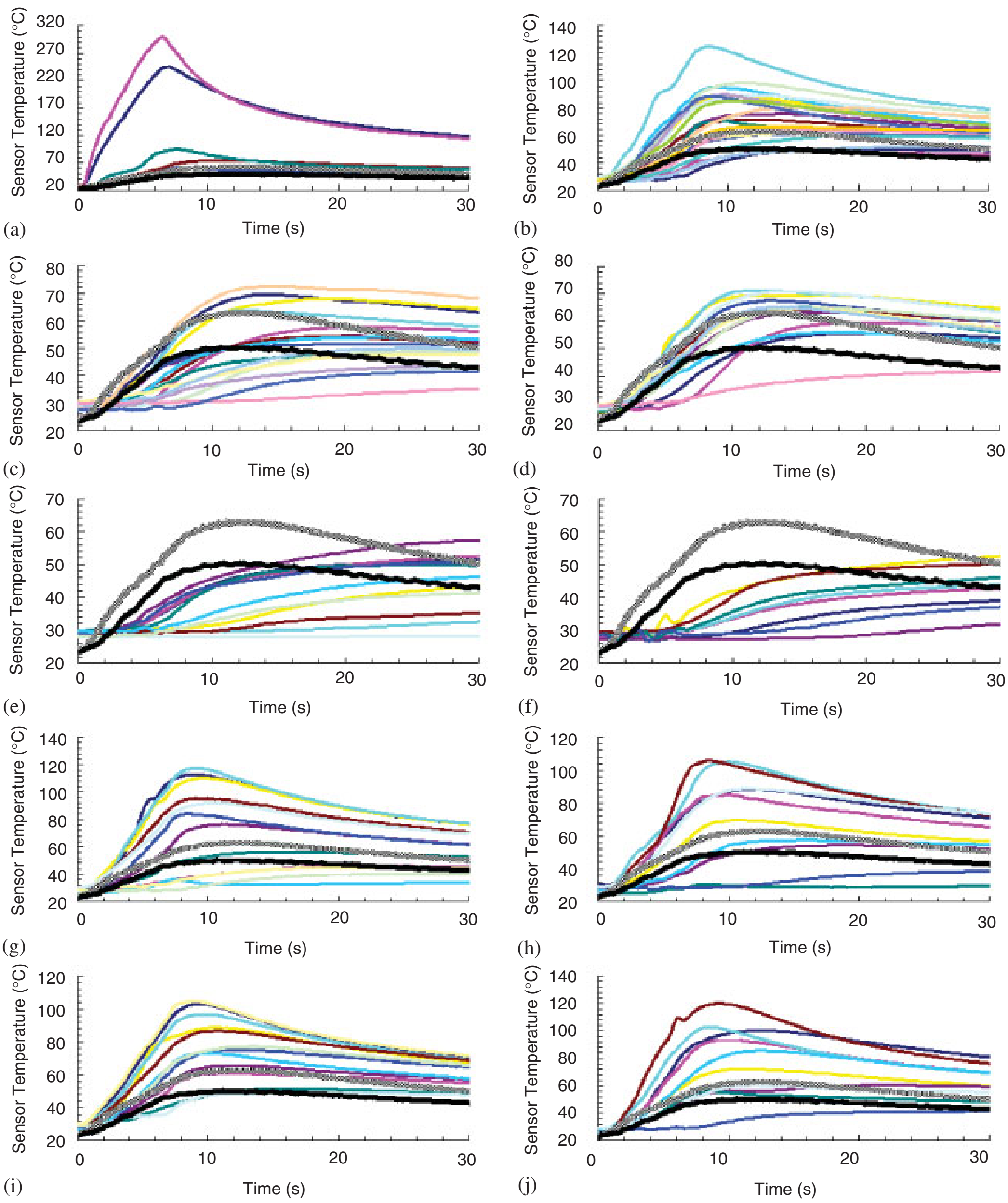

Plate 3. Heat sensor temperature comparison for clothing configuration 1A between manikin (color) and bench-scale (black, upper curve—zero air gap; lower curve—6.35mm air gap) tests: (a) head, front and rear; (b) arm, front and rear; (c) front chest; (d) rear chest; (e) front arm; (f) rear arm; (g) front left leg; (h) rear left leg; (i) front right leg; (j) rear right leg.

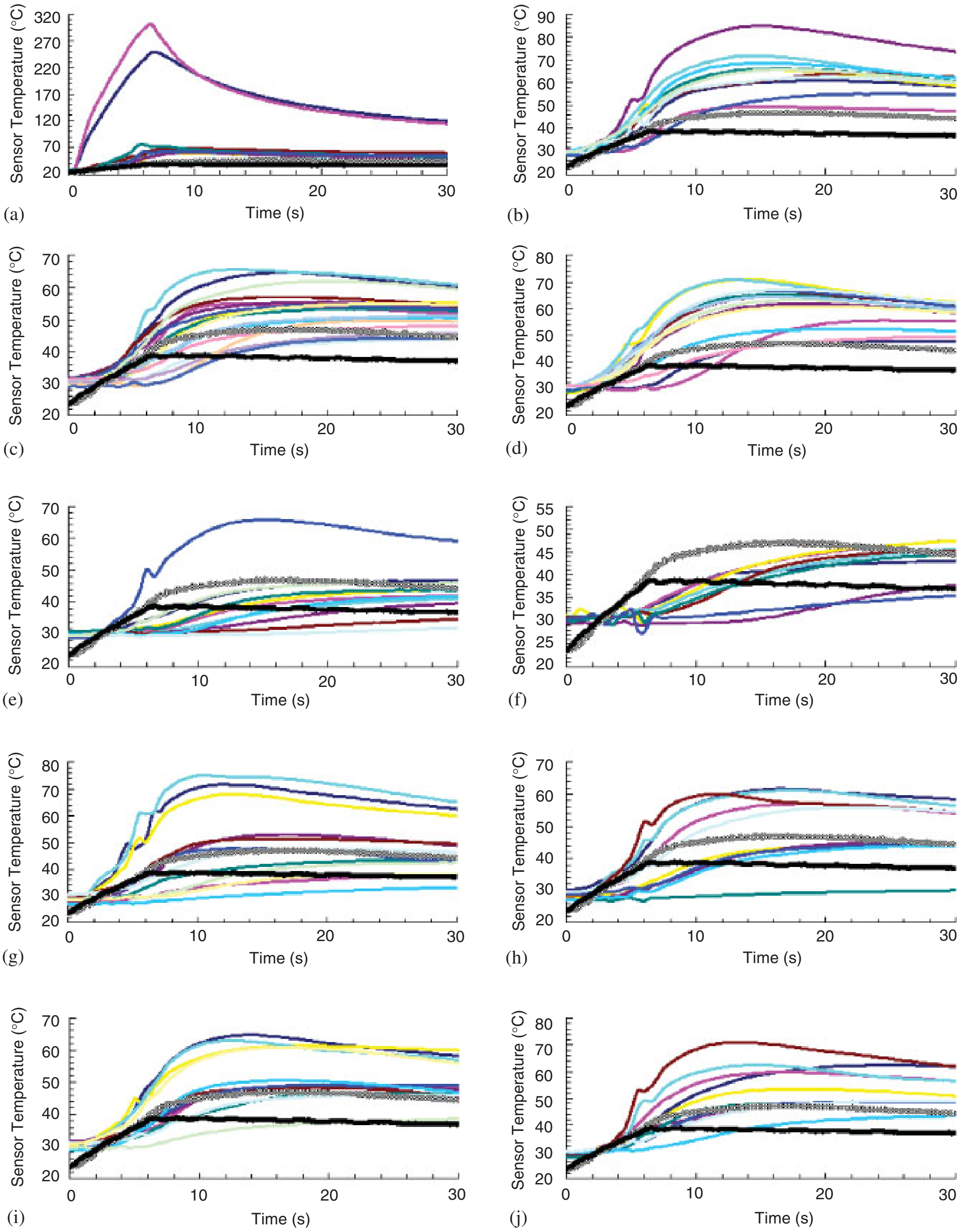

Plate 4. Heat sensor temperature comparison for clothing configuration 3A between manikin and bench-scale tests: a–j, same locations as in Plate 3.

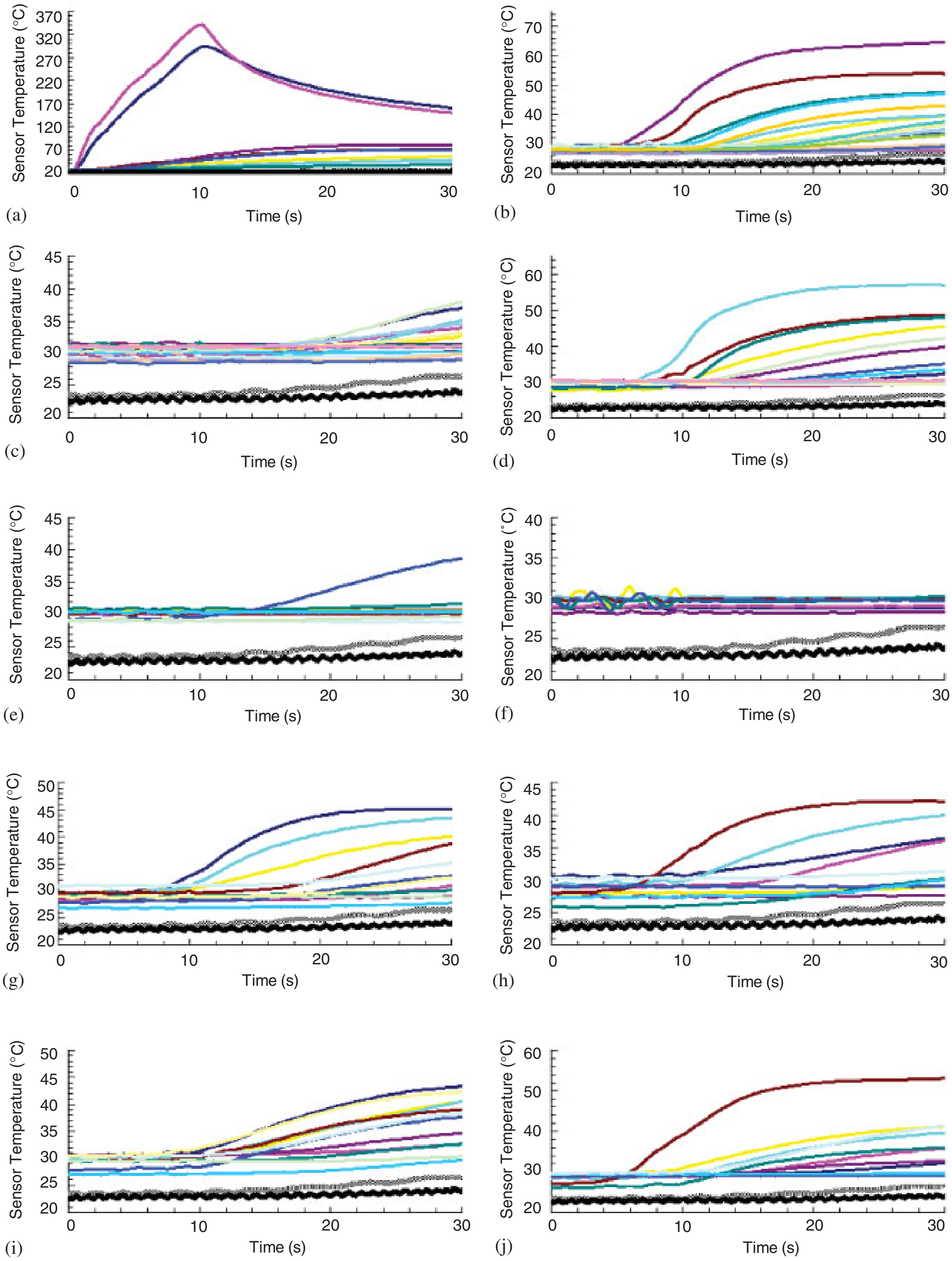

Plate 5. Heat sensor temperature comparison for clothing configuration 5A between manikin and bench-scale tests: a–j, same locations as in Plate 3.