Maximum allowable exposure to different heat radiation levels

Versie: 1.2, 25 april 2016

Instituut Fysieke Veiligheid
Facilitair Dienstencentrum
Postbus 7112
2701 AC Zoetermeer
Zilverstraat 91, Zoetermeer
www.ifv.nl
info@ifv.nl
079 330 46 00

Colofon

Opdrachtgever:	NEN
Contactpersoon:	Walter Reurink, MSc.
Titel:	Maximum allowable exposure to different heat radiation levels
Datum:	25-4-2016
Status:	final
Versie:	1.2
Auteurs:	Drs. Ronald Heus
Projectleider:	Drs. Ronald Heus
Review:	Dr. Ir. Jos Post
Eindverantwoordelijk:	Ing. Hans Versnel

Summary

In perspective of the revision of the directive PGS 29 ('Publicatiereeks Gevaarlijke stoffen' 29, Guideline for above ground storage of flammable liquids in vertical cylindrical tanks) there was a need to investigate the safe working conditions of first responders in the '1', '3' and higher kWm^{-2} heat radiation contours.

In a study performed by the Textile Protection and Comfort Center (T-PACC) in the College of Textiles at North Carolina State University (NCSU) three types of protective clothing (operator, firefighter and aluminized) were analysed at 4 different levels of heat radiation (3.0, 4.6, 6.3 and 10.0kWm^{-2}) in two different postures (standing and walking) with RadMan™. Time till pain threshold of 43°C is set as a criterion to stop regular activities.

Operators clothing does not fulfil requirements to serve as protective clothing for necessary activities at heat radiation levels above 1.5kWm^{-2} as was stated in an earlier study of Den Hartog and Heus (2006). If people with operator's clothing are situated in areas with higher heat radiation levels they should escape as quickly as possible from that area.
With firefighter's clothing (EN469) it is possible to perform activities with a duration of almost 3 minutes till 4.6kWm^{-2}. At higher heat radiation levels people wearing firefighter's clothing should move as soon as possible to lower intensity heat radiation levels. If activities at these higher levels are necessary to prevent from escalating an incident it is necessary to wear special aluminized firefighter's clothing. Till heat radiation levels of 6.3kWm^{-2} the limit in operating time is set at five minutes with aluminized clothing. Working at heat radiation levels of 10.0kWm^{-2} (emergency conditions) even with aluminized clothing is not allowed. Between heat radiation levels of 6.3kWm^{-2} and 10.0kWm^{-2} first responders with aluminized clothing should not perform activities and move immediately to an area with heat radiation levels of 6.3kWm^{-2} and lower.

Samenvatting

Vanwege de herziening van de richtlijn PGS 29 (Publicatiereeks Gevaarlijke stoffen '29, Richtlijn voor bovengrondse opslag van brandbare vloeistoffen in verticale cilindrische tanks) bestond de behoefte om de veilige werkomstandigheden van operators, bedrijfshulpverleners (BHV) en brandweermensen binnen de '1', '3' en hogere kWm^{-2} warmtestraling contouren nader te onderzoeken.

In een studie uitgevoerd door de Textile Protection and Comfort Center (T-PACC) van het College van Textiel aan de North Carolina State University (NCSU) zijn drie typen beschermende kleding (operator, brandweerman en gealuminiseerde) geanalyseerd tijdens 4 verschillende niveaus van warmtestraling (3,0, 4,6, 6,3 en $10{,}0kWm^{-2}$) in twee verschillende werkhoudingen (staan en lopen) met RadMan™. Tijd tot pijngrens van 43°C is vastgesteld als een criterium om reguliere activiteiten te stoppen.

Ui het onderzoek bleek dat operator's kleding niet voldoet om als beschermende kleding te dienen voor noodzakelijk geachte activiteiten tijdens stralingsniveaus boven de $1{,}5kWm^{-2}$ zoals eerder al in een studie van Den Hartog en Heus werd aangegeven. Als mensen met dergelijke kleding zich in gebieden met hogere stralingsniveaus straling bevinden moeten ze zo snel mogelijk uit dat gebied wegkomen.
Met brandweerkleding is het mogelijk om gedurende een kleine 3 minuten activiteiten uit te voeren tot een stralingsintensiteit van $4{,}6kWm^{-2}$. Bij hogere stralingsniveaus is een inzet met de standaard brandweerkleding EN469 niet toegestaan. Als toch activiteiten bij deze hogere niveaus gewenst zijn om te voorkomen dat een incident escaleert is het noodzakelijk om speciale gealuminiseerde brandweerkleding te dragen. Tot stralingsniveaus van $6{,}3kWm^{-2}$ kunnen gedurende 5 minuten incident gerelateerde werkzaamheden worden uitgevoerd in gealuminiseerde kleding. Werken bij stralingsniveaus van $10kWm^{-2}$ (noodsituaties) moet zelfs met aluminium verbonden kleding worden afgeraden. Bij stralingsintensiteiten tussen 6,3 en $10{,}0kWm^{-2}$ mogen geen incident gerelateerde activiteiten plaatsvinden en moeten mensen in gealuminiseerde kleding zich zo snel mogelijk naar gebieden met stralingsniveaus van $6{,}3kWm^{-2}$ en lager begeven.

Preface

The formal client for this study is NEN, but the study is also made possible by the Dutch Safety Centre Brandweer BRZO (LEC), VNCI, VNPI and VOTOB who sponsored this project. I want to acknowledge the following members of the advisory board of this project: Walter Reurink and Arie van den Berg (Dutch Safety Centre Brandweer BRZO (LEC)), Jan Maarten van Dixhoorn (VNCI)), Roger Slegt (VNPI), and René van Dort (Inspectie SZW)
The experimental phase of this study is performed by T-PACC of the Textile College of North Carolina State University, Raleigh USA and the interpretation of the data is done by the Knowledge Centre Occupational Safety of the Institute for Safety (IFV).

Index

1 Introduction

1.1 General

In perspective of the revision of the directive PGS 29 ('Publicatiereeks Gevaarlijke stoffen' 29, Guideline for above ground storage of flammable liquids in vertical cylindrical tanks) there was a need to investigate the safe working conditions of first responders in the '1' '3' and higher kWm^{-2} heat radiation contours. The '1' and '3' contours were originally meant for prevention of heat stress during longer duration firefighting and rescue activities. However there was a need to define safe exposure limits for short term emergency response actions (less than 15 minutes) during incidents in the (petrochemical) industry. In the report of Den Hartog and Heus (2006) it was already mentioned that injuries related to heat stress at short term activities were nihil, however they did not go into details on the risks of skin burns.

Stakeholders in the (petrochemical) industry (Bedrijfsleven VNCI; VNPI; Votob; NOVE (Equal split)) did want to take this into account in the revision of PGS29. So a study was proposed to look at 'short' term exposure of first responders to different levels of heat radiation based on realistic scenario's needed to diminish the escalating effects related to an incident. Starting point must be that incident related activities may not lead to harmful effects of the health and safety of the involved employees.

This study is meant to give guidelines for safe employment times under heat radiation exposure conditions not leading to health and safety hazards for the employees. Due to European legislation (Directive 89/686/EEC - personal protective equipment, 1989) health and safety of employees must always be guaranteed. So it is not allowable to mention at what time people can develop skin burns (health damage) (Matthews, 2016) despite the use of personal protective equipment (Article 2.1).

Article 2

1. Member States shall take all appropriate measures to ensure that the PPE referred to in Article 1 may be placed on the market and brought into service only if it preserves the health and ensures the safety of users without prejudice to the health or safety of other individuals, domestic animals or goods, when properly maintained and used for its intended purpose.

So in this report no reference will be made to development 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 (2013)[1] mention a maximum skin temperature for pain of 43-45°C. According to Rossi (2003) skin temperature can still increases even when the heat source has already been removed after notification of pain at 43°C, and therefore skin burns can occur when safety measures have been taken. In the frequently used diagram (Figure 1) of Hoschke (1981) it is shown that at $4.0kWm^{-2}$ heat radiation pain occurs within 15 seconds and within 30 seconds bare skin will burn. So without proper protection it is not possible to operate in environments with high heat radiation levels.

[1] http://www.arbozone.nl/11652/325-huidverbranding

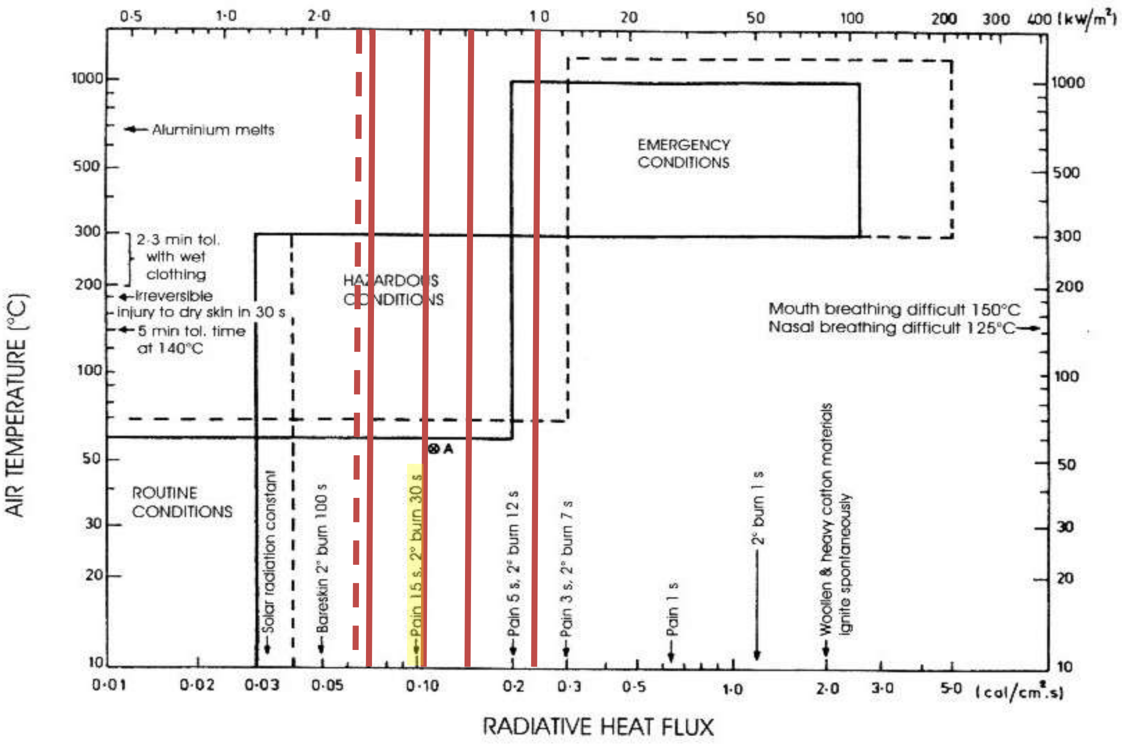

Figure 1 Firefighter's exposure conditions

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 (e.g. Hatton, A.P. and Halfdanarson, 1982; Stoll and Chianta, 1969).

1.2 Goal

The goal of this project is to conduct an experimental study on which both industry and government together focus on an assessment framework for (short-term) employment of personnel in an environment with increased heat radiation intensity at foreseeable actions during an incident.
For both governmental fire brigades and the industry the study must lead to useful information for employment of personnel during incidents on (petro)chemical plants. Of course the results of this study can be translated to other situations with high heat radiation levels (e.g. wildland firefighting, heat related firefighter training)

1.3 Research question

General question of the study is:

Can be determined to which combinations of time and intensity of heat radiation people with appropriate personal protective equipment may be exposed without experiencing pain?

To answer the above question we exposed a manikin clothed in diverse types of protective clothing to different heat radiation levels in different postures to determine after how much time the pain threshold is reached on a certain location of the body. So the aim of the study is to set tolerance times to prevent from damage of the skin during necessary activities in an incident in the (petro)chemical industry.

2 Materials and methods

2.1 Materials

Multiple ensembles were submitted to the Textile Protection and Comfort Center (T-PACC) in the College of Textiles at North Carolina State University (NCSU). These ensembles were evaluated for resistance to low level radiant heat exposures on a manikin.

2.1.1 Tested ensembles

The ensembles identified as '**Operator**', '**Firefighter**' (EN469), and '**Aluminized**' (EN1486) were tested as received, with a short sleeve cotton t-shirt[2] and boxer brief worn under each ensemble (Figure 2).

Figure 2 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

[2] In some experimental settings a long sleeve shirt was used, see paragraph 2.2.4

2.2 Methods

2.2.1 General

Measuring the amount of heat transfer a garment allows to a manikin during a low level radiant simulation can be expressed in multiple ways. This can be done by measuring the absorbed 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, if a sufficient amount of energy has been transferred, to predict either pain or skin burns (Appendix A), based on the calculated surface temperature rise of the skin and the temperature at the epidermal/dermal junction. Only results for time to safe skin temperatures (based on manikin surface heat flux) are given in this report, i.e. no skin burns prediction is allowed.
Tolerance times till pain are indicative for the moment skin burns can occur. The purpose of this study was to set a matrix of different levels of heat radiation against maximal employment time till pain is reached. Limit for pain is set by T-PACC at skin temperatures of 44°C. T-PACC will also provide the times to first, second and third degree burn values. However those data will not be integrated in this report, but will be given as an example in Annex A. Although workload is mainly of influence on the body core temperature, effects on the skin temperature are possible. However this variation in skin temperature is not taken into account in the experimental study, because of the uncertainty of effects on skin temperature. The influence of produced sweat on the tolerance time lead to an extension of time as was shown previously by Heus et.al (1992). Sweat on the skin has the possibility to evaporate and extract heat from the skin which is lowering the skin temperature. If necessary those effects can be studied later in an experimental study.
The results must be valid within an environmental temperature range of 0 till 28°C as can be normally expected in the Netherlands. Lower environmental temperatures usual lead to an extension of the tolerance time. That is why it is allowed to perform the studies at the ambient temperatures of the laboratory of T-PACC which was 23.9 till 29.4°C at the time of the experiments. The differences in temperature were inevitable due to the intensity of the heat radiation panel.

2.2.2 Scenarios

The scenarios are examples from the daily work practice. A set of realistic scenarios were provided to T-PACC. In Table I an overview of these scenarios are given.

Table I All proposed scenarios

RadMan™	Day 1	Day 2	Day 3	Day 4
	3 kWm^{-2}	4.6 kWm^{-2}	6.3 kWm^{-2}	10 kWm^{-2}
	Air temperature			
	0°C / 28°C	0°C / 28°C	0°C / 28°C	0°C / 28°C
Regular operators' personal protective equipment Regular firefighters' personal protective equipment Aluminized protective clothing	Standing/walking postures for max 5 minutes simulating: • manual opening / closure of a butterfly valve (1 min) • manual opening / closure of a 24 inch gate valve with a wheel clamp (3-5 min) • manual opening / closure of a 4 inch gate valve (1-2min) • manual tripping of a 'deluge system' (1 min) • placement of a mobile monitor or a vertical water screen (2-3 min)	Standing/walking postures for max 5 minutes simulating: • manual opening / closure of a butterfly valve (1 min) • manual opening / closure of a 24 inch gate valve with a wheel clamp (3-5 min) • manual opening / closure of a 4 inch gate valve (1-2min) • manual tripping of a 'deluge system' (1 min) • placement of a mobile monitor or a vertical water screen (2-3 min)	Standing/walking postures for max 5 minutes simulating: • manual opening / closure of a butterfly valve (1 min) • manual opening / closure of a 24 inch gate valve with a wheel clamp (3-5 min) • manual opening / closure of a 4 inch gate valve (1-2min) • manual tripping of a 'deluge system' (1 min) • placement of a mobile monitor or a vertical water screen (2-3 min)	Standing/walking postures for max 5 minutes simulating: • manual opening / closure of a butterfly valve (1 min) • manual opening / closure of a 24 inch gate valve with a wheel clamp (3-5 min) • manual opening / closure of a 4 inch gate valve (1-2min) • manual tripping of a 'deluge system' (1 min) • placement of a mobile monitor or a vertical water screen (2-3 min)
	Walking, bending and crouching postures for as long as possible reaching critical skin temperatures simulating: • handling sandbags (25 kg) for closure of ditch/gutter	Walking, bending and crouching postures as long as possible reaching critical skin temperatures simulating: • handling sandbags (25 kg) for closure of ditch/gutter	Walking, bending and crouching postures for as long as possible reaching critical skin temperatures simulating: • handling sandbags (25 kg) for closure of ditch/gutter[a)]	Walking, bending and crouching postures for as long as possible reaching critical skin temperatures simulating: • handling sandbags (25 kg) for closure of ditch/gutter[a,b)]

a) only in regular firefighters' personal protective equipment and aluminized protective clothing
b) only in aluminized protective clothing

Some of the activities in the scenarios in the above table are at static objects (e.g. manual opening/closure of a 24 inch gate valve with a wheel clamp by 2 persons and estimated time 3 to 5 minutes) and part of the activities are more flexible (placement of a mobile monitor or a vertical water screen (2-3 min). For practical feasibility by T-PACC changed the scenarios to a standing and walking posture to fit all measurements within the possibilities of their manikin (RadMan™). Although RadMan™ is flexible, he is not able to make real-time movements during the experimental conditions. Bending and crouching postures were removed from the experimental postures, due to the possibilities of RadMan™ and because of the lower height of these postures leading to a lower heat radiation exposure.

2.2.3 RadMan™

The evaluation was performed with a special manikin called RadMan™. The RadMan™ System consists of a number of components, designed to work together to measure the performance of protective clothing under low level radiant exposure conditions. The layout of the system is shown in Figure 3.

Exhaust Hood: RadMan™ and the natural gas fired radiant panel are housed under a large exhaust hood to evacuate by-products that could be released by the garments during a test exposure.

Water Chiller: RadMan™ has an active water cooled skin surface which is designed to simulate the skin surface temperature rise of humans. The water flow is kept at 32.5°C through the use of a chilled water system.

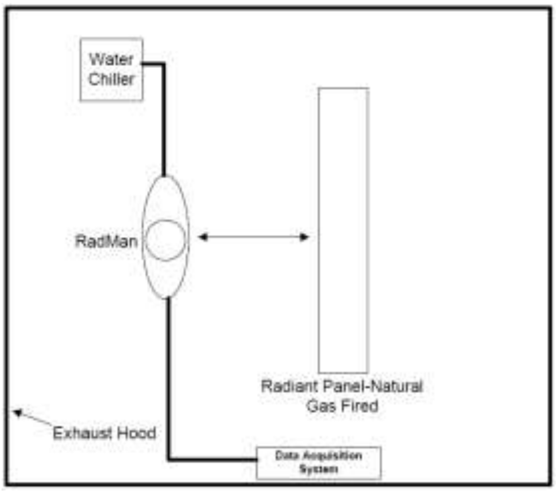

Figure 3 Layout of System Components

Radiant Natural Gas Panel: The radiant heat exposure is accomplished via a natural gas radiant panel, measuring 152,4 x 153,7cm (W x H) and situated 54.6cm from the floor. It consists of 28 individual panels, 4 rows and 7 columns.

Data Acquisition System: Data is acquired by the system at a rate of 10Hz and is used to calculate the incident heat flux, temperature rise of the skin, predicted burn injury for each sensor during and after the exposure, and to produce a report and graphics after each test.

RadMan™: The test manikin is based on the 50th percentile male CAD geometry, made from a high temperature epoxy composite shell structure, capable of withstanding incident heat flux of 8.4kWm^{-2} for 60 seconds. There are thin film heat flux sensors distributed along the front and right side of the manikin. (Figure 4)

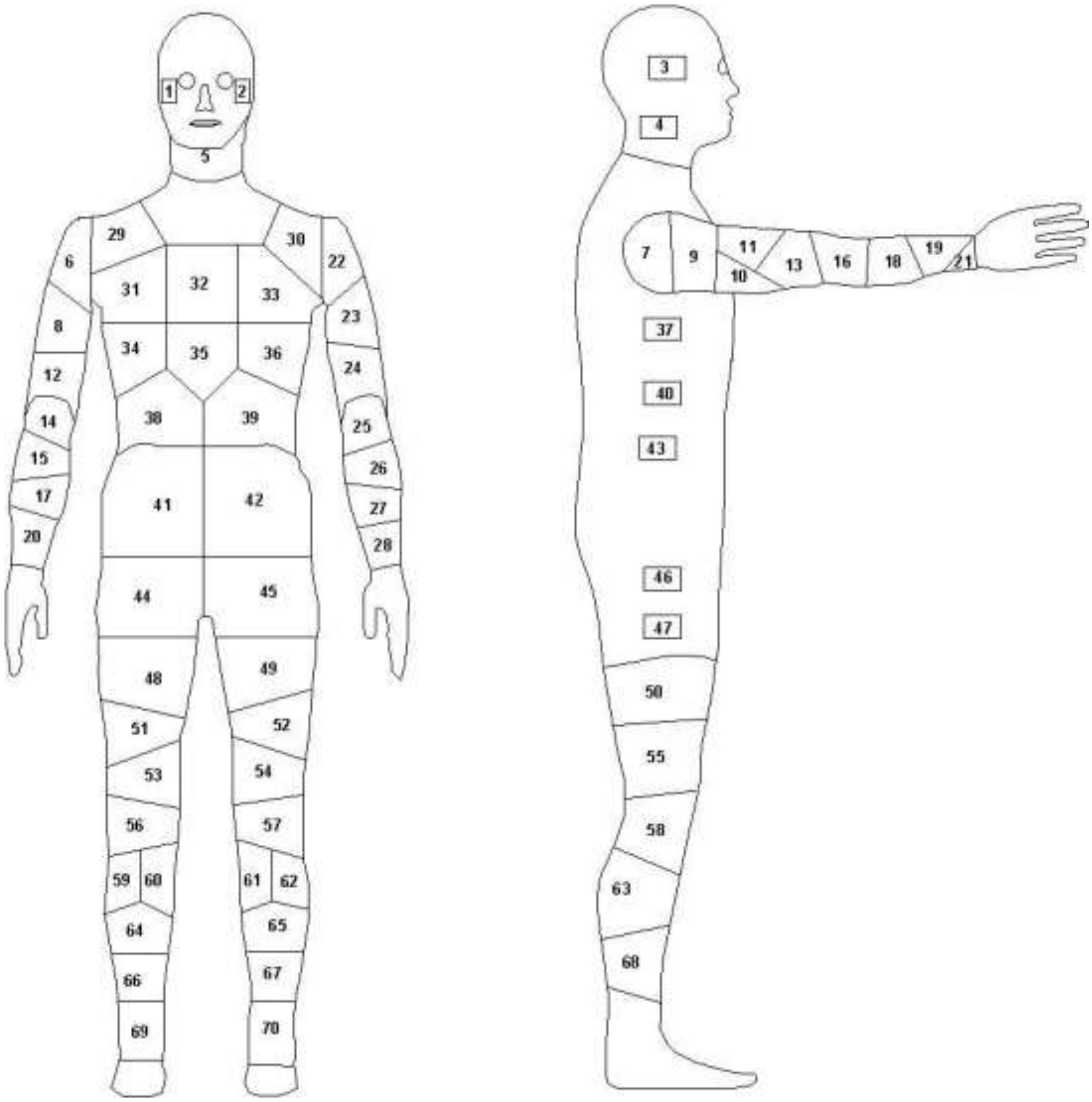

Figure 4 RadMan™ Sensor Locations

2.2.4 Experimental conditions

Incident radiant exposure conditions were set by placing the frontal portion of the manikin facing the gas fired panel for a period of 20, 15, or 10 seconds (dependent on the heat flux intensity) and measuring the absorbed heat flux via all 70 sensors. Because the manikin is not a flat surface the levels of heat flux can vary widely, so the sensors on the torso and the legs with the highest values were averaged and used to set the final incident heat flux. All ensembles were tested at radiant heat flux levels of 3.0kWm^{-2}, 4.6kWm^{-2}, 6.3 kWm^{-2} and 10.0kWm^{-2} as indicated in the Hoschke diagram (Figure 1) in standing and walking configurations (Figure 5).

Figure 5 Operator in standing posture, Aluminized in walking posture

Additional exposures were run at 3.0kWm^{-2} and 4.6kWm^{-2} using the operator ensemble and a long sleeve undershirt in the standing and walking configuration instead of the standard undershirt with short sleeve. One final exposure was run at 2.7kWm^{-2} with the operator ensemble, long sleeve t-shirt in the standing configuration. According to the diagram of Hoschke (1982) (Figure 1) all conditions are characterized as hazardous with the exception of the 10kWm^{-2} condition (emergency).

The exposure duration time for garment configurations were predetermined to be as long as possible without damaging the manikin and allowing the maximum possible amount of information to be acquired from the heat flux sensors. Tables II and III list the exposure times vs. heat radiation level vs. clothing configuration vs. working posture

Table II Maximum exposure times in seconds of different ensembles in standing and walking position (short sleeve undershirt) at four radiant heat levels

	Standing			Walking		
Exposure Level (kWm^{-2})	Operator	Firefighter	Aluminized	Operator	Firefighter	Aluminized
3	2000	2700	2700	2700	2700	2700
4.6	1800	2700	3000	1800	2700	3700
6.3	1200	2700	3700	1000	1800	3700
10	300	1800	3700	300	1200	3700

Table III Maximum exposure times in seconds of operator ensembles in standing and walking position (long sleeve undershirt) at three radiant heat levels

	Standing	Walking
Exposure Level (kWm^{-2})	Operator	Operator
2.7	700	-*
3	700	700
4.6	700	700

-* Testing was not done in the operator configuration-walking at the 2,7kWm^{-2} level

Data were provided with calculated values at each sensor location for surface skin temperature, epidermal-dermal junction temperature, and time between 32.5 and 44.0 degree temperature rise at the surface of the skin at a rate of 2.5Hz.

In this report only surface skin temperatures calculated from the data measured by the heat flux sensors on the manikin's surface of torso, legs and arms are used to set the threshold for experience of pain. The pain receptors are located in the epidermis above the epidermal-dermal junction (Figure 6) and fire earlier than skin burns occur. The calculated temperature of the epidermal-dermal junction is used for prediction of skin burns, which will not be used in this report.

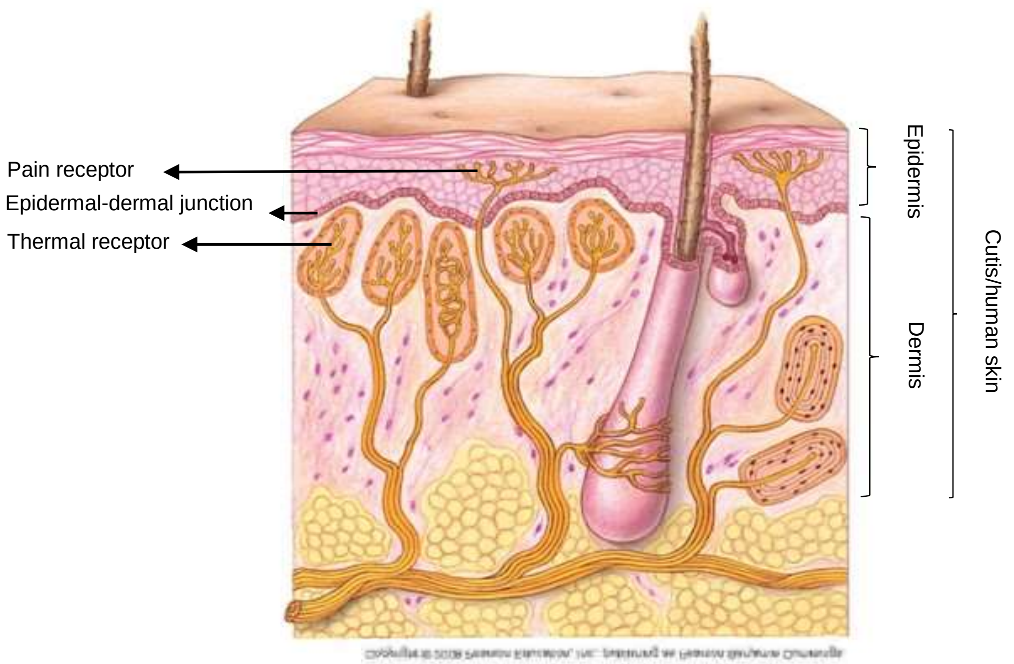

Figure 6 Detail of human skin with thermal and pain receptors

In figure 7 is shown which areas of the skin are damaged at different degrees of burning.

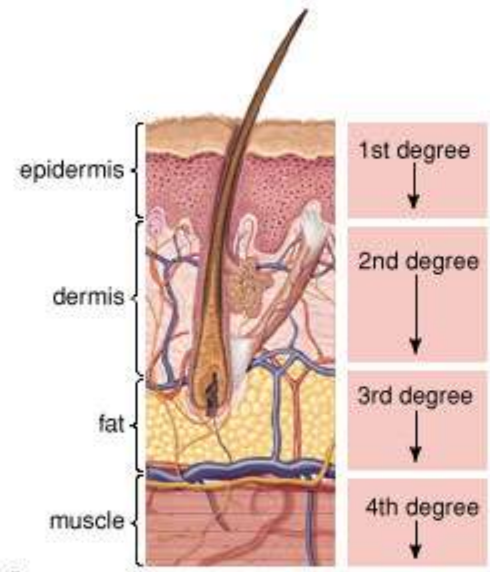

Figure 7 Degrees of burns of the human skin

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 is given as a safe operational time under the given experimental conditions.

3 Results

3.1 Introduction

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.

3.2 Tolerance times

In Table IV 'skin locations' on the manikin (Figure 4) are mentioned that reached critical skin temperatures for experience of pain during the exposure time.

Table IV Heat flux sensors (first and second one) at 'skin' locations[3] of RadMan™ that reached pain threshold (43°C).

Exposure Level (kWm^{-2})	Standing posture								Walking posture							
	Operator				Firefighter		Aluminized		Operator				Firefighter		Aluminized	
	Short sleeve		Long sleeve						Short sleeve		Long sleeve					
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
2.7	-	-	53	60	-	-	-	-	-	-	-	-	-	-	-	-
3	24	25, 54	14	54	31	14	X	X	11	61	56	57	54	57	X	X
4.6	14	23	51	60	51	14	X[1)]	X[1)]	61	54	57	51	53	60	66	62
6.3	11	24	-	-	31	23	X	X	57	54, 52	-	-	57	54	60	12
10	24	52	-	-	31	23	60	53	12	54	-	-	57	52	24	65

-: no measurements; X: no pain
[1)] Two sensors at this condition reached values just above 43°C, but stayed below 44°C (limit for skin burns).

In Table V maximum tolerance time till pain threshold was calculated when the first of the above mentioned heat flux sensors reached the critical temperature for thermal pain. An exception is made for the aluminized clothing, because no measurements were done with long sleeve undershirts in combination with this garment.

[3] For the exact locations see Figure 3 of this report.

Table V Maximum tolerance times (in seconds) till pain threshold (43°C) in seconds of different ensembles under the various heat radiation exposures in standing and walking position of RadMan™.

Exposure Level (kWm^{-2})	Standing posture				Walking posture			
	Operator		Firefighter	Aluminized	Operator		Firefighter	Aluminized
	Short sleeve	Long sleeve			Short sleeve	Long sleeve		
2.7	-	68	-	-	-	-	-	-
3	48	88	430	no limit	40	33	105	no limit
4.6	45	58	168	no limit[1)]	43	20	173	160[2)]
6.3	68	-	120	no limit[1)]	18	-	73	250
10	20	-	88	70	13	-	60	85

-: 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)

Typical arbitrary graphs for the weak spots in the clothing ensembles that were limitative for pain threshold in a specific condition (6.3kWm^{-2} walking operator and 4.6 kWm^{-2} standing firefighter (EN469)) are given in Figure 7 and Figure 8.

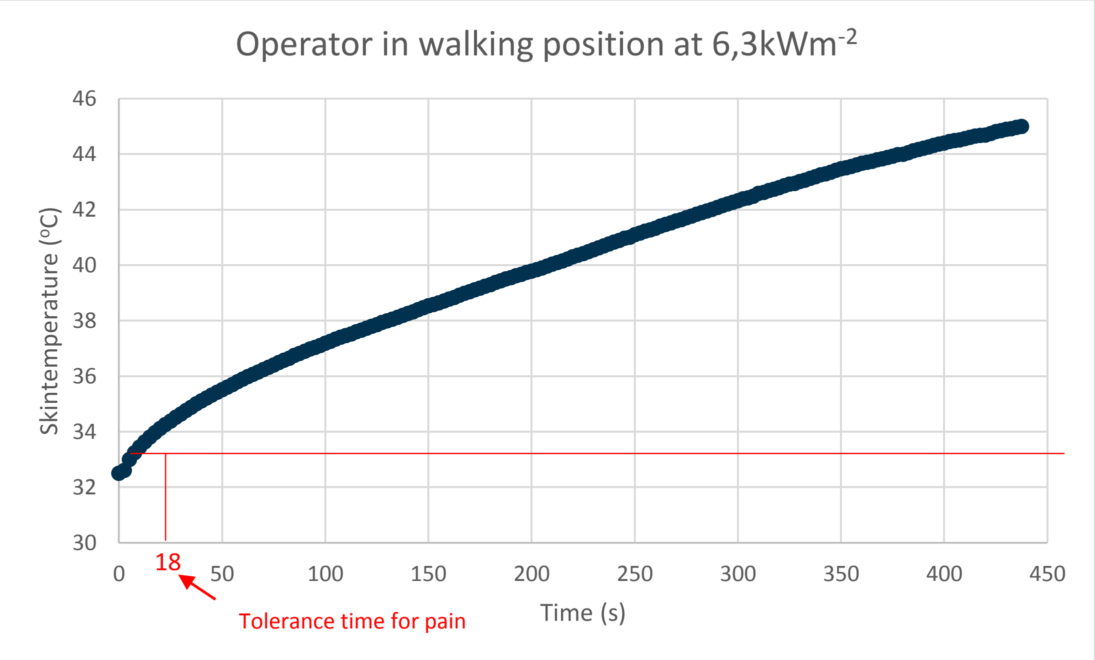

Figure 7 Increase in skin temperature of left knee at 6.3 kWm^{-2} in operator's clothing

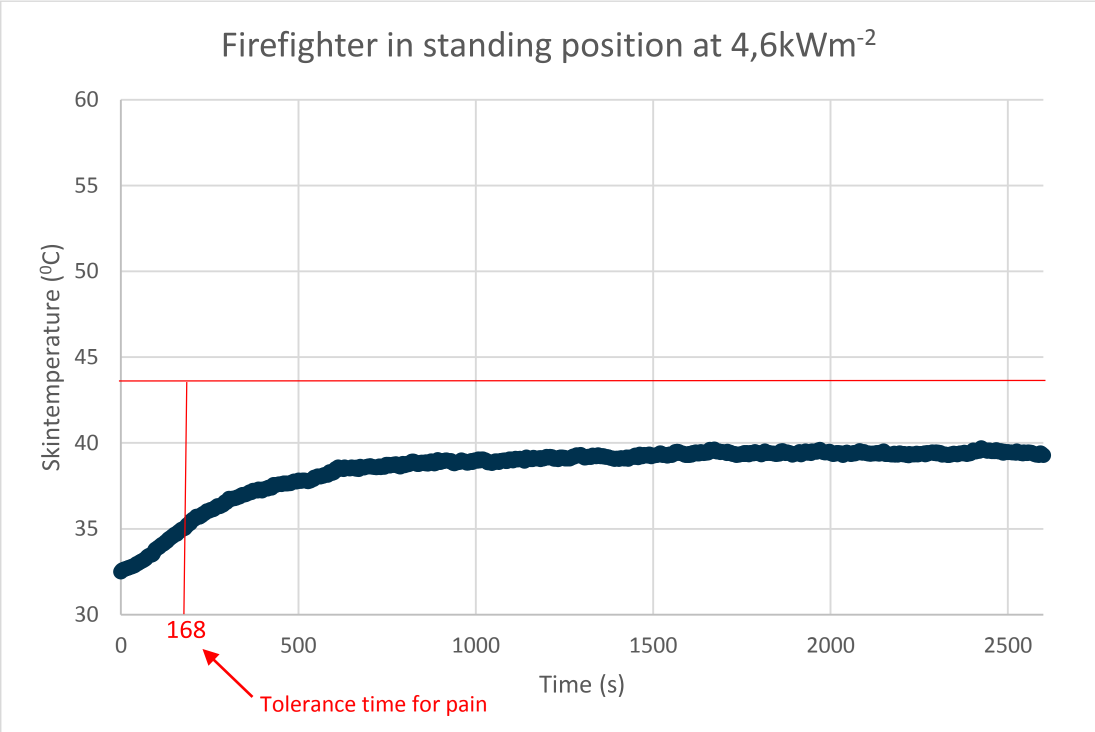

Figure 8 Increase in skin temperature of right thigh at 4.6 kWm^{-2} in firefighter's clothing

4 Discussion

These data characterize the properties of materials or assemblies in response to radiant and convective 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 specific laboratory exposures; extrapolations to other types of heat exposures or different combinations of radiant, convective and conductive assaults cannot be made without taken 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 calculated 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 is only mentioned to give rough guidelines for carrying out necessary activities during an outdoor incident in the petrochemical industry in order to prevent damage to health and safety of the employees.
That is why in this report the experience of pain is the upper limit for exposure to high radiant heat exposures. The experience of pain is a good indicator to prevent from skin burns No reference will be made to first, second or third degree burns of the skin. This is conform European legislation (Directive 89/686/EEC (1989)).
It is also important always to keep in mind that under actual fire conditions personal protective equipment is the last line of defence against the hazards of an incident (OSHA, 2006), when all other protection means are impossible to use or have failed.

Although no clear limit values are given for pain experience in literature, temperature values between 43 and 45°C are most common (Havenith and Daanen, 2013). However conform European legislation in this report the norm of 43°C is used as mentioned in EN-ISO9886 (2004) the international standard for pain at high temperatures. NCSU set the limit in their data files at 44°C (limit for skin burns). Where skin temperatures exceed 43°C it is mentioned in Table V. These are critical conditions, because it has been taken into account that protective clothing has a certain heat capacity that can still cause skin burns after removing the primary heat source as was stated by Rossi (2003).

For safety reasons, when pain threshold is reached in less than 2 minutes (120s) it is assumed that it is only possible to escape from such an area. In that case it is not possible to perform incidence related activities.

For operator's ensembles it is possible to escape from a heat radiation contour between 3.0 and 4.6kWm^{-2}, but it is not allowed to perform incidence related activities, because the tolerance time is only 20s in walking position at 4.6kWm^{-2}. Although in standing position the

tolerance is more than twice as long compared to walking position, the tolerance time is still much less than 120s for both the 3.0 and 4.6kWm^{-2} conditions.
In line with the previous study of Den Hartog and Heus (2006) the present data showed that more protection than standard workwear is needed at heat radiation levels of these intensities. So there is no need to change the present safe heat radiation contours for use of operator's clothing (Den Hartog and Heus (2006)) in the perspective of pain experience. Den Hartog and Heus (2006) reported that under medical supervision it is allowed to perform activities till 1.5kWm^{-2} related to heat stress. So for short term incidence related activities this level can be accepted in relation to pain sensation.

It is possible to perform incident related activities till 4.6kWm^{-2} In firefighters clothing (EN469), but only if these activities do not last for a duration a little less than 3 minutes (168s in walking and in standing position (173s). So compared to the previous study of Den Hartog and Heus (2006) the maximum tolerable heat radiation level to perform incident related activities in firefighter's clothing (EN469) has been shifted from 3.0kWm^{-2} to 4.6kWm^{-2} for incident related activities lasting for not longer than two minutes and 48 seconds. With firefighter's ensembles it is also possible to escape from a heat radiation contour between 4.6 and 6.3 kWm^{-2}, but it is not allowed to perform incidence related activities.

Firefighters in aluminized clothing can perform emergency response activities up to 6.3 kWm^{-2}. So for short term incident related activities it is possible to increase the safe heat radiation contour to 4.6 kWm^{-2} in firefighters clothing and to 6.3 kWm^{-2} for employees with aluminized clothing. Although the results with aluminized clothing showed that there is a limit of about four minutes (250 seconds) in walking condition it is safe to set a maximum time for incident related activities on 5 minutes in this type of clothing. Reason for this extended exposure time is 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 time limit is that no long sleeve shirt was worn underneath this aluminized clothing. So it is not foreseen that pain threshold will be reached within 5 minutes if proper underclothing is worn. Remarkable is that at 4.6kWm^{-2} the tolerance time in walking position with aluminized clothing (EN1486) is much shorter (160s) compared to the values at 6.3kWm^{-2}. However it is not likely that this is a realistic value compared to the other results. So this result is neglected in the final conclusions.

The results of this study showed that in aluminized clothing incidence related activities can be safely executed for a longer period than required for emergency response. However taking into account the people are in an hazardous environment there is chosen to limit the time in these conditions up to 5 minutes i.e. the time required to perform the foreseeable incidence related activities. However this limit has no direct relation with reaching the pain threshold and/or heat stress.
As can be seen in Table V in general tolerance times in standing posture are longer than in walking posture as could be expected. In walking posture clothing has more contact points with RadMan™ compared to the standing posture. The latter posture allows more air layers between the clothing and the surface of RadMan™ which lead to more insulation. However this is not representative for real walking, because real walking leads to a pumping effect of air through the clothing (Havenith et.al 1990). This effect can lead to lower or higher temperatures depending on the air temperature that is pumped through the clothing. Only studies with real subjects can give more information about this uncertainty.

As mentioned before some inconsistency is seen in the data. For example the tolerance time (45s) at 4.6kWm^{-2} is lower than tolerance time (68s) at 6.3 kWm^{-2} in operator's clothing while standing. This is 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 small tolerance times with operator's clothing these results do not really affect the guidelines for safe heat radiation contours with different levels of protection.
However also unexpected results are noticed with firefighter's clothing (EN469) in walking position showing a lower tolerance time (105s) at $3.0kWm^{-2}$ compared to $4.6kWm^{-2}$ (173s). This is of influence on the previously set minimal time (120s) for performing incidence related activities. In this case it is not allowed to perform activities in firefighter's clothing in walking position at $3.0kWm^{-2}$, but it is at $4,6kWm^{-2}$. Looking to all results it is decided to neglect the value at $3.0kWm^{-2}$. Only repeated measures of all conditions could give more insight in these deviating results. Due to the limited budget of the project and the length of one single measurement it was not possible to perform one or more replications of the conditions.

As can be derived from table V short term activities (up to two minutes), as opening and closing a valve or placing a mobile monitor, can be carried with firefighter's clothing (EN469 certified) till the $4.6kWm^{-2}$ contour. For essential activities at higher heat radiation levels it is necessary to use specialized protective clothing (aluminized). However it is important always to keep in mind that the table is constructed with data obtained from ideal laboratory measurements. Due to weather conditions the theoretically derived heat radiation contours can vary largely. The actual local weather conditions should always be kept in mind when first responders are employed during an incident in the petrochemical industry. The results as found in this study are in line with the requirements in prEN ISO23251 (2011)[4]. The guidelines in this report can also be used for other types of incidents accompanied by high heat radiation levels (e.g. wildland firefighting)

The present data to predict pain sensation to prevent from skin burns do not give significant other insights in maximum allowable heat radiation contours compared to a previous study to heat stress at different heat radiation contours (Den Hartog and Heus, 2006). In that study it was shown that firefighters could operate safely till $3.0kWm^{-2}$ and operators till $1.5kWm^{-2}$ (that model study took into account medical controlled conditions) Additional to that study we now can conclude that short term operations (up to two minutes and 48s) with firefighter's clothing (EN469) are allowed till $4.6kWm^{-2}$. At higher heat radiation levels aluminized clothing has to be worn. The acceptable working time under $3.0kWm^{-2}$ differed significantly in this study from the previous study of Den Hartog and Heus (2006), because that study was focussed on heat stress and did not took into account local skintemperatures and only averaged skintemperatures. Averaged skintemperatures in this study also did not exceed the critical valuers. So the lower tolerance time is based on possible local skin burns.

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.

The results of this study are applicable for dry skin conditions. Effects of wetted underclothing (due to sweating of the person) on pain sensation refer to Heus who showed that wetted underclothing led to an extension of the tolerance time (Heus et al 1992). 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.

The general research question can be partly answered. It is possible to give tolerance times to reach pain for different types of protective clothing and in different working postures as is

[4] Identical with API 521

shown in Table V, but due to the present inconsistency it is not possible to show a clear relation between tolerance time and heat radiation intensity for different types of protective clothing and working postures.

5 Conclusions and recommendations

The results of this study are applicable in case of incidents that have a stable course. . Sudden expansion of the fire or explosion in the scenarios leading to more dangerous situations is not foreseen.

This study showed that it is possible to set safe exposure times till pain is experienced for different combinations of protective clothing and heat radiation. However due to inconsistency in the data it is not possible to provide a diagram to set heat radiation intensity against time to pain threshold.

Based on this study we can draw the following conclusions:

- Operator's clothing should not be used for incidence related activities at all tested heat radiation levels. So the previously set values of 1.5kWm^{-2} can be maintained.
- With operator's clothing it is possible to escape within 20 seconds from areas with a heat radiation of 4.6kWm^{-2} and lower.
- From heat radiation levels above 1.5kWm^{-2} till 4.6kWm^{-2} at least firefighter's clothing (EN469) should always be worn during incident related activities..
- Firefighters in adequate protective clothing can work up till almost three minutes in a heat radiation contour of 4.6kWm^{-2}.
- It is not justified to perform incident related activities with firefighter's clothing (EN469) above heat radiation levels of 4.6kWm^{-2}.
- If necessary, for incident related activities at higher heat radiation levels than 4.6kWm^{-2} , specialized firefighter's clothing (aluminized clothing, EN1486) should be worn.
- With aluminized clothing (EN1486) till 6.3kWm^{-2} can be worked safely during incident related activities up to five minutes.
- It is not justified to perform incident related activities with aluminized clothing (EN1486) above heat radiation levels of 6.3kWm^{-2}.
- Because the data have been obtained under static laboratory circumstances, use of the results in daily practice should take into account adverse weather conditions (e.g. windy conditions) that may influence existing heat radiation contours.

To validate these results of this study to daily practice the following recommendations are given:

- Perform repeated measures with RadMan™, based on the results of this study.
- Study more heat radiation levels between 1.0 and 3.0kWm^{-2} and between 6.3 and 10.0kWm^{-2}.
- Gather heat radiation data of real incidents in the petrochemical industry.
- Gather heat radiation data of realistic training exercises.
- Perform a human subject study with heat radiation levels up to 6.3kWm^{-2} to validate the results of this study.
- Validate existing models with these data.
- Development of a dynamic manikin instead of a static manikin.

References

Directive 89/686/EEC (1989). COUNCIL DIRECTIVE of 21 December 1989 on the approximation of the laws of the Member States relating to personal protective equipment (89/686/EEC)

Den Hartog, E.A and Heus, R. (2006). Safe radiation contours at incident related to heat stress for first responders (in Dutch). TNO-rapport TNO-DV3 2006 C024, Soesterberg, the Netherlands (in Dutch).

EN 469 (2006). Protective clothing for firefighters - Performance requirements for protective clothing for Firefighting.

EN 1486 (2007). Protective clothing for fire-fighters - Test methods and requirements for reflective clothing for specialised fire-fighting.

EN-ISO 9886 (2004). Ergonomics - Evaluation of thermal strain by physiological measurements.

Hatton, A.P. and Halfdanarson, H. (1982). Role of Contact Resistance in Skin Burns, J. Biomedical Engineering, 4, 97-102.

Havenith, G., Lotens, W.A. and Heus, R. (1990). Resultant clothing insulation: a function of body movement, posture, wind, clothing fit and ensemble thickness, Ergonomics, 33(1), 67-84.

Havenith, G. and Daanen, H.A.M. (2013). Practical guidelines for the management of the risks of heat stress during work, 2e revised edition, 2013© Sdu (in Dutch).

Heus, R. et.al. (1992). A comparison of six fire fighter garments against a reference suit; simulated tests for general use and comfort. Rep. No. IZF 1992, C-12, Soesterberg, the Netherlands (in Dutch).

Hoschke, B.N. (1981). Standard and specifications for firefighters' clothing, Fire Safety Journal, 4(2), 125–137.

Matthews, D.G. (2016). Convenor of CEN/TC162/WG2 and convenor of CEN/TC162 JWG FFPPE[5]. Personal communication.

OSHA (2006). OSHA Factsheet. Personal Protective Equipment.

PGS 29 (2008).Guideline for above ground storage of flammable liquids in vertical cylindrical tanks (in Dutch).

prEN ISO 23251 (2011). Petroleum, petrochemical and natural gas industries - Pressurerelieving and depressuring systems (ISO/DIS 23251:2011).

[5] Joint Working Group Firefighter's Personal Protetcive Equipment.

Rossi, R. (2003). Fire fighting and its influence on the body, Ergonomics, Vol. 46 (10), 1017-1033.

Stoll, A. M. and Chianta, M. A. (1969). Method and rating system for evaluation of thermal protection, Aerospace Medicine, 40, 1232-1238.

Appendix A

Burn injury predictions with RadMan^{TM} at 6.3kWm^{-2} in standing position