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Article *in* Ergonomics · September 2003

DOI: 10.1080/0014013031000121968 · Source: PubMed

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ERGONOMICS, AUGUST, 2003, VOL. 46, NO. 10, 1017–1033

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Fire fighting and its influence on the body

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Keywords: Fire fighting; Core temperature increase; Sweat rate.

Working conditions for fire fighters can be described according to the environment temperature and the incident radiant heat flux. Measurements for this study in buildings for fire fighting training have shown that fire fighters are typically exposed to radiant heat fluxes of between 5 and 10 kWm^{-2} during this kind of exercise. The heat load can nevertheless be much higher. In one case, 42 kWm^{-2} was measured. The temperatures reached between 100 and 190°C at 1 m above ground, going up to 278°C in one case. Human trials have been performed with 17 fire fighters. After exercises (about 15 min) in a heated room, the mean core temperature of the fire fighters rose by 0.6°C with a surrounding temperature of 31°C and 1.0°C with 38°C. The sweat production varied from 0.7 to 2.1 lh^{-1}; 16% to 45% of sweat remained in the clothing layers. During the exercises in the training buildings, a mean of 48°C has been measured between fire fighters' clothing and workwear. These conditions lead to an increase of the relative humidity in all the jackets up to 100%. When the fire fighters came out of the fire, the humidity remained at this level in the PVC coated jackets while it was in some cases strongly reduced in breathable jackets.

1. Introduction

While fighting fire, fire fighters are not only exposed to one thermal hazard but two: burns and heat stress (Holcombe 1981). The external heat and the working load do not affect the core temperature in the same way: heat from the environment has first to get through the clothing and the skin before it may influence the core temperature. The work load provokes heat flux in the contrary direction: first the core temperature increases before the excessive heat is transmitted to the skin.

When the outside temperature is higher than the skin temperature, the body can only get rid of excessive heat by evaporation of sweat on the skin. The evaporative cooling should furthermore compensate for the heat storage due to the external heat.

American statistics (Karter and Leblanc 1995) show that 52% of injuries occur while fighting fire. Only 10% of these injuries are burns. In 22% of the cases, over-exertion is given as the cause of injury. The percentage of lethal accidents while fighting fire is 48% (Washburn *et al.* 1996). Over 50% (23 out of 43) died of heart attack and 5 deaths were due to burns. The cause of 48% of the deaths was heat stress.

Mäkinen (1991) estimates that 80 to 90% of injuries are due to human failures because of misinterpretation of the situation. Wenzel and Piekarski (1982) showed

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Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online
http://www.tandf.co.uk/journals
DOI: 10.1080/0014013031000121968

that the concentration is greatly reduced as soon as the core temperature increases. The number of mistakes increases in proportion. As the core temperature of fully-equipped fire fighters increases even at moderate temperatures (Schopper-Jochum *et al.* 1997), it can be supposed that a great number of injuries are due to overheating of the body.

1.1. *Conditions encountered when fighting fire*

In fire situations, the heat exposure is mostly due to radiation (over 80%) but convection and conduction can also occur (Krasny 1986). The radiant heat intensity can reach 40 kWm^{-2} during domestic fires and over 200 kWm^{-2} during large fuelled fires (Schoppee *et al.* 1986). Fires usually reach flame temperatures of 800 to 1100°C and radiate heat at wavelength of 1 to 6 μm, the maximum being at about 2 μm (Abbott and Schulman 1976).

As the intensity of radiant heat is reduced the square of the distance, the heat load depends strongly on the distance of the fire fighter from the fire. The intensity is also dependent on the amount of smoke. Every kind of screen between the fire and the fire fighter reduces the effect of radiation.

The exposure conditions of a fire fighter have been classified in three categories (figure 1) (Abbott and Schulman 1976, Hoschke 1981):

- Routine conditions are generally equivalent to a hot summer day. According to several fire fighters, these conditions account for over 80–90% of the conditions encountered in Switzerland.

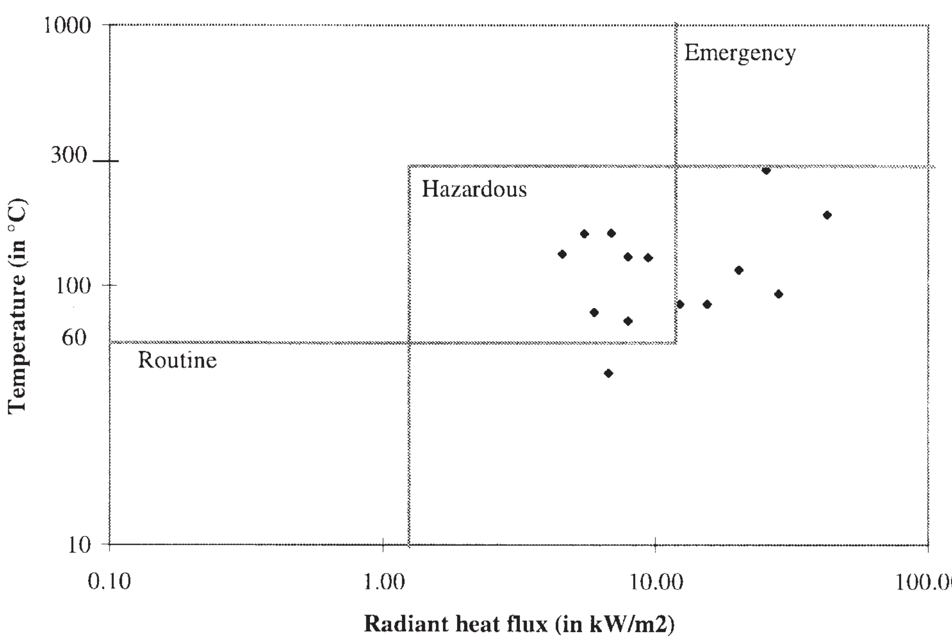

Figure 1. Fire fighters' exposure conditions (diagram following Hoschke 1981) (logarithmic scale) (◆ = measurements for this study).

- Hazardous conditions are typical of those that would be encountered outside a burning building. The more severe conditions of this category are applicable to fire fighters who are first into a burning building.
- Emergency conditions are encountered in very close proximity to the fire. The worst case would be a 'flashover'.

Unfortunately, this classification does not specify where and how these temperatures have been measured. More recent studies (Lawson 1997) seem to show that very high heat fluxes may also happen with low temperatures. One measurement gave a heat flux of 30 kWm^{-2} but 'just' 175°C on the ground. High heat fluxes (> 50 kWm^{-2}) can also occur outside of burning buildings (McGuire 1965) although the surrounding temperatures are quite low.

1.2. *Burns*

According to Holcombe and Hoschke (1986), the main factors for burns are:

- the incident heat flux intensity and the way it varies during exposure
- the duration of exposure (including the time it takes for the temperature of the garment to fall below that which causes injury after the source is removed)
- the total insulation between source and skin
- the extent of degradation of the garment materials during exposure
- Condensation on the skin of any vapour or pyrolysis products released as the temperature of the fabric rises.

As some textiles can have a relatively high content of moisture, a high amount of heat can be transferred because of the last cited point (Davies *et al.* 1965). The behaviour of the skin when exposed to intensive heat sources has been analysed with experimental animals. The time for burns is dependent on the heat flux but hardly on the absorbed energy: when the heat flux is low, the body can absorb more energy before skin damage as it is transmitted to deeper skin layers (Derksen *et al.* 1961). The body acts as a heat sink. This obviously increases the risk of heat stress. The maximum surface temperature increase leading to a burn is much higher when the heat exposure is short and intensive: about 22°C at 6 kWm^{-2} and about 35°C at 50 kWm^{-2}. Time to pain is reached at a skin temperature of about 44°C (Stoll and Chianta 1969). A problem may be that the skin temperature still increases even when the heat source has already been removed, and therefore burns can still occur (Freeston 1971, Claus 1973).

1.3. *Body temperature*

Aschoff *et al.* (1971) and Wenzel and Piekarski (1982) have described the human metabolism: during every activity, the body produces a certain amount of heat lying between 80 W while sleeping and over 1000 W during most strenuous works. One can estimate that fire fighters will produce about 300–500 W during their work. The surplus energy can be transferred to the environment by three means: respiration and release of dry (radiation, convection and conduction) and evaporative heat through the skin. The total heat loss at moderate temperatures and 50% RH is divided in 20% evaporation, 25% conduction, 45% radiation and 10% respiration. At low temperatures, respiration can account for over 30% of the heat loss. When the ambient temperature is over 35°C, evaporation is the only way to cool the body.

Evaporative cooling is a very efficient means of heat dissipation, as one litre of evaporated sweat removes 672 Wh from the body. The body evaporates at least 0.05 $Jcm^{-2}\ min^{-1}$ (about 22 gh^{-1} *perspiratio insensibilis*), up to 4 lh^{-1} during short periods of time. During longer work periods, the amount of sweat produced is reduced (1 lh^{-1} for 6 h work, 0.5 lh^{-1} for 12 h). When heat stress sets in, the amount of sweat increases more in the trunk than in the other surface regions. The higher the core temperature, the lower the skin temperature when sweating starts.

The metabolic balance of the human body can be described as follows:

$$M - P_{ex} = H_{res} + H_c + H_e \pm \frac{\Delta S}{\Delta t} \quad (1)$$

with M: metabolic heat (in W)
P_{ex}: muscular power
H_{res}: heat emission per time unit by respiration
H_c: heat emission per time unit by dry heat
H_e: heat emission per time unit by evaporation of sweat
$\Delta S/\Delta t$: change in the body heat content

Ideally, ΔS should be zero, which means that the body should be in equilibrium with the environment. In the field of fire fighting, the insulation of the clothing is so high that storage of heat in the body can often not be avoided.

Apart from studies on the threshold times for burns, much work has been done on the load of the fire fighter's equipment on the body (Duncan *et al.* 1979, Behman 1983, Veghte 1984, 1988, Ilmarinen and Mäkinen 1992, Louhevaara *et al.* 1995, Bilzon *et al.* 2001, Smith *et al.* 2001). The results can vary greatly depending on the set parameters: measurements at low temperatures and/or low relative humidity [22°C and 20% to 45% RH (Reischl and Stransky 1980); 20°C and 50% RH (Bartels and Umbach 1997); 45/65°C and 15% RH (Sköldström and Holmèr 1983), 22°C and 56% RH (Ftaiti *et al.* 2001)] resulted in great differences in the skin and core temperatures increases for different jacket types (PVC, Neoprene or leather vs. breathable materials). As soon as the temperature or the humidity of the environment approaches the conditions near the skin, the differences become smaller. Schopper-Jochum *et al.* (1997) stated that the increase of body core temperature in an environment of 30°C and 50% RH was independent of the jacket type. Griefahn *et al.* (1996) did not find any significant differences between different protective clothing during exercises at increased temperatures either.

The weight of the equipment represents an additional load for the fire fighter. An equipment set of 24 kg, for instance, reduces the performance of the wearer by 25% (Louhevaara *et al.* 1995). The size of the clothing and the number of textile layers (Teitlebaum and Goldman 1972, Lotens 1983) also increase the energy consumption of the wearer and thus the required heat loss.

As the maximum core temperatures allowed during work are known, maximum work times could be theoretically defined for each work situation. It should then be taken into account that the core temperature still rises for several minutes even if the work has been completed (Duncan *et al.* 1979). Unfortunately, these calculations are not so easy as the work conditions of a fire fighter can quickly radically change. Predictive models are therefore of limited use. Furthermore, the heat emission through sweating is different for each individual and depends on age, fitness and acclimatization (Gautherie and Quenneville 1973).

Human trials in laboratories can only give hints about work duration for fire fighters, as a good heat acclimatization can enhance the sweat rate by 50 – 150% in relation to the same core temperature (Wyndham 1967). Furthermore, some factors such as the psychological stress on duty are not accounted for. However, most studies are performed in laboratories for the sake of repeatability and there are limited data about stress in fire situations.

2. Measurements

The goal of this study was to measure the temperatures and radiant heat loads during simulated fire fighting situations in training buildings and in heated rooms. This study also gives indications about the sweat rate and the core temperature rise of 17 fire fighters during practice related exercises in the heat.

2.1. *Temperatures and radiant heat fluxes assessment during simulated fire situations*

Measurements of heat and radiation loads were performed during different fire fighters' courses. Domestic fires were simulated in buildings for fire fighting training. From time to time, when the fire became too large, fire fighters extinguished part of it with water. The goal of these exercises was to gather experience of dealing with fires. The responsible person for these exercises commented that these conditions were very seldom encountered in practice in Switzerland.

The measurements of temperature and radiant heat flux were performed with a specially constructed apparatus. Radiant heat was assessed with a NiCrNi thermocouple (type K) fixed on an aluminium plate and temperature with a thermocouple type K.

As the thermocouple was mounted at the front of the apparatus, the results of temperatures were influenced by radiation as well as by convection. The thermocouple was blackened to allow the assumption that the increase in temperature would be similar to that of clothing. The sensors assess temperatures of – 100 to 1300°C in chosen intervals of 1 s. Data were stored in a data logger, placed in a Dewar recipient and insulated with glass wool to avoid an excessive increase of temperature inside the box.

The thermocouples were pre-calibrated by their suppliers. The aluminium plate was calibrated to correspond to the calorimeter used in EN 366 (1993) (test of radiant heat protection).

The measuring device was placed either on or 1 m above the ground, next to the fire fighters, that is 1 – 2 m from the fire. The measurements thus gave the approximate values experienced by the fire fighters. About 20 measurements were made in three different training buildings and the 14 highest temperature rises were evaluated.

2.2. *Physiological measurements*

Seventeen male fire fighters volunteered for the tests. They were equipped with temperature and humidity sensors. The sensors were coupled with data loggers to perform one measurement every 4 s. They were placed on the left shoulder of the fire fighters, between the fire fighters' clothing and workwear. This place had been chosen because the highest temperatures occur there as the air layer is at a minimum (Heus *et al.* 1992). The highest quantities of sweat are produced on the trunk (Aschoff *et al.* 1971). Nevertheless, the sensors could not be placed directly on the back, as the breathing apparatus would have covered them. The shoulder thus was a good compromise between high sweat production and external heat production. Furthermore, some fire fighters were equipped with temperature sensors on the skin and between underwear and workwear.

The participants swallowed a miniaturized temperature sensor in the form of a pill 30 min before the beginning of the first exercise. This pill registers the intra-abdominal temperature. It works with a battery and every 30 s sends the actual core temperature to a receiver with a precision of 0.1°C.

The fire fighters and each part of their equipment were weighed before and after the exercises (precision of the scales: 10 g) to assess the amount of produced sweat and the percentage released to the atmosphere.

The fire fighters wore three types of jackets: two breathable (A and B) and one PVC-coated (C). The trousers were all PVC-coated. Underneath the protective clothing, all participants had workwear. In Switzerland, as over 99% of the fire fighters are voluntary, the underclothing is not defined. This situation was also reflected in this study as all the participants had different kinds of underwear (T-shirts, shirts with long sleeves, pullovers, etc.).

Apart from the exercises in the fire fighting training buildings, measurements were also conducted during a training course in heated rooms. The fire fighters were fully equipped (with breathing apparatus, total weight 20 kg) and had to go through a certain path in complete darkness. The path was made difficult by different obstacles and the participants had to carry additional weights. The room was heated between 31°C and 38°C with a relative humidity of 50%. The participants wore the same clothing as in the fire fighting training buildings and were again weighed before and after the exercise.

3. Results and discussion

3.1. *Exercises in the buildings for fire fighting training*

3.1.1. *Temperatures and radiant heat load in the buildings*: The values assessed in the training buildings more or less correspond to the Hoschke diagram (figure 1). Temperatures of about 50 to 130°C were measured on the ground; 100 to 190°C at 1 m above the ground. One measurement even reached 278°C with a radiant heat flux of 26 kWm^{-2}. The temperature was very dependent on how many times the door and the windows were opened. The highest temperature was assessed at the beginning of a course when the first group entered the fire. There was generally a temperature gradient of 100°C between the ground and 1 m above.

The values of radiation usually reached between 5 and 10 kWm^{-2}. However, these were surpassed five times, the maximum value being 42.6 kWm^{-2}, corresponding to the highest value obtained during domestic fires.

Additional measurements were performed during fires lit in rooms of a house due to be demolished. The task of the fire fighters was to extinguish them as fast as possible. This exercise was probably more realistic than the ones in the training buildings. Unfortunately there was no possibility for the fire fighters to carry an additional measuring device. For this reason, temperature sensors (with data logger) were placed on the outside of the jackets of eight fire fighters during four missions (one on the collar or in the middle of the chest and the other on the lower end of the jacket). With the first sensor, maximum values of 50 to 120°C have been assessed; with the second, values between 40 and 70°C.

It was not possible to measure the relative humidity under these circumstances. It can be supposed that it must be partly very high, as the black smoke turned to white mist when the fire fighters started extinguishing the fire. The partial pressure could therefore be near saturation.

3.1.2. *Microclimates in the jackets during the exercises in the training buildings*: As soon as the fire fighters entered the building, temperature and humidity increased rapidly as expected. There was no difference between the three types of jackets (breathable materials and PVC) in the temperatures between protective clothing and workwear (mean of 48°C). Therefore, heat protection of all measured jackets was probably comparable. The maximum registered temperature was 62°C. At this temperature, the fire fighter got slightly burnt on the left shoulder.

The temperature on the skin has been assessed with six fire fighters. There were relatively constant values between 39°C and 45.5°C. The fire fighter who suffered burns obtained a maximum temperature of 42°C. This means that he got burnt at a lower temperature than others. The fact that several fire fighters reached higher temperatures without feeling pain states, may be because, as said before, burn injuries are not only due to a temperature increase.

There were hardly any differences in relative humidity in both jacket types during the exercise in the training buildings (figures 2 and 3 show examples of temperature and relative humidity curves of two participants. The curves of the others were similar): in every case, humidity jumped near to 100% when the fire fighters entered the building. This can be explained by the fact that heat and relative humidity were higher in the environment than near the body and that even breathable jackets could not evacuate sweat (water vapour) to the outside under these circumstances.

The differences between the two jacket types became visible when the fire fighters came out of the fire: even though both did not open their jackets, humidity remained higher than 80% for fire fighter 5A (figure 2) whereas it dropped to 60% for fire fighter 6A (figure 3). For some test persons who did not go so near from the fire, the breathable jackets could still release part of the moisture to the outside and were therefore superior to the PVC coated jackets.

As stated before, one fire fighter got slightly burnt on the shoulder. As he was wearing a PVC coated jacket which stores all the moisture in the textile layers, it may be supposed that he got scalded through his own sweat. After a while near the fire, condensed sweat can evaporate and come back towards the body, which could cause burns. This kind of burn is less common with breathable jackets.

3.1.3. *Core temperature increase*: The core temperature of the fire fighters increased very quickly. After 15 min exercise, the core temperature of one fire fighter was 0.79°C higher. The whole exercise lasted for about 1 hour and some fire fighters entered the training building several times. The core temperature of all fire fighters rose by 0.6°C to 1°C. This increase was mostly due to the heat exposure and not because of heat produced by the body, as the fire fighters did not work as hard near the fire as they would in a real fire situation. In real cases, the core temperature increase could therefore be much higher.

3.1.4. *Water absorption of the jackets*: Between two entries into the training building, most of the fire fighters sprayed their equipment with water in order to reduce its temperature. During this procedure, some jackets absorbed a

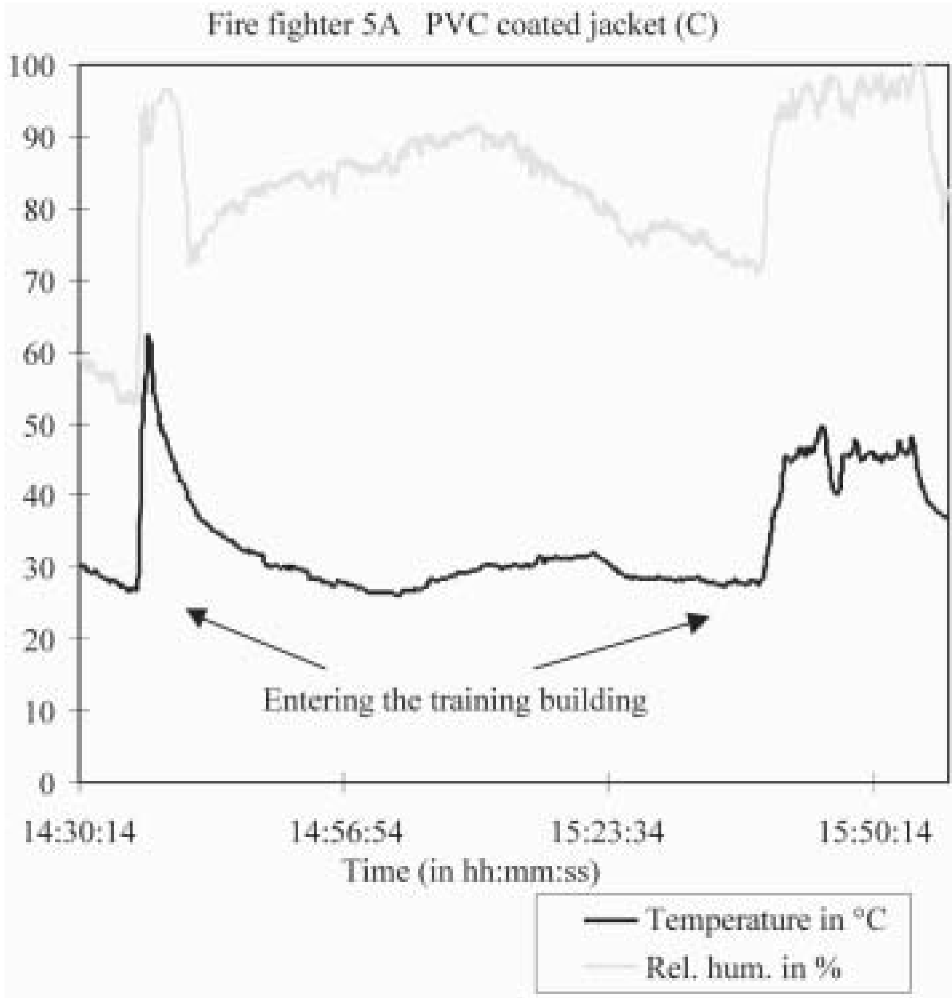

Figure 2. Temperature and relative humidity between jacket and workwear during the exercise in the fire fighting training building.

considerable amount of water. As the moisture barriers of breathable jackets are not on the outside surface, the outer layer has to be impregnated to be water repellent. After several washes, this finish can be washed out. Four out of the ten breathable jackets tested absorbed over half a litre of water. Obviously this does not mean that these jackets were not watertight, as the moisture barrier hinders any water penetration to the inner side of the jacket. The seven PVC coated jackets absorbed at most 280 g humidity, but it could not be determined whether it was condensed sweat or water that had penetrated through the collar.

3.2. *Exercises in the heated room*

3.2.1. *Metabolic heat production during the exercise course*: The metabolic heat production of the fire fighters could not be analysed during the exercise in the heated

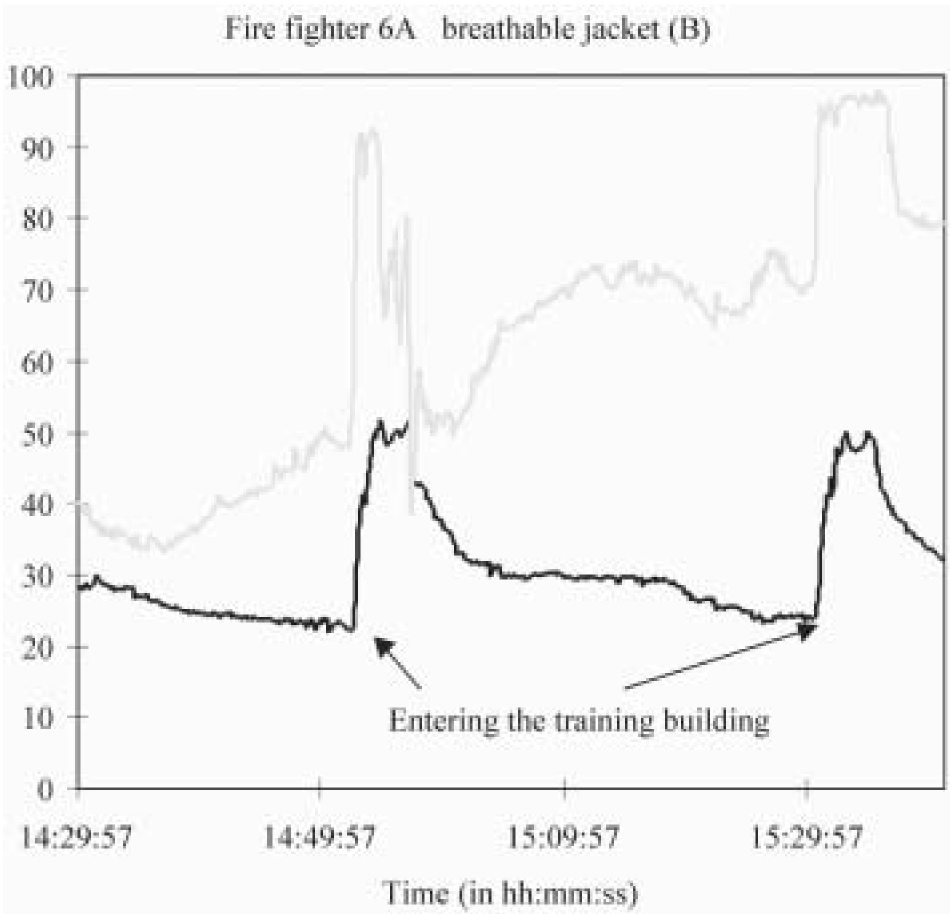

Figure 3. Temperature and relative humidity between jacket and workwear during the exercise in the fire fighting training building.

room, as an analysis of the exhaled air would have been necessary. Data from the literature can give a rough approximation of the energy consumption (Spitzer *et al.* 1982):

Walking at 4 kmh^{-1}, flat and even ground	235 W
Walking at 4 kmh^{-1}, flat and even ground, half bent	337 W
Walking upwards (3 kmh^{-1}, 10% raise) with heat protective clothing (11.8 kg)	438 W
Walking at 4 kmh^{-1}, flat and even ground with 10 kg load	252 W
Walking at 4 kmh^{-1}, flat and even ground with 20 kg load	383 W

For all these values, the heat production at rest (about 80 W for a man with 1.7 m stature and 70 kg) has to be added. These values can increase somewhat at a higher room temperature (Spitzer *et al*. 1982). During this exercise, the heat production was thus at least 500 W and reached 1000 W for some of the participants.

3.2.2. *Sweat release*: At these climates and loads (the equipment weighs over 20 kg), the body sweats strongly even during low efforts to cool down efficiently. This is not suprising as the comfort temperature for a nude participant at rest is about 29°C (Aschoff *et al.* 1971). As expected, the amounts of sweat varied a lot for the 17 participants (between 0.7 and 2.1 lh^{-1}).

Under the set conditions, the body sweats as much as it can. Yet, it is not sufficient to allow the surplus heat to be released to the outside. This is the reason why the amount of produced sweat is on average only slightly higher at 31°C in comparison to 38°C. The differences between the jackets are not great either. As the exercise did not last for too long, the participants had no dangerous dehydration [tolerance 4% of body weight (Bittel *et al.* 1983)]. Fire fighter 4B who sweated the most, lost 0.67% of body weight in sweat.

Fire fighter 3B who had by far the highest core temperature raise (5.1°Ch^{-1}) had also the lowest sweat release. It can be supposed that he was not as well trained as the others (acclimatization) or had a health problem, which reduced his sweat capacity.

3.2.3. *Core temperature rises in the heated rooms*: The differences in the load become obvious when analysing the core temperatures: the room temperature of 31°C caused core temperature rises of 0.32 to 0.76°C (2.85°Ch^{-1} on average), 38°C caused rises of 0.82 to 1.35°C (3.54°Ch^{-1}). These increases in core temperatures prove that even at 31°C, the fully equipped body is not able to produce enough sweat to cool the person down.

Thus, the bodies produced more heat than they could get rid of. The core temperature raise allows the calculation of the heat uptake:

$$\Delta S = C_K M_K \Delta T_{rek} \tag{2}$$

with C_K: heat capacity of the body ($C_K = 3.48\ kJkg^{-1}K^{-1}$)
M_K: mass of the fire fighter
ΔT_{rek}: core temperature change

The change in body heat content ΔS varied between 95 kJ (13 Whm^{-2}) for fire fighter 2A and 398 kJ (55 Whm^{-2}) for fire fighter 3B. According to ISO 7933 (1989), fire fighter 3B lays between the warning and the danger level. Body heat storage of 60 Whm^{-1} can be dangerous for certain participants.

At these temperatures, dry heat loss through convection and radiation is almost not possible any more; an outside temperature of over 36°C will even induce a dry heat uptake from the environment. The surplus heat can only be released by evaporation. However, under these circumstances, the partial pressure difference between the skin and the environment is not very big. The required sweat rate (E_{req}) to avoid a core temperature raise can be determined as follows:

$$E_{req} = E + \frac{\Delta S}{\Delta t} \tag{3}$$

To compensate the heat storage $\Delta S/\Delta t$, fire fighter 3B should additionally evaporate 309 $gm^{-2}\ h^{-1}$ sweat (heat of vaporization of water at 35°C: $\varphi = 672\ Whkg^{-1}$). When supposing that no cooling has taken place during this study

(E = 0), the minimum evaporative cooling can be determined, thanks to the heat storage:

$$E_{req}^{min} = \frac{\Delta S}{\Delta t} \qquad (4)$$

Thus, the required steady-state water vapour permeability or the maximum water vapour resistance R_{et}^{max} [definition according to ISO 11092 (1993)] can be determined for these conditions:

$$R_{et}^{max} = \frac{(p_h - p_a) \cdot A_{Du}}{\Delta S / \Delta t} \qquad (5)$$

with p_h: partial pressure on the skin [$p_h(35°C) = 56.22$ mbar]
p_a: partial pressure of the environment
A_{Du}: body surface

At 38°C and about 50% RH ($p_a = 33.12$ mbar), R_{et}^{max} of fire fighter 3B should be 11.1 m^2PaW^{-1}. This value is very low and is (for the moment) not reached even by the best fire fighters' clothing [in the revision of EN 469 (1995), a limit of 45 m^2PaW^{-1} is proposed]. An increase of the core temperature under these circumstances cannot be avoided.

3.2.4. *Temperatures and relative humidity in the jackets during the exercise in the heated room*: The temperature and humidity sensors were all placed on the left shoulder of the participants between the different textile layers. The evolution of temperature was similar for all participants and could not be classified according to the jacket type. As shown on figure 4 and as expected, the temperature between the jacket and the workwear was the lowest when the participant entered the heated room. As soon as the exercise started, the temperatures rose quickly. Surprisingly, the temperature between underwear and workwear was the highest for most of the participants. A possible explanation is that underwear and workwear absorb quite a lot of moisture, which releases thermal energy. After a certain time, the curves approached each other. In some cases, the three curves came together after 10 min and run in parallel. At the end of the exercise, the single temperatures varied between 36°C and 39°C.

As expected, the amount of evaporated sweat was higher for the breathable jackets than for the PVC coated. On average, jacket A (breathable) released 75% of sweat to the outside, jacket B (breathable) 72% and jacket C (PVC) 59%. Even if the outside temperature was higher than the skin temperature, part of the sweat could be released as the relative humidity in the room was relatively low (about 50%) and thus the outside partial water vapour pressure lower than near the skin.

Looking at the results (table 1), it might be thought that the PVC coated jacket al so released an important part of moisture to the outside, but the different parts of the equipment were weighed after having been taken off by the fire fighters. The percentages must therefore be too high for all the clothing combinations, as part of the moisture could escape to the atmosphere whilst they were opened and taken off. It is also possible that sweat dripped onto the ground without allowing any cooling. Only moisture that evaporates near the

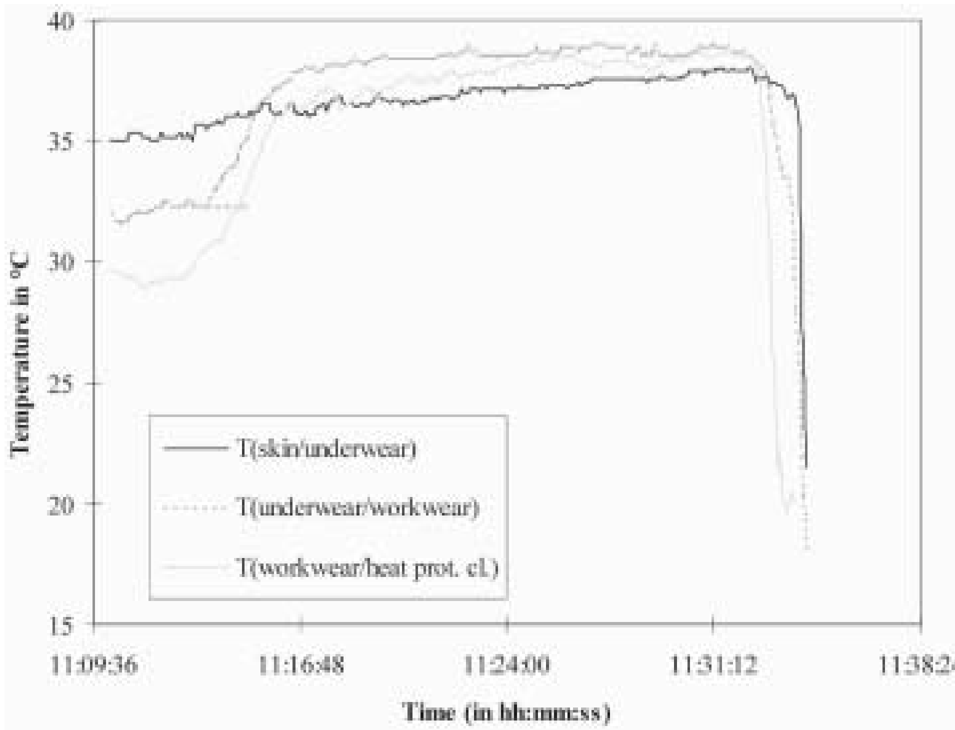

Figure 4. Evolution of temperature in the jacket during the exercise (participant 4A, outside temperature: 38°C; start of the exercise: 11 h12).

skin can cool the body. Furthermore, parts of the humidity are released through respiration.

The higher amount of evaporation for the breathable jackets was also visible in the climate between jacket and workwear: humidity increases for both participants but this raise was faster for the PVC coated jacket (jacket C). This jacket allowed nearly no moisture transfer and therefore, a state where the fire fighter felt uncomfortable (wet) was quickly reached. As can be seen on figure 5, the breathable jacket (jacket B) also came near to saturation (100% RH) by the end of the exercise.

Humidity in the jacket also rose constantly when the outside temperature was 31°C (figure 6). The increase was nearly the same as in figure 5 even if the partial pressure difference was higher in this case and therefore the evaporation should have been higher. The underwear of the fire fighters may explain this comparable increase: most of them wore cotton underwear, which has the property to absorb and to store moisture easily. Thus, sweat remained near the body and could not be transferred through the breathable layer.

4. Conclusions

The radiant heat load experienced by the fire fighters in the training buildings reached over 40 kWm^{-2} in one case, which is considered as the highest value for domestic fires. Thus, the conditions reproduced in the buildings sometimes certainly corresponded to emergency situations. The values matched quite well with the

Table 1. Physiological data after the course.

Participant	Jacket	Temperature in the room (in°C)	Duration of exercise (in min)	Core temperature rise (in°C)	Core temperature rise (in°Ch^{-1})	Sweat release (in kg)	Sweat release (in lh^{-1})	Evaporated amount of sweat (in% of release)
1A	A	31	13	0.5	2.3	0.24	1.11	75%
1B	B	31	13	0.76	3.5	0.20	0.92	70%
2A	B	31	11	0.32	1.7	0.14	0.76	71%
2B	C	31	11	0.71	3.9	0.18	0.98	66%
3A	B	38	16	1.04	3.9	0.22	0.82	84%
3B	A	38	16	1.35	5.1	0.20	0.75	82%
3C	C	38	16	0.82	3.1	0.28	1.05	64%
4A	A	38	19	0.9	2.8	0.30	0.95	68%
4B	C	38	19	0.9	2.8	0.66	2.08	55%
5A	C	37	24	–*	–	0.56	1.4	61%
5B	C	37	24	–*	–	0.3	0.75	60%
6A	B	37	17	–*	–	0.32	1.1	69%
6B	B	37	17	–*	–	0.24	0.82	83%
7A	C	39	11	–*	–	0.33	1.8	52%
7B	B	39	15	–*	–	0.28	1.5	79%
8A	B	39	16	–*	–	0.44	1.65	50%
8B	C	39	16	–*	–	0.36	1.35	56%

A and B: breathable jackets, C: PVC coated jackets
*Not assessed

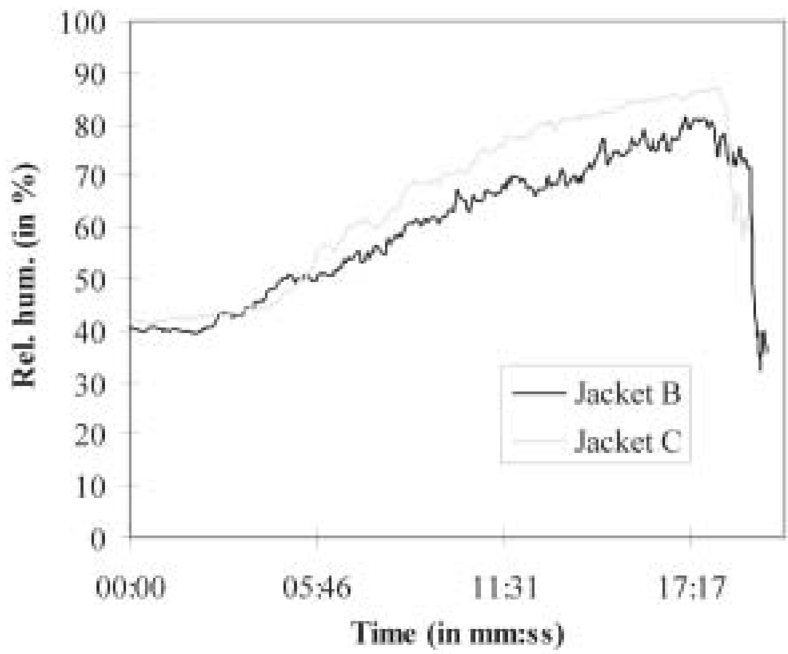

Figure 5. Relative humidity between jacket and workwear during the exercise course at 38°C and about 50% RH (participant 3A with jacket B and participant 3C with jacket C).

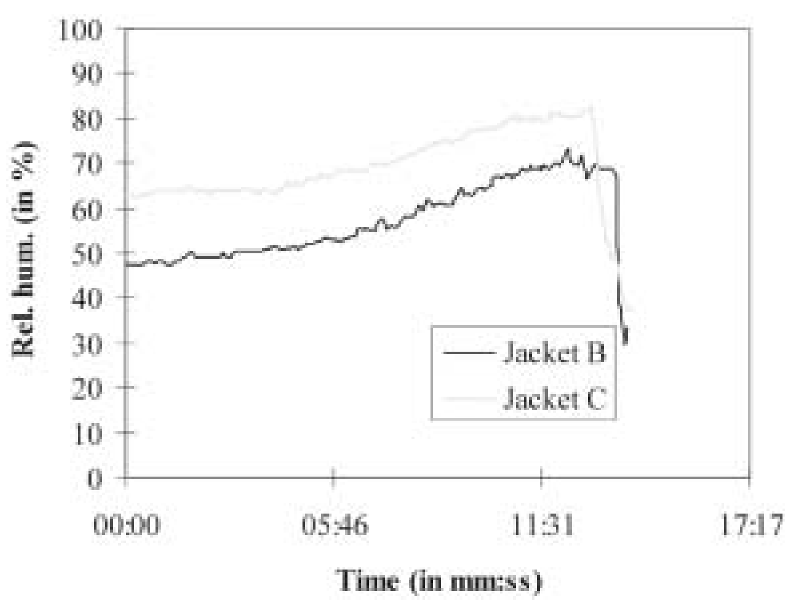

Figure 6. Relative humidity between jacket and workwear during the exercise course at 31°C and about 50% RH (participant 2A with jacket B and participant 2B with jacket C).

Hoschke diagram, which is commonly used for the description of fire fighters' exposure conditions. Nevertheless, the radiant heat intensities were partly higher than described by Hoschke (1981) for a temperature range between 100 and 280°C and tend to confirm the statements of Lawson (1997) that high radiant heat flux can also occur for 'moderate' temperatures.

The body core temperatures rose quickly in the hot environments of the fire fighting training buildings but also in the heated rooms, which had temperatures of around 35°C. The performance of the fire fighters can thereby be reduced drastically. They may have more difficulties in concentration and possibly make more mistakes. An increased concentration and motivation may compensate for a reduction of performance. But if the core temperature is too high, there is danger of a heat collapse. A rectal temperature of 38.0°C to 38.3°C is considered as bearable; 38.9°C to 39.2 are excessive (Wenzel and Piekarski 1982). The measurements during the exercise course in the heated room have shown that a fire fighter on duty in warmer environments can reach the limit of strain.

During the exercises in the fire fighting training buildings, some of the breathable jackets took up a large amount of water. This was due to an insufficient hydrophobicity of the outer shell. The fire fighters did not get wet as the waterproof liner protected them. Nevertheless, any weight increase means an additional load for the fire fighter. Furthermore, wet clothing can strongly alter the protection against heat (Rossi and Zimmerli 1996). For this reason, the water repellency should be checked after each wash and, if necessary, the jacket should be impregnated again. In this study, the PVC coated jackets offered much better water protection than the breathable jackets.

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