Maximum allowable exposure to different heat radiation levels in three types of heat protective clothing

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Abstract: To determine safe working conditions in emergency situations at petro-chemical plants in the Netherlands a study was performed on three protective clothing combinations (operator's, firefighter's and aluminized). The clothing was evaluated at four different heat radiation levels (3.0, 4.6, 6.3 and 10.0 k·W·m^{-2}) in standing and walking posture with a thermal manikin RadMan™. Time till pain threshold (43°C) is set as a cut-off criterion for regular activities. Operator's clothing did not fulfil requirements to serve as protective clothing for necessary activities at heat radiation levels above 1.5 k·W·m^{-2} as was stated earlier by Den Hartog and Heus[1]. With firefighter's clothing it was possible to work almost three min up to 4.6 k·W·m^{-2}. At higher heat radiation levels firefighter's clothing gave insufficient protection and aluminized clothing should be used. Maximum working times in aluminized clothing at 6.3 k·W·m^{-2} was about five min. At levels of 10.0 k·W·m^{-2} (emergency conditions) emergency responders should move immediately to lower heat radiation levels.

Key words: Heat radiation, Protective clothing, Tolerance time, Skin temperature, Exposure

Introduction

Most research on protection against fire and radiant heat has been conducted to serve the first responders. In the industrial health sector, however, there is also a significant need in fire protective clothing (following requirements such as NFPA 2112[2] and EN 11612[3]) as well as fire fighter protective clothing. Especially in the oil and gas industry, where large volumes of flammable liquids are stored, incidents are battled by industrial emergency responders and firefighters. When such incidents occur they are marked by very high levels of radiant heat and flames, much different from structural fires. In industrial safety these fires are modelled and radiant heat loads are calculated to estimate safe working distances from the fire. Generally the distance where the calculated radiant heat loads are 1 k·W·m^{-2} and 3 k·W·m^{-2} [4] respectively are expected to be safe distances from these large scale fires. These calculated distances are called the 1 k·W·m^{-2} and 3 k·W·m^{-2} radiation contours. In perspective of the revision of guideline for above ground storage of flammable liquids in vertical cylindrical tanks[4] there was a need to validate these safe working conditions for emergency responders in the 1 k·W·m^{-2}, 3 k·W·m^{-2} and higher heat radiation contours. The '1' and '3' k·W·m^{-2} contours were originally meant for prevention of heat strain during longer duration firefighting and rescue activities. Additionally, a need was identified to define safe exposure limits for short term emergency response actions (15–30 min) during incidents in the (petrochemical) industry. In a study by Den Hartog and Heus[1] it was reported that thermal strain injuries[5] related to radiant heat stress at short term activities were improbable, however

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Fig. 1. Clothing ensembles; upper left under garments, upper middle long sleeve undershirt[*], upper right operator's clothing, lower left firefighter's clothing, lower right aluminized clothing.

[*] Additional used in 3.0 and 4.6 kWm^{-2} and operator's clothing

they did not go into details on the risks of skin burns.

This study intended to generate guidelines for work times under heat radiation exposure conditions not leading to health and safety hazards for the employees. Due to European legislation health and safety of employees must always be guaranteed and injuries avoided. Therefore, it is not allowed to determine safe work times referring to the time people will develop skin burns (health damage)[6] despite the use of personal protective equipment[7]. As a consequence for generating European guidelines no reference will be made to risk of skin burns and the results will be limited to the possible experience of pain by the wearers of the protective clothing and equipment.

Havenith and Daanen[8] mentioned a maximum skin temperature for pain of 43–45°C. Based on the present knowledge maximum skin temperatures of 43°C can be accepted as a relatively safe limit to prevent from harmful skin burns. Most references in literature show that skin burns can occur at skin temperatures from 44°C[9, 10]. According to Rossi[11] skin temperature can still increase even when the heat source has already been removed after initial sen-

sation of pain at 43°C. So adequate protection is needed to operate in environments with high heat radiation levels.

The goal of this study was to determine which combinations of time and intensity of heat radiation people with appropriate personal protective equipment could be exposed without experiencing pain.

Materials and Methods

Multiple ensembles were evaluated for resistance to low level radiant heat exposures on a thermal manikin. The ensembles identified as '**Operator**' (similar to NFPA 2112)[12], '**Firefighter**' (EN469)[13], and '**Aluminized**' (EN1486)[14] were tested as received, with a short sleeve cotton t-shirt and boxer brief worn under each ensemble (Fig. 1).

The evaluation of the ensembles was performed with a special manikin called RadMan™. The RadMan™ system is a water cooled thermal manikin that allows measurement of heat flux at the skin will keeping the skin temperature fixed. The system is designed to measure the performance
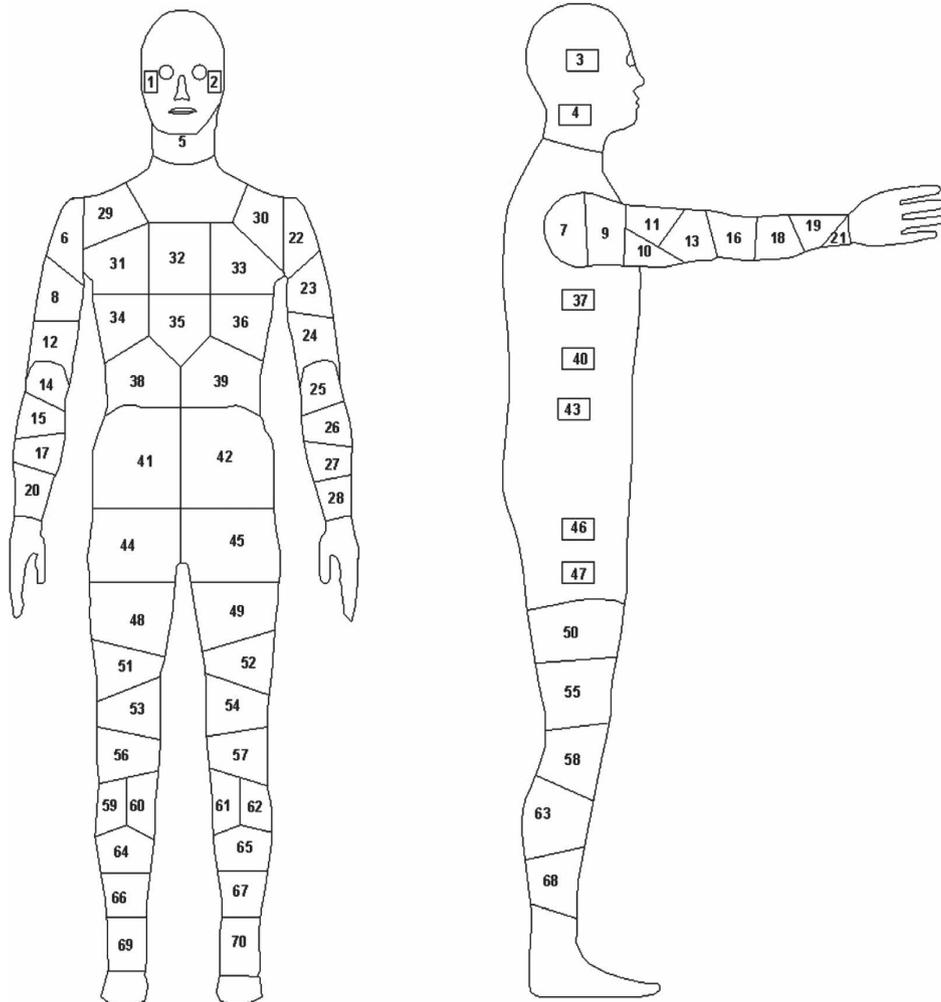
Fig. 2.   RadMan™ Sensor locations.

of protective clothing under low and medium level radiant exposure conditions[15] (Fig. 2).

The test manikin is based on the 50 th percentile male Caucasian geometry[16], made from a high temperature epoxy composite shell structure, capable of withstanding incident heat flux of 8.4 k·W·m^{-2} for 60 s. There are thin film heat flux sensors distributed along the front and right side of the manikin "skin". All temperature data are acquired by the system at a rate of 2.5 Hz (every 400 ms). Measuring the heat transfer through the ensembles was done by measuring the heat flux at the manikin surface to calculate changes in the temperature throughout the different layers of human skin including the epidermis, dermis, and subcutaneous layers. These temperatures can then be used, to predict pain following the Stoll equation[9]. The limit for pain is set at skin temperatures of 43°C.

The results of this study must be valid within an environmental temperature range of 0 to 28°C as can typically be expected outside in the Netherlands, with lower environmental temperatures usual leading to an extension of the tolerance time. Therefore, studies at ambient laboratory temperatures of 23.9 to 29.4°C were deemed representative. The differences in air temperature were inevitable due to the intensity of the heat radiation panel.

Multiple activities would be expected under these circumstances in reality. For practical feasibility for manikin testing only a standing and a walking posture were used. Although RadMan™ is flexible, he is not able to make real-time movements during the experimental conditions, bending and crouching postures were, therefore, removed from the experimental postures. All ensembles were tested at radiant heat flux levels of 3.0 k·W·m^{-2}, 4.6 k·W·m^{-2}, 6.3 k·W·m^{-2} and 10.0 k·W·m^{-2} generated by a controlled infrared radiant heat panel. The chosen heat flux levels are based on working distance for emergency responders during incident scenario's in the petrochemical industry. The

Table 1. Maximum tolerance times in seconds till pain threshold (43°C) is reached (as measured by the corresponding sensors on RadMan™) of different ensembles under the various heat radiation exposures in standing and walking position of RadMan™

Exposure Level ($k \cdot W \cdot m^{-2}$)	Standing posture				Walking posture			
	Operator		Firefighter	Aluminized	Operator		Firefighter	Aluminized
	Short Sleeve	Long Sleeve			Short Sleeve	Long Sleeve		
3	48 s (24)	88 s (14)	430 s (31)	no limit	40 s (11)	33 s (56)	105 s (54)	no limit
4.6	45 s (14)	58 s (51)	168 s (51)	no limit[1]	43 s (61)	20 s (57)	173 s (53)	160 s (66)[2]
6.3	68 s (11)	—	120 s (31)	no limit[1]	18 s (57)	—	73 s (57)	250 s (60)
10	20 s (24)	—	88 s (31)	70 s (60)	13 s (12)	—	60 s (57)	85 s (24)

—: no measurements;

[1] Two sensors at this condition reached values just above 43°C, but stayed below 44°C (limit for skin burns).

[2] This unexpected value is not taken into account in the recommendations (see Discussion section).

Corresponding sensor between parentheses

heat exposure levels were calibrated on the location of the Radman™ manikin prior to the experiments. All conditions were measured three times to obtain information on repeatability. Additional exposures were conducted at 3.0 $k \cdot W \cdot m^{-2}$ and 4.6 $k \cdot W \cdot m^{-2}$ using the operator ensemble and a long sleeve undershirt in the standing and walking configuration instead of the standard undershirt with short sleeve.

The exposure duration time for garment configurations varied between 300 s for operator's clothing at 10 $k \cdot W \cdot m^{-2}$ till 3,700 s for aluminized clothing at 10 $k \cdot W \cdot m^{-2}$ and were only terminated early for risk of damage to the manikin. As stated earlier data were collected at each heat flux sensor location at a rate of 2.5 Hz. In this article only surface skin temperatures calculated from the data measured by the heat flux sensors on the manikin's surface of torso, legs and arms were used to set the threshold for experience of pain. For every experimental condition the first two surface locations of the manikin that reached the pain thresholds are given in the results. The minimal time till the pain threshold was reached was considered to be representative for a safe operational time under the given experimental conditions.

Results

One of all heat flux sensors, number 70 (lower shin), did not measure properly and was marked during all experiments as invalid. No problems with the other sensors were detected.

In Table 1 maximum tolerance times till pain threshold are presented, which represent the time when the first mentioned heat flux sensors (between parentheses) reached the critical temperature for thermal pain.

Typical arbitrary graphs for the weak spots in the clothing ensembles that were limitative for pain threshold in a specific condition (6.3 $k \cdot W \cdot m^{-2}$ walking operator and 4.6 $k \cdot W \cdot m^{-2}$ standing firefighter (EN469)) are given in Fig. 3 and Fig. 4.

From Table I it can be seen that, as expected, the exposure time to pain generally decreases with increasing radiant heat load. Furthermore, exposure time increases with added protection, again as expected. And adding a long sleeve t-shirt also added the exposure time as expected.

The illustrative graphs for the weak spots in the clothing ensembles that were limitative for pain threshold in a specific condition (6.3 $k \cdot W \cdot m^{-2}$ walking operator and 4.6 $k \cdot W \cdot m^{-2}$ standing firefighter (EN469)) are given in Fig. 3 and Fig. 4.

Discussion

This data characterizes the properties of materials or assemblies in response to radiant energy under controlled laboratory conditions and are not representative to appraise the safety benefits or risk of protective materials, products, or assemblies under actual fire conditions.

The collected data are only the results of these specific laboratory exposures; extrapolations to other types of heat exposures or different combinations of radiant, convective and conductive exposures cannot be made without taking into account the unpredictable conditions during a real incident. On the contrary to the laboratory conditions, outdoor conditions are influenced by weather conditions as air temperature, wind (speed and direction) and relative humidity that can lead to variations in theoretically calcu-

Firefighter in standing position at 4.6k·W·m⁻²
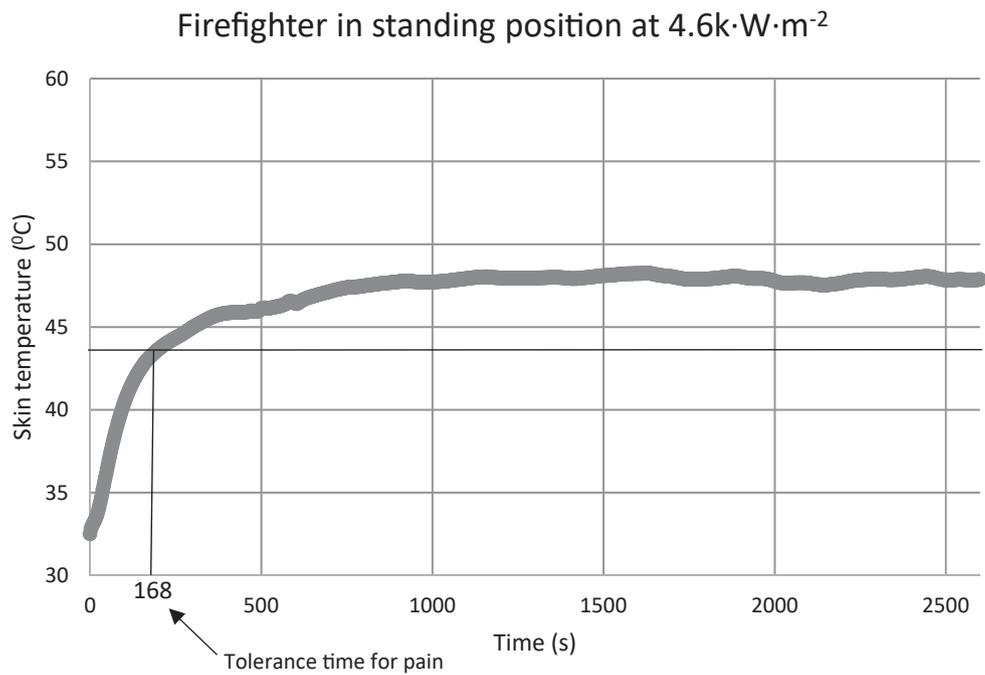
Fig. 3.   Increase in skin temperature at the right thigh (sensor 51) at a radiant exposure of 4.6 k·W·m⁻² in firefighter's clothing. The x-axis denotes the experiment time. The horizontal red lines indicate the time pain limit of 43°C is reached (tolerance time). In this case after 168 s.

Operator in walking position at 6.3k·W·m⁻²
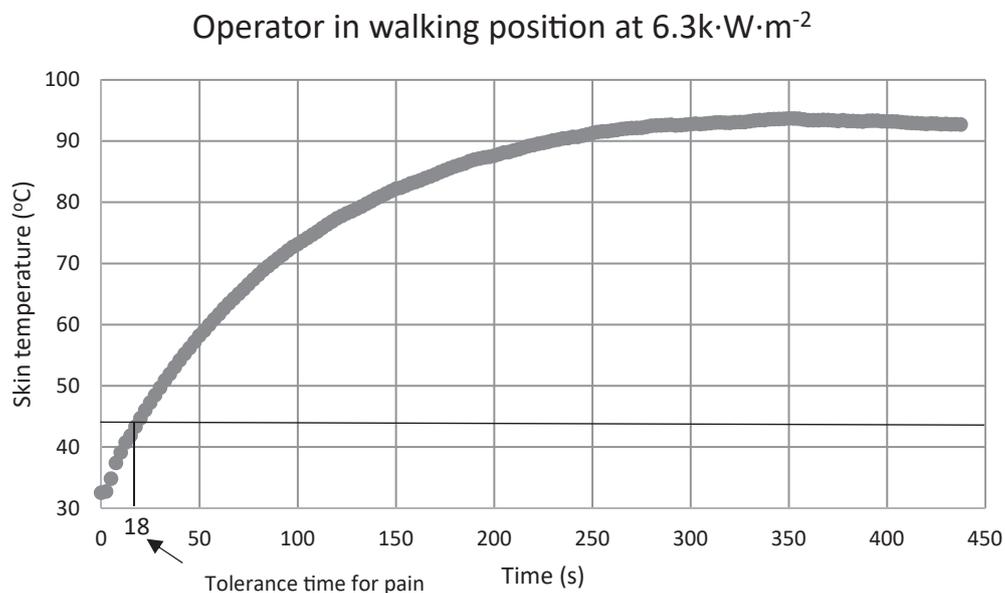
Fig. 4.   Increase in skin temperature of left knee (sensor 57) at 6.3 k·W·m⁻² in operator's clothing. The x-axis denotes the experiment time. The horizontal red lines indicate the time pain limit of 43°C is reached (tolerance time). In this case after 18 s.

lated heat radiation contours. Due to these weather variations, outside conditions can be more favourable or more unfavourable compared to the laboratory conditions. So the present data are not presented to predict all types of field conditions where the nature of the thermal exposures can be physically complicated and unqualified.

It is emphatically emphasized that it is not the intention of this study to recommend, exclude, or predict the suitability of any (commercial) personal protective equipment for a particular end-use during incidents in the (petro) chemical industry or other conditions with high radiation levels. The study merely intended to provide guidelines for safely carrying out necessary activities during an outdoor incident in the petrochemical industry.

The experience of pain was considered a good indicator to prevent from skin burns, without requiring reference to first, second or third degree burns of the skin, conform European legislation[7]. For safety reasons, when pain threshold is reached in less than 2 min (120 s) it is assumed that it is only possible to escape from such an area. In that case it is not possible to perform incident related work activities.

For operator's ensembles it would be possible to escape from a heat radiation contour between 3.0 and 4.6 k·W·m^{-2}, but it would not be allowed to perform work, because the tolerance time was only 20 s in walking position at 4.6 k·W·m^{-2}. Although in standing position the tolerance time was more than twice the time in walking position, the tolerance time was still much less than 120 s for both the 3.0 and 4.6 k·W·m^{-2} conditions.

In line with the previous study of Den Hartog and Heus[1] the present data showed that protection of standard workwear was not sufficient at heat radiation levels above 1 k·W·m^{-2} and 3 k·W·m^{-2}. As a result this study did not generate a need to change the present safe heat radiation contours for use of operator's clothing[1].

It was possible to perform incident related activities till 4.6 k·W·m^{-2} in firefighters clothing[13], but only if these activities did not last for more than about 3 min (168 s in walking and in standing position (173 s). So, compared to the previous study of Den Hartog and Heus[1] the maximum tolerable heat radiation level to perform incident related activities in firefighter's clothing[13] could be shifted from 3.0 k·W·m^{-2} to 4.6 k·W·m^{-2} for incident related activities lasting no longer than two min and 48 s. With firefighter's ensembles it was also possible to escape from a heat radiation contour between 4.6 and 6.3 k·W·m^{-2}, but it would not be allowed to perform incidence related activities.

Firefighters in aluminized clothing could perform emergency response activities up to 6.3 k·W·m^{-2}. So, for short term incident related activities it would be possible to increase the safe heat radiation contour to 4.6 k·W·m^{-2} in firefighters clothing and to 6.3 k·W·m^{-2} for employees with aluminized clothing. Although the experimental results with aluminized clothing showed that there seemed a limit

of about four min (250 s) in the walking condition, it was interpreted to be safe to set a maximum time of 5 min in this type of clothing. Reason for this extended exposure time was that only one sensor on the elbow exceeded the 43°C, but never exceeded 44°C (limit for skin burns). An additional argument for this expanded time limit was that no long sleeve shirt was worn underneath this aluminized clothing. So it would not be expected that the pain threshold would be reached within 5 min if proper underclothing is worn. Remarkable was that at 4.6 k·W·m^{-2} the tolerance time in walking position with aluminized clothing[14] was much shorter (160 s) compared to the values at 6.3 k·W·m^{-2}. However it was not likely that to be a realistic value, compared to the other results and these results were disregarded. This outlying data point does provide some insight into the measurement variability and some caution to the still somewhat limited size of this dataset. To further build confidence in the guidelines and these experimental data, more experiments with the Radman™ manikin would be most valuable.

As can be seen in Table I in general tolerance times in standing posture were longer than in walking posture as could be expected. In walking posture clothing had more contact points with RadMan™ compared to the standing posture. In this position the tolerance time was mainly determined at the upper leg. This is probably due to the direct contact of the protective clothing with the manikin. While in standing position the upper region of the body (breast and upper arms) is limiting for tolerance the heat, where clothing is more in contact with the manikin. The standing posture in general allowed more air layers between the clothing and the surface of RadMan™ which led to more insulation. However this was still not representative for real walking, because this would lead to a pumping effect of air through the clothing[17]. This effect can lead to lower or higher temperatures depending on the actual local air temperature that is pumped through the clothing. True dynamic studies with a moving manikin and/or with human subjects could give more information about these effects. So a further analysis of the present differences in skin temperature between walking and standing position are too speculative for the purpose of this study.

Some inconsistency was also observed in the data, e.g. the tolerance time (45 s) at 4.6 k·W·m^{-2} was lower than the tolerance time (68 s) at 6.3 k·W·m^{-2} in operator's clothing while standing. This was probably due to differences in how the clothing is draped around RadMan™ leading also to differences in air layers between the clothing and RadMan™. Because of the relative short tolerance times

with operator's clothing, these results did not really affect the guidelines. However also unexpected results were noticed with firefighter's clothing[12] in walking position showing a lower tolerance time (105 s) at 3.0 k·W·m^{-2} compared to 4.6 k·W·m^{-2} (173 s). This affected the previously set minimal time (120 s) for performing incidence related activities. In this case it was not allowed to perform activities in firefighter's clothing in walking position at 3.0 k·W·m^{-2}, but it was at 4.6 k·W·m^{-2}. Analysing all results it was decided to disregard the value at 3.0 k·W·m^{-2}. Additional experiments would be needed to further obtain confidence in the guidelines and decrease confidence intervals of the estimated safe working times.

As can be derived from Table I short term activities (up to two min), as opening and closing a valve or placing a mobile monitor, should be feasible with firefighter's clothing[13] up to the 4.6 k·W·m^{-2} contour. For essential activities at higher heat radiation levels it would be necessary to use specialized protective clothing (aluminized). However it should always be kept in mind the table was derived from ideal laboratory measurements. Real life working conditions would always somewhat affect these heat stress conditions so local judgement would always be required. The results as found in this study are in line with the requirements in prEN ISO23251[18] [1]. The guidelines in this report could also be used for other types of incidents accompanied by high heat radiation levels (e.g. wildland firefighting).

Though this study was focussed only on protective clothing, it must be kept in mind that also other necessary protective equipment as helmet, face protection, gloves and boots must be worn during incident related activities. Furthermore, as RadMan™ is not a human being and cannot sweat, the results of this study are only applicable for dry skin conditions. Effects of wetted underclothing (due to sweating of the person) on pain sensation may lead to an extension of the tolerance time[19]. Sweat can evaporate at the skin and extract heat from the skin leading to lower skin temperatures. So even at environmental temperatures much higher than 43°C skin temperatures can have lower values due to the evaporation process at the human skin.

Conclusions

The present data did not generate significantly different insights in maximum allowable heat radiation contours compared to a previous study to heat stress at different heat radiation contours[1]. In that study it was shown that firefighters could operate safely till 3.0 k·W·m^{-2} and operators till 1.5 k·W·m^{-2}. Additional to that study we now can conclude that short term operations (up to close to 3 min) with firefighter's clothing[13] are allowed till 4.6 k·W·m^{-2}. At higher heat radiation levels aluminized clothing[14] has to be worn.

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