Ergonomics of Protective Clothing

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Arbetslivsinstitutet
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Foreword

The European Directives on personal protective devices have increased the interest in protective and functional properties of work clothing and intensified standardisation work as well as stimulated research in areas with limited knowledge. There is a long tradition of research and information exchange in the Nordic countries on the subject. The NOrdisk KOordineringsgruppe om BEskyttelseskläder som TEknisk Forebyggelsesmiddel (Nordic Coordination Group on Protective Clothing as a Technical Preventive Measure) was founded in 1984. NOKOBETEF is an independent society of professionals from the Nordic as well as other countries. NOKOBETEF has since its foundation organised symposia in Copenhagen (1984), Stockholm (1986), Gausdal, Norway (1989), Kittilä, Finland (1992), and Elsinor, Denmark (1997).

The conferences have long had a good attendance from European countries and from overseas. The 6th Nokobetef conference was organised as the 1st European Conference on Protective Clothing to emphasize the European dimension. During the conference the European Society for Protective Clothing was founded. One of its first tasks will be to prepare for the 2nd conference to be held in Switzerland in 2003.

The proceedings of this conference cover a broad spectrum of the subject protective clothing. Emphasis was given to the ergonomics aspects, which is in line with the present interest and priorities of the European standardisation bodies (CEN). A functional and comfortable use of protective clothing is a key element for a succesful implementation of this kind of preventive and protective measures in the workplaces. A total of 77 papers are presented in this book. They represent a qualified source of new, valuable and useful information for the advancement of the knowledge and the application of protective clothing.

Solna in May 2000

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Past, present and future trends in protective clothing

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Introduction

Protective clothing has a long history. If not already the fig-leafs of Adam and Eve, at least the armour of ancient warriors and the medieval knights may be designated the first real protective clothing. For the purpose of this paper, however, we will not look so far to the past but we will concentrate on the last few decades, the time period during which the most of the development of modern protective clothing has happened. Anyhow, due to space limitations, this review will be far from complete. An extensive compilation of the past development of protective clothing has been presented several years ago in an issue of Textile Progress (Bajaj, 1992).

Protective clothing is used to achieve safety for people in professional and other sur-roundings. Safety is defined as "Freedom from unacceptable risk of harm" (ISO, 1986). The measures to achieve safety can be divided into three levels:

1. First of all, processes, equipment and products have to be made safe, which means that they have to be conceived in such a way that any risk of harm is excluded or spatially separated from the people involved.
2. If for any reason persons nevertheless have to come near to the source of risk, they have to be protected by appropriate protective equipment.
3. A last mean to avoid people being exposed to a risk is to put a warning sign in front of the source of risk.

From this concept we can see that the use of protective clothing is clearly not the first choice among the safety measures. However, it is nevertheless a very important measure and protective clothing of all kinds will in the future be of growing importance in the oc-cupational sector as well as in the field of leisure and sport.

After some general remarks, the technical development and trends will be shown at the example of two different types of protective clothing. The thermophysiological comfort of protective clothing, which is a very important aspect, will also be highlighted. A look at the test methods, standards and market development will conclude this review.

General remarks

Looking at the general tendencies in the development of protective clothing, one can see that in the beginning people were looking at the protective properties of normal clothing, which they then tried to improve in one way or other. If for example they realised that a clothing material had good thermal insulation properties and therefore offered certain protection against heat, they used this material for the whole garment and, if necessary, in a greater thickness. At a later stage, specialised materials with optimised protective properties were developed and used for the manufacture of protective clothing. These were the so-called technical textiles. Later it was realised how strong the influence of the

manufacturing on the protective properties of the ready-made garments is. Therefore, protective clothing is now developed more and more as a complete protective system, using modern materials, sometimes also the so-called intelligent materials. This trend will continue and even become stronger in the future.

Technical development and trends

Thermal protective clothing

Protection against convective (flames), radiative and contact heat, against sparks and drops of molten metal, against severe cold and frost is a prime requirement of protective clothing in occupational, leisure and sports application. Key properties of materials used in this domain are thermal conductivity, flammability and heat resistance. To achieve a high insulation of textile materials, it was soon realised that it is necessary to develop bulky materials with much air enclosed and with low compressibility. For protection against heat radiation highly reflective outer materials were used. The necessary insulation is determined by the limiting heat flow that does just not create harm to the wearer of the clothing. In the case of heat protective clothing it is the tolerance of human tissue against burn injuries (Stoll & Chianta, 1969). Most of the performance requirements of heat protective clothing are based on these values.

In order to reduce the flammability and increase the heat resistance – these two properties are strongly coupled – two different ways have been chosen. The first is to treat natural fibres, mainly wool and cellulosic fibres, but also not inherently flame-resistant man-made fibres chemically, in order to make them flame retardant. A lot of chemicals have been developed which fulfil this purpose. The other way is to develop inherently flame-resistant man-made fibres. In this field a lot of work has been done during the last decades: Aramid, PBI, Chlorofibres, carbon and mineral fibres to mention just a few. In the construction of protective clothing against heat and flame these chemically treated or inherently flame-resistant fibres were used for the complete clothing or at least for the outer shell, depending of the severity if risk the user is exposed to. In the last years also thermophysiological aspects have more and more been taken into account (see next chapter). This means that ways have been sought to get rid of the sweat and excessive body heat without neglecting the protective demands against external heat. This can be done either by including special openings or by using new, specially designed materials like phase change material (PCM) or materials with variable insulation or humidity absorbing capacity, so-called intelligent materials. Similar techniques apply for cold protective clothing with the exception that the use of heat resistant and flame-retardant materials is not necessary.

The trend in the future will go into the direction of complete multifunctional protection systems using optimised manufacturing techniques and new, intelligent materials. High attention will be given to thermophysiological aspects and other use properties.

Chemical protective clothing

Modern technological developments have brought with them a multifold increase in the kinds of chemical hazards to which a worker is exposed. These hazards range from liquids (spray), gases to dust occurring in sectors like chemical, pharmaceutical, petrochemical, electroplating industry and agriculture (fertilisers). They necessitate the wearing of clothing that is impermeable and resistant to chemicals, provides a tight seal against toxic gases, or filters dangerous dust. The big variety of hazardous chemicals and

the manifold of the application of these chemicals seem to create the necessity to develop an unlimited set of chemical protective clothing. One very essential step in the past developments was therefore to create a systematic classification of the necessary protection systems. The different ways of influence of the chemicals led to a series of about six types, some of them even subdivided, of protective clothing, ranging from totally encapsulated, gas tight suits to clothing protecting only parts of the body. The selection of the materials used for the manufacture of the clothing depends on the chemicals against which it has to protect. Here too a systematic of chemicals was created which divided them into a series of classes of substances having similar penetration, permeation and degradation effects on the materials. For all these effects also relevant test methods with appropriate levels of performance were developed and standardised. As it was soon recognised that it was not possible to find one material, which protects against all chemicals, new, multilayered material combinations were created which could offer a broad range of protection. In the manufacturing of the clothing new joining and sealing techniques were developed. For totally encapsulated suits ventilation and cooling systems were worked out which were stationary or portable, depending on the use of the suit. A big problem that had and will still have to be solved is the decontamination and/or the disposal of used. The fact that in many cases the disposal is easier than the decontamination led to the increasing use of single use disposable garments mostly made from nonwovens.

The trend in chemical protective clothing in the future will certainly go in two directions. One is the development of sophisticated, broad range protective systems using new high-tech materials and considering all aspects of use, wearing properties and decontamination. These products will be in the high-price segment. The other direction is the increasing use of cheap, single use, disposable garments for which the protective performance is optimised for one specific hazard situation.

Thermophysiological aspects

It has been highlighted already in different papers (Stull, 2000; Zimmerli, 1996 and 1998) that the thermophysiological properties of protective clothing are not, as the commonly used term "clothing comfort" would suggest, some kind of luxury, but that they have a very strong safety aspect. The higher the risk is, against which the clothing (e.g. fire fighters' clothing, totally encapsulated chemical protective suit) has to protect, the less permeable for body heat and evaporated sweat is the clothing. By this fact and the amount of work the wearer has to perform, the risk of heat stress becomes very great. At the end, it doesn't help the user that he wears a garment with a protection suitable for the external risks he is exposed, when the same garment on the other hand creates itself an internal risk of overheating the body by the excess of metabolic heat. The statistics of NFPA (Washburn et al, 1999) show that about 50 % of the fatal accidents of fire fighters in the USA are due to heat stress. So the modern design philosophy for protective clothing is concentrated on optimising protection and simultaneously making the wearer more comfortable and more productive. The trend for the future in this respect will also go in the direction of developing complete protective systems, using new, "intelligent" materials and considering the physiological aspects as much as the demands of protection.

Test methods and standards

There are different reasons why standardised test methods and performance requirements for protective clothing are necessary. The users of protective clothing need to be certain that they are sufficiently protected. The manufacturers want to show to the users that their product fulfils their needs of protection. And the test laboratories want to have approved and standardised test methods in order to get reproducible results and standardised performance requirements as a guideline for the certification of products.

The International Organisation for Standardisation (ISO) started to develop standards in the field of protective clothing in 1964 in the Technical Committee (TC) 94 "Personal safety - Protective clothing and equipment". In 1966 the Subcommittee (SC) 11 "Protective clothing against chemical products" and in 1968 SC 9 "Protective clothing against heat and fire" held their first meetings. In 1981 it was decided that SC 9 and SC 11 should be amalgamated to form the new SC 13 "Protective clothing". At present SC 13 consists of 6 working groups (WG).

When the European Community (EC) decided to establish the European common market by the end of 1992, the 'New approach' was formulated. The philosophy of this 'New approach' is that the EC does not establish detailed legislation on the rules for the common market but it restricts itself on the edition of the so-called 'New approach' directives. All the details are then regulated in harmonised European standards, which ensure that the essential requirements of the directive are fulfilled. In the field of personal protective equipment (PPE) there exist two 'New approach' directives, one (EEC, 1989/2) for the manufacturing and another (EEC, 1989/1) for the use of PPE.

As a consequence of the 'New approach', a mandate was given to the European Committee for Standardisation (CEN) by EG to establish harmonised European standards in the field of PPE. In 1989, among others, the CEN/TC 162 "Protective clothing including hand and arm protection and lifejackets" started to work. At present TC 162 has 12 WGs. In the last years efforts have been made to have identical standards in CEN and ISO. The "Vienna Agreement" between ISO and CEN, signed in 1991, is a tool to develop standards only once, to have parallel votes on identical documents in ISO and CEN and finally to have also identical standards.

In the United States, the committee F23 of the American Society for Standardisation and Materials, ASTM develops standards on protective clothing since 1977. The work is done in 9 different SCs. The National Fire Protection Association (NFPA) writes performance standards for fire fighters' clothing, based on test methods standardised by ASTM. A co-operation in the standardisation work between ISO, ASTM and CEN started several years ago. Since 1994, the chairmen of the relevant committees in the three organisations have regular meetings. However, it is much more difficult to have a similar co-operation as the one between CEN and ISO fixed in the Vienna agreement. This is due to different reasons. The main reason is that ISO and ASTM started their work independently and, as a consequence, two different sets of standards existed already when the co-operation started. A lot of laboratories had bought or built the test equipment based on their respective standards and it was unacceptable to either side to abandon its test methods and equipment. One way to overcome this problem has been tried in the ISO standard on protective clothing for fire fighters (ISO, 1999). Therein the CEN and NFPA standards are amalgamated, leaving to the user the choice, which test methods and corresponding performance requirements he wants to select. Another reason to render the co-operation more difficult lies in the different working procedures and standard format of ASTM in comparison with CEN and ISO. But certainly these differences may be over-

come and hopefully in the near future we will reach the goal to have only one set of standards for protective clothing all over the world.

The trend in the test methods followed the development of the protective clothing itself. At the beginning mostly material tests were used and in some cases these methods were widened to make the assessment of the properties of seams, joints and closures possible. The problem of standardised tests is always that they have, for the sake of reproducibility and repeatability, to be conceived so that the test conditions are far away from the conditions in real use (Zimmerli, 1996). In the last years more and more the understanding came up, that the complete protective clothing has to be tested, either in a practice test with test persons or with an instrumented manikin (Zimmerli, 2000). In addition, it will be necessary to assess the protective and the comfort properties simultaneously, because in most cases there is a strong interaction between both.

Market development

The following information on the market situation for protective clothing fabrics is based on a study which David Rigby Associates (DRA), Manchester, UK, made for the 1997 TechTextil Messe in Frankfurt. It shows that even on a relatively conservative definition, the European protective clothing market is substantial and continues to grow at an attractive rate. DRA estimate that over 200 million m^2 of fabric are consumed in Western Europe in the production of protective clothing, about 60 % thereof being nonwovens. Included in this figure are only the conventional types of protective clothing (against fire, heat, gas, chemicals, dust, particulate, NBC agents and extreme cold as well as high visibility clothing). Not considered in this compilation are the products for cut and abrasion protection (mostly gloves), for ballistic protection, foul weather clothing and protective garments for purely sporting applications. How these 200 million m^2 are distributed among the major product functions and end-use segments is shown in Table 1.

The medical sector represents by far the largest individual end-use sector in terms of fabric consumption. The trend in this domain goes in the direction of disposable nonwoven products with high level of barrier performance. In the industrial sector there is in Europe a steady decline of people working in traditional manufacturing and heavy industry and in addition a reduction of the exposure to risks at the workplace. On the other side there is an overall increase in the level of protection (more protective layers and/or higher performing products). Due to the more stringent regulations and the higher insurance liability of the employers, protective clothing is more generally used. As a consequence the conventional protective clothing against fire, heat, stab and abrasion forms still a considerable part of the overall consumption and will be growing in the future.

In order to have a general idea of the future development of the protective clothing market, DRA has made a forecast, the result of which is shown in Table 2.

For the purpose of this forecast protective clothing has been more broadly defined, including foul weather clothing and protective garments for non-occupational use. Two main trends can be seen from this forecast. The first is that the nonwoven consumption is growing at a much higher rate than that of "conventional" fabrics (knits and wovens). The second is that, although the European market is still growing at an attractive rate, some product/market segments will reach saturation, whereas the market in developing countries will show a faster expansion.

Table 1. Estimated West European Consumption of Fabric in Protective Clothing, 1996, (million m^2) (Davies, 1998).

Product function	End use	Public utilities	Military	Medical	Industry, construction, agriculture	Total
Flame retardant, High temperature	Woven/knit	5	2	-	15	**22**
	Nonwoven	-	-	-	-	**-**
	Total	5	2	-	15	**22**
Dust and particulate (Barrier)	Woven/knit	-	-	12	22	**34**
	Nonwoven	-	-	62	10	**72**
	Total	-	-	74	32	**106**
Gas and chemical	Woven/knit	1	1	-	4	**6**
	Nonwoven	3	-	-	47	**50**
	Total	4	1	-	51	**56**
Nuclear, biological, chemical (NBC)	Woven/knit	-	2	-	-	**2**
	Nonwoven	-	2	-	-	**2**
	Total	-	4	-	-	**4**
Extreme cold	Woven/knit	-	1	-	2	**3**
	Nonwoven	-	-	-	-	**-**
	Total	-	1	-	2	**3**
High Visibility	Woven/knit	11	1	-	3	**15**
	Nonwoven	-	-	-	-	**-**
	Total	11	1	-	3	**15**
Totals	Woven/knit	17	7	12	46	**82**
	Nonwoven	3	2	62	57	**124**
	Total	**20**	**9**	**74**	**103**	**206**

Table 2. Forecast annual growth rates for "Protective Clothing" consumption by product type, by region, 1995-2005, (% per annum, weight terms) (Davies, 1998).

	Knits/Wovens	Nonwovens	Total
Western Europe	2.5 %	7.7 %	5.7 %
North America	2.7 %	3.2 %	3.0 %
Rest of World	5.1 %	14.4 %	10.0 %
World Total	3.6 %	8.0 %	6.3 %

Conclusions

The development of protective clothing, as highlighted in this paper, showed a considerable improvement over the last decades. From the use of normal clothing with some protective properties until the conception of complex, multifunctional protection systems using sophisticated modern materials and manufacturing techniques was a long way to go. The variety of end use sectors has widened too in the course of time. Whereas in earlier times the occupational sector dominated, nowadays the use of protective clothing in the leisure and sports sectors has gained great importance. This is due to the fact that the modern society sets a high value on leisure activities and extreme sports.

On the technical side, the requirements protective clothing has to fulfil have become much more complex. When in the beginning only the protective function was dominating, today the combination of different, partly contradictory requirements like protection, comfort, fashion and other functional properties makes the development of a modern protective clothing a complex task. But, seeing which improvement of safety, health and quality of life it can produce, it is also a highly satisfying task.

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Integrated CAD for functional textiles and apparel

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Clothing requirements of modern consumers

Extensive consumer research has shown that modern consumers require clothing to not only look good, but also feel good in dynamic wear situations. The comfort and superior functional performance of clothing have been identified as the most important attributes demanded by modern consumers, especially under dynamic wear situations (Figure 1). It has been noted that sports buffs are focusing on functional products and classic style as fashion is now of secondary importance. A recent survey in the US showed that 81 % of US consumers signalled comfort as their top choice (Hong Kong TDC, 1999). In China, consumers ranked comfort in the top three most important attributes of apparel product. Therefore, comfort and functional performance have become a major focal point for manufacturers to gain competitive advantages in global apparel markets.

Over years of research, it has been found that clothing comfort consists of three major sensory factors: thermal-moisture comfort, tactile comfort and pressure comfort, as shown in Figure 2. The three sensory factors contribute up to 90 % of overall comfort perceptions, and the relative importance of individual factors varies with different wear conditions. For active sportswear, thermal-moisture comfort is the most important factor, followed by tactile comfort and pressure comfort. Thermal-moisture comfort is determined by the heat and moisture transfer behaviour of clothing during dynamic interactions with human body and external environment. Tactile and pressure comfort is related to the mechanical behaviour of clothing during wear. Therefore, heat and moisture transfer and the mechanical behaviour of clothing materials are the two major dimensions in determining the comfort and functional performance of apparel products.
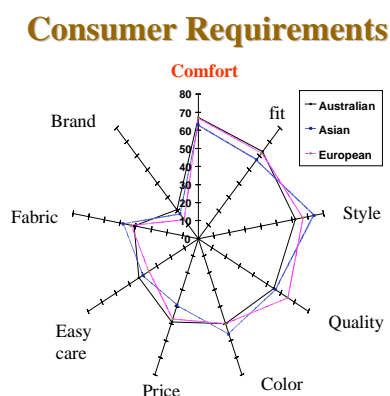
Figure 1. Clothing consumption requirements of modern consumers.
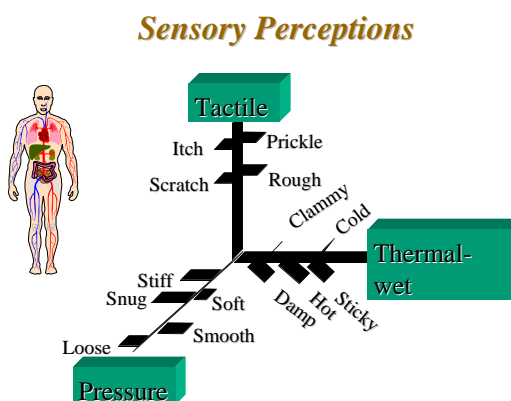
Figure 2. Sensory comfort of apparel products.

Computer technology has successfully been used in the textile and apparel industries, and CAD techniques are widely used for fashion and textile design. The main purpose behind the utilization of CAD is to increase productivity and flexibility during clothing

fashion design process. As modern consumers demand personal comfort, CAD for fashion design alone cannot satisfy the needs of manufacturers to develop functional and comfortable products that can meet the requirements of consumers. However, CAD for clothing functional design has not been developed and applied in fashion industry. One of the major reasons is that the heat and moisture transfer and the mechanical behavior of textiles and clothing are extremely complex. Sound scientific understanding and mathematical simulation of the coupled heat and moisture and fabric mechanical behavior are essential requirements for developing CAD technologies for the functional design of apparel and textiles.

CAD for fashion design

Obviously, fashionable outlook of clothing is a major attribute that influences the psychological comfort and satisfaction, as well as the purchase decision of consumers. There are a number of dimensions in fashion design such as colour, texture, pattern, drape (or appearance) style and fit. Colour, texture and pattern are important components of artistic creativity during design processes, which have been enhanced successfully by CAD technology for textile design and directly linked to printing and dyeing processes. Commercial technological packages including software and hardware have been developed and applied successfully in fashion industry. Fabric drape is more difficult to be simulated and visualized by computing technology alone, as it is determined largely by the mechanical behaviour of clothing materials and its dynamic interaction with the body and external mechanical forces such as air movement. There is some CAD packages providing artificial simulations by computing image manipulations without considering the mechanical behaviour of clothing materials. Extensive research activities have been carried out around the world to develop numerical simulation of the drape effect on basis of fabric mechanics.
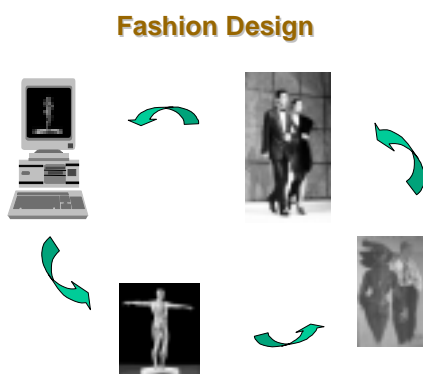
Figure 3. 3D CAD technology for fashion design.
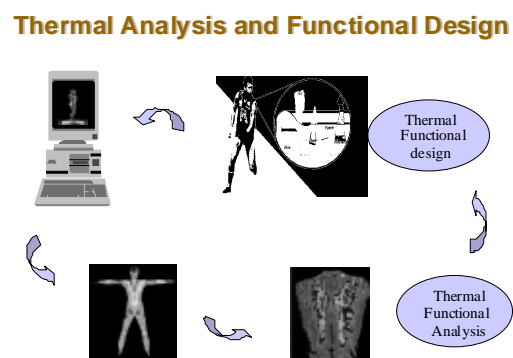
Figure 4. CAD technology for thermal functional design.

The effect of style and fit is related to body size and shape, 2D fabric cuttings and 3D wrapping to human body, as well as the mechanical behaviour of clothing materials. To simulate and visualize the 3D effect, we need measuring body size and generate 3D geometric body shape (i.e. numerical geometric human model), on which 2D fabric cuttings determined by style and fit can be wrapped. By adding on the effects of colour, pattern, texture and drape, designers and/or consumers are able to view the artistic and fashionable effect. Extensive R&D activities have been in both academic institutions and commercial organizations to develop such technology.

CAD for thermal functional design

On the basis of the numerical geometric human model, a model simulating the thermo-regulation of human body (i.e. numerical thermal human model) needs to be developed. The numerical thermal human model will be integrated with the model of heat and moisture transfer in clothing materials and in the external environment to simulate the heat and moisture generation and transfer processes of the body-clothing-environment system as the basis of thermal functional design.

Using such a numerical simulation system, we are able to investigate the influence of fibers, fabrics, clothing, the physical activities of the body and external environment on the thermal comfort and functional performance, as shown in Table 1. The mathematical models developed and improved by various researchers such as Henry (1939) and Farnworth (1986) to describe the complex coupled heat and moisture transfer in textiles have laid a sound scientific basis to achieve this goal. For instance, Li and Holcombe (1998) interfaced a fabric heat and moisture transfer model with Gagge's two-node thermo-regulatory model of the body to investigate the impact of fiber hygroscopicity on the dynamic thermoregulatory responses of the body during exercise and on protection of the body against rain.

Table 1. Input and Output variables in thermal functional design

Input variables	Output variables
• Fiber structural and properties, such as fiber diameter, fiber density, moisture sorption isotherm, heat of sorption, and water diffusion coefficient, specific heat;	• profile of temperature in the fabric;
• Fabric structural and thermal properties, such as thickness, porosity, tortuosity, thermal conductivity and volumetric thermal capacity;	• profile of moisture content of fibers; • profile of moisture in the air of the fabric void space;
• Skin thermal properties: thickness, thermal conductivity, water diffusion coefficient, volumetric thermal capacity;	• profile of temperature at the skin surface; • the neurophysiological responses of thermal receptors in the skin;
• Ambient boundary conditions: temperature, relative humidity and air velocity;	• Intensity of subjective perception of thermal and moisture sensations.
• Style and fit of apparel products.	

CAD for mechanical functional design

On the basis of the numerical geometric human model, a model simulating the biomechanical behaviour of human body (i.e. numerical mechanical human model) needs to be developed. The numerical mechanical human model will be integrated with the model of fabric mechanics to simulate the dynamic mechanical interactions between the body and clothing. Using such clothed numerical mechanical human model, similar to thermal function design, we are able to study the effect of structural and mechanical properties of fibers, yarns and fabrics, and clothing style and fit on the mechanical comfort and functional performance of apparel products (Figure 5). The extensive research on modeling fabric mechanics in the last century has laid down a sound scientific knowledge foundation to achieve this aim. For example, Zhang and Li et al (1999) studied the physical mechanisms of woven fabric bagging and developed mathematical simulation of fabric bagging behavior. During bagging, fabrics are exposed to sophisticated multi-dimensional deformation inserted by the contact force from human body parts such as the knees. The understanding of physical mechanisms and modeling methodology of fabric bagging can be applied to simulate the mechanical behavior of garments and mechanical comfort of the wearer by modifying the boundary conditions and specifying different fiber mechanical properties and fabric structural characteristics.

Mechanical Analysis and Functional Design
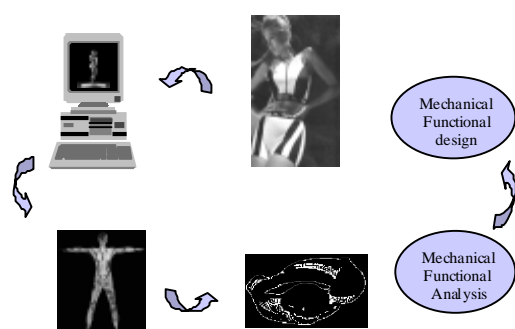
Integrated Design

Figure 5. CAD technology for mechanical functional design.
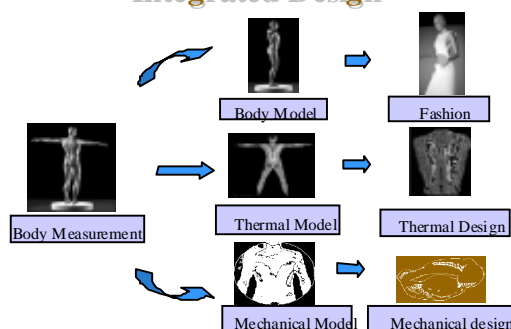
Figure 6. Integrated CAD technology for design of functional apparel products.

Integrated CAD technology

The fundamental research in modelling and simulating the heat and moisture in textiles and fabric mechanics has establish a good foundation to develop integrated CAD, which is able to introduce science into the apparel design process. By integrating the CAD technologies for fashion design, thermal functional design and mechanical functional design, we are able to reveal the outlook, the comfort and functional of clothing before it is actually made, as shown in Figure 6. Using the mathematical models with advanced computational techniques, we are able to simulate the dynamic heat and moisture transfer processes from the human body and clothing to the environment, and the dynamic mechanical interaction between the body and clothing. The simulation results can be visualized and characterized to show the dynamic temperature and moisture distribution profiles in human body, clothing and environment and stress distributions in clothing and on the body. Thus, we are able to demonstrate how changes in physical activities, environmental conditions and/or different design of clothing will influence the thermal and mechanical comfort of the wearer. Therefore, on the basis of the scientific mathematical models we can develop integrated CAD technologies that are workable as advanced engineering design tool for textile and clothing industry.

Acknowledgement

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Influence of air permeability on thermal and moisture transport through clothing

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Introduction

The physiologic properties of clothing are usually assessed under well-defined conditions. In practice however, the climatic conditions can change quite rapidly and influence the insulation of the clothing. Depending on the air permeability of the clothing, wind will more or less go through the textile layers and favour the release of heat and the evaporation of moisture. This effect of wind will change the range of use of clothing and can therefore cause a hypothermia of the body.

The goal of this study was to analyse the effect of wind on the thermal insulation and the water vapour permeability of ready-made, single-layered garments. For the measurements, a "sweating arm" was used.

Identical sleeves were made from fabrics with different air permeability, put on the sweating arm and exposed to different climatic conditions (variable temperatures, relative humidity and wind speeds). The heat loss was assessed either in dry conditions or with release of moisture and correlated to the air permeability of the fabrics.

Methods

Test apparatus

For this study, the sweating arm (Weder et al., 1996) was used, that corresponds from its dimensions and geometry to a man's arm. It is usually heated up to 35 °C, corresponding to skin temperature and releases moisture in vaporous form. As the measurements are made under non-isothermal conditions, the effects of condensation in the textile layers can be assessed. The apparatus is divided into five parts, which can be heated up to defined temperatures (usually 35 °C). Additionally, the forearm and the upper arm can "sweat", that is they are equipped with different nozzles, which can release as much water as a human being would. The humidity can be released in liquid or vaporous form.

The water supply is regulated through two pumps for the two parts of the arm. The supplied water is absorbed by a cotton fabric and distributed homogeneously over the whole surface. A cellophane foil is placed as outermost layer to avoid that liquid water comes into contact with the fabric sample and to obtain a moisture release only in vaporous form.

In order to avoid the loss of heat through conduction, the sweating arm is protected by two guards placed at both ends of the arm. The guards can be heated up to the same temperature as the arm to avoid heat exchanges by conduction. The effect of wind is simulated by a fan. 4 different wind velocities (1, 2, 4.4 and 13.3 m/s) and 3 different outside temperatures (5, 15 and 20 °C) were chosen to analyse the effect of wind on thermal and mass transfer, and the influence of condensation in the sleeves. The sleeves were closed at both ends to avoid any transfer through the openings.

Samples

Identical sleeves were made of seven different polyester fleece fabrics. The air permeability of the fabrics was determined according to EN ISO 9237 and is shown in Table 1.

Table 1. Air permeability of the samples.

Sample	IA	IB	IIA	IIB	IIIA	IIIB	IIIC
Air perm. in l/m²s	225	> 950	252	647	149	0	250

Results and discussion

Thermal resistance

Depending on the air permeability of a fabric, wind will change the convective heat flow around the sample, but also penetrate the fabric and disturb the still air layers in the microclimate between the arm and the sample. The influence of wind on a cylindrical sample is not the same as on a flat one as wind can pass round the same in the first case but must pass through the fabric in the other. Furthermore, the heat loss is not symmetrical: while it is very dependent on the wind speed on the windward side, heat loss on the lee (opposite) side is relatively low and insensitive to the wind (Kind et al., 2000).
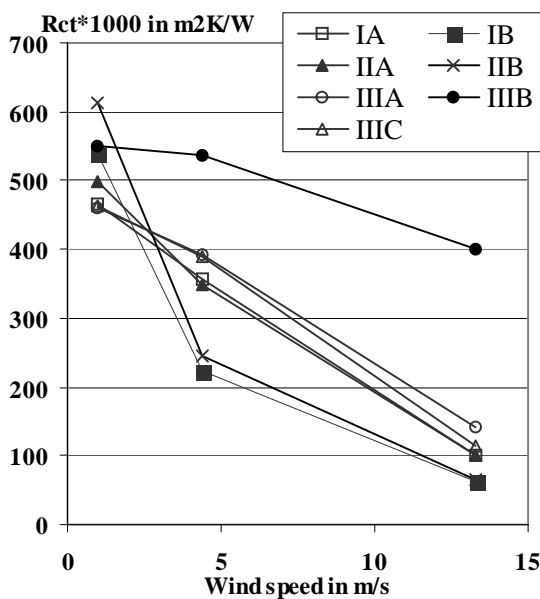
Figure 1. Thermal resistance at different wind speeds.
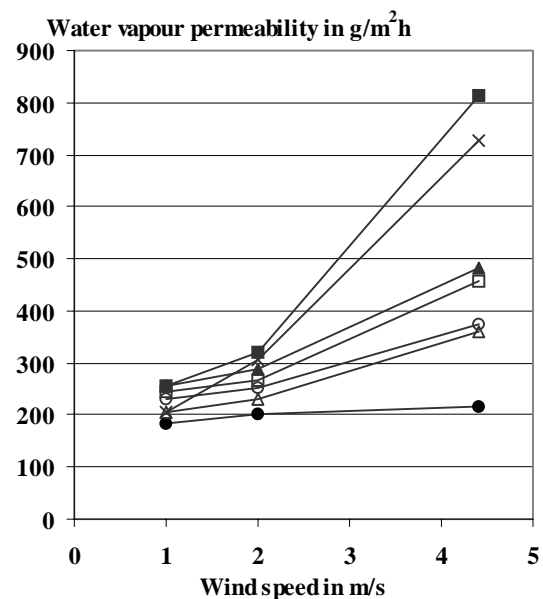
Figure 2. Water vapour permeability at different wind speeds.

The reduction of insulation of the different samples is dependent on their air permeability (Figure 1). Sample IIIB with an air permeability of 0 l/m²s has the lowest reduction in thermal resistance whereas samples IB and IIB have the highest. Sample IIB has only about 10 % insulation left at 13.3 m/s compared with 1 m/s. The reduction of the thermal resistance with the wind speed is nearly linear for the samples with air permeabilities between 150 and 250 l/m²s (IA, IIA, IIIA and IIIC).

Water vapour permeability

The moisture transport behaviour of the different sleeves was similar to the one of thermal transfer (Figure 2). The samples with the higher air permeability had the highest increase of water vapour permeability with increasing wind speed. Stuart et al. (1983) developed a model that describes the heat and moisture loss from a cylinder as depending linearly on the air permeability and on the second power of the wind velocity. Lamb et al. (1990, 1992) used a more complex model that depended, among others, on material parameters as thickness and thermal conductivity as well as physical constants of the air as the viscosity or the density.

The results of the present study (Figure 2) showed that the relationship between water vapour permeability and wind speed can be approximated quite well with a polynom of second order for low to moderate wind speeds (<10 m/s). For higher wind speeds, the increase slowed down for the samples with high air permeability (IB and IIB) as the sweat release of the sweating arm could not rise indefinitely.

The relationship between the moisture transfer (as well as the heat transfer) and the air permeability can very roughly be approximated by a linear curve (Figure 3) as suggested by Stuart et al. (1983), although an equation of the following type gives more precise results:

$$WVP = k1 + k2 \cdot (AP)^n \text{ with n between 0 and 1 (k1, k2: constants) (Equation 1)}$$

(WVP: Water vapour permeability, AP: Air permeability)

$y = a1 + a2*(AP)^{0.26}$
$R = 0.99$

$y = b1 + b2*(AP)^{0.73}$
$R = 0.98$

$y = c1 + c2*(AP)^{0.49}$
$R = 0.92$

$y = d1 + d2*(AP)^{0.003}$
$R = 0.66$

Wind speed: ◆ 1 m/s ▲ 2 m/s × 4.4 m/s ■ 13.3 m/s
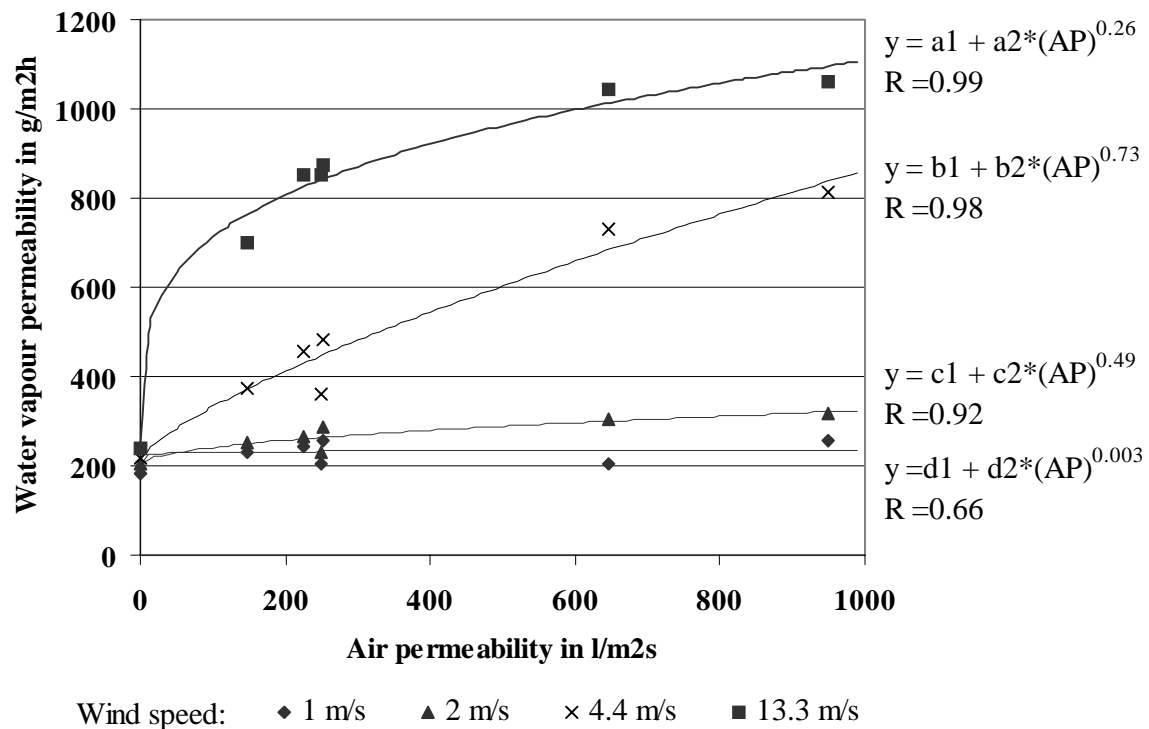
Figure 3. Water vapour permeability in dependence of the air permeability (measurements at 20 °C, 65 % RH).

The results of water vapour permeability were nearly identical for the three outside conditions (20, 15 and 5 °C), although the amount of condensation was logically much higher for the tests at 5 °C (over 100 g/m^{2}h) for some samples) than for the other two atmospheric conditions. The permeability of the samples was therefore not disturbed by the moisture uptake of the materials for the whole duration of the test (40 minutes). It can

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nevertheless be foreseen that with a longer test duration, the condensed moisture would create a barrier to humidity.

Influence of air layers within the clothing system

The correlation between a standardised test to determine the water vapour resistance (sweating guarded hot plate according to EN 31092) and the sweating arm were assessed for different fabrics for fire fighter's clothing (Rossi, 1999). The measurements on the upper arm alone (without air layers) were made under the same climatic conditions as required by EN 31092 (35 °C, 40 % RH) but with a wind speed of 2 m/s instead of 1 m/s with the sweating guarded hot plate.
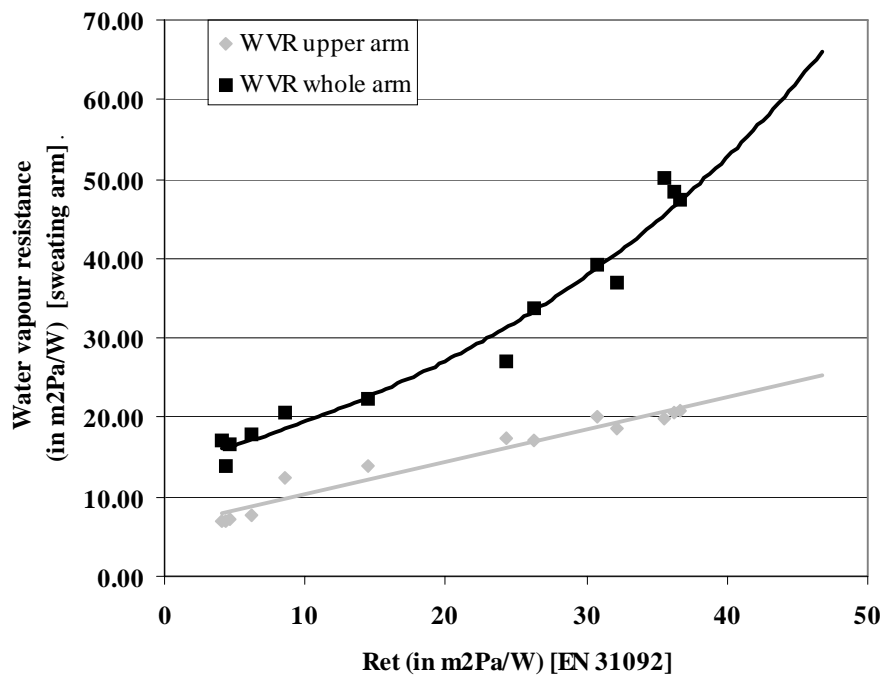
Figure 4. Water vapour resistance (WVR) on the sweating arm compared to the standardised test according to EN 31092.

There is a good correlation between the upper arm measurement and the standardised test (Figure 4, correlation coefficient R = 0.97). The values on the upper arm are lower than the standardised test, confirming previous findings (Meinander, 1985). This is due to a possible chimney effect and a larger outer surface of the sample onto the cylinder. The results are less differentiated with the upper arm (between 7 and 21 m^2Pa/W) than with the plate (between 4 and 36 m^2Pa/W). This could be due to the fact that the still air layer is completely removed on the plate whereas the wind flow passing round the upper arm will not ideally remove the air layer as the wind was only generated from one direction.

The relationship between the water vapour resistance on the plate and on the whole arm seems not to be linear any more and shows an exponential tendency. A possible explanation of this outcome is that the measurements on the whole arm were made under non-isothermal conditions (outside climate: 20 °C and 65 % RH). When the resistance of the material increases, there will be more and more condensation during the non-isothermal tests and the moisture amount released to the environment may decrease.

Conclusions

In this study, a relationship between the air permeability and thermal and water vapour resistances could be established. Nevertheless, the dependency of the water vapour permeability with the air permeability is not generally valid. Especially if several windtight materials were used, the results would have been totally different.

It has also been shown that the relationship between the water vapour resistances measured with air layers (sweating arm) and without air layers (only upper arm or sweating guarded hot plate) is not linear, even if the making of the sleeves is identical. Under identical atmospheric conditions, however, the results on a cylindrical apparatus (upper arm of the sweating arm) correlate very well with the results on a flat plate (sweating guarded hot plate).

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New algorithms for prediction of wind effects on cold protective clothing

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Introduction

The European Pre-Standard for protective clothing against cold ENV 342:1998 suggests that the testing of thermal insulation should be made on a moving thermal manikin. In this way the value can be used to match requirements specified by the IREQ-method (ISO/TR-11079, 1993) or as realistic input for prediction of thermal stress in other standards. It is known from prior work (Olesen et al, 1982; McCullough & Hong 1992; Nilsson et al, 1997) that the clothing insulation can be reduced by wind and body movements by up to 70 % from the value measured on a standing thermal manikin.

This paper will focus on the principals of reduction made on total insulation calculated according to methods presented in ENV 342:1998.

Materials and Methods

The thermal manikin used is one in the TORE-series that has been described earlier (Hänel, 1983; Nilsson et al, 1992). The power transmission, in the walking apparatus, has been made with pneumatic cylinders, which gives a simple and durable construction with a minimum of mechanical components.

TORE was positioned in the controlled environment of the climatic chamber until steady state was reached. Then the insulation was calculated from the measured heat loss. In this investigation 10 types of cold protective working clothes with total insulation values from 2.24 to 4.61 clo with an air permeability between 1 and 1000 l/m^{2}s.
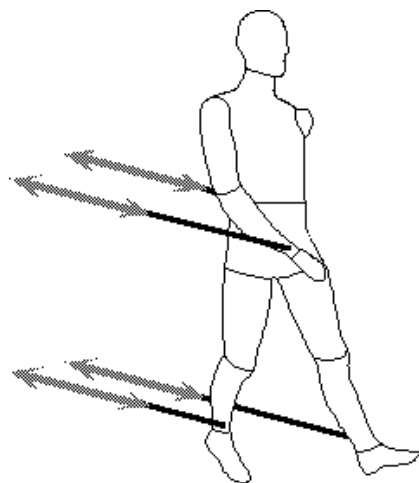
Figure 1. The moving thermal manikin TORE, measuring according to ENV 342:1998.

The walking speed of the manikin was set to 0 to 1.2 m/s and the wind speed was set in six levels from 0.4 to 18 m/s. The repeatability for the method used for determination of insulation values was high, the difference between double determinations was less than 5 % of the mean value of the two measurements based on 228 independent measurements.

Results

The results are given as percentage of the total insulation (I_t) measured with a standing manikin during wind still conditions (0.3 to 0.5 m/s, ENV 342:1998). Calculations where also made of the intrinsic value (I_{cl}) where the insulation of the air layer was subtracted as recommended in the standard without correction for the increased surface area.
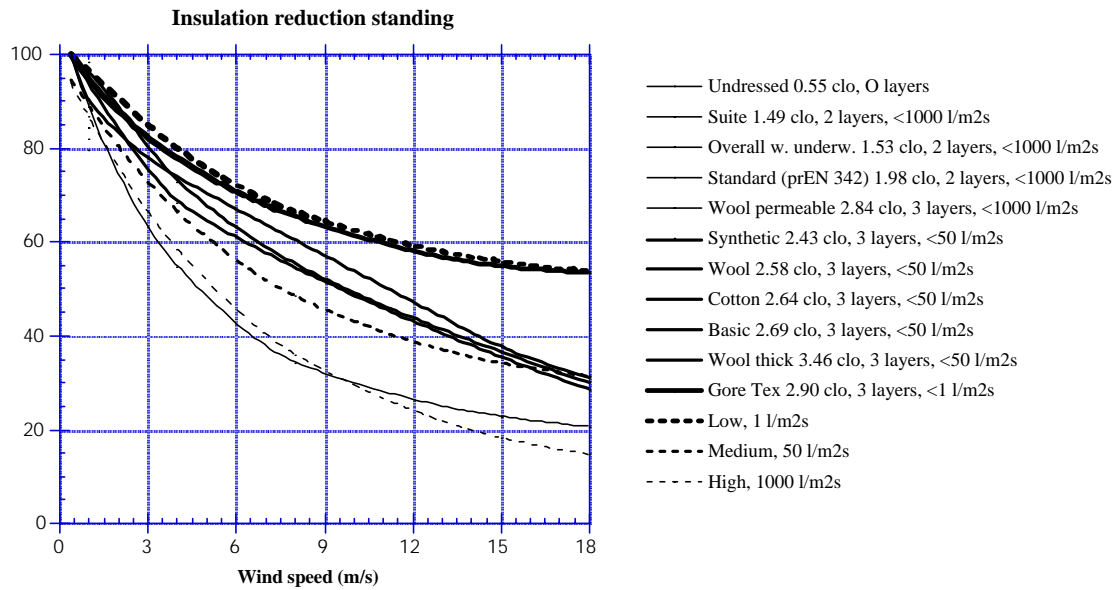
Figure 2. The combined effect of air permeability, wind on TORE standing still.

The relationship with wind and walk influence as well as different clothing air permeability have been examined. The insulation reduction ($I_{t,r}/I_t$) as a function of air permeability (p, l/m^{2}s), wind speed (v, m/s) and walking speed (w, m/s) is now calculated with:

$$I_{t,r}/I_t = 0.54 \cdot e^{(-0.15 \cdot v - 0.22 \cdot w)} \cdot p^{0.075} - 0.06 \cdot \ln(p) + 0.5 \qquad (1)$$

The equation is derived from three dependent regressions, one for wind and walk (R = 0.885) and one for the inclination of the permeability (R = 0.965) and one for the intercept of the permeability (R = 0.998). The standard deviation of the difference between measured and calculated data ($I_{t,r}/I_t$) is 4 % (Max/Mean/Min 15/5/0) based on all 228 independent data sets. The validity interval for the equation is 0.4 - 18 m/s wind speed, 0 - 1.2 m/s walking speed and an air permeability of 1 to 1000 l/m^{2}s. The equation is plotted in Figure 3 for low air permeability - 1 l/m^{2}s (Figure 3a) as well as high air permeability - 1000 l/m^{2}s (Figure 3b).

Discussion

The clothing insulation is strongly affected by wind and movements. A reduction of the clothing insulation measured with a static thermal manikin is consequently needed. The

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insulation is reduced exponentially with increased step frequency (walking speed) and increased wind speed (Nilsson & Holmér, 1997).
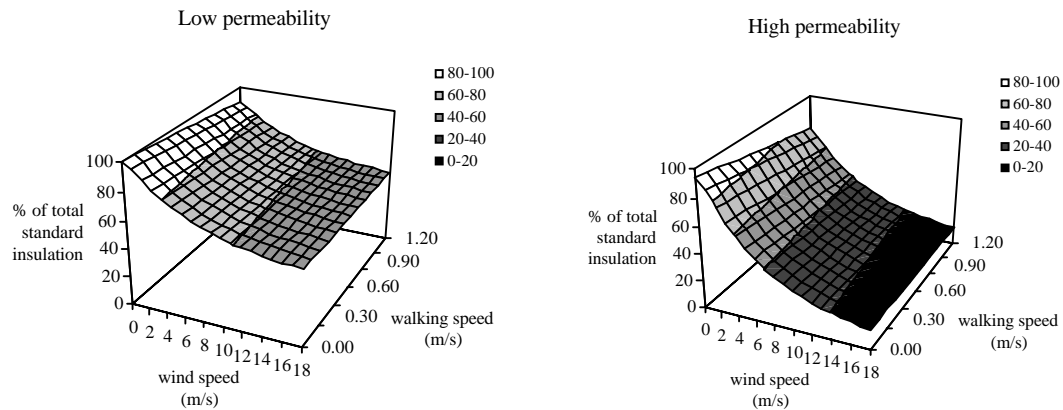
Figure 3a - b. The combined effect of wind and walking speed for TORE while walking at 0 to 1.2 m/s with wind speed from 0.4 to 18 m/s. For clothing combinations with 2-3 layers with a total insulation of 1.49 - 3.46 clo and an air permeability of 1 l/m²s (left) and 1000 l/m²s (right).

In Figure 2 are three lines shown for high, medium and low air permeability respectively. In our study 8 out of 10 ensembles fitted into these categories, as most winter clothing do.

It is also clearly seen in Figure 2 that that the air permeability has little influence on the insulation for wind speeds below 2 m/s. For calculations below such a limit the formula then could be reduced, by insertion of i.e. $p = 1$ in equation 1, to only take wind and walk into consideration.

$$I_{t,r}/I_t = 0.54 \cdot e^{(-0.15 \cdot v - 0.22 \cdot w)} + 0.5 \qquad (v < 2m/s) \qquad (2)$$

Conclusions

A general equation that takes into account the insulation reduction effects from wind, permeability and walk has been developed. The equation makes it possible to calculate more realistic values for the actual insulation during different activity and weather conditions for most winter work clothing, if the static clothing insulation is known from measurements or tables.

The air permeability has little influence on the insulation for wind speed below 2 m/s. For calculations below such a limit the air permeability could be omitted.

In the future only measurements on standing manikin should be needed. The wind, permeability and walk reductions will be calculated from this value.

To validate the relationships more measurements on subjects exposed to wind and activity in working life are needed.

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Limitations of using a single-exponential equation for modelling clothing ventilation

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Introduction

The thermal load that a clothing ensemble might impose can be calculated from its thermal and evaporative resistances, traditionally measured using a static thermal manikin. However, physical activity of the wearer and increased environmental airspeed greatly reduce these resistances - by disrupting the boundary air layer and by increasing exchange between air trapped within the clothing and the surrounding air (clothing ventilation). Clearly, if the effect of clothing on human heat balance is to be understood fully, it is essential that these influences be quantified.

Many equations have been developed to describe the disruption of the boundary air layer, all are of the same form (see, for example, Winslow *et al*., 1939) but the heat exchange by clothing ventilation is more complex. Nilsson *et al*. (1992) used an articulated, thermal manikin to derive empirical corrections to static manikin thermal resistance to take account of the clothing ventilation. Havenith *et al.* (1990) extended these corrections to include evaporative resistance. However, corrections based on manikin measurements clearly have a practical limit – manikins cannot replicate the complex movement of humans in the work-place. A more general approach would be to measure clothing ventilation when the clothing ensemble is worn in the work-place by human test subjects, and use the clothing ventilation data to calculate its effect on heat balance.

Clothing ventilation is the product of the rate of air exchange (*ie* the number of times per unit time that a volume of air in the clothing equal to the clothing microenvironment volume is exchanged with ambient air) and the clothing microenvironment volume. A method for measuring the rate of exchange between air trapped within the clothing and surrounding air was developed by Crockford *et al*. (1972). The method has two stages: First, record the dilution curves obtained by flushing the clothing with a tracer gas (nitrogen), then monitoring the concentration of oxygen as it returns to the clothing. Second, calculate the rate constant of the dilution curve by fitting a single exponential. The rate constant can be shown to be equal to the rate of air exchange.

Birnbaum & Crockford (1978) developed a method to measure the clothing microenvironment volume. They multiplied this value (V_T) by the measured rate of air exchange (*r*) to calculate what they called the 'ventilation index'. However, this quantity is not an index, so in this paper we refer to it as clothing ventilation.

The Problem

Crockford *et al.* (1972) used a single exponential equation (Equation 1) to calculate the clothing ventilation from the oxygen dilution curves:

$$p(t) = p_{air} - p_1 e^{-rt}$$

where:

r	is the rate of air exchange	(min^{-1})
p(t)	is the concentration of oxygen in the clothing microenvironment	(%)
p_1	is such that p_{air}-p_1 is the initial concentration of oxygen in the clothing microenvironment at t=0	(%)
p_{air}	is the concentration of oxygen in the surrounding air	(%)

Equation 1. Single exponential model of clothing ventilation.

The single exponential equation of clothing ventilation is based on a single compartment model of a clothing ensemble (Figure 1), which makes several assumptions, that:

1. there is complete mixing within the clothing ensemble so that the concentration of oxygen in the clothing microenvironment is homogeneous;
2. the rate of air exchange is constant;
3. the volume of the clothing microenvironment is constant;
4. the air (and oxygen) in the clothing microenvironment do not permeate the skin.
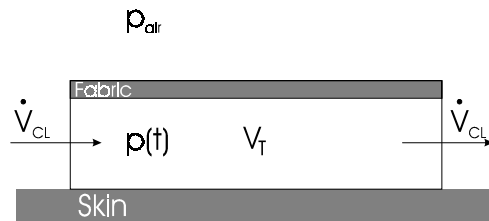
where:

$\dot{V}_{CL}$	is the clothing ventilation	(l.min^{-1})
V_T	is the volume of the clothing microenvironment in clothing layer 1	(l)

Figure 1. 1-layer model of clothing ventilation.

It is not certain that these assumptions are valid. For example, Lotens & Havenith (1988) showed that higher-order exponentials could be a better fit, because the concentration of oxygen is not homogeneous - there are pockets of trapped nitrogen, regions of slow air exchange, and clothing layers that restrict gas diffusion. The purpose of this investigation was to determine the magnitude of any errors introduced into the calculation of clothing ventilation when assumption 1 above was violated.

Methods

Numerical exploration of implications of the assumptions

To explore the effectiveness of modelling 2-layer ensembles with the single exponential equation, a simple numerical 2-compartment model, representing 2 layers of clothing, was produced (Figure 2). In the 2-compartment model an additional assumption was made - that the rate of air exchange between the compartments ($\dot{V}_{diff}$) is constant.
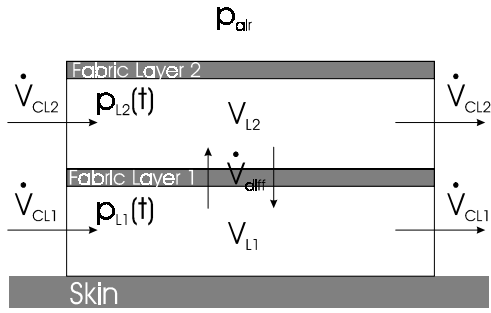
where:

$\dot{V}_{CLi}$ is the clothing ventilation for the layer i   (l.min^{-1})

   ($\dot{V}_{CL2}$ includes ventilation through fabric layer 2)

V_{Li} is the microenvironment volume of clothing layer i   (l)

$p_{Li}(t)$ is the concentration of oxygen in the clothing layer i   (%)

p_{air} is the concentration of oxygen in the surrounding air   (%)

$\dot{V}_{diff}$ is the rate of air exchange between the clothing layers   (l.min^{-1})

Figure 2. 2-compartment model of clothing ventilation.

Application of the numerical model

The numerical model of a 2-layer clothing ensemble was used to produce oxygen dilution curves for known clothing ventilation and rates of air exchange between clothing layers ($\dot{V}_{diff}$). The single exponential equation was fitted in 2 ways: 1. to the average oxygen concentration in the 2-layers together; 2. to the oxygen concentration in each layer separately. In each case, the predicted rate of air exchange (r) was derived. The predicted clothing ventilation was then calculated as the product of r and the microenvironment volumes used in the 2-layer model. This value was compared to the ventilation used in the model. The error of the single exponential approach was defined as the percentage difference (error) between the model's known ventilation and the predicted values. This process was repeated for different rates of air exchange between the 2 clothing layers.

Results

Inputs: $\dot{V}_{CL1}$ = 5 l.s^{-1}, V_{L1} = 20 l, $p_{L1}(0)$ = 10 %, $\dot{V}_{CL2}$ = 10 l.s^{-1}, V_{L2} = 20 l, $p_{L2}(0)$ = 15 %, p_{air} = 20.6 %
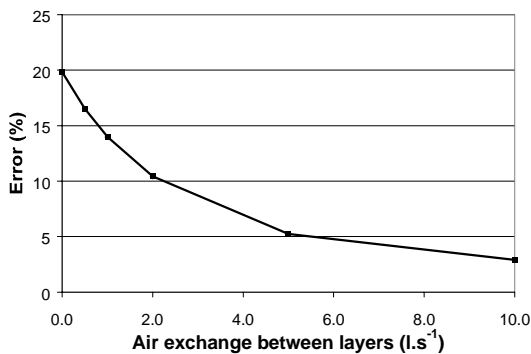
Figure 3. Error when using a single exponential to calculate ventilation of a 2-layer clothing ensemble.
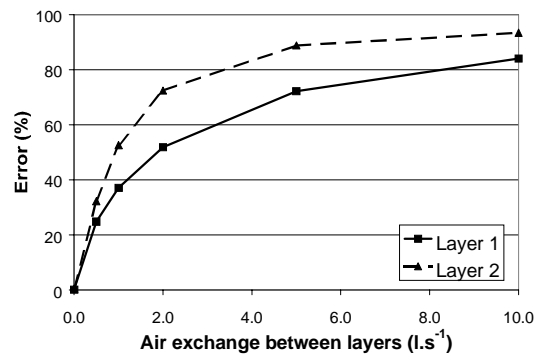
Figure 4. Error when using a single exponential to calculate ventilation in each layer of a 2-layer clothing ensemble.

The calculated errors when applying the single exponential to both clothing layers, and to each layer separately, are shown in Figures 3 and 4 respectively. These graphs show only the magnitude of the errors, not their direction. In Figure 3 the single exponential under-estimates clothing ventilation. In Figure 4 the ventilation in layer 1 is over-estimated; ventilation in layer 2 is underestimated.

Fitting a single exponential to the 2 layers together resulted in errors greater than 10 % for low rates of air exchange between layers. Errors were less than 10 % for the higher exchange rates. Fitting a single exponential to each of the layers individually (Figure 4) gave errors that increased with increasing rates of air exchange between layers. Only at very low exchange rates was the error less than 10 %.

Discussion

The microenvironment next to the skin is often the most important determinant of the ensemble's ability to transfer heat away from the body. Therefore, measurements of ventilation in this layer (including the exchange with adjacent layers) must be accurate. Figures 3 and 4 show that using a single exponential equation may not give the required accuracy. They also imply that using a single exponential equation for multi-layer clothing with low water vapour or air permeable layers leads to inaccurate calculation of clothing ventilation. Some protective and military clothing ensembles exhibit these properties. Air exchange between layers cannot be calculated using a single exponential.

In order to calculate the clothing ventilation of multi-layer clothing with internal layers with low water vapour and air permeabilities, or to calculate the ventilation of layer 1 (next to the skin), current experimental procedures need to be extended. The microenvironment volume of each clothing layer must be measured; the concentration of oxygen in each layer must be recorded; a model more complex than the single exponential (single compartment) one is needed.

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Effects of skin pressure by clothing on thermoregulation and digestive activity

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Abstract

I talk on physiological parameters, i.e., core temperature, skin temperatures, salivary melatonin, urinary noradrenaline and amounts of feces under the influences of skin pressure (foundation). Main findings are summarized as follows: 1) Rectal temperature was kept significantly higher throughout day and night under the influence of skin pressure due to foundation garments. 2) Diurnal decrease of leg skin temperature was significantly greater and its nocturnal increase was significantly suppressed under the skin poressure, which was responsible for upward shift of core temperature. 3) Nocturnal increase of salivary melatonin was significantly suppressed by skin pressure due to foundation. 4) Urinary noradrenaline was significantly suppressed by skin pressure due to foundation. 5) The amount of feces was significantly smaller while wearing the body compensatory brassiere than while not wearing it. These results suggest how deeply human body is influenced by skin pressure due to clothing. It seems problematic in terms of health maintenance.

Ergonomics of protective clothing

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Introduction

Testing of workwear and specialised protective clothing has in the past mainly concentrated on testing the properties of the materials used. A typical example of this can be found in the testing and evaluation of fire-fighting garments. Presently, these fire-fighter garments are usually tested to standards, which concentrate mostly on requirements for the materials (e.g. prEN469). Additional standards are under development, e.g. for assessment of the risk of burn injury using an instrumented manikin, but mostly tests refer to material heat and vapour resistance, flammability, retro-reflection properties etc. Though all these tests evaluate important properties of the clothing, this testing often neglects the effect the manufacturing process of the garment has on the material properties (stitching, seems, treatments), the effects of clothing design, sizing and fit, as well as the interaction of the clothing with other components of the standard gear for the profession. Such effects can only be tested by looking at the protective clothing ensemble as a whole, and such test should be incorporated in more detail into future PPE standards (e.g. prEN469).

This paper deals with methods of testing protective clothing ensembles, which go beyond the material standards. These tests, often referred to as tests on the ergonomics of clothing, consider the complete outfit, and involve manikin (insulation) and human subject testing. The tests described here, which will be the human subject tests only, are based on extensive developments of ergonomic testing methods at TNO Human Factors over two decades (Heus et al, 1995, 1999), and were applied to various types of PPE (fire-fighting, motorcycle clothing, military clothing, chemical protective clothing). Human subjects tests for comfort, physiological load, cold or heat protection, ergonomical design, fit, loss of performance, rain/moisture protection and conspicuity/visibility of the clothing will be described and proposed for further development into standards for ergonomic clothing evaluation. In the description of these methods, the example of testing fire-fighting gear will be followed, but the principles of the testing can be used in most types of protective clothing.

Selection of tests and conditions

An important advantage of many material test methods is that they are designed to produce accurate and repeatable results, both within and between laboratories, at minimal cost. In order to achieve this, test conditions are chosen to provide a high sensitivity for differences in the parameter under study. In practice this also implies however that the test circumstances do not always reflect the actual use conditions. Real use conditions can be highly variable however, and it is unfeasible to test clothing ensembles in all possible conditions. Hence, the first step in any clothing evaluation should be a proper task analyses to identify the main functions of the clothing, during what tasks it would be

used, in what environments that would be, and how the different requirements should be rated in terms of priorities (risk assessment, see e.g. prEN469). Doing this should identify the main requirements for the clothing to which subsequently testing procedures can be adapted.

To follow the example of testing of fire-fighting gear, 'typical' scenarios may involve different 'typical' climatic circumstances:

- Indoor fire attack
  High air temperature, medium to high radiation, smoke, water exposure, high activity levels
- Outdoor extinguishing activities
  Low air temperature, low to high radiation, water exposure, low to high activity levels
- Roadside rescue
  Ambient temperature, low radiation, exposure to rain, low to high activity levels, risk from traffic

Within these scenarios, typical aspects of the clothing that may be considered as determining clothing performance are:

- Insulation (protection from cold, heat (convective and radiant)
- Vapour permeability
- Air permeability
- Visibility
- Water protection (repellency, waterproofness, absorption)
- Mechanical protection

In addition to measuring/determining these parameters in the materials tests, they should now be determined in relevant scenarios. The main protective and other functional aspects of the clothing present in the fire fighter scenario's can be determined in the following tests:

Test for physiological load

Relevant practical conditions: Exposure where time is limited by SCBA or by heat strain: high air temperature (above skin temperature) with medium radiation and medium work load allows for working times up to 30 minutes. The heat strain will be mainly determined by the ability of the wearer to lose his body heat through the clothing to the environment. Considering the high air temperatures, dry heat transfer will be towards the body, and heat loss will have to be through evaporation.

Experiment: Different ensembles are compared to each other and to the clothing currently in use, using a within subject design. Each subject wears all clothing types in a balanced fashion to avoid any order effects on the results. The clothing, including SCBA, is worn while performing moderate work (walking at $\pm$ 3.5 km per hour, stepping over low benches [± 250 W·m^{-2}) in a room with air temperature of $\pm$ 60 °C and a black globe temperature of about 95 °C. Body core temperatures are monitored, as is sweat loss and sweat absorption/desorption in the clothing. The clothing's performance is measured in terms of tolerance time (time for the wearer to reach an 8 J·g^{-1} body heat storage), dry heat gain, evaporative heat loss and evaporative heat loss efficiency (sweating efficiency). Subjective ratings of subjects are taken as well.

Test for heat protection

Relevant practical conditions: Exposure where time is limited by heat protection against high radiant loads. The high radiant load will increase suit temperature and the heat can penetrate the suit fast leading to skin burns.

Experiment: Using the same experimental design as in the physiological load test, subjects in the clothing to be tested are now exposed to very high radiant loads (7 kW·m^{-2}) in a hot chamber (>100 °C). In front of well-controlled propane burners delivering this load they perform a light bench stepping exercise. The clothing will increase in temperature very quickly, as will skin temperature. The clothing's performance is measured as the tolerance time, which is either defined by the subjects withdrawal, or by any skin temperature of the subject coming within 1 °C of the pain threshold limit of 45 °C. The maximal exposure time for this test is 120 seconds.

The function of the exercise is mainly to keep the clothing moving to and from the skin. A high risk of burns would be present if clothing was left static. In that case it's temperature could increase to very high values, and then when the person wanted to withdraw the hot clothing would touch the skin and cause a burn.

Experience has shown that subjects voluntary withdraw at skin temperatures around 44 °C. Thus, as long as precautions are taken that the clothing isn't static, with the associated risk of high clothing temperatures, no risk of skin burns in this type of testing is present.

Water protection

Relevant practical conditions: Exposure to neutral ambient conditions where 'comfort' and health risk is determined by rain or spray-water protection.

Experiment: In the same within-subject design as above, the clothing is worn in a well-defined artificial rain environment. Subjects need to walk in line with the others while doing a small obstacle course at low speed. This consists of climbing over objects, as well as crawling under objects and e.g. moving crates from low to high positions and vice versa. These movements test the design of the clothing (no gaps when bending over), the waterproofness of materials, seems etc., in normal conditions and under pressure (knees, elbows). The clothing's performance is measured in terms of water absorption, water penetration to the underclothing (both by weighing the respective garments), the leakage locations and the subjects subjective judgement.

Freedom of movement

Relevant practical conditions: Task performance where freedom of movement is determining movement speed, flexibility and energy expenditure. Any hampering of the wearer's movements increases risk.

Experiment. In the same within-subject design as above, subjects in the gear (without SCBA) are asked to complete an obstacle course at maximum speed. This involves relevant activities for the profession (climbing ladders, through windows, over, under and through obstacles). The clothing's performance is measured in terms of time to complete the obstacle course, in relation to the time to do it in a training suit. In addition various small tests (time needed for donning, sprint, running in 8 shaped pattern underneath a lowered bar, sit and reach and stand and reach test, sargeant's jump) can be added to evaluate the way in which the clothing hampers the movement.

Ergonomical design assessment

Relevant practical conditions: When all the clothing and equipment worn during a certain task is combined the clothing still should be functioning properly and provide the basic functions (protection, storage, etc.) to the wearer.

Assessment: For this aspect an expert panel (ergonomics and topic specialist) assesses the clothing. While the clothing is worn by subjects of different statures and builds, as well as by panel members, the clothing is evaluated for freedom of movement, proper design (overlap between jacket and trousers, arm length), compatibility with other equipment (e.g. accessibility of pockets while SCBA is worn). The clothing performance is measured using consumer evaluation type tables (scores much better, better, equal to, lower/worse etc. than average or than old suit or a reference suit)

Visibility/Conspicuity

Relevant practical conditions: Exposure during tasks where the wearer's visibility is important. Any activity in traffic, or in obscure areas will have a high risk if visibility of the wearer is insufficient.

Experiment: As not only the materials used and their total surface area, but also the patterns used are relevant in this case, tests are done in a set-up modified from the CEN tests on retro-reflective clothing materials (EN471). In a set-up simulating lighting condition of a car approaching in full darkness, using the car's driver viewpoint when the car is 100 meters away from the subject, pictures with defined exposure time are taken of the suits in frontal, lateral and rear view. Later, these pictures are evaluated by the expert panel. The clothing's performance is measured in terms of visibility of the subject (total visible surface), as well as in terms of recognition as a human (pattern of visibility material).

Human subjects as evaluation tools

As mentioned before, material test standards are geared towards accurate and reproducible results, In the tests proposed here, measurements are performed using human subjects as 'evaluation tools'. This implies that the experimenter will have to expect human variability to influence the results. While inter-subject variability is desirable, in order to evaluate the PPE for use by different populations, intra-subject variation (differences between days etc.) is undesirable and efforts should be made to minimise this. Pre-test conditioning of clothing and subjects are thus important, as is the subjects motivation level which needs to remain high. Though this variability will increase noise levels in the data, experience shows that the tests described here can discriminate well between different clothing ensembles for various PPE types, and that they are very sensitive in exposing typical weak spots in the clothing design or manufacturing process. We are therefore convinced that adaptation of these or similar test procedures for use in PPE standards would advance the quality of PPE testing substantially.

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Application of the product planning chart in quality function deployment to improve the design of a fireman's safety harness

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Introduction

This paper discusses the use of a systematic planning tool called Quality Function Deployment (QFD), which has been used to improve the design of a belt/buckle assembly used on a Fireman's safety harness. QFD is a tool, which provides the development team with a structured planning approach to new product development that is driven by the 'voice' of the customer. This is achieved by linking customers requirements to ways of achieving them, while taking into account both customer and competitors' product performance. As a tool QFD has been growing in influence both in Japan and the USA, as well as in Europe.

The planning process used in Quality Function Deployment is usually split into Four Phases, and charts are used to help facilitate planning during each phase. The first phase is used to define the overall requirements that are deemed to satisfy the customer, the remaining three are used to define the parts, processes and production requirements in development (Bossert, 1991; Day, 1993). For the purpose of this paper, the first phase in the QFD planning process is discussed. As a consequence, the format of this paper is based around the activities that are required to build the first phase QFD chart formally known as the Product Planning Chart.

From the analysis of the Product Planning Chart, and knowledge of the company's existing budgetary constraints, the development team decided to begin development that looked at alternate buckle designs that would make the replacement and refitting of the Belt/Buckle easier.

QFD project planning

Before the project could commence, senior management with the aid of a Product Manager formed a multi-functional development team, with members from the Product Design, Manufacturing, Purchasing, Accounts, Technical Documentation, Marketing, and Quality business functions.

Once the team was formed, based on the Project Goal to '*Improve the existing design of the Belt/Buckle Assembly on a given range of Safety Harnesses*', the objective to *Investigate the implications on Belt/Buckle Material, Testing and Physical Size* were agreed. From these objectives a schedule of work was formulated highlighting the tasks to be completed, making sure that this project tied in with the company's existing busi-

ness plan. The remainder of this paper is based on the schedule of work relating to build the first QFD Chart for Product Planning, which can be found in Table 1.

Customer 'voice' data collection and analysis

Using an interview guide, a representative sample of customers were interviewed to identify their requirements. A questionnaire was then developed based on the findings of the interviews and used to establish the importance for each customer requirement. From the questionnaire it was found that the most important customer requirement for the Belt/Buckle Assembly was that *"the unit should be easily replaced and refitted"*.

The Customer Requirements were then grouped using Affinity Diagrams so that they could be put into the QFD Chart in a structured tree format, along with the importance ratings.

In order to generate Customer Competitive Assessment Data, the development team obtained belt buckles used by a leading competitor and asked company personnel outside the development activities to rate the belt/buckle assembly against the competitor's buckle on the issues that came to light in the questionnaire.

The Customer Competitive Assessment Data was then put in the QFD Product Planning Chart, and the development team met to establish specific objectives for the Belt/Buckle Assembly project, and brain-storm the Technical Requirements from the Customer Requirements. Once all of the low-level Technical Requirements had been identified, the development team then grouped them into categories using Affinity Diagrams.

As the Belt/Buckle used by the company in question was very similar in design to the competitor's buckle, the Customer Competitive data revealed that the customer and competitor ratings were similar, however the customer rated the competitor's buckle much higher for *"ease of replacement/refit"*.

Conduct technical competitive benchmark studies

At the end of the first meeting, it was agreed that the team members from the Product Design and Manufacturing Functions should carry out relevant tests on their own, and on their competitors', Belt/Buckle assemblies. By carrying out such tests Technical Competitive Data were then generated, preliminary target values were computed, and the orientation for each Technical Requirement formulated.

QFD product planning chart building

With the Customer and Technical Competitive Data incorporated into the Product Planning Chart, the development team had a second meeting to complete the Relationship Matrix, establish the Absolute and Relative Importance Weightings for each Technical Requirement, and review the whole of the QFD Chart. In this meeting, the QFD chart was built-up using software that was projected onto a screen for the development team to observe.

In order to complete the Relationship Matrix, the development team established the level of relationship (strong, medium, or weak) between the Technical and Customer Requirements by assigning a correlation value 9, 3, 1 respectively (by brainstorming).

The Absolute and Relative Importance Values for each Technical Requirement were then calculated by the QFD software using the following equations:

Absolute Importance $I_{j \, abs} = \sum_{i=1}^{i=n} W_i * R_{ij}$ (After Santow and Clauing, 1993)

Relative Importance $I_{j \, rel} = \dfrac{I_j}{\sum_{j=1}^{j=n} I_j}$ (After Santow and Clausing, 1993)

where:

I   Technical Requirement Importance value
W   Customer Requirement Rating (eg: any value 1 to 10)
R   Correlation factor (eg: 1, 3, or 9) between each Customer Requirement and Technical Requirement

Subscripts

i   Customer Requirement Row Reference Number
j   Quality Characteristic, Design Requirement (or HOW) Column Reference Number
n   Any number of Customer Requirements and Technical Requirements >1

Consequently, $I_{j \, abs}$ is the absolute importance value of the jth Technical Requirement, W_i is the weight of the ith Customer Requirement, and R_{ij} is the correlation value between the two.

$I_{j \, rel}$ is the relative (technical) importance value for the jth Technical Requirement, divided by the arithmetic summation of all Technical Requirement relative importance values from j=1, to j=n expressed as a percentage.

Analysis of the chart data quite clearly showed that one weakness in the existing design of the buckle was that it could be improved in relation to ease of replacement and refitting. Also, the customer rated both companies as average for "*operation when hot or cold*", consequently this could be seen as a marketing opportunity.

From the analysis of the Product Planning Chart, and knowledge of the company's existing budgetary constraints, the development team decided to begin a development programme that looked at alternate buckle designs that would enable easier replacement and refitting of the Belt/Buckle.

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Table 1. QFD Product Planning Matrix for Belt/Buckle Assembly.

Planning matrix (Customer Requirements and assessment columns):

Customer Requirements (A)		Degree of Importance (B)	Our Company Sales (C)	Competitors Rating (D)	Planned Level (E)	Improvement Ratio (F)	Sales Point (G)	Importance Weight (H)	Relative Weight (%) (I)
Ease of Use	Connect	8	4	4	4	1.00	1.5	12	7
	Disconnect	8	4	4	4	0.00	1.5	0	0
	Not Come Apart Accidentally	10	4	4	5	1.25	1.2	15	9
	Two Finger Application	8	4	4	4	1.00	1.0	8	5
Safety	Flame Retardant	7	2		3	1.50	1.0	11	6
Environment	Water Resistance	7	5	6	4	0.80	1.0	6	3
	Chemical Resistance	8	3	4	4	1.33	1.0	11	6
	Work when cold	8	2		4	2.00	1.0	16	9
	Work when Hot	8	2		4	2.00	1.0	16	9
Life	Last Long Time	7	4		3	0.75	1.5	8	5
	Be Easily Replaced/Refitted	9	1	3	5	5.00	1.5	68	40
	Total	1802						169	

Technical Requirements (J) — Target Values (N), Absolute Importance Weight (L) and Relative Weight % (M):

Technical Requirement	Group	Target Value (N)	Importance Weight (L)	Relative Weight (%) (M)
Acid/Alkaline Resistance	Material	Test 5 mins PH1-14	88	4
Water Resistance	Material	Water Test 5 mins	68	4
Tensile Strength 22 C	Material	65 MPa	76	4
Flash Heat Resistance	Material	UL94-V0	79	4
Pull Strength	Testing	1000N	27	1
Assembly Effort 22 C	Testing	10 N	78	4
Disassembly Effort 22 C	Testing	22 N	41	2
Assembly Effort -30 C	Testing	17 N	163	9
Disassembly Effort -30 C	Testing	60 N	126	7
Operation Life Test	Testing	10,000 Cycles	42	3
Replacement Time	Testing	5 Minutes	356	28
Locking Gap	Physical Size	53 mm	73	4
Weight	Physical Size	32 grams	45	2
Height	Physical Size	69 mm	195	6
Width	Physical Size	90 mm	185	6
Depth	Physical Size	15.2 mm	96	5
Finger Operation Size	Physical Size	Dia 30mm	229	13

Chart Area Key:

- (A) Customer Requirements
- (B - I) Customer Competitive Assessment Data
- (J) Technical Requirements
- (K) Relationship Matrix
- (L) Technical Requirement Absolute Importance Weight
- (M) Technical Requirement Relative Importance Weight
- (N) Technical Requirement Target Values
- (O) Technical Requirement Orientation
  - ☐ -Maximum
  - ◊ -Minimum
  - ◯ - Target
- (P) Technical Competitive Assessment Data

Competitive Comparison key (Worst to Best, 1–5):
- ⊗ = Our Company
- ◯ = Competitor

Technical Comparison (P):
- ☐ = Our Company
- △ = Competitor

An adaptive approach to the assessment of risk for workers wearing protective clothing in hot environments

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Introduction

The human body responds to the microclimate between the skin and the clothing and any risk of heat strain will be as a response to that climate. The properties of the microclimate will be determined by the external environment and the clothing heat and vapour transfer characteristics as well as the metabolic heat produced by the body due to activity. Traditional heat stress assessment methods will attempt to take the above factors into account and predict the thermal strain caused to the clothed person. The risk of unacceptable heat strain is therefore directly related to the environment, clothing and activity. In practical situations the risk of heat strain is not dependant upon such a passive system. If people are subject to unacceptable environments then they will attempt reduce the effects of the environment. There are a number of ways in which this can be done including reducing work rate, altering clothing or posture, moving out of the hot environment and more. The risk of heat strain can then be viewed as the lack of ability, potential or opportunity for a person to act or adapt to reduce the heat strain. This provides an adaptive approach to assessment where by contrast with traditional methods, for the same environment, clothing, activity and person, a context with restricted opportunity to avoid heat strain would provide a much greater risk than a context where it is possible to act to reduce the heat strain.

Current methods for defining the thermal properties of clothing take no account of human behaviour. How people wear clothing and its dynamic interaction with tasks, workplaces and environments, however is of major importance in human thermoregulation with often dominant significance for human comfort, performance and survival. The degree of freedom of an individual to behave appropriately in any context therefore should be a major component in any assessment of risk of thermal strain in hot and cold environments. This paper presents the concept of the adaptive approach to assessing risk and demonstrates how it can be used in practical application with particular reference to the effects of protective clothing.

Specification of clothing properties

Specification for the thermal properties of clothing has evolved from an index of the thermal properties of materials, involving the measurement of heat and vapour resistance using materials fixed to a 'flat plate' under standardised conditions, to indices which represent those properties in clothing on the human body. Indices include the Tog value for materials (Pierce & Rees, 1946) where 1 Tog = 0.1 $m^2 \cdot K \cdot W^{-1}$, and vapour transfer properties measured in $m^2 \cdot kPa \cdot W^{-1}$. For these indices the term 'm^2' represent one square metre of material. This can be contrasted with indices of the thermal properties of clothing

where the Clo value is used (Gagge et al., 1941), where 1 Clo = 0.155 $m^2 \cdot K \cdot W^{-1}$ and is the thermal resistance provided to the human body by clothing as if the clothing had been spread across the whole body. A similar concept for the vapour transfer properties of clothing provides units of $m^2 \cdot kPa \cdot W^{-1}$. For clothing indices however, the 'm^2' term refers to a square metre of the human body surface (often taken as $1.8 m^2$ for an average man). The thermal resistance of a pair of socks would therefore have a material resistance similar to that of trousers or a shirt (e.g. 0.1 $m^2 \cdot K \cdot W^{-1}$) whereas the socks would have a Clo value of around 0.1 Clo (0.155 $m^2 \cdot K \cdot W^{-1}$), as the surface area of the socks is small compared to that of the human body when compared to a shirt or trousers where surface areas are greater and Clo values will be around 0.3 to 0.4 Clo.

The properties of clothing are measured on thermal manikins which represent the shape and temperature distribution of the human body. They can also be calculated from the physiological responses of human subjects when wearing the clothing. Intrinsic resistance values represent the 'intrinsic' properties of clothing and are independent of environmental conditions. Total clothing insulation values include not only the intrinsic properties of clothing but also the resistance of the environment surrounding the body. This will depend upon environmental conditions and human body movement. Developments in quantifying the thermal properties of clothing include the ventilation index (Birnbaum & Crockford, 1978) which quantifies the air exchange between the microclimate within clothing and the external environment. All of the above indices can be used in the assessment of the thermal strain of clothed workers in hot environments.

A practical example

Consider a worker in protective clothing (estimated insulation value of 1.0 Clo, normal vapour permeation properties) carrying out heavy manual work (estimated 200 $W \cdot m^{-2}$) for 1 hour in an air temperature of 35 °C with no significant thermal radiation, 50 % relative humidity and low air flow (0.2 ms^{-1}). Using a simple 2-Node model of human thermoregulation, based upon Gagge et al (1971), the predicted responses of the workers are that skin temperature would rise rapidly and the skin would be completely wet with sweat within 15 minutes of work. Core temperature would rise above 38.0 °C within 40 minutes and would be at around 38.5 °C after one hour of work. An assessment of the risk of unacceptable heat strain in those conditions would reasonably conclude that there is some risk to the worker after one hour of exposure.

In practice, whether there is unacceptable risk will depend upon the opportunity for the worker to adapt to the work. For example, when the worker becomes 'too hot' or 'too sweaty' then it may be possible to take off a jacket or slow down. A reduction in Clo value to 0.7 Clo and metabolic heat production to 150 $W \cdot m^{-2}$ after 15 minutes of exposure, according to the 2-Node model, slows the rate of increase of skin temperature and sweating and maintains a body core temperature below 38 °C even after one hour of exposure. If an opportunity to adapt is available then there is a low risk and if the opportunity to adapt is not available then there is high risk.

The 2-Node model of human thermoregulation was used to represent a 'traditional' static model of assessment and other methods would provide a similar result (e.g. ISO 7933, 1989). When assessing the risk of unacceptable heat strain for workers wearing protective clothing, therefore, it is important to determine the 'degrees of freedom' a worker has to adapt to the environment.

Risk assessment – an adaptive approach

An assessment of risk of unacceptable heat strain for work in hot environments must consider factors that influence human response, hence air temperature, radiant temperature, humidity and air movement making up the environment and metabolic rate and clothing of the worker. These provide insight into how to use an adaptive approach in risk assessment. That it, a consideration should be given to the opportunity to adapt to or adjust the environment, work rate or activity level, and clothing.

Environment

A method of reducing heat strain would be to reduce the strain caused by the environment. Examples of how this could be achieved include moving away from the hot area, shielding from radiation or increasing air flow across the body. An ability to recover in a cool area is also important.

Activity

High levels of activity with protective clothing should always be regarded as high risk. The ability to vary the pace of work will provide a major method for reducing thermal strain and avoidance of heat stroke. Many jobs will allow this and varying activity level and hence metabolic heat production, probably explains why workers can perform jobs when traditional assessment methods predict that heat stroke will occur. Some jobs however will not allow variation in activity level. For example, in situations where exposure time may be limited, the environment is hot and protective clothing must be worn and the task must be completed. This should be regarded as high risk. The social context of the work is also relevant. Highly motivated people may increase their workload and maintain it even to heat stroke. Military personnel and sportsmen and women, may be particularly susceptible and any adaptive opportunity should be viewed in a social, cultural and motivational context.

Clothing

Clothing restricts evaporative heat loss which is the main physiological mechanism for the body to lose heat in a hot environment. The ability to remove clothing or adjust it to allow heat loss will provide a major adaptive opportunity in a hot environment and clothing design should take this into account. However, protective clothing is often impermeable and closed to protect against hazards such as airborne toxins. It may not be possible therefore to adjust clothing. The ability to remove clothing if a worker collapses or to place gloved hands into cold water for example will be important in reducing thermal strain and the avoidance of injury. Clothing designed to allow air exchange through pumping will provide an adaptive opportunity.

Other adaptive methods

Other factors which provide adaptive opportunity include technological 'solutions' such as opening windows and turning on fans. These would alter the environment as described above. Changing posture can also be regarded as an adaptive response. If a person must consistently work in a crouched posture, the surface area for heat loss from the body will be greatly reduced.

Practical questions for risk assessment

The above discussion has demonstrated that for an effective assessment of risk in hot environments the ability for workers to adapt should be considered. In practice this would add to a checklist or procedure for assessment. The questions that should be asked could be as follows.

- Is there an opportunity for the worker to change the environmental conditions in terms of air temperature, radiant temperature, humidity or air velocity?
- Could a worker change his or her level of activity if he or she became too hot?
- Could a worker remove or adjust clothing if he or she became too hot?
- Could the worker change posture to reduce heat strain if he or she became too hot?
- Does the social, motivational and cultural climate allow adaptive opportunities to be taken?
- Can you identify other adaptive opportunities that will reduce the risk of unacceptable heat strain?
- Are the workers sufficiently trained to take advantage of adaptive opportunities?
- Have the workers been advised of adaptive opportunities at this workplace?

Conclusion

This paper has demonstrated that the opportunities, or lack of opportunities, for workers to adapt to hot environments by, for example, varying work rate or reducing clothing levels, has significance in assessing the risk of heat strain. It provides the basis for a more comprehensive study into the inclusion of the adaptive approach for consideration in risk assessment.

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Radiation protective clothing in a hot environment and heat strain in men of different ages

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Introduction

The aim of the study was to compare thermal strain of older men of different ages at rest and during exercise in a hot environment without and with heat radiation and then without and with radiation protective clothing and to assess if older men are at a greater risk for hyperthermia in these conditions.

In a hot working environment it is often necessary to use reflective protective clothing against radiant sources. This kind of clothing is aluminized and greatly disturbs heat dissipation from the human body and may result in excessive heat storage. Older working population is constantly growing in industrialized countries. More older people are also exposed to occupational thermal stress.

Some studies related to thermoregulation indicated that middle-aged (45-64 years) men and women tolerate work in the heat less and sustain a greater physiological strain during heat acclimation than young ones (Hellon et al. 1956). However other studies showed only low attenuation of thermoregulatory responses from the fifth and sixth decades of life for aerobically trained and relatively lean men and women (Armstrong & Kenney 1993).

Thermal strain of men and women of different ages during acute heat exposure or acclimation at rest and during exercise is in general the same or even lower in middle-aged men and women if they are matched for level of aerobic fitness and selected morphological factors such as: surface area, weight, percentage body fat (Kenney 1988, Tankersley et al. 1991).

Methods

Studies were conducted at rest (24 subjects) and during exercise (20 subjects) in a hot environment at maximal thermal load determined by hygienic standards of around 29 ℃ WBGT and around 26 ℃ WBGT at rest and during exercise, respectively (Table 1).

Table 1. Thermal environment conditions in the study at rest and during exercise ($\bar{x} \pm$ SD).

Thermal environment conditions	Rest study		Exercise study	
	No protective clothing	Protective clothing	No protective clothing	Protective clothing
WBGT (℃)	29.1 ± 0.6	28.3 ± 1.2	26.5 ± 0.6	25.7 ± 0.6
t_g (℃)	37.6 ± 0.8	41.4 ± 1.5	36.5 ± 0.6	40.5 ± 1.0
t_{nwb} (℃)	25.4 ± 0.6	22.2 ± 2.0	22.3 ± 1.0	19.4 ± 0.8

Note: WBGT – wet bulb globe temperature, t_g – black globe temperature, t_{nwb} – natural wet globe temperature.

In experiments without protective clothing subjects wore only shorts, socks and tennis shoes (0.09 clo) whereas in experiments with protective clothing garments included cotton long-sleeve and long-leg underwear, a three-part aluminized protecting set (jacket, trousers, gloves), socks and leather shoes (1.17 clo).

During the experiments, rectal (t_{re}) and skin temperatures, heart rate, heat storage, body mass loss, and the subjective ratings of thirst, thermal sensation and perceived effort (in the exercise study) were collected.

The subjects were divided into three age groups: young (Y, 20-29 years), middle-aged (M-A, 41-55 years) and older (O, 58-64 years).

The rest study lasted one hour and the age groups were matched on the basis of the subjects' activity level in leisure time. In the exercise study, groups Y and M-A represented average while the subjects in the O group had high maximal oxygen uptake (VO_{2max}) for the respective age groups. In the study, subjects exercised for 30 minutes on a cycloergometer at 40 % VO_{2max}.

Results and discussion

At rest in experiments where protective clothing was used in all groups a tendency to higher body mass loss was observed: 189.0 ± 79.2 g, $191,9 \pm 89.0$ g and 167.5 ± 69.4 g in the "no-protective clothing" experiment 279.9 ± 106.0 g, 245.3 ± 64.4 g and 302.8 ± 124.9 g in protective clothing in groups Y, M-A and O respectively. There were significantly worse subjective ratings of sweating in all groups compared to experiments without protective clothing (Table 2).

There were no significant differences in thermoregulatory responses during passive heat exposure of men of different ages. The thermal load applied in the study was probably not high enough because Lind et al. (1970) indicated that older men tolerated heat significantly less than young ones when thermal conditions were more acute compared to moderate ones.

Table 2. Subjective ratings at the end of experiments in a hot environment at rest and during exercise ($\bar{x} \pm SD$).

Subjective ratings	Groups	Rest study		Exercise study	
		No protective clothing	Protective clothing	No protective clothing	Protective clothing
Thirst (scale 0-4)	Y	2.7 ± 0.9	2.8 ± 1.0	2.50 ± 0.50	2.75 ± 0.83
	M-A	2.4 ± 0.7	2.6 ± 0.7	2.33 ± 0.75	2.67 ± 0.75
	O	1.5 ± 0.5[*1]	2.0 ± 0.9[*1]	1.67 ± 0.75[*1]	1.83 ± 0.69[*1]
Sweating (scale 1-7)	Y	5.7 ± 0.7	6.9 ± 0.3[*2]	6.7 ± 0.3	6.7 ± 0.0
	M-A	5.4 ± 1.0	6.3 ± 0.9[*2]	6.2 ± 0.4	5.8 ± 0.0
	O	5.3 ± 0.8	6.7 ± 0.5[*2]	6.3 ± 0.0	6.5 ± 0.2

[*1] $p<0.05$ compared to Y, [*2] $p<0.05$ compared to "no protective clothing" experiment

During 30-min exercise in a hot environment older men with higher physical capacity for their age had significantly lower increase in t_{re} and lower heat storage than in young men with average physical capacity (Table 3). Simultaneously body mass loss in older men was similar to that in young men.

Table 3. Heat strain indices during exercise in a hot environment ($\bar{x} \pm SD$).

Heat strain indices	Groups	No protective clothing	Protective clothing
Δt_{re} (°C)	Y	0.53 ± 0.04	0.52 ± 0.05
	M-A	0.58 ± 0.05	0.55 ± 0.06
	O	$0.38 \pm 0.07*^1$	$0.42 \pm 0.08*^1$
Heat storage (Wm^{-2})	Y	51.7 ± 10.4	68.2 ± 9.9
	M-A	62.3 ± 11.4	73.2 ± 7.8
	O	$41.1 \pm 11.1*^2$	$52.1 \pm 17.8*^2$
Body mass loss (g)	Y	354 ± 112.6	437 ± 97.2
	M-A	350.0 ± 70.2	412 ± 112.1
	O	351.6 ± 80.8	370.0 ± 146.9

*[1] $p< 0.05$ compared to Y, *[2] $p< 0.05$ compared to M-A.

In the study significantly lower thirst of older men compared to young ones was observed in all the experiments – at rest and during exercise (Table 3). Philips et al. (1991) obtained similar results but at different stimulations. They indicated reduced thirst of older men after infusions of hypertonic and isotonic saline and lower drinking during 30-min rehydration period compared to young men. These authors concluded that reduced thirst in older men was primarily related to a lower thirst sensitivity to hypertonicity and these older men showed trends towards an increased thirst threshold compared with younger men.

Conclusions

It was shown that the older group did not tolerate protective clothing worse than young one.

In the study, the tolerance of passive heat exposure was similar in the young and older groups matched on the basis of their physical activity. It was shown that the tolerance of 30-minute exercise at temperate intensity and at similar relative physical load was even better in the older group with higher physical capacity for their age than in the young group with average physical capacity. However, lower thirst in older men observed in all the experiments indicates that prolonged exposure of older men to a hot environment may carry a potential risk factor of dehydration, especially at a similar sweating rate as in young men.

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Management of Safety and Health Protection on building sites – under special consideration of use of personal protective equipment

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Introduction

In many working environments the "management of safety and health protection" emphasises the use of "personal protective equipment". The EC - guideline 89/656/EEC established the ordinance on the use of personal protective equipment, which contains the obligation of employers to select and provide personal protective equipment for the employees, if other measures of the maintenance of industrial health and safety standards do not offer any sufficient protection for the employees. In addition to that it is necessary to instruct the employees on how to use their personal protective equipment the right way.

The mentioned topic shall be clarified in the following with the example "management of safety and health protection on building sites". Compared with other fields of work the employees on building sites are exposed to particularly high accident and health risks. Changing working conditions and weather influences as well as appointment pressure and the simultaneous activities of employees of different employers permanently increase the endangering risks on building sites.

Methodology

Years of experience in coordinating safety and health protection on over 50 construction sites in Germany and Austria with a building volume between 250.000 and 7.000.000 EUR delivered the basic data for the discussion of the above mentioned topic.

The empirical value of these data are emphasizing the need for an effective management of safety and health protection on building sites under special consideration of the use of personal protective equipment.

Safety engineers who have been trained to coordinate safety and health protection on construction sites are witnessing dangerous situations involving people who are working on construction sites everyday. A lot of these situations could be less dangerous if employees would be sufficiently instructed and job sequences organized and optimized. Safety engineers on construction sites are confronted with these – often difficult – tasks in their daily work and their experiences helped to develop training measures.

Results and Discussion

In Germany the accident rate (accidents per 1000 full workers) lies more than twice as high in the building sector than in the average of the commercial economy - both at the

reported and the particularly serious work accidents. Almost every second fatal accident still happens in the building and construction industry - according to the statistical evaluations of fatal work accidents.

Table 1. Number of work accidents - Building and construction sector compared to the average annual accident rate of the Commercial economy (HVBG, 1997).

	1970	1980	1985	1990	1995	1996	1997
Building and construction sector	420.485	306.101	214.607	251.742	364.773	321.958	312.975
Commercial economy	143.600	110.087	83.319	95.100	101.099	90.461	87.252

Most of the fatal accidents are due to falling of scaffoldings, roofs etc.. About 60 per cent of the fatal accidents happen in connection with transport and subsidies building machines, processing machines as well as scaffoldings, in which every fifth piece of equipment shows safety technical defects. It can be assumed that every eighth accident wouldn't have gone out fatally, if personal protective equipment had got specified, posed and used.

Table 2. Ranking of severe accidents on building sites.

Cause of accident	Percentage of accidents
Falls from great height and other falls	38 %
Transport events: construction site vehicles and construction site machines	19 %
Collapses - also collapses with masses in movement	14 %
Objects and materials falling down	10 %
Electric blow	8 %
Suffocating, drowning	4 %
Fires, explosions	3 %
Other	4 %

Conclusions

Because of the reasons mentioned above the management of safety and health protection under special consideration of personal protective equipment is so important on building sites. Especially on building sites it proves difficultly to check the retention of protection regulations, such as carrying personal protective equipment. To improve the safety and health protection of the employees on building sites the EC - building site guideline 92/57/EEC was passed in June 1989. In the meantime this ordinance was converted into national law in the member countries of the EC and shall improve the working conditions at the building sites as well as reduce work accidents, occupational diseases and work conditional health dangers.

Especially on building sites it is crucial for the employees that executives can be taken as examples in wearing personal protective equipment. That is the only way to guarentee that the employees sense of duty to wear personal protective equipmet can be increased. Architects - for example - who enter a building site without helmet and safety shoes are just one unsuitable negative example for the employees. Building sites offer a special challenge, because a lot of executives do not act as models for their employees. The employees observe certain behaviors and take these over as their own behavior. This kind of ‚learning by observing the behavior of other people‘ may lead to negative behavioral aspects which are very hard to reverse once they are established. To reverese these be-

haviors intensive training programmes are indispensable. The goal must be to prevent these behaviors from developing by improving the executive duties to manage safety and health protection under special consideration of personal protective equipment.

It is therefore inevitable to train those who are responsible for empoyees on construction sites to enable them to manage safety and health protection – paying special attention to the use of personal protective equipment. Special training classes have been developed during the last two years and have already proved to be successful. Evaluating data will have to be elevated.

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Clothing trials as a part of worker training

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Introduction

According to an extensive survey in Finland the construction workers are most occupationally exposed to cold in their work (Hassi et al, 1998). There are a large number of risk assessment methods as well as safety norms and recommendations for the construction industry (Lappalainen et al, 1991). These recommendations do not pay attention to the effects of the cold on human beings. An ISO standard for working practises in the cold is under development. It will provide a comprehensive strategy for risk assessment and management practices of cold risks (ISONP 15743).

A development project was conducted in order to improve the management of cold related health and safety risks in the construction industry. The cold risks in house building work were assessed at a target site by means of a questionnaire and ISO standardised assessment methods. According to the questionnaire the workers had experienced cold related disease symptoms, cold injuries, discomfort, decline in working capacity, and reduced working motivation. The most problematic ambient factors were wind, cold materials and wet conditions. The work place assessments showed a risk of extremity cooling in many work phases and a risk of whole body cooling during the cold season in tasks involving low heat production.

From the basis of risk assessment, immediate development measures were carried out. As a learning organization, the company participated actively in developing its organization culture (Ruohotie 1993). At first foremen and key persons of the construction site were trained to recognise and manage the cold risks in construction work. The worker training was then conducted in information campaign at the target site. Further written learning and guidance material was provided. Information was given about the effects of cold on physical performance and health as well as cold protection. Field trials of protective clothing and equipment were an important part of the training.

Methods

At first, the workers were informed about the aim of the project and the forthcoming actions at the target site. The cold induced health and safety risks were assessed at the target site by using a primary questionnaire and ISO standardized methods. The analysis of the present state showed needs for immediate development measures.

The workers received the cold guide booklet (Figure 1) as a basic information package about the cold. Information about the effects of cold and protection against cold was delivered at the target site in 30 minutes information sessions. Written material was included in the dissemination of information (Figure 2).

In the development actions the concept of "learning by doing" was applied. The clothing trials were connected with the information sessions. The tested garments and equip-

ment were chosen from the needs that had risen in the risk assessment stage. The aim of the trial and the function of the test garments were explained to the workers.
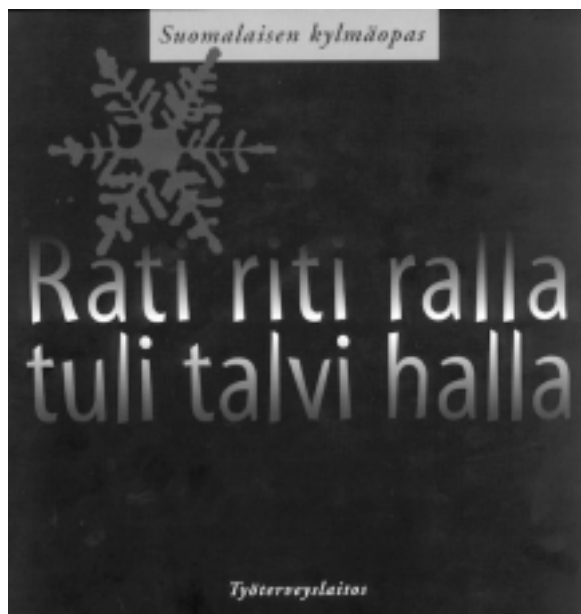
Figure 1. The Finnish Cold Guide.
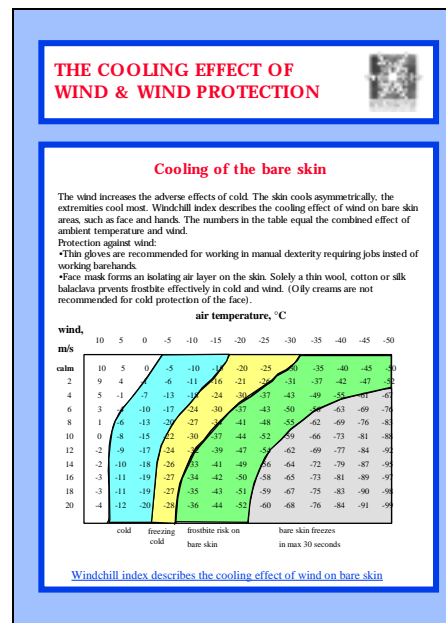
Figure 2. Example of given information.

Results and discussion

After the winter period the workers evaluated the information they had received about the different issues by using a scale of "a lot of new information - some new information - no new information". This feedback was given anonymously. The clothing trials were evaluated by open questions.

The workers indicated that they had received new knowledge about the effects of cold and cold protection. The feedback about the given information is shown in Table 1. The workers' subjective evaluations about the clothing trials are shown in Table 2. The concept of multilayer clothing helped in maintaining the thermal comfort in changing work situations and reduced excess bulkiness of the clothing. Especially protection of the hands against the cold felt to be improved.

Table 1. The workers´ feedback about the information blitzs given at their workplace (% of the answerers). The workers were asked to evaluate the new information they had received.

	A lot of new information (%)	Some new information (%)	No new information (%)
1. Underwear as a part of multilayer clothing	36	64	0
2. Mid-layer as a part of multilayer clothing	45	45	9
3. The water-repellency of outer garnments	55	45	0
4. The cooling effect of wind and protection against it	36	64	0
5. The effects of cold on physical performance	27	64	9
6. The effects of cold on health	45	55	0
7. Decreasing the contact cooling	45	45	9
8. Cold protection of the feet	27	45	27
9. Clothing as personal protective equipment	18	73	9
10. Rati-riti-ralla, Cold quide for the Finns	27	73	0

Table 2. The workers´ feedback about the clothing trials and immediate development actions conducted at the target site.

The trial	Products	Subjective evaluations
Underwear as a part of multilayer clothing	underwear, 30 % PP / 70 % WO undershirt, mesh 100 % PP	• very good: breathing, comfortable on the skin • mesh shirt in spring, mesh + polo shirt in cold • high collar protects well / collar too tight
Mid-layer as a part of multilayer clothing	pile mid-layer, 100 % PES	• really warm • never had better • really warm: it makes you sweat when working
The water-repellency of outer garments	water-repellency treatment of outer garment	• it works for a while • the garments are treated, but not yet in use
The cooling effect of wind and protection against it	construction worker's winter work clothing	• protects angainst the wind • best I ever had, I would surely wear this throughout the winter season • a PP mesh shirt and a CO sweatshirt are sufficient underwear and mid-layer
The cooling effect of wind and protection against it	wind proof insulated vest	• it was warm and allowed more room in sleeves, the clothing does not press the arms, it was easier to work than with a sweater
Protection of the hands against cold and wetness, decreasing contact cooling	knitted gloves, 100 % PP	• good under rubber gloves (no cold sensations, no sweating) • good under rubber gloves when T_a < -10°C • keep the fingers warmer and dryer
Decreasing contact cooling	insulating tool handles with rubber tape	• I could better hold the tools in my hands • non-slippery, insulated
Cold protection of the feet	sock with terry sole, 40 % WO / 40 % PAC / 20 % PA	• the sole insulates well against coldnes • I already had similar ones, really good • warm, good
Cold protection of the feet	loose inner soles	• keep the feet warm • reduced cold pain in my heels

Abbreviations: CO cotton, PA polyamid, PAC polyacrylic, PES polyester, PP polypropylene, WO wool.

Conclusions

The training associated with clothing trials had an impact on the attitudes of the workers. The workers felt that they had received new information about the effects of cold and means for protection against it. The training encouraged the workers to take responsibility for their own well-being while working in the cold. In the follow-up survey the workers also showed willingness to participate financially in purchase of additional clothing and equipment for cold work.

The project will proceed by developing an action model for assessing and managing the cold related occupational health and safety risks at construction sites. The model is integrated into the occupational health and safety manangemant system of the company. The development work standard proposal ISO NP 15743 "Working practices in cold environments" is used as a framework for the action model.

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Properties of foul weather clothing for construction workers after use

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Introduction

Construction workers often have to use foul weather clothing to be able to work efficiently at their workplace and to prevent them from conditions injurious to health. One of the most important criteria of this sort of clothing is the protection against bad weather in all circumstances and a sufficient mechanical resistance.

The aim of this project that was carried out jointly by the Centre for Safety Engineering (Erkrath, Germany) and EMPA (Switzerland) was to analyse the properties of typical foul weather clothing used by construction workers in a new state as well as after use (Heffels et al., 1999). The main focus was put on watertightness of the jackets, which was assessed according to different methods. Standardised tests (hydrostatic pressure (EN 20811) and Bundesmann rain shower test (EN 29865)) and own developments like the rain tower test with a manikin were used.

Methods

Six jacket types were analysed in this study (Table 1), corresponding to clothing commonly used by construction workers in Germany. For this study, two jackets of types 1, 2, and 3 were available and one of all the other types.

Table 1. Description of the samples.

Jacket	Watertight layer	Closure system	Hood	Damages in the used jackets
1N (new) 1U (used)	PVC	Push buttons with vertical gutter	yes	Stains on the outside, no visible damage
2N (new) 2U (used)	Compact PU	Buttons	no	Mildew stains, small damages in the coating
3N (new) 3U (used)	Compact PU	Buttons	no	Only light stains, no visible damage
4N (new) 4U (used)	Compact PU	Zipper	yes	Stains, one hole in the back region
5N (new) 5U (used)	PES membrane	Push buttons with zipper underneath	yes	Stains, Zipper torn out, no visible damage
6N (new) 6U (used)	PTFE membrane	Push buttons with vertical gutter	yes	Stains, no visible damage

Several methods were used to assess the watertightness, the mechanical properties and the wearing comfort of the jackets:

- Hydrostatic pressure (EN 20811) on the fabrics and on the seams
- Bundesmann rain shower test (EN 29865)
- Raintightness of the whole garment

- Tear strength (ISO 4674 A2)
- Seam strength (prEN ISO 13935-2)

Raintightness of the whole garment

This method (Rossi et al., 1998) consists of exposing the jacket to be tested, worn by a manikin, to a defined rain. The manikin is equipped with 22 humidity sensors and wears a cotton shirt underneath the jacket to get a good water uptake and to be able to make a visual assessment of the wet surface after the exposure to the rain. The tests were performed with three kinds of rain: cloudburst, persistent rain and drizzle. For the cloudburst (about 450 l/m^2h), the rain comes down onto the manikin from a height of 10 m to get similar dynamics as in practice. The raindrops (diameter about 5 mm) correspond to those described in the Bundesmann rain shower test standard (EN 29865). For the two other types of rain, nozzles are placed at about 3 m height, which release drops of about 0.5 mm (40 $l//m^2h$) for the drizzle and 1 mm (100 $l//m^2h$) for the persistent rain.

Results and discussion

Watertightness according to the standardised test methods

Table 2. Watertightness according to the hydrostatic pressure test and the Bundesmann rain shower test.

Jacket	Hydrost. Pr. (cm) [StD]		Bundesmann (ml/h) [StD]
	surface mat.	seam	
1N	- *)	379 [242]	- *)
1U	123 [196]	33 [11]	3 [6]
2U	11 [4]	4	124.8 [135.1]
3U	500 [0]	0	0 [0]
4N	- *)	500 [0]	- *)
4U	18 [11]	134 [244]	21.1 [22.6]
5N	- *)	408 [184]	- *)
5U	151 [235]	33 [11]	0 [0]
6N	- *)	500 [0]	- *)
6U	15 [2]	15 [3]	1.1 [1.4]

*) not tested

The watertightness according to EN 20811 was assessed up to a hydrostatic pressure of 500 cm. In order to be able to calculate the mean value of the different samples, the value of 500 cm was used even if the sample had reached higher pressures. This test was only performed on seams for the new samples as it was admitted that the surface material was tight in any case (Table 2). Jackets 2N and 3N were not assessed, as their seams were not sealed. The Bundesmann rain shower test (EN 29865) was also only performed on the used jackets. For both test methods, the samples were taken from the shoulder region.

The seam seals of the jackets 1N, 4N, 5N and 6N can be qualified as good, as they reach the best classification (class 3, without pre-treatment) according to ENV 343 (hydrostatic pressure ≥ 130 cm). Nevertheless, the standard deviation of jackets 1N and 5N are quite large as for each jacket, one sample got a lower result (16 cm for jacket 1N and 132 cm for jacket 5N). In the case of jacket 1, one seam was not properly sealed.

The results of the used jackets were totally different: only jacket 3U was completely watertight. Jackets 1U, 4U (on seam) and 5U had each one sample with high water-tightness (respectively 472, 500 and 500 cm), explaining the high standard deviation. All

other results of the jackets were lower than 80 cm, which is the limit to reach the lowest class of water penetration (class 1) according to ENV 343. The consistently low results show that most of the shoulder region of all the used jackets was damaged.

On the Bundesmann rain shower test, the used jackets 3U and 5U were tight. The result of jacket 5U shows that the hydrostatic pressure test is more stringent for the membrane than the Bundesmann test. It allows the detection of very small holes in the structure, not visible from the naked eye. For jacket 2U, a connection could be found between the watertightness and the surface covered by mildew, showing that mildew attacked the coating. The distribution of mildew was obviously not uniform, which explains the large standard deviation of this jacket.

An informal test of the repellency rate on only one sample per new jacket showed that all the jackets reached low values: jacket 6N obtained a rate of 2-3; jackets 1N, 2N and 3N a rate of 2 and jackets 4N and 5N a rate of 1. This low rate could favour the water ingress through wicking effect if it gathered near the end of the sleeves or at the hem, or near a non-sealed seam.

Raintightness of the whole garment

The test with the cloudburst is very stringent and thus, a jacket that remains tight for one hour in this type of rain will withstand most of the weather conditions. Jackets 1N, 4N, 5N and 6N resisted the rain for over one hour (Figure 1). However, jacket 4N stayed only tight if the hood was covered by a plastic bag to avoid water ingress through the collar region. The hood seam of this jacket was not sealed properly; this is a quite common mistake of the making. Jacket 5N resisted 59 minutes in the cloudburst but the results were very different for the three repetitions of the test. This was due to the fact that water mostly penetrated through the zipper and the collar region, where the water penetration is very much dependent on how the jacket is placed on the manikin. The relatively bad results of the jackets 2N and 3N are not very astonishing, as the seams of these jackets were not sealed. However, the water ingress mostly occurred at the end of the sleeves, showing that water gathered at the lower ends and was wicked inside through the seams.
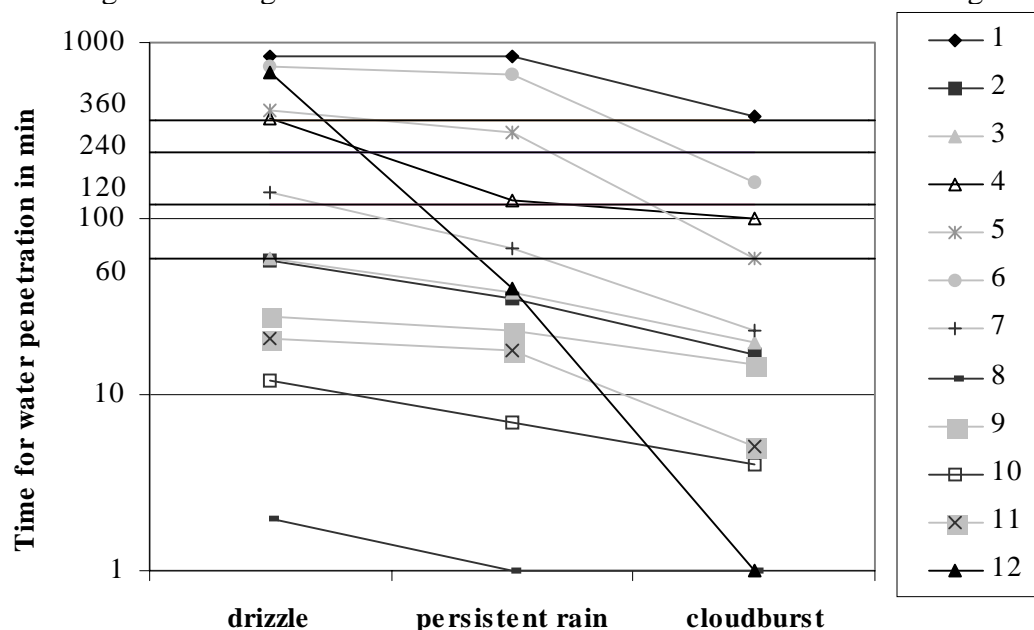
Figure 1. Time for water penetration with the 3 types of rain.

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From all the used jackets, Nr. 1U and 3U showed the best results. All the others had water ingress after no longer than 5 minutes. Water mostly penetrated the shoulder region, showing a weakening of the material or a detachment of the seam seals.

The ranking of the jackets remained approximately the same with the persistent rain and the drizzle, obviously with higher values. Only jacket 6U obtained a very good result with the drizzle, whereas it leaked very quickly in the cloudburst. This means that this jacket did not resist drops with higher kinetic energy. The drizzle had not a sufficient impact to press the drop through the jacket.

A survey among the users of this type of clothing (Heffels et al., 1999) showed that they complained mostly about the tightness of seams, shoulder and collar regions. The tests with the manikin confirm that these areas (especially the shoulder region) are particularly delicate for used jackets.

Tear strength and seam strength

All the jackets (apart from 2N, resp. 2U) showed a reduction of the tear strength for the used jackets. Jacket 2N obtained a significantly worse result in warp direction (i.e. the weft threads are torn) than jacket 2U, which raise the question whether the construction of both jackets was identical or if the two jackets had not the same slippage resistance of the warp-weft compound. The standard ENV 343 requires at least 25 N and even though there is a reduction during use, the used jackets all reach this value.

There were no significant changes in the seam strength between the new and used jackets. In two cases (jackets 3U and 5U), the value of the used jacket was even higher than the new one. EN 343 requires seam strength of minimum 225 N, which was only reached by the two breathable jackets 5N and 6N (resp. 5U and 6U).

Table 3. Mechanical properties of the jackets.

Jacket	1N	1U	2N	2U	3N	3U	4N	4U	5N	5U	6N	6U
Tear str., warp *)	60.5	47.8	56.7	58.7	60.9	46.9	- **)	44.0	64.4	55.2	74.7	61.8
Tear str., weft	40.8	43.6	39.9	65.2	44.0	28.1	42.7	27.7	35.6	27.9	52.9	52.3
Seam str.	105.0	111.9	199.4	187.5	224.1	361.8	184.3	154.0	374.1	586.0	308.6	294.6

*) weft threads are torn   **) not tested

Conclusions

In this study, the tightness and the mechanical properties of foul weather clothing for construction workers were analysed in a new as well as in a used state. The results show that the used jackets, that are usually replaced after about two years are used for a too long period of time as they all offered insufficient rain protection, mostly in the shoulder region. As this area is the most exposed to rain, it would be sensible to reinforce this region with a watertight material that offers a good resistance to ageing. The repellency of the jackets should in any case be improved to avoid any wicking of water to the inside of the jacket.

The survey among the users revealed that they wished a better mechanical resistance of the material. As all the samples complied with the requirements of ENV 343 for the tear strength, the wishes of the end users should be considered during a revision of this standard. It is nevertheless astonishing that all the compact coated jackets did not reach the minimum requirement of the seam strength.

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Physiological optimisation of protective clothing for users of hand held chain saws

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Introduction

Users of hand held chain saws like forest workers, members of technical welfare organisations, or fire-fighters have to wear cut resistant protective clothing permanently or occasionally. However, up to now the available protective clothing is criticised or even refused by the wearers. This is mainly because of a too small water vapour permeability ("breathability") of the clothing system. It could hardly been used over a longer period of time without leading to a critical overheating of the body, especially during the warm season and with heavier physical activity. Therefore, in a research project the textile's construction and pattern of the single components (trousers with cut resistant inlays, underwear, foul weather suit) of a protective clothing system for users of hand held chain saws were investigated. The aim of the research project was to derive constructional guidelines for a cut resistant protective clothing system, which offers sufficient protection and noticeably better physiological wear properties as the products presently available.

Within the research project, different aspects of wear comfort have been investigated:

- The *thermophysiological comfort* describes, how the thermoregulation of man is supported by clothing. It contains parameters like thermal insulation, water vapour permeability, and buffering capacity against sweat.
- The *skin sensorial comfort* deals with the direct mechanical contact between skin and textile. It is related to perceptions like softness or smoothness, but also to stiffness, scratching, or itching.
- The *ergonomic comfort* is a matter of garment design. The pattern and fit have also an influence on the thermophysiological properties, because they influence convection and ventilation in the clothing system.

More detailed descriptions can be found in (Umbach, 1987a; Umbach, 1987b; Umbach, 1993).

Materials and methods

In order to survey the *thermophysiological properties of textiles*, constructions from the actual production of textile manufacturers as well as possibly improved samples have been tested with the Skin Model (Sweating Guarded-Hotplate Test) according to ISO 11092 and internal standard-test specifications (Umbach, 1987a; Umbach, 1987b; Umbach, 1993; Bartels & Umbach, 1999a). These measurements simulate different wear situations from "normal" (insensible perspiration) up to "heavy sweating" (liquid sweat on the skin) including stationary as well as instationary experiments.

The *skin sensorial properties* of textiles have been tested by 5 specific apparatus, measuring the clinging to sweat wetted skin, the surface roughness, the number of contact points between skin and textile, the wettability, and the stiffness.

Physiological tests of garment systems have been performed with the manikin "Charlie" (see Figure 1) measuring the thermal insulation. Combined with Skin Model experiments, these data also allowed to determine the water vapour resistance of the clothing system and to perform predictive calculations of the physiological impact on the wearer (Umbach, 1987a; Umbach, 1987b; Umbach, 1993; Bartels & Umbach, 1999b).

Results and discussion

The research project led to numerous results, how to optimise the physiological function of protective clothing for users of hand held chain saws. These were converted into constructional guidelines, some of which are compiled in Table 1. There, the innovative constructional parameters are given together with their physiological advantages. These results have been implemented in a prototype which is shown in Figure 1. In the following, some of these constructional guidelines are discussed.

Figure 1. Prototype of a physiologically optimised protective clothing system for users of hand held chain saws during the tests with the thermal manikin "Charlie".

Cut resistant inlays

Protective clothing for users of hand held chain saws contains a package of 9 to 10 layers of a synthetic woven, in order to be protected against injuries caused by the saw. Because of its thickness, this package has a high thermal insulation and a high water vapour resistance, which can cause a significant heat stress for the wearer. Hence, the thickness of the cut resistant inlay has to be reduced.

From a pure physiological point of view, a reduction of the number of cut resistant layers would be most effective. However, in this case the level of protection becomes unsatisfactory, therefore a decreased number of layers cannot be recommended.

A better solution to reduce thickness is a wide stitching, keeping the level of protection unaffected. In this case, the single layers cannot rub against each other and the inlay is not swelling up by the movements of the wearer or by washing. A typical example of a 10-layer inlay is given in Figure 2: Here stitching reduces the thermal insulation by 32 % and the water vapour resistance by 25 %, and improves the buffering capacity against vaporous sweat (moisture regulation index) by 10 %.

Table 1. Overview on main results obtained in the described research project for the physiological optimisation of protective clothing for users of hand held chain saws. Constructional guidelines have been used for the prototype given in Figure 1.

clothing component	innovative construction	physiological advantages
cut protective clothes		
cut resistant inlay	stitching	low thermal insulation good breathability
outer fabric	PES/CO 65/35 215 g/m² 2/2 twill-weave brushed inside not hydrophobic	good skin sensorial properties short drying time
lining	PES-knitwear brushed inside	very good skin sensorial properties very high liquid sweat transport short drying time
pattern	with waistband (no dungarees) vents adjustable rubber band at waist pair of braces (no belt) more width	low thermal insulation high ventilation rate wider range of utility high breathability
underwear	double face PES inside, CO outside	high sweat transport short drying time
foul weather suit	3-layer-laminate PTFE-membrane	good breathability high buffering capacity against vaporous sweat

Lining of the cut resistant inlay

The cut resistant inlay is separated from skin by a lining. It has been shown during the project that currently available lining constructions are not optimal: Cotton linings are soaked up with sweat during high levels of activity and dry too slowly. On the other hand, synthetic linings are usually too smooth and have too many contact points with the skin, thus leading to clinging on sweat wetted skin and a poor skin sensorial comfort.

In the research project, a new material has been proposed which is based on a polyester knitwear. The recommended textile is brushed on its inside and hydrophilic. It has a very good transport of vaporous and liquid sweat, dries quickly, and offers a superior skin sensorial wear comfort.

Outer fabric

Similar problems as described with linings were also found for so far available outer fabrics of protective clothing for users of hand held chain saws: Cotton products were showing thermophysiologi-
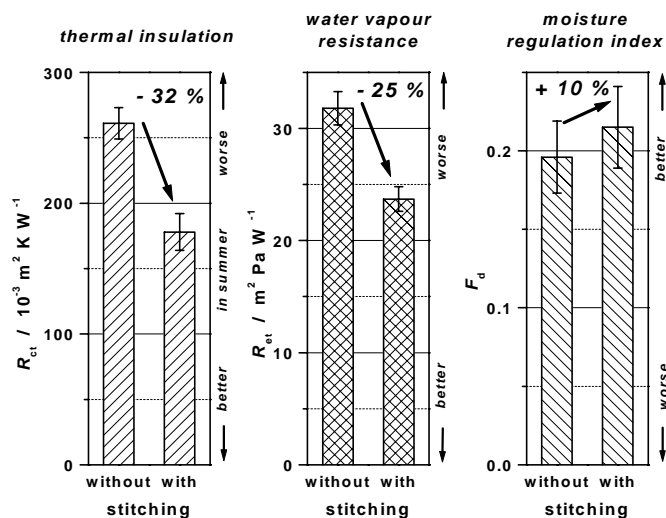
Figure 2. Physiological advantages of stitching a cut resistant inlay with 10-layers.

cal disadvantages, whereas synthetic materials offered an only poor skin sensorial comfort, being especially too stiff. Most materials were hydrophobic, thus leading to a poor transport of liquid sweat. Therefore, in the project a 2/2 twill-weave PES/CO 65/35 material with a weight of 215 g/m² is proposed, which is again brushed on the inside and hydrophilic. It leads to a fast transport of sweat, dries quickly, and offers a good skin sensorial wear comfort.

Pattern

The pattern of the protective clothing system has been investigated as well. It has been shown, that a high ventilation rate can be obtained by a wider cut, using no belt but a pair of braces, and including vents. In the prototype (see Figure 1), the high ventilation rate can reduce the thermal insulation and the water vapour resistance by up to 25 %.

Conclusions

In the research project presented a systematic physiological optimisation of protective clothing for users of hand held chain saws was carried out. As a result, thermophysiological as well as skin sensorial improvements have been proposed and realised in a prototype. The research project has provided the knowledge, how to construct the different components of this type of protective clothing, in order to achieve optimal physiological wear properties and additionally fulfil the necessary safety demands.

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The need for a rational choice of cold protective equipment in a refrigerated working environment

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Introduction

In Japan, the frozen food chain stores have developed and the capacity of refrigerated warehouses has increased remarkably. Even after the Japanese bubble economy collapsed in 1992, the still high growth is shown (Figure 1). The setting temperatures in the refrigerated warehouses have become lower and the cold environments below –20 °C have increased. Several studies (Tanaka et al., 1993; Tochihara et al., 1990) have been carried out until now to investigate the work environments in refrigerated warehouse industry and the health problems and physiological strains of the workers, but the details have not been fully clarified. The objective of the present study was to investigate the present state and problems in the refrigerated warehouse industry from the viewpoint of industrial health. To achieve this, we carried out a field survey for three refrigerated warehouses in Japan. Special attention was paid to how much and how long the cold workers are cooled during work and how they use cold protective equipment in the workplaces.
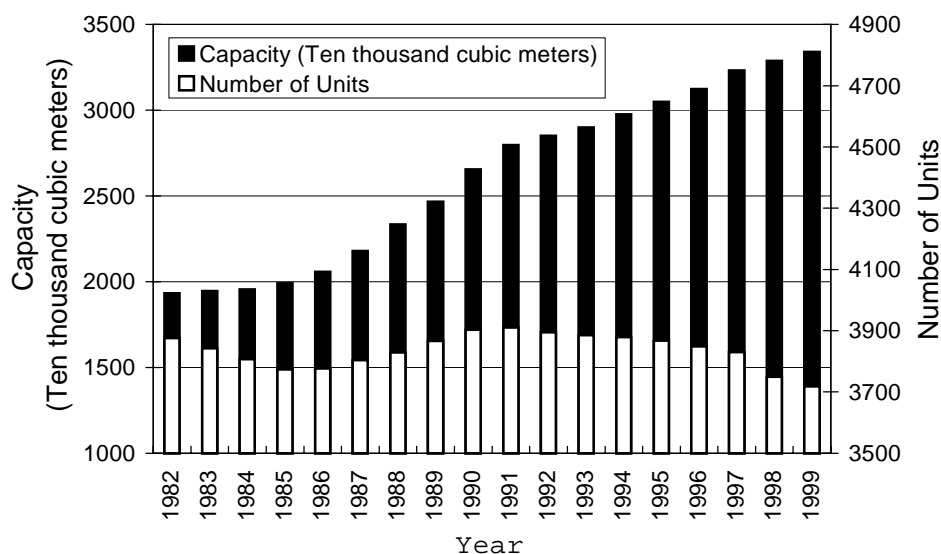
Figure 1. Recent change in the capacity and number of units of refrigerated warehouses in Japan (Jpn Assoc Refrig Storage, 1999)

Methods

A field survey for three refrigerated warehouses in Japan was carried out during March in 1999. The refrigerated warehouse "SA", "YO", and "KA" is located in Sapporo (the annual mean temperature is 8.2 °C; region near sub-arctic in Japan), Yokohama (15.2 °C; temperate zone region), and Kagoshima (17.6 °C; region near sub-tropical), respectively

(Table 1). To investigate the present state and industrial hygienic problems in the refrigerated warehouse work, we interviewed the foremen of the refrigerated warehouses about the scale of the workplace, the working conditions, the working hours, the work type, the type and brand of work clothes and cold protective equipment which are used during work, the work/rest schedule, what is in trouble during work and to be improved, the complaints or health problems which are conspicuous for the cold workers etc. To estimate how long the workers are exposed to cold stress and how much they are cooled, skin temperature of peripheral parts of the body (finger and hand), body core temperature (oral temperature) and the ambient temperature of the vicinity of the workers were also measured for some of the workers from the start to the end of a working day.

Results

Characteristics of the refrigerated warehouse work

As shown in Table 1, air temperatures in the refrigerated warehouses were set at below 20 °C and above 0 °C. The average age of the workers was 46.1 years in SA, 42.5 years in YO, 36.0 years in KA, respectively and a small proportion of workers (10 %) was made up of young persons below 30 years old.

Table 1. The refrigerated warehouses investigated in the present study.

Refrigerated Warehouse	Region	Number of cold workers	Average and range in age of workers	Setting temperature in the warehouses (°C)
SA	Sapporo (Sub-arctic)	10	46.1 (32-55)	0, -20, -21, -24.5
YO	Yokohama (Temperate)	6	42.5 (28-57)	0, 5, -23
KA	Kagoshima (Sub-tropical)	10	36.0 (22-48)	13, 1, -23, -25, -50

Main job of the workers was to carry frozen objects in or out of the refrigerated warehouses by operating a forklift (forklift work) or by pulling a loaded hand cart (manual work). Cold exposure time per one entrance was shorter for forklift work than for manual work, but frequency of entrance into refrigerated warehouse was higher. The workers tended to work for hours without taking few regular rests except for lunch break (12:00-13:00). There was some individual variation in methods of getting back body warmth during rest periods.

Use of cold protective equipment

The companies supplied both cold protective equipment and work clothes for the workers. The cold protective equipment consisted of insulated jacket, insulated trousers, helmet, hat etc. These were chosen by the foremen of the companies on the basis of their experiences without any information available for their thermal insulation level. Thermally low-insulated gloves such as cotton gloves were commonly used as a result of giving priority to the workability.

Thermal loads and health problems

The forklift workers were frequently exposed to large temperature differences by coming in and out of refrigerated warehouses many times in a working day (Figure 2). Especially

the facial cooling seemed to occur frequently in forklift-operating workers because their faces were not covered with any cold protective equipment during work.

The manual workers tended to stay longer in the inside of the refrigerated warehouses than the forklift workers. The finger temperature in some manual workers decreased to below 10 °C during work (Figure 3). This appeared to be due to the fact that the manual workers usually loaded and unloaded the frozen objects directly by their hands during work. Despite this excessive finger cooling, the workers tended to have little complaints about pain and cold sensation.
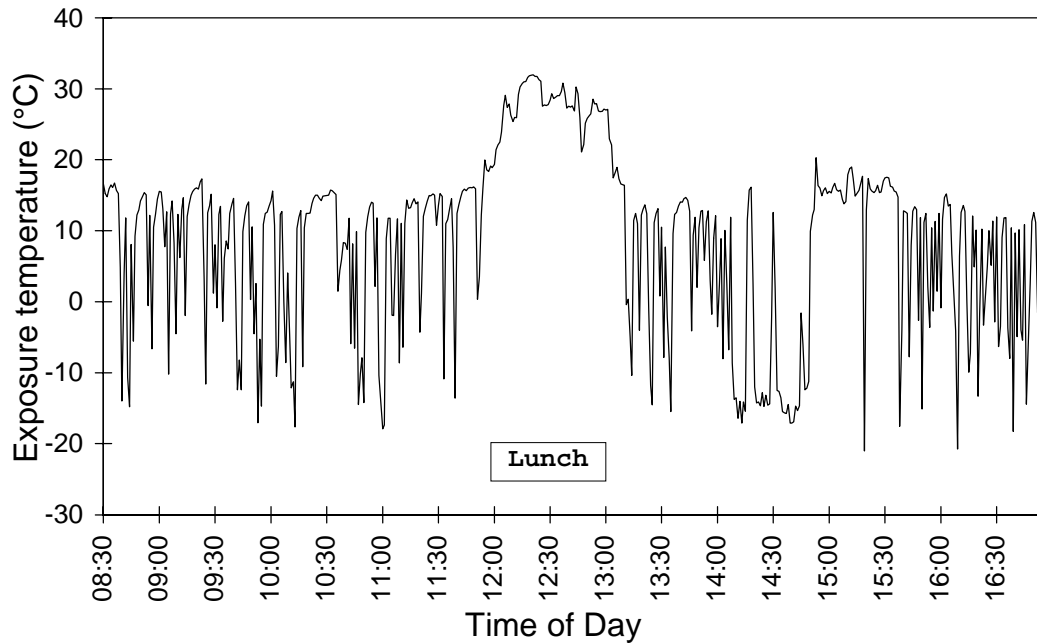
Figure 2. A typical continuous recording in an ambient temperature of the vicinity of the worker who is engaged in the forklift work in the refrigerated warehouse in a working day.
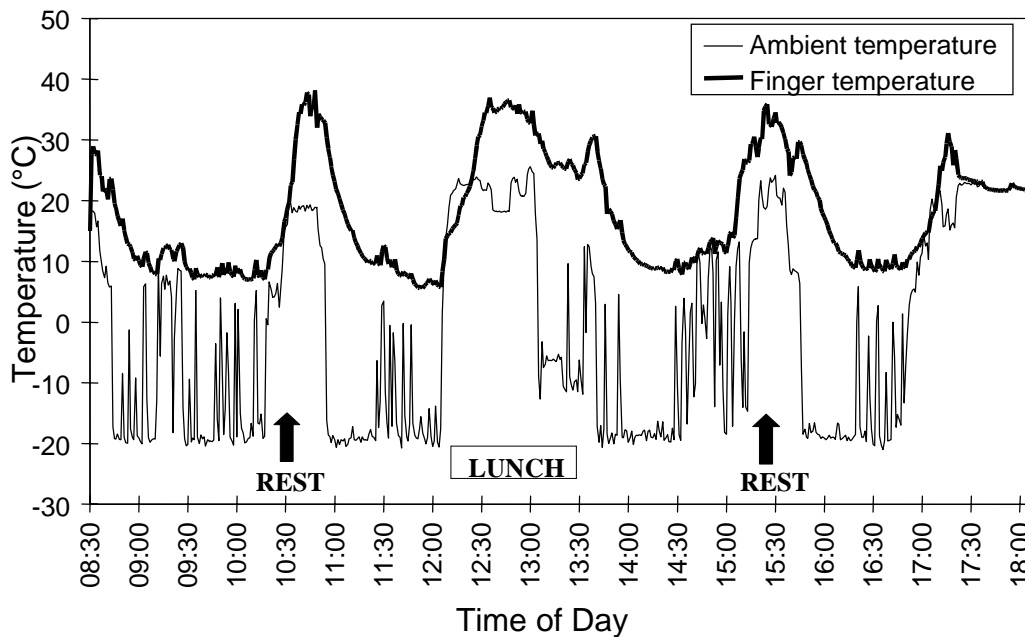
Figure 3. A typical continuous recording in skin temperature of a finger and ambient temperatures of the vicinity of the worker who is engaged in the manual handling work in the refrigerated warehouse in a working day.

Figure 4 shows the oral temperature change of the workers in the refrigerated warehouse "KA". Four out of seven workers (worker 1,4,6,7) had excessive body core cooling as indicated by oral temperature below 36 °C. Despite this excessive body core cooling, some of the workers tended to have little complaints about subjective discomfort and cold sensations.

As the main health problems, backache, hemorrhoid, hypertension, frostbite, and mucus during work were reported by the foremen and workers.

Greater increase in subjective thermal loads during work in summer was complained by the workers even in the refrigerated warehouse "SA" of sub-arctic region as well as "YO" of temperate and "KA" of sub-tropical regions. This seemed to be due to the greater temperature difference between inside and outside of the refrigerated warehouse in summer.
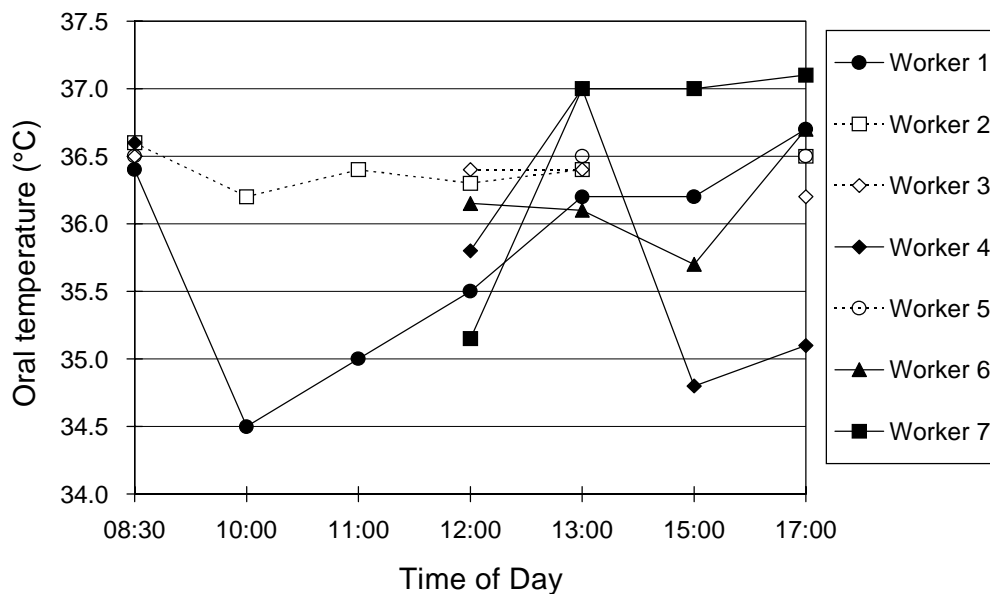
Figure 4. Oral temperature changes of the seven workers in the refrigerated warehouse "KA". Four out of seven workers (Worker 1,4,6,7) had excessive body core cooling as indicated by oral temperature below 36 °C.

Discussion

The recent problems in refrigerated warehouse work indicated by the present survey are (1) few young workers in the workplace, (2) longer working time and shorter resting time, (3) frequent and intermittent exposures to large temperature differences by frequent coming in and out of refrigerated warehouses, (4) common use of thermally low-insulated gloves as a result of giving priority to the workability, (5) increase in subjective thermal loads during summer, (6) excessive cooling of peripheral body parts during manual work, (7) intermittent facial cooling of forklift-operating workers with low metabolic rate, (8) individual variation in methods of getting back body warmth during rest periods, and (9) greater decline in oral and finger temperatures without subjective discomfort or cold sensation in some workers. Problem (9) is consistent with the results of our previous laboratory studies (Sawada et al.,2000; Sawada et al.,1998) which examined the effect of intermittent cooling of fingers and the whole body. The findings of the present study strongly suggest the need for a rational choice of cold protective equipment, which are not dependent on the workers' subjective judgement in refrigerated warehouse work.

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Diversified design needs of personal protective devices and clothing in cold climate: An example in the design needs of protective outdoors winter shoes

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Introduction

The use of personal protective devices (ppd) and clothing have become essential in many hazardous work situations. But unless the workers wear the ppds during the maximum period of exposure, protection from the hazards is not guaranteed. Many surveys in the use of ppd have revealed that they have not been adequately worn by the workers due to mainly the discomfort caused by the lack of wearability needs in their design (Abeysekera and Shahnavaz, 1988). During the past 10 years there has been a continuously increasing interest to improve the human factors or user needs of ppds. This is clearly evident from the Conference Proceedings of NOKOBETEF during the past 16 years. From a very negligible number of papers presented on ergonomics or wearability aspects in NOKOBETEF 1, 2, and 3, over the years human factors of ppds have gained importance. The current NOKOBETEF 6 and the First European Conference on Protective Clothing has as its theme 'Ergonomics of Protective Clothing'. The breakdown of the papers presented in NOKOBETEF is shown in Table 1.

Table 1. From papers presented in NOKOBETEF Symposia over the years.

Year and Number	On Protective Aspects	On Ergonomic Aspects
1984 NOKOBETEF 1	21	3
1986 NOKOBETEF 2	11	3
1989 NOKOBETEF 3	26	3
1992 NOKOBETEF 4	36	6
1997 NOKOBETEF 5	31	7
2000 NOKOBETEF 6	46	16

In safety helmets used to protect from falling objects in indoor climates the protection needed is for one type of hazard. The wearability needs e.g. fitness, low weight, ventilation, etc., for such helmets usually are not difficult to achieve (Abeysekera et al., 1997). However when ppds are used in the cold climate, apart from the protection from a work hazard the ppd must also protect the worker from the cold exposure. While trying to achieve both protections the wearability needs of such ppds become very difficult to incorporate (Bergquist and Abeysekera, 1994a). A safety helmet worn outdoors in cold climate must have the possibility to protect the head from impact injuries as well as provide insulation of the head from the cold. In trying to achieve both demands the correct fitting of the helmet is affected. Ppds used in cold climate can become clumsy and uncomfortable for the wearer in trying to achieve the double protection demand.

In safety gloves used in cold environments the wearer must be protected from impact hazard or chemical hazard as well as from the cold exposure of the hands. Achieving both protection demands can result in significant loss of hand dexterity (Geng et al., 1997).

In very rare situations one type of ppd has to meet the 3rd protection demand. A good example is safety footwear worn outdoors on snow and ice. The three protection demands are: protection from foot impact injuries, protection of feet from exposure to cold climate and protection from slips and fall accidents. To satisfy the 3 demands, a steel toecap, insulated shoe material and high friction sole material respectively are the basic design needs. Providing wearability needs for such ppds is a challenge to the shoe designers. These needs are so diversified and appropriate priorities obtained from research have to be adopted in such designs.

An example using protective footwear in cold climates

Working under cold conditions present more problems than working in indoor climates. The two protection needs viz. protection from impact injuries and protection from the cold lack co-ordination in their demands. This will cause the wearing of such shoes clumsy and bad fitting. A questionnaire survey was conducted by Bergquist and Abeysekera (1994b) among 100 outdoor workers in the north of Sweden, 100 manufacturing companies from 12 countries and 15 experts. The respondents were asked to rank the importance of 11 ergonomic demands when designing safety shoes for the cold climate. 90% of users, 20% of manufacturers and 75% of the experts responded to the questionnaire. The ergonomic demands were ranked from the most demanded to the least demanded in the following order: Fitness: Thermal Comfort: Protection from work hazards: Low weight: Anti slip: Mobility: Ease to don / doff: Durability: Adjustability: Good appearance and Moderate price.

The extremities viz. hands and feet are affected by cold exposure as they are in frequent contact with cold surfaces. Therefore both design needs e.g. protection from impact as well as protection from cold injuries are important. In consideration of thermal properties of winter shoes, factors that are important are heat conductivity of material, avoiding dampness of the fabric and allowing air trapped inside the fabric for insulation. A steel toecap is incorporated in most safety shoes for protection of the feet from impact injuries.

Experiments and surveys carried out in the past on thermal effects of steel toecaps have revealed contradictory results. Påsche et al (1990) reported no cooling effect from steel toecap. A questionnaire survey conducted by Bergquist and Abeysekera (1994b) on protective shoes revealed that a major problem regarding thermal comfort was the alleged cooling effect of the steel toecap. However Kuklane and others (1999) in their investigations have observed small differences of insulation of some types of boots with and without steel toecaps. They have also shown that steel toecaps may show an "after-effect" which may be caused by higher mass and thermal inertia of the toecaps, which affects cooling of the feet.

The most demanded ergonomic need of the users was fitness of the shoe (Bergquist and Abeysekera, 1994b). The fitness has to be adjusted to the insulation needed, which in turn depends on the air trapped inside the fabric and between foot and shoe. Therefore shoes must be big enough to accommodate thick socks. Shoes must also allow the pumping effect for the air-layer inside the shoe to escape out which is also influenced by the shoe fitness.

It has been reported that increased shoe weight can increase the work load of the wearer (Smolander, 1989; Jonas et al., 1984). Walking on snow layers can also be physically demanding (Pandolf et al., 1976).

Slips and falls on ice and snow

The third and by no means the least protection need in safety outdoor winter shoes is the prevention of slips and falls. The major focus on current research on protective footwear for cold environments has been on thermal insulation (Kuklane, 2000). Prevention of slips and falls however has not caught much attention. The available research studies on slips and falls have concentrated more on improving the friction of shoes on oily and wet shop floor surfaces. Considerable interest on the design of anti-slip winter shoes on snow is fast developing as in Nordic region, slips and falls on icy roads are a major problem during winter. Recently several studies have been carried out on shoes used on ice and snow and researchers have come up with information on the aetiology of slips and falls, which have to be considered by the designers of such shoes. Poor grip and low friction between footwear and the underfoot surface have been considered as major factors for slips which calls for increasing the friction of the shoes as well as the walking surfaces (Grönqvist, 1995; Gao and Abeysekera, 1999). Many other factors have been revealed in studies that contribute to prevention of slips: viz. postural control and gait (Grönqvist, 1995), perception of risk, hardness (low) of sole (Leclereq et al., 1994), roughness to increase the friction (Manning et al., 1990). Studies on tread pattern and contact area have not yet given conclusive results (Stevenson, 1997; Grönqvist, 1995). Recent studies carried out by Gao (1999) have shown no significant effect from the Center of Gravity (COG), hardness, roughness and sole contact area (static and dynamic) on the coefficient of friction (COF) of the shoes. Experiments by Gao and Abeysekera (1999) have clearly indicated that safety shoes, which are to be used outdoors in winter, are not adequately provided with anti-slip sole material. Results of observations of 25 subjects walking on five types of icy roads wearing 4 types of shoes (4x5x25 trials) on ice at 0 ^{0}C are shown in Table 2. COF values measured on 4 different pairs of miscellaneous shoes and 3 types of safety shoes showed that COF values of safety shoes (Group B) were significantly lower (p<0.0006) than COF of miscellaneous shoes (Group A, Table 3). It can be seen from the number of occasions of tendency to slip (during 500 trials) and low values of COF in safety shoes that the designer of safety shoes has incorporated no special anti-slip precautions. It is observed from recent research on slips and falls on ice and snow that unlike the design demands for protection from impact injuries and insulation from cold climates, the design demands for prevention of slips and falls in safety shoes are seldom provided.

Table 2. Results of tendency to slip.

Shoe Type	Times tendency to slip/fall
Winter shoes	156
PU occupational footwear	175
Safety boot with steel toe-cap	150
Farmers protection boot	136

PU: → Polyurethane

Table 3. Comparison of COF values.

Group A	COF
Winter with metal stud	0.14
Shoes with anti-slip fibre component	0.18
Work shoes	0.18
Normal footwear	0.13
Group B	
Safety shoes with nitrile soling	0.09
Safety boots	0.09
Safety shoes with PU soling	0.09

Group A: → Winter, work and normal shoes
Group B: → Safety shoes with steel toecap

Discussion and Conclusions

Users frequently demand the comfort and wearability of ppds if not provided will make them very unpopular. Protection and comfort are contradictory demands. When the same ppd has more than one protection to provide it becomes harder for the designer to provide human factor needs. In a questionnaire conducted on users of ppd in the cold climate the following complaints have been made (Bergquist and Abeysekera, 1994a): Cold sensation from steel toecap; lack of dexterity from gloves; difficult to work with large gloves; helmets are heavy and not fitting; walking difficulties with heavy safety shoes and trauma from the shoes. From the example of the use of safety shoes used outdoors in the cold the diversified design demands in protection and their influence on wearability are shown in Figure 1.

Protection Demands   **Design Demands**   **Influence on Wearability**

| Impact Injuries Falling Objects | ⇒ | Steel Toe Cap Thick Shoes Thick heels & soles | ⇒ | Thermal Discomfort Heaviness Walking Difficulty |

| Cold Climate Cold Injuries | ⇒ | Insulation Heat conductivity Permeability Leak proofness Pumping effect | ⇒ | Fitness Thermal Comfort |

| Slips and Falls | ⇒ | Friction Roughness, Hardness Tread pattern Contact area Durability | ⇒ | Weight Perception of risk Gait Postural balance |

Figure 1. Protection and design demands and their influence on wearability of winter safety footwear

Regarding the design and use of ppds Crockford (1979) quoted as follows: "From the designers point of view he designs a shell or a piece of environmental armour which keeps all the nasty aspects of the environment away from the wearer. From the wearer's point of view, the designer places a barrier around him which makes work more difficult." From the above discussion it will be necessary to complement Crockford's statement with the following: "From the ppd Standard Committee's point of view the main aim is to achieve a distinct level of protection performance to protect the user from injury or disease. From the researcher's point of view research in ppds has to be developed in a specific area e.g. protection, comfort etc, to achieve the maximum possible level. Lastly in the human factor specialists point of view a ppd must achieve optimum protection at optimum comfort or wearability to the wearer.

Some of the demands are contradictory with each other. Therefore future research in ppds should be directed towards an integrated or systems approach to achieve the optimum protection as well as optimum wearability. Researchers, users and designers should adopt an iterative process in designing ppds requiring more than one type of protection. Standard setting committees and designers must take cognisance of contradictory protection demands and their influence to wearability needs of ppds

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Footwear for cold work: a limited questionnaire survey

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Introduction

This questionnaire survey was initiated to acquire information for preparation of a series of field studies (Gavhed, Kuklane & Holmér, 1999a; Gavhed, Kuklane, Karlsson & Holmér, 1999b). The paper deals with questions that were related to the thermal responses of the feet and footwear performance. Other data is shown for reference and background.

Materials and methods

A brief questionnaire was sent out to various companies about their workers' cold exposure and if they were interested to take part in a more thorough study about work in cold. Three companies answered positively and to them was sent a thorough questionnaire (Gavhed et al., 1999b). Thirty questions were directly related to feet and/or footwear.

Results and discussion

Work organisation and background data

In total 43 questionnaires out of 66 were returned: 18 from a harbour company (HC), 16 from a telecommunications company (TC), 8 from a customs office (CO) and 1 from a construction worker working at the institute by contract. The persons represented a wide variety of jobs that have to be carried out in cold working conditions. The age of the workers was between 21 and 60 years. In average they had worked in the company for 18.5±10.4 years.

The work load for an ordinary day was rated as very light by 18.7 % of the respondents, light 23.2 %, moderate 21.5 %, heavy 29.3 % and very heavy 7.3 %. 57 % of the work time was spent in cold environment. The total amount of cold exposure during a full working day depended on the environmental temperature and was at average more than 4 hours at 0 °C, about 4 hours at -10 °C and 2-4 hours at -20 °C. The length of cold exposure was dictated by the job needs. Temperature of -20 °C was considered enough severe to limit the exposure time. The length of one work period in cold was usually 1-2 hours. At -20 °C it was under 1 hour, except for the CO where work periods were always around 1-2 hours. It was possible to take a warm break when a person felt cold, but there could be as well occasions where there was not possibility to take a break because of feeling cold. Sometimes the workers themselves did not choose to take a break for warming up even when there was a possibility. Generally, there were breaks in warm locations about 3 times per day. The length of an average break was about 30 minutes. If there were more breaks, then these were usually shorter. There were seldom (1-2 times)

tasks at warm locations. At the CO some tasks were done in warm locations up to about 5 times per day. The work periods in warm places usually lasted 15-60 minutes.

Most of workers (72 %) considered the wintertime to be the most troublesome season regarding the footwear. Cold was the main reason for that. The other reasons were wetness, snow and ice, bulkiness (weight) of the winter boots that makes it difficult to carry out some tasks (reduced moving ability), darkness. Two workers (<5 %) considered the spring and fall periods as the worst. One of them considered in his answer the difficulty to choose the right footwear for work due to the quick weather changes. Nine workers did not answer the question and 1 had not had any trouble with the footwear.

The footwear

Only one of 43 workers said that he did not use the safety shoes (footwear with steel toe cap). However, 8 (3 from TC and 5 from CO) said that the safety shoe was not compulsory (including one who didn't wear them) and one did not answer on the question. Generally the same pair of the footwear was worn longer than 6 months (44 % 6-12 months, 28 % 1-2 years and 26 % more than 2 years). 67 % used the same safety footwear every day and 30 % used the same footwear both during summer and winter. At CO all wore the same footwear every day (at HC 2/3 and at TC more than half) and only one used different boots during summer and winter. At the TC only two persons reported use of the same footwear during summer and winter (HC 5).

At the HC most of the workers (12) used footwear with warm lining during winter. Half of them used also footwear without lining occasionally (5) or regularly (4). The TC workers used warm boots and one of them used footwear without lining occasionally while at the CO all the workers regularly wore footwear without lining. They had high leather boots with a zipper and/or a cord. At other companies the leather was the most common footwear material, too. However, some footwear of synthetic material (3 at both) or rubber boots (2 at HC and 1 at TC) were used as well. At TC the used footwear was usually of boot type, while at HC on 50 % of cases the shoes were used. The most common high footwear was with the zipper, while low shoes commonly had cords.

General problems with cold

Most of the persons reported trouble with cold. Often the cold became most unpleasant when it was connected with wind (23 % always, 40 % at least once per week and 23 % 1-2 times per month). The most common cold body parts were feet and toes (84 %) followed by hands and fingers (79 %) and face with its parts (ears, chin, cheek etc., 79 %). The cold sensation was the severest in hands and fingers, followed by feet and toes and then face and its parts. The legs were the next to feel cold. The three most highly ranked factors for cold sensation of feet were boot material (42 %), contact with cold surfaces (37 %) and work at varying activity levels (14 %). In addition, the jobs that require long periods of standing still were mentioned as a factor for cold feet.

Some workers (14 %) had a cold injury at work and some (14 %) during free time. One person reported a cold injury both at work and free time at the same location. Some had cold injury at two or more locations. The listed sites were toes (5 cases), fingers (3), ears (3), nose (1), under chin (1), eyelid (1), cheek (1) and an unspecified location on face (1). Some workers had stumbled because their feet were cold (16 %).

50 % of workers were satisfied with their clothing. However, this picture was different in various companies. At HC 40 % answered that their clothing does not protect well enough against cold. At TC the percentage of dissatisfied was 30, while none from CO

was satisfied with cold protection of their clothing. The footwear was considered to be the worst (30 %) followed by outer garments and gloves (both 23 %). At the companies the dissatisfaction was different: at HC (18 workers) the three biggest problems were footwear (33 %), gloves (28 %) and outer garments (22 %). At TC (16) there was most few complains on clothing: footwear 19 %, gloves 13 % and on socks, cap and gloves all 6 %. The most dissatisfied were CO workers (8): 75 % complained on outer garments and 50 % on footwear and gloves. At all companies 44 % used thick warm socks. Extra insoles were used by 19 %. Some of the complaints were cold steel toe cap in footwear and "footwear too small to allow additional insoles or socks".

Problems with footwear in cold

47 % of the workers (HC 50 %, TC 31 % and CO 75 %) had experienced problems with footwear in the cold climate. This was well related to the type of the used footwear. Twenty one workers gave their comments on what could be the problem. Nine of them (43 %) directly point out steel toe cap or other steel objects in footwear as a cause of cold feet. Other problems were: cold soles (6), slippery soles (3), shoes were experienced colder than boots (however, some jobs, e.g. driving a forklift truck, were seen more comfortable with them), jobs that require long periods of standing still, fresh snow after heavy snowfall (more than 20-30 cm), missing a good support at ankle, too low footwear, not insulated footwear (especially CO) or just cold itself. Finally, there was a suggestion to use boots with cords that fit better around the ankle instead of ordinary leather boots.

The most common problems connected with footwear were feeling cold in feet (30 of 43) followed by risk to slip (16) and wet (15) or sweaty (12) feet. The main reasons for cold feet was seen to be footwear without warm lining or bad insulation (3), steel toe cap in safety footwear (3), work that requires long periods of standing still (2) or low sole insulation (1) and severe cold in itself (1). The supposed reasons for slipping were wrong choice of the sole, incorrect soles and that the rubber becomes stiff with cold. Stiffness and missing good support at the ankle joint were the problems connected with boot material and construction (2). Slippery working/walking surfaces were mentioned by 2 workers. Wet or sweaty feet were related to water from outside (snow, water and rain, 3) or inside (sweating, 1), shifting between cold and warm locations during day (1), no ventilation in footwear (1), wrong choice of footwear (1) and no insulation (1). Bad fit (9) was related to not enough tight around shin, bad support for ankle, stiffness, wrong choice of shoes, can't find the shoe fitting particularly one's foot (all 1). Stiffness was brought out separately on 8 cases. Difficulties to walk (6) and restricted mobility (6) were related to stiffness (3), clumsy shoes, cold and slipperiness (all 1). Five (5) workers thought that their shoes affect the working and one (1) related it to the need to be more careful. Four (4) workers had had chafed feet. For one of them the reason was a hard heel-cup. One (1) mentioned the difficulty to put on/take off the shoes. Because of missing good support at the ankle and slipperiness the footwear was considered not to give enough protection against injuries (1). One (1) recommended laced boots against spraining and 1 mentioned the footwear tightness to be the reason for wet feet.

Slipping

Slipping was considered as the next biggest problem after cold. 30 (70 %) workers had slipped and 22 (51 %) had fallen during last two winter seasons. Only one of 43 workers had used some kind of anti-slip device and even that was used seldom and when it was a part of the safety footwear. Another worker mentioned that he used the boots with ribbed

soles. Both of them thought that such footwear functions quite well. Of these 30 workers who had slipped, 6 had slipped often (at least once per week), 12 sometimes (1-3 times per month) and the rest seldom. Of the 22 workers who fell half had fallen sometimes and half seldom. In five cases it had ended with an injury: ligament injury, caudal vertebrae contusion, muscle strain and tooth injury, foot sprain and lumbago. The biggest slipping risks differed somewhat at various workplaces. At HC the highest risk was connected with slippery deck (2), stepping on and off the machines (2), climbing up to crape off ice from machine windows, new machines, on top of the containers, under the crane and at small height differences (all 1). At TC the highest risks were connected with icy masts (4) and climbing up the mast, walking at parking lots near stations or just on ground (all 1). At CO were the problems connected with climbing on and off the trucks (4), oily terminals, slippery deck and brisk walk (all 1). The workers recommended to use salt (2), sand, chip the ice and shovel it away and better soles (all 1).

Some proposals on how to improve the situation were given: to use laced boots (similar to hiking boots) that are more tight around the ankle and shin area (2); there are available good boots on market, but the company (employer) provides just one type (2); purchase boots with better quality (2); boots with warm lining needed (2); use another material for toe cap instead of steel; cover the seam at sole with sole material (rubber) to restrict water entering the footwear; use materials with high friction (tested for oily and icy surfaces) for soles; use materials of GoreTex type on sides to improve ventilation (all 1).

Conclusions

According to the respondents the problem with footwear was low insulation that resulted in cold feet. This supports the need for further research and development of footwear. Often the companies do provide footwear to their workers. Better communication between workers and employers could be helpful for purchasing footwear according to the workers' needs. Simultaneously, it requires more knowledge and information on products and insulation requirements in various conditions.

Slipping was ranked second after cold by the workers. Half of the respondents had fallen due to slippery surfaces or soles. Some of the falls were accompanied by serious injuries. Further research in this area is needed to reduce the risks and injuries.

Acknowledgements

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Footwear for cold work: a field study at a harbour

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Introduction

Quite a few laboratory studies dealing with feet and footwear have been reported (Kuklane, Geng & Holmér, 1998; Rintamäki & Hassi, 1989; Tochihara, Ohnaka, Tuzuki & Nagai, 1995). Field studies of cold work are more rare and are often related to jobs in cold stores (Enander, Ljungberg & Holmér, 1979). Needs to investigate the thermal conditions with special regards to the feet at various cold workplaces initiated a series of field studies (Gavhed, Kuklane & Holmér, 1999a; Gavhed, Kuklane, Karlsson & Holmér, 1999b). The studies were expected to give information on:

- how the results from various laboratory experiments could be used in practice,
- how to design future tests that will be directly related to actual working conditions,
- how to validate and improve existing prediction models and develop new requirements.

   This paper deals with a study at a harbour and the main attention is paid to the thermal responses of the feet and footwear performance. Other data are shown as reference and background data.

Materials and methods

The study was carried out in February (Gavhed et al., 1999b). February is usually one of the coldest months in Sweden. However, on the measuring week the weather was relatively warm and calm.

   Eight male workers were the subjects: 31-62 years, 89 kg (70-104), 180 cm (170-187). They were selected among volunteers who carried out four different jobs in pairs. Two persons (construction workers) were cutting asphalt (oxygen consumption (VO_2) 0.91 and 0.94 l/min), 2 were securing steel to platforms for loading to ships (VO_2 1.23 and 1.35 l/min), 2 were securing paper to platforms for loading to ships (VO_2 0.95 and 1.30 l/min) and 2 were controlling the loading of the trailers to the ships (VO_2 0.85 and 1.29 l/min).

   The mean air temperature (Table 1), globe temperature, wind velocity and relative humidity for each job and day were following: cutting asphalt 4.0 °C, 7.6 °C, 2.5 m/s (max 5.2 m/s), 56 %, securing steel to platforms 7.3 °C, 8.6 °C, 3.7 m/s (max 11.6 m/s), 70 %, securing paper to platforms 6.7 °C, 7.3 °C, 0.14 m/s (max 0.3 m/s), 68 % and signalling during loading the trailers 8.0 °C, 0.6 m/s (max 2.5 m/s), 79 %.

   The workers could choose clothing of their personal choice from the company's store. All the clothes were weighed separately in the beginning and at the end of the workday. The clothing was manufactured by Fristads AB and Taiga AB Sweden. The warm winter boots were provided by the experimenters and they were model 520 (Woodman) manufactured by Stålex, Arbesko Gruppen AB. The insulation of a boot (size 41) was measured on a thermal foot model (Kuklane & Holmér, 1998). The insulation when standing dry with a load of 35 kg and a sock was 0.34 m^2°C/W. As the sizes 45 and bigger were not present, one subject used his own footwear. His shoes were Stålex model 732. The

shoes were without warm lining. The insulation of the shoe was estimated to around 0.23 $m^2°C/W$.

Two types of socks were in use: A. 67 % wool, 26 % nylon and 7 % lycra (Arbesko, model 106), B. 80 % cotton, 20 % stretch. Subjects 1-5 used sock A. The others used sock B.

Temperature sensors (StowAway temperature logger, Onset Computer Corporation) were taped to the second toe and dorsal foot. The workers were observed during the whole workday. Their subjective responses on thermal sensation were recorded and at the end of the day they filled in a questionnaire on that particular day (Gavhed et al., 1999b). Four questions were directly related to feet and/or footwear.

Results and discussion

The data are shown in Table 1. As the weather was relatively mild throughout the whole study period, the toe and foot temperatures stayed at high levels in the insulated winter boots. Only one subject with his own shoes experienced cold feet.

Table 1. The footwear and sock weight, foot and toe skin temperature (mean (min-max)), air temperature (mean (min)), moisture accumulation, oxygen consumption and thermal sensation in feet (mean over work period (lowest during work period)) data of the subjects. Data was ranked by foot skin temperature.

Footwear (subject)	Footwear (sock) weight (g/pair)	Foot temp. (°C)	Toe temp. (°C)	Air temp. (°C)	Total moisture accumulation (g)	Thermal sensation
Shoes (7)	1447 (80)	29.2 (27.8-30.8)	21.5 (17.9-25.3)	8.0 (7.3)	16.6	-0.7 (-1)
WS (2)	1784 (79)	29.9 (28.3-30.9)	19.7 (17.3-22.9)	4.0 (0.3)	32.5	2.2 (2)
WS (3)	2021 (74)	32.7 (31.5-34.2)	22.1 (19.8-25.1)	7.3 (6.7)	23.6	0.2 (0)
WS (4)	1764 (64)	32.7 (31.3-34.3)	27.0 (20.1-33.5)	7.3 (6.7)	60	2.0 (2)
WS (1)	1756 (81)	33.1 (32.3-34.6)	28.6 (21.9-33.9)	4.0 (0.3)	44.3	1.8 (1)
WS (5)	1863 (82)	33.2 (30.4-34.6)	29.1 (19.8-33.6)	6.7 (5.5)	27.8	1.7 (1)
WS (6)	2021 (70)	33.2 (30.9-33.9)	30.3 (23.6-32.0)	6.7 (5.5)	59.7	1.0 (0)
WS (8)	1736 (82)	33.4 (29.8-35.5)	31.7 (25.4-35.0)	8.0 (7.3)	51.2	1.5 (0)

Questionnaire at the end of the day

During the day the workloads varied and for each type of job the workload was somewhat different. In average the test persons rated their exertion very light 23 %, light 20 %, moderate 47 % and heavy 10 % of total work time. In average they were working outdoors 4-6 hours and the length of an average work period outdoors was 1-2 hours. In average the test persons had 2-4 breaks during the day and the length of an average break was 30-45 minutes. The duration of warm work was less than 15 minutes per day. The workers were not disturbed by cold or were disturbed just occasionally. The workers related the cold sensation in feet to the footwear material (1 subject) and sweating (1) and considered these days similar or warmer compared to usual cold season workdays.

The footwear was considered comfortable except by one worker - he had chosen a too big size. Remaining problems with the footwear were: difficulty to walk, limited mobility and poor fit (1 subject), limiting effect on work ability (2 subjects), cold feet (the subject with shoes) and sweaty feet (1 subject). A person, who often had to climb up and down platforms, considered the boots to be too heavy. Generally the boots were considered good and some workers were eager to get similar shoes. Two workers mentioned the boots to be "very good safety boots". No subject had problem with slipping.
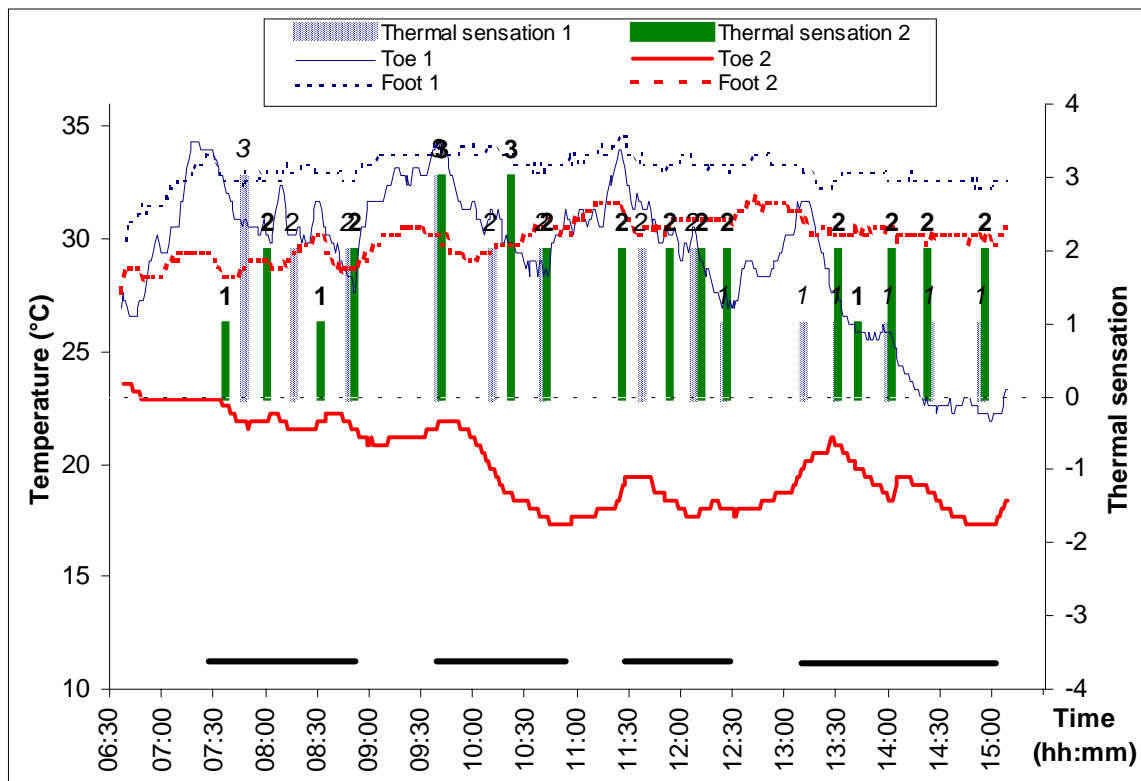
Figure 1. Foot and toe temperatures of subjects 1 and 2 (asphalt cutting). Thick lines at time axis show work periods in the cold. Columns and numbers show the thermal sensation in feet (*1* - subject 1; **1** - subject 2) at given time point.

Foot skin temperatures

The foot skin temperature over a day is shown in Figure 1. The foot skin temperatures stayed relatively high, usually over 30 °C. In subject 2 the foot skin temperature was somewhat lower already in the beginning. However, during the workday it raised higher than 30 °C. Enander et al. (Enander et al., 1979) showed similar values for food processing workers in cold halls doing various jobs at an air temperature of 1-13 °C. The warm boots kept the foot skin temperature relatively constant for the whole workday. The thermal sensations of the feet (scale from +4 to -4) were often warm or very warm. The exception was subject 7 who had his own shoes and during most of the day felt slightly cold in the feet. His foot skin temperatures stayed below 30 °C for most of the workday.

However, the toe temperatures varied more than the foot temperatures. This could be related to the lower insulation of the toe zone (Kuklane & Holmér, 1998) and to the fact that the vasomotor activity is high in peripheral body parts. The lowest toe temperatures were occasionally between 17-18 °C. Commonly they stayed higher than 25 °C for most of the workday. In the beginning of the day most of the subjects had toe skin temperatures between 20-25 °C. It could depend on the preparation of the study, i.e. taping the sensors to the skin, while subjects were minimally dressed. Subjects 5 and 6 had the most stable toe temperatures if to exclude the start of the day. These subjects took off the footwear during the breaks and wore slippers instead. It is difficult, however, to say if the high and relatively stable toe temperature depended on that. The toe temperatures were in average 6 °C lower than foot skin temperatures. Toe temperature changes did not considerably affect the thermal sensation of feet as has been shown before (Kuklane et al., 1998; Tochihara et al., 1995). The reason could be that the skin temperatures stayed relatively high.

Moisture accumulation in footwear

The moisture accumulation in the footwear was at average 20 g per day and foot (range 10 - 30). If the moisture accumulation rate is assumed equal to sweat rate then it corresponds to about 1.3-3.8 g/h. Around 2 g of that stayed in the socks at the end of the day. The amount of moisture, that was accumulated in the footwear of subjects 5 and 6 (took off the footwear during breaks) did not differ from the others. Sweating seems to affect footwear insulation depending on sweat rate, sweat amount, and probably also absorption capacity and evaporation resistance of the footwear. During sweating tests on a thermal foot model (Kuklane & Holmér, 1998) a considerable reduction of footwear insulation was shown. During those tests a sweat rate of 10 g/h was simulated. At sweat rates of this study the insulation reduces less, resulting in drier socks and thus more comfortable feet.

Conclusions

The provided boots had too high insulation (0.34 m^2°C/W) for the particular weather conditions (+4 to +8 °C). At the same time the insulation of another type of shoes (0.23 m^2°C/W) seemed to be insufficient (one subject). Under the studied climatic and work conditions the recommended insulation would be between 0.25 and 0.30 m^2°C/W.

The foot temperatures of the subjects who took off footwear during warm breaks stayed at a constant and high level. This supports the recommendation to doff the footwear during breaks for rewarming and ventilation.

The wetness of footwear, mainly due to sweating, was a source of some complaints. Sweating intensity can be related to high insulation of footwear, bursts of high activity and warm weather, but also to individual differences.

Acknowledgements

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Footwear for cold work: a field study about work on high masts

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Introduction

A series of field studies at cold workplaces were initiated (Gavhed, Kuklane & Holmér, 1999a; Gavhed, Kuklane, Karlsson & Holmér, 1999b). The studies were expected to give information on:

- how the results from various laboratory experiments could be used in practice,
- how to design future tests that will be directly related to actual working conditions,
- how to validate and improve existing prediction models and develop new requirements.

This paper deals with the study at a telecommunication company and the main attention is paid to the thermal responses of the feet and footwear performance. Other data are shown as a reference and background data.

Materials and methods

The study was carried out in February (Gavhed et al., 1999a). Eight male workers were the subjects with a mean age of 40 (22-50) years, mean weight of 87 kg (72-105) and mean length of 177 cm (173-184). They were selected among volunteers who carried out various jobs on high masts on four different days. The work was done in pairs on four different masts in Sweden. A short period of time (10-20 minutes) was used to measure oxygen consumption (VO_2) during climbing the masts. The maximum VO_2 during climbing was 2.45 l/min (1.18-3.33 l/min). The average VO_2 during the work periods over whole workday was estimated to lay around 0.74 l/min (0.64-0.86 l/min).

The length of the cold exposure depended on the task. The shortest total work time in cold on the mast was on the third day (*Day 3,* changing a warning light): 2 hours 40 minutes. At the same time it was one of the longest cold exposures. The longest total work time in cold was on the second day (*Day 2,* fastening new cables to the mast, half time operating in a mast elevator): 4 hours and 55 minutes (length of a whole work day 6.5 hours). It was divided into two work periods. The longest work day was 7 hours and 30 minutes (*Day 4* mounting up two new parabolas). 4 hours and 30 minutes of that was work outdoors near or on the mast. This day was divided into 4 work periods in cold. The first day (*Day 1*, fastening new cables and taking down old) was 5 hours 40 minutes long and 4 hours of that was spent on or near the mast. The work outdoors was divided into two periods. The time to drive to the mast, preparation for the measurements and ending the measurements were not included above. In addition, communication and waiting for the details took some time, too. The mean outside air temperature (measured near body) and wind velocity are shown in Table 1.

The workers used their ordinary clothing. Standard (company recommended) clothing were Ullfrotté underwear and outer layer by Taiga AB. All the clothes were weighted

separately in the beginning and at the end of the workday. During the breaks the workers usually changed footwear and clothing.

Subjects 1-4, 7 and 8 had boots of model 520 (Woodman) that were manufactured by Stålex, Arbesko Gruppen AB. Subject 5 used Graninge boots and subject 6 model 529 (Varm-varm, Stålex, Arbesko Gruppen AB). The weight of the footwear is shown in Table 1. The insulation of model 520 (size 41) was measured on a thermal foot model (Kuklane & Holmér, 1998). The insulation when standing dry with a load of 35 kg and a sock (34 g) was 0.34 $m^2°C/W$. The insulation of the other boots was estimated to be at the same insulation level, i.e. between 0.33 and 0.35 $m^2°C/W$.

The workers used two pairs of socks (thin and thick), except subject 6 who used 1 pair of thin cotton socks. Usually various woollen socks were worn, but also cotton, fibre-pile and synthetic socks, usually together with a woollen sock. By the weight socks could be divided into three groups: thin (54-82 g), thick (100-107 g) and extra thick (133-165 g, Table 1). The socks could add about 0.02-0.05 $m^2°C/W$ to the insulation.

Temperature sensors (StowAway temperature logger, Onset Computer Corporation) were taped to the second toe and dorsal foot. The workers were observed during the whole workday. Their subjective responses on thermal sensation were recorded over the day and at the end of the day they filled in a questionnaire about the workday. Four questions were directly related to feet and/or footwear.

Results and discussion

The data are shown in Table 1. Some data were lost, probably due to the strong electro-magnetic field near the antennas.

Table 1. The footwear and sock weight, foot and toe skin temperature (mean (min-max)), air temperature near body (mean (min)), air velocity (mean (max)), moisture accumulation and thermal sensation in feet (mean over work period (lowest during work period)) data of the subjects. Data was ranked by foot skin temperature.

Footwear (subject)	Footwear (sock) weight (g/pair)	Foot temp. (°C)	Toe temp. (°C)	Air temp. (°C)	Air velocity (m/s)	Total moisture accumulation (g)	Thermal sensation
Varm-varm (6)	1828 (63)	26.7 (25.9-27.1)	Missing	1.9 (-2.4)	9.7 (13.5)	6	0.1 (0)
WS (3)	1988 (69+104)	27.7 (20.8-31.2)	23.2 (11.0-30.5)	1.5 (-11.5)	3.6 (6.1)	35	0.8 (-2)
Graninge (5)	1808 (69+143)	29.3 (27.9-31.2)	17.2 (14.9-19.5)	2.1 (-2.1)	9.7 (13.5)	12	-0.1 (-1)
WS (4)	1982 (54+106)	30.4 (25.9-34.3)	23.4 (9.8-33.7)	3.9 (-0.6)	3.6 (6.1)	56	0.0 (-2)
WS (2)	1681 (80+100)	30.8 (27.1-34.3)	26.9 (12.7-34.7)	2.9 (-0.6)	3.4 (9.1)	54	0.1 (-2)
WS (1)	1754 (65+107)	31.4 (28.2-33.8)	17.1 (13.9-20.9)	-4.1 (-10.9)	3.4 (9.1)	63	0.7 (0)
WS (8)	1910 (67+133)	31.8 (26.7-34.8)	29.6 (18.0-35.2)	3.8 (-5.6)	1.7 (4.6)	94	0.8 (-1)
WS (7)	1783 (82+165)	32.0 (29.3-34.2)	Missing	8.8 (-1.2)	1.7 (4.6)	39	0.7 (-1)

Questionnaire at the end of the day

The observed work times fit relatively well with work times from the questionnaire. The test persons estimated their work exertion and the time worked at certain exertion level the in following way: very light in average 1.6 (1-2.5) hours (4 persons), light 2.1 (1-4) hours (7 persons), moderate 1.4 (1.5-6) hours (4 persons), heavy 0.5 (0.5-1) hours (5 persons) and very heavy 0.5 hours (4 persons). Five workers worked outdoors 4-6 hours, one 2-4 hours and two 0.5-2 hours (observed 2.3-5 hours). The length of an average work period outdoors was more than 2 hours for 4 persons, 1-2 hours for 2 and less than 1 hour for one person (observed average 1.8 hours). One did not answer the question. Three persons had 3-5 breaks per day, three had 1-2 and 2 did not have any breaks. The length of a break was estimated to be 0.5-1 hour (3 persons), 15- 30 minutes (1) and less than 15 minutes (2). Two worked once or twice in warm locations, but duration of warm work

was less than 15 minutes. The workers were not disturbed by cold (2 persons) or were disturbed just occasionally (6). The workers related the cold sensation in feet to the wind (2 subjects), contact with cold surfaces (2), footwear material, the way of using footwear and standing still (each 1). The subjects felt to be similar (6) or warmer (2) compared to usual cold season workdays.

The footwear was considered comfortable except by 1 worker and 1 had no opinion. Problems with the footwear were reported to be stiff in the cold (1 person), cold feet (1), sweaty feet (2) and wet feet (1). One person slipped during the day, but did not fall.
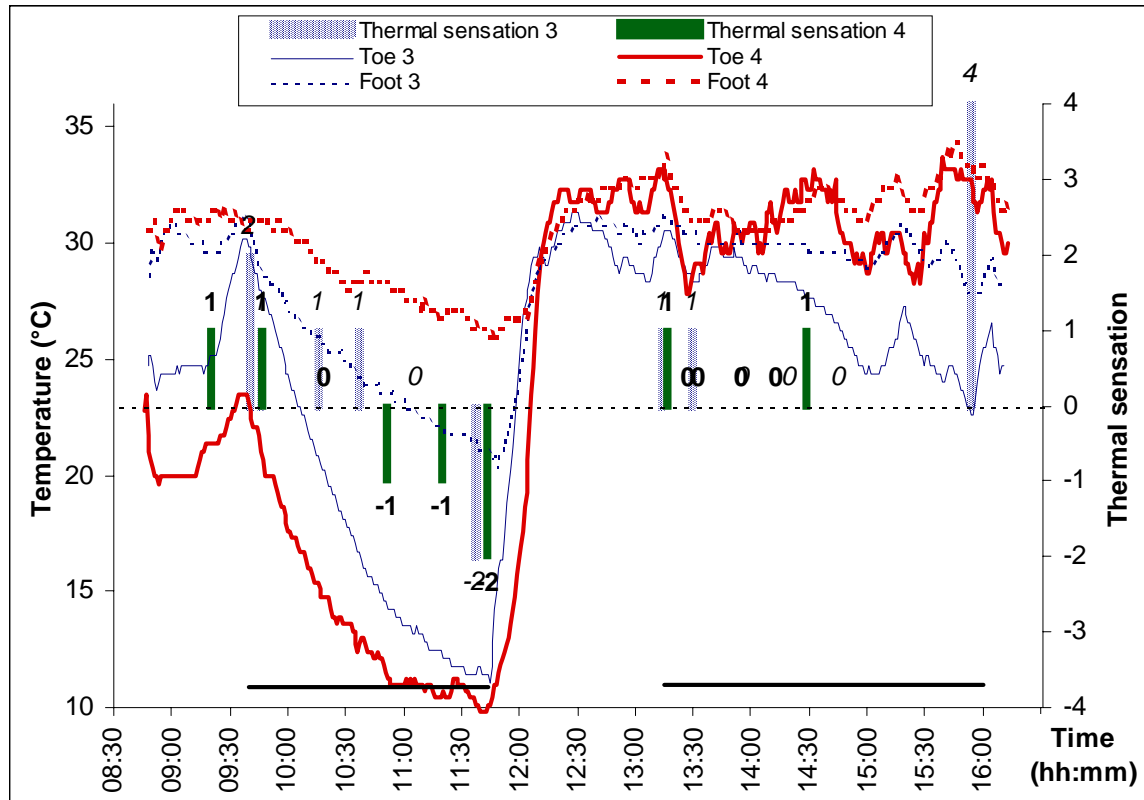
Figure 1. Foot and toe temperatures of subjects 3 and 4. Thick lines at time axis show work periods. Columns and numbers show the thermal sensation in feet (*1* - subject 3; **1** - subject 4) at given time point.

Foot skin temperatures

The foot skin temperature over a day is shown in Figure 1. During colder weather the foot skin temperatures were lower than during warmer weather. There was also a tendency that before lunch the foot, and especially the toe temperatures were lower. This could be related to lower air temperatures before noon. The subjective responses followed the skin temperatures. The lowest average foot skin temperature was 26.7 °C and this was measured in subject 5 (one pair of thin socks). However, his subjective ratings were usually at comfort (0). This subject had also the smallest amount of sweat accumulated in the footwear and sock. Probably due to the influence from the electromagnetic field his foot data recording was stopped relatively early and toe temperature data were lost.

The lowest measured foot skin temperature was 20.7 °C. This subject (3) had also the next lowest average foot skin temperature (27.7±3.1 °C). His job in the morning consisted of standing on the elevator roof and fastening of new cables to the mast. The highest mean foot skin temperatures were in subject 7 (32.0±1.4 °C, toe skin temperature missing).

The footwear (0.34 m²°C/W, use of extra socks not considered) used during work on high masts at lower mean environmental temperatures (-2 to -8 °C) gave in average 2.2 °C lower foot and 3.4 °C lower toe temperatures than during work in harbour (same footwear, ambient temperature +4 to +8, Gavhed et al., 1999b). The subjective responses were in average colder by about 1-2 points (scale 4 to -4) during work on masts, however being still somewhat warmer than neutral.

The mean difference between the toe and foot skin temperatures was 7 °C. All the subjects had toe temperatures under 18 °C at least once (data for 2 subjects are missing). Subject 1 had the lowest mean toe skin temperature (17.1±2.2 °C). Subject 4 had the lowest measured toe temperature (9.8 °C). This subject was also the one who in the questionnaire pointed out cold feet. The highest mean toe skin temperature was measured on subject 8 (29.6±5.7 °C). He had also the second highest foot skin temperature, and the highest sweat gain in footwear and socks (94 g). The high foot and toe temperatures of subjects 7 and 8 can be related to the warmer weather and lower air velocity than during other days. These subjects had also relatively high activity throughout the whole day.

Moisture accumulation in footwear

The moisture accumulation in the footwear was on average 37 g (6-94 g) per day. Around 4 g of that stayed in the socks at the end of the day. However, the length of the workday varied. If the moisture accumulation rate is assumed equal to sweat rate then it corresponds to 7.5±3.7 g/h (2.2-12.9 g/h).

Conclusions

The footwear in combination with the chosen socks worked well in the particular weather conditions (-2 to -8 °C). However, more attention should be paid to the cold protection of toes. During low activity the toe temperatures dropped relatively quick at air temperatures of about -10 °C and/or high wind speeds (about 10 m/s).

The workers reported relatively few complaints on their footwear. However, in some cases the foot and especially toe skin temperatures dropped to low levels that are connected with cold and discomfort sensation.

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Innovations in fibres and textiles for protective clothing

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Millions of people world-wide have working environment which exposes them to specific risks from which their bodies need protection. In many industrial sectors, military and energy services, hospital environments, human beings are subjected to various types of risks and each sector has its own requirements for protective clothing.

The end-use applications for protective clothing include

- Chemical splash and vapour protection
- Clean-room apparel
- Cut resistant gloves
- Dirt and dust
- Fire fighting
- Ballistic protection
- Paint spray
- Puncture resistant clothing
- Pharma cantical manufacturing
- Dry chemical handling

The performance requirement of all types of protective clothing often demand the balance of widely different properties of drape, thermal resistance, liquid barrier, water vapour permeability, anti-static, stretch etc. The seemingly contradictory requirement of creating a barrier e.g., towards heat, cold, chemicals, bacteria, and breathability in high functional clothing has placed challenging demands on new technologies for producing fibres, fabrics and clothing design. Among the contributing factors responsible for successful marketing of such products have been advances in polymer technology and production techniques for obtaining sophisticated structures of fibres, yarns and fabrics (Shishoo, 1988).

Innovations in fibres

The evolution of fibre developments have gone through the phases of conventional fibres, high-functional fibres and high-performance fibres (Mukhopadhyay, 1993).

Improved fibre spinning techniques in melt spinning, wet spinning, dry spinning and new techniques such as gel spinning, bicomponent spinning, microfiber spinning, have made it possible to produce fibres with characteristics more suitable for use in protective clothing.

Today a wide range of high performance fibers is commercially available for technical and industrial applications. Among the specialty fibers already established can be mentioned the following types.

- Aramid fibres
  - p-aramid fibre to provide high strength and ballistics.
  - m-aramid fibre to provide flame and heat resistance.

- Ultra-high tenacity polyethylene fibers (UHMWPE)
  Gel spun, ultra-high molecular weight polyethylene fibers with extremely high specific strength and modulus, high chemical resistance and high abrasion resistance.
- Polyphenylene sulphide fibers (PPS)
  Crystalline thermoplastic fiber with mechanical properties similar to regular polyester fiber. Excellent heat and chemical resistance.
- Polyetheretherketone fibers (PEEK)
  Crystalline thermoplastic fiber with high resistance to heat and to a wide range of chemical.
- Novoloid (Cured phenol-aldehyde) fibers
  High flame resistance, non melting with high resistance to acid, solvents, steam, chemical and fuels. Good moisture regain and soft hand.
- Polybenzimidazole fibers (PBI)
  Moisture regain 15 %, high resistance to chemicals especially at elevated temperatures.

Aramid fibres

A number of different types of *p-aramid fibres* are commercially available as the basis material for protective clothing. The brands include Kevlar by DuPont, Twaron by Acordis and Technora by Teijin. Para-aramid fibre's combination of high strength, non-flameability and high temperature resistance makes this type of fibre suitable in applications such as

- ballistic protection in armour vests and helmets,
- cut through protection in safety gloves, aprons, work wear and shoes for high risk jobs,
- high temperature protection e.g., spatter-resistant clothing.

These fibres are also well-known for their dynamic energy absorbing properties (Van Zijl et al., 1999).

For thermal stability purposes *m-aramid fibres* has the right attributes. Meta-aramids have high temperature resistance, moderate tenacity and low modulus but excellent resistance to heat (Gorashi & Stocks, 1995).

These fibres are very useful when outstanding thermal protection and electrical insulation properties are required. The brands include Nomex and Corex.

The m-aramid fibre Kermel is currently used in protective clothing. It has excellent thermal properties against high temperature. "flash" exposures and is easily blendable with other fibres (Cassat & Hoessi, 1995).

DuPont-Toray in Japan have also produced new spun-dyed Kevlar p-aramid fibres. Twaron made by Acordis is also being produced as a microfibre with a dtex of 0.93.

High-performance polyethylene fibres

UHMPE with high modulus and high strength together with exceptional strength-to-weight ratios are available with trade names Dyneema from DSM, Spectra from Allied Signals, Tekmilon from Mitsui.

This type of fibres has

- very high specific strength, specific modulus and high energy to break
- low specific gravity

- very good abrasion resistance
- excellent chemical and electrical resistance
- good UV resistance
- low moisture absorption

In protective clothing applications, many impact helmets used by runners and mountain climbers, for example, are made of UHMPE composites.

High performance PE fibres are also used for protection against cutting, sawing, puncturing, and ballistics. A very high growth in the use of fibres such as Dyneema and Spectra is predicted for use as body armour. Knitted fabrics made of UHMPE are used for personal protection viz., gloves, chain saw protection and fencing suits (Jacobs & Mencke, 1995; Van Gorp & Van der Loo, 1995).

Novoloid fibres

Kynol woven and nonwoven fabrics display the following advantages:
   In flame:

- high flame resistance; non-melting at any temperature
- retention of textile integrity; no embrittlement or breakage
- minimal evolution of smoke, nearly no shrinkage
- virtually no toxic off-gassing (no HCN, halogens, etc.)
   And in general:
- outstanding resistance to acids, solvents, bleaches, fuels and other chemicals, steam
- excellent thermal and electrical insulation
- good moisture regain and soft hand; comfortable to wear and use
- light weight (specific gravity 1.27)
- available as 100 % novoloid and in various blends.

Melamine-based fibres

Basofil (BASF), a high temperature and fire resistance fibre, is a melamine-based staple fibre which has a LOI of 31-33 with no melt dripping and a continuous service temperature of about 200 ºC. (Berber, 1995; Ott, 1995).

PEN & PBO fibres

Recently some new exciting fiber types such as PEN and PBO have been introduced in the market. Compared to the standard polyester, PEN, polyethylene-2, 6-naphtalat, fiber yarns have a significantly higher modulus, high dimensional stability, higher glass-transition temperature and better resistance to hydrolysis and LOI of 31.

Toyobos' high performance PBO fiber, Zylon, p-phenylene-2, 6-benzobisoxazole, has strength and modulus far exceeding than any of the known fibers. PBO fiber has the decomposition temperature of 650 ºC, tenacity 5-8 Gpa and modulus of 180-250 Gpa (Shishoo, 2000; Toyobo, 1998; KoSa Co, 1999).

Other types

The market for FR-treated celllulosic fibres for use in apparel. Flame-retardant arments made from cellulosic fibres continue to find application even in the most demanding of

working environments such as those encountered by fire-fighters. Polyester Trevira is another example of a flame retardant fibre.

Flame-resistant heavy-duty PES multifilament yarns are also available from e.g. KoSa.

Electro-conductive fibres

Many synthetic fibres are excellent electrical insulators and therefore very susceptible to static charges. One approach for solving this problem is to increase fibre conductivity by applying conductive finishes to the surface. Most of these finishes are easily removed by washing however, hence do not provide durable protection against the hazards of static electricity. Metal fibres have been successively replaced by electro-conductive organic fibres in the past decade. One commercial approach to make a permanently antistatic fibre is to blend a conducting polymer into the non-conducting fibre. Many polyblend fibres of this type now are commercially available (Shishoo, 1988).

Novel yarn spinning technology

Novel yarn spinning technologies are commercially available today for producing hybrid yarns for various applications including protective clothing. Two technologies are used to manufacture such yarns

- the conventional spinning by intimately blending two different yarns
- the core yarn spinning making a core of a certain fibre type covered with a sheath of a different fibre type.

One can thus combine the functions of two different fibre qualities to produce fabric of varied functions. For example the core can be made of p-aramid, the sheath of m-aramid, cotton or polyester. Sensitive core-materials can be protected by he sheath fibres (Bontemps, 1995).

High functional and high performance fabrics

Microfibre based light woven constructions

The very first example within this group is the ventile fabrics made of 100 % cotton, where a very large reduction in the interfibre pore sizes is achieved as a result of swelling in fibres in wet state.

New techniques for spinning extremely fine polyester filaments of 0.1-0.3 denier have resulted in many interesting developments of woven and nonwoven structures of high functional characteristics. For example the superfine yarns are woven into various constructions such as Oxford and taffeta, in which individual filaments are packed so tightly that the resultant fabric develops high hydrostatic resistance in combination with good water-vapour permeability and drape. These properties can be further improved by treatment with liquid repellent finishes.

Some of the most interesting developments lie in the production of multi-layer knitted and woven constructions. A multi-knit fabric of 2 or 3layered structure using 100 % polyester and polypropylene yarn has characteristics of quick water absorption, ability to evaporate water and a dry touch, being capable of transporting perspiration from the skin to the outer surface and then quickly dispersing it (Shishoo, 1988).

Breathable fabrics

Laminated fabrics (microfibrous membrane)
One of the most significant developments in breathable waterproof was the introduction of the GORE-TEX rainwear fabric in 1976. GORE-TEX is a microporous polymeric film made of polytetrafluoroethylene (PTFE). The GORE-TEX film is supposed to contain micropores of size 0.2 micron at the rate of more than 1.3 billion/cm², and it provides a barrier to water, airborne particles and bacteria. Being very hydrophobic, PTFE will resist wetting of the surface. At the same time because of the pore distribution water vapour can readily diffuse through the film.

GORE-TEX film has been bonded to a variety of substrates and constructions. Both 2-layer construction, where a single layer of fabric is bonded to one side of the film, and 3-layer, where fabrics are bonded to both sides of the film, are available as high functional fabrics.

A similar principle is used in MICRO-TEX film from Japan. A fabric for outwear is laminated with porous film of PTFE resin containing micropores of size 0.6 micron at the rate of approx 1 billion/cm² (Shishoo, 1988).

Coated fabrics (microporous caoting)
Polyurethane is one of the most widely used polymers for coating of apparel fabrics. One reason for this is the availability of numerous combinations of polyols, isocynates and amines for its synthesis. Poromeric polyurethane coatings are produced by either a wet coagulation process or a direct coating system. The general procedure in a wet coagulation system is to impregnate the fabric with a special polyurethane formulation dissolved in an appropriate solvent. Before evaporation of the solvent the coated fabric is immersed in a water bath which precipitates a coherent but highly porous polyurethane layer. In a direct coating system, the microporous structure develops during subsequent drying and curing process.

Numerous developments in microporous polymer structures for use in direct coating, and as a film for laminating into 2 or 3 layer structures, have taken place world-wide. These microporous structures function by allowing the passage of water vapour molecules (approx 0.0004 micron in dia) whereas large diameter (>100micron) water drops get blocked by these structures. For a given porosity and thickness of the coating the water vapour permeability increases if one reduces the pore size (Shishoo, 1988).

Laminated fabrics (hydrophilic membrane)
High functional fabrics are engineered by combining with hydrophilic membranes. Water-vapour transmission through these membranes is achieved by the physical processes of adsorption, diffusion and desorption. Because the membrane is a non-porous material one can expect no clogging of pores.

AKZO Nobel has introduced SYMPATEX, which is a nonporous high breathable polyester membrane. This product is washable and dry cleanable and is claimed as watertight, windtight and having high wear resistance. Its development has included work in polymeric composition, membrane process, laminating process and the seam-sealing technique. AKZO Nobel has developed a special seam-sealing tape for this purpose (Spijkers, 1995).

Thermal insulation materials

Waterproof and breathable fabrics are often used in combination with synthetic heat insulating materials. Because of fashion and function requirements and demands, developments have taken place for producing thin but warm fibrefills. Since air has a very low conductivity in the newly developed materials, heat insulating property is imparted and improved by confining as much air as possible in the microspaces between and/or within the fibres and so checking heat losses by convection. These materials are made by producing Coweb-like structures from superfine fibres, or by making the fibres hollow in order to contain air and prevent air movements.

These new materials have 2-3 times as much thermal insulation as that of conventional polyester wadding or down of the same thickness (Shishoo, 1988).

Nonwoven protective clothing

Protective coveralls, suits, gowns, lab coats and accessories are used in industry and institutions to protect workers from exposure to hazardous materials and to protect sensitive products from human contamination. Nonwoven are used for limited use protective clothing and as components in reusable clothing. Spunbonded olefins are the leading materials used and are often used in composites with barrier films.

Medical/surgical disposal represent about 11% of the European nonwoven market whereas these disposal are the second largest market for nonwoven in the US. This product group includes surgical packs, drapes and gowns, surgical face masks, caps and head covering, patient and staff clothing. Spunlaced pulp/polyester, spunbonded, spunbonded/meltblown components and wet laid pulp/polyester nonwovens are the leading fabric types used for medical disposables.

Heatbonded and calendered polyethylene spun-bonded fabric Tyvek from DuPont is a fine example of a very successful nonwoven material for protective clothing.

Tyvek 1431N, nonwoven structure made of 100% HDPE offers excellent particle hold and properties down to particle size of 3 microns. For protection from particles smaller than 3 microns, DuPont recommends the coated fabric Tyvek C and laminated fabric Tyvek F.

For dust protection Corvin Company's spunbonded nonwoven "Multidenier" using different spunbonded technologies demonstrate a new group of innovative products (Bernstein & Thiele, 1995).

Photoluminescent material

Inorganic luminescent pigments which are composed of zinc-sulphide crystals. The crystal lattice of the pigment is able to absorb visible high energy and to store that energy through various levels of the electrons. The energy will be set free under the emission of light when the activating light source disappears. This process can be repeated as often as wanted. The cause of photoluminescence is a transport of electrons. These materials are free of radioactive substances and are non-toxic. The size, formation and the quantity of the zinc-intensity of the light emission. The base material carrying the photoluminescent is a soft-coating blend of polyester and cotton (Simpson, 1995).

Interactive textile materials

There have been some interesting developments taking place in recent yarns regarding smart textile materials. These materials readily interact with human/environmental conditions to produce change in material properties.

Shape Memory Polymers

The shape memory effect is observed in metal alloys and polymers and results in an object reverting to a previously held shape when heated. Early shape memory polymers were blends of glassy thermoplastics and elastomers.

More recently, Mitsubishi has made shape memory polyurethanes available. These are thermoplastic polymers that can have reversion temperatures in the range –30 ℃ to +100 ℃. Shape memory polyurethanes are block copolymers having hard and soft segments. The hard segments, which contain the urethane linkage and chain extenders, are present in sufficient numbers to form a continuous crystalline phase. Constituted from polyether or polyester diols, the soft segments make up the glassy phase (Russel et al., 1999; Technical Textiles International, 1999b).

In effect, the shape memory polyurethanes are thermoplastic elastomers that can have glass transition temperatures within an unusually interesting range. For instance, this includes ambient temperatures (about 25 ℃), the temperature of the human body (37 ℃) and the temperature of boiling water (100 ℃).

The prototype design is a laminated film consisting of:

- a film of shape memory polymer having a glass transition temperature of 25 ℃;
- a layer of a compatible elastomeric, a thermoplastic polyurethane having a much lower glass transition point (such as a conventional shoesoling grade).

The films can be made on an extrusion/calendering line and the laminates can be compression moulded in conventional equipment. To promote the circulation of air and moisture vapour within the interstitial space, as well as reducing the weight of the film, holes and cut-outs can be made in the laminate.

On cooling below 25 ℃, the shape memory layer should shrink linearly by some 3 % and become rigid while the conventional elastomer remains largely unaltered. As a result, an out-of-plane deformation of the laminate is expected to occur.

It is anticipated that deformed films of these laminates will provide a reversible response to cold conditions.

Phase Change Materials (PCM)

Protective textiles with microencapsulated Phase Change Material are now commercially available, e.g. Outlast Technologies. The PCMs used in this technology consists of carbohydrates with different chain lengths, whose phase change take place in a temperature range close to that of the human skin (Pause, 1995; Pause, 1999; Technical Textiles International, 1999a; Leitch & Tassinari, 2000).

The PCM, are encapsulated in small spheres in order that they are contained when in a liquid state. The microcapsules possess approximate diameter of 1-10 µm and are resistant to abrasion, pressure, heat and chemicals. At present this-technology is only applicable to acrylic fibres using the wet-spinning process.

For coating applications, the PCM microcapsules are dispersed in e.g. a polyurethane coating, which is then applied to a fabric.

For foam applications, the PCM microcapsules are dispersed in a polyurethane foam matrix. These foams are often laminated to a fabric.

Textile structures with PCM microcapsules for protective clothing have following interactive functions:

- absorption of surplus body heat;
- an insulation effect – caused by heat emission of the PCM into the textile structure;
- a thermo-regulating effect – which keeps the microclimate temperature nearly constant.

Cooling fibres

Other relatively new technology of interest is cooling fibres by the introduction of water-retaining fibres into the fabric structure. These fibres are sandwiched between a breathable out fabric e.g. cotton and Nomex and an inner layer conducting heat and moisture from the body (Leitch & Tassinari, 2000; Stull, 2000).

Concluding remarks

The driving technology force in material development for protective clothing has been spear-headed by advances in fibres, polymers, chemical technology and fabric/web forming technologies. The technological trends and challenges ahead will be determined by market pull demands, increasing environmental awareness, personal safety and comfort, and performance requirements. The advances in material and technologies should lead to products with sought-after characteristics e.g., laminates able to meet multiple functional requirement, coating which can be tailored for specific end-uses, fibres and fibre-blends for demanding applications and sophisticated fibrous structures.

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High visibility warning clothing

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Introduction

High visibility warning clothing is necessary to signal out the presence of the worker to detect and quickly percept of the worker that work in dangerous conditions, in any luminosity conditions, on day time (including on bad weather conditions: mist, rain etc.), on night time (including headlights) or working places where adequate lighting condition can not be ensured (for example mines, work in pipes, tunnels). In order to produce high visibility warning clothing there are used textile fabrics which should correspond the main performing parameters, concerning:

- chromacity characteristics
- colour fastness to rubbing, perspiration, washing, bleaching and washing agent
- mechanical characteristics: tensile strength, tearing strength

In this respect the poster will present the accomplished results of the researches concerning:

- designing and accomplishing the woven structures fluorescent Yellow and fluorescent Red-Orange
- accomplishing of 2nd and 3rd class of high visibility warning clothing

High visibility materials

The higher visibility materials can be classified as retro-reflective, photo-luminescent and fluorescent. They should provide:

- signs of the worker presence
- quick detection and perception of the workers who are working in:
  - dangerous conditions
  - any conditions of luminosity
- day time (including the presence of rain and haze)
- night time (including the light of the headlights)
  - working places where it is not provided an adequate lighting (mine, tunnel, pipes)

The photometric characteristics of the background material are shown in Table 1. The physico-mechanical characteristics of the background material are following:

- tensile strength (minimal)   warp   1000 N
                               weft   850 N
- tear strength (minimal)   warp   50 N
                               weft   30 N
- abrasion strength (minimal)   500 cycle
- water permeability (minimal)   50 mg/sqcm 24 h

Table 1. Photometric characteristics of the background material.

	Fluorescent	
	Yellow	**Orange - Red**
Chromaticity co-ordinates	X = 0.4235	X = 0.5980
	Y = 0.5296	Y = 0.3641
Reduced luminance factor (β)	0.9400	0.4008
Dyeing resistance on		
– abrasion	4 – 5	4
– perspiration	4 – 5	4
– washing	4 – 5	4 – 5
– chemical cleaning	4 – 5	4 – 5
– bleaching	4	4
– ironing	5	5

High-visibility warning clothing: 2nd class

Structure
Background material: 85 % PES / 15 % Co fabric 50 mm width retro-reflective stripes, 100 % Co fabric. 2nd visibility class (Figure 1):

- background material: 0.70 sqm
- retro-reflective material: 0.20 sqm

Destination
Protective clothing for preventing hurting the person, by coming up against objects, that are moving with max. 50 km/h velocity, because this type of clothing provide the signs of the person in any humidity conditions against superficial mechanical aggression of medium intensity (abrasion, tearing).

End-uses
- public roads, with velocity restriction, for moto / auto vehicles
- railway traffic
- wood industry

Figure 1. 2nd visibility class.

High-visibility warning clothing: 3rd class

Structure
Background material: 85 % PES / 15 % Co fabric 50 mm width retro-reflective stripes. 3rd visibility class (Figure 2):

- background material: 2.50 sqm
- retro-reflective material: 0.37 sqm

Destination
Protective clothing: for preventing hurting the person, by coming up against objects, that are moving with high velocity, because this type of clothing provide the signs of the person in any humidity conditions against superficial mechanical aggression of medium intensity (abrasion, tearing).

End-uses
- public roads, for moto / auto vehicles
- railway traffic
- wood industry

Figure 2. 3rd visibility class.

The effectiveness of phase change materials in outdoor clothing

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Introduction

Phase change materials (PCMs) used in textiles are combinations of different types of paraffins - each with different melting and crystallization (i.e., freezing) points. The PCMs are enclosed in a microcapsule to prevent leakage of the material during its liquid phase (Bryant & Colvin, 1992). PCM microcapsules can be incorporated into the spinning dope of manufactured fibers (e.g., acrylic), incorporated into the structure of foams, and coated onto fabrics.

When the encapsulated PCM is heated to the melting point, it absorbs heat energy as it goes from a solid state to a liquid state. This phase change produces a temporary cooling effect in the clothing layers. The heat energy may come from the body or from a warm environment. Once the PCM has completely melted, the storage of heat stops. If the PCM garment is worn in a cold environment where the temperature is below the PCM's freezing point, and the fabric temperature drops below the freezing point, the PCM liquid will change back to a solid state, generating heat energy and a temporary warming effect.

The developers and producers of phase change materials in textiles claim that garments made with PCMs will keep a person warm longer than conventional insulations when worn in cold environments and decrease the thickness and weight of the clothing required (Pause, 1998). In order for a phase change material to improve the thermal comfort characteristics of a clothing ensemble in the cold, it must produce enough heat in the garment layers to reduce the heat loss from the body to the environment. Since there is a temperature gradient from the warm skin surface to the clothing layers to the cold environment, some of the PCMs may not change phase.

In addition, small increases and decreases in skin temperature resulting from changes in body heat production (activity) may not be enough to keep the phase change process going in the cold.

The magnitude and duration of the phase change heating and cooling effects on a clothed body have not been documented in the scientific literature. Most of the published research that is available was conducted on small pieces of fabric (Pause,1995; 1998). Therefore, there is a need for independent research on the use of PCMs in clothing systems.

The purpose of this project was to quantify the effect of PCMs in fabric-backed foams on heat loss from a thermal manikin's surface to the environment during environmental temperature transients and on human subjects' physiological responses and comfort perceptions during environmental temperature transients and changes in activity. Identical fabrics and garments - with and without the PCMs - were compared.

Methodology

An open-cell, hydrophilic polyurethane foam was produced directly on a fabric substrate of polyester knitted fleece. The experimental foam contained 60 % PCM microcapsules and 40 % foam by weight. Approximately 40 % of the PCM microcapsules changed phase at 28.3 °C (83 °F), and 60 % of them changed phase at 18.3 °C (65 °F). Suits for the manikin tests consisted of a fitted long-sleeved top and long pants. Ski jackets and pants were made for the human tests.

Environmental step change tests with a manikin

A life-size, computerized, thermal manikin was used to simulate the heat loss from a person to a cooler environment and to measure the insulation (clo) value of the clothing systems. The manikin has 18 body segments which provide independent temperature control and measurement. His skin temperature distribution simulates that of a comfortable human.

The environmental temperature transient was achieved by using two adjacent chambers under still air conditions: one simulated a warm indoor environment: 25 °C (77 °F) air temperature, 13.9 °C (57 °F) dew point temperature, and one was a cold outdoor environment: 10 °C (50 °F) air temperature, 5.8 °C (42.4 °F) dew point temperature.

First, the insulation value of the clothing and the average level of body heat loss was measured in the warm chamber according to ASTM F 1291. Then the manikin (hanging from a track by a hook in his head) was moved quickly to the adjacent cold chamber, and the power to the manikin was recorded every minute during the transient. After the transient was over, the process was repeated as the manikin was moved back to the warm chamber.

Exercise/rest tests with human subjects

Sixteen male subjects wore ski ensembles with and without PCMs during a 90 minute exercise/rest protocol that simulated skiing. The experiment began with the subjects sitting (1 MET) in a warm chamber with an air temperature of 25 °C (77 °F) and a dew point temperature of 13.9 °C (57 °F). Then the subjects sat in an adjacent cold chamber with an air temperature of -4 °C (24.8 °F) and a dew point temperature of -7.1 °C (19.3 °F). Every 15 minutes, they alternated walking on a treadmill at 4.0 mph and a 3 % incline (5.5 MET) and sitting in the cold.

The subjects' four skin temperatures were measured every minute during the exercise/rest protocol using a computerized data acquisition system. Subjects' perceptions were measured at the end of each 15 minute period using ballots. Thermal sensation was rated from #1 very cold to #5 neutral to #9 very hot. Clothing comfort was rated from #1 uncomfortable to #5 comfortable and from #1 clammy to #5 dry using a semantic differential scale. In addition, the amount of unevaporated sweat in the ski ensemble was determined by weighing the garments before and after the 90 minute experiment.

Results of manikin tests during environmental transients

Insulation values for the PCM suits were slightly higher than those measured for the suits without PCM. The one layer suit with PCM was 1.57 clo and without PCM was 1.48 clo.

The two layer suit with PCM was 2.07 clo and without PCM was 1.95 clo. The insulation values for the ski ensembles with and without PCM were the same (2.19 clo).

Heat loss data from two replications of the environmental transient tests with the manikin were averaged for each minute of the data collection period. Unfortunately, the experimental suits – with and without the PCM – were not *exactly* equivalent with respect to their heat loss and insulation values under steady-state conditions. To correct this problem, the average heat loss measured for each suit at steady-state was used to correct the transient data. Then the difference between the PCM curve and the no-PCM curve was plotted for each suit type. The difference curves indicated that the effect of PCMs on body heat loss lasted approximately 15 minutes. Therefore, the magnitude of this buffering effect was calculated and reported as the integrated total difference in heat loss for the 15 minute period (J) and as the average difference in the rate of heat loss during the 15 minute period (W). (See Table 1.) This is not the amount of heat actually produced or stored by the PCM in the material. Some of this heat is lost to or gained from the environment.

Table 1. Heating effects of clothing for first 15 minutes of warm to cold temperature transients.[a]

Garments with PCM compared to garments without PCM	Average heat-effect (W)	Total energy gain (J)
One layer suit with PCM vs. without PCM	6.5	5 850
Two layer suit with PCM vs. without PCM	13.2	11 880
Two layer suit (inner layer with PCM, outer layer without PCM) vs. two layer suit without PCM	4.5	4 050
Two layer suit (outer layer with PCM, inner layer without PCM) vs. two layer suit without PCM	9.9	8 910
Two layer suit with PCM on top 39 % of body no PCM on bottom 42 % of body vs. two layer suit without PCM	6.3	5 670
PCM ski ensemble vs. ski ensemble without PCM	5.9	5 310

[a] Cooling effects were similar to heating effects, so they were not given here to conserve space.

The manikin lost an average 6.5 W less heat during the first 15 minutes of wearing the PCM suit as compared to the control suit in a warm to cold transient. The heating effect of the two layer suit was approximately double that for the one layer suit. The heating effect of the two layer suits containing only one layer of PCM were less than the effects produced by the two layer PCM suit. There are less PCM microcapsules in one layer of clothing (as compared to two layers) to go through the phase change. In addition, there was a larger heating effect when the PCM layer was on the outside than when it was on the inside, next to the body. These layering differences may not be as great in clothing systems that fit more loosely on the body and contain thicker air layers. The heating effect of a two layer suit containing PCM on the top half of the body only was less than the effect produced by the two layer PCM suit with full coverage. In conclusion, the magnitude of the heating and cooling effects associated with phase change materials in clothing increases as the number of PCM garment layers increases and as the amount of body coverage with PCM fabrics increases.

Results of exercise/rest tests with human subjects

An analysis of variance was conducted on the skin temperature data and subjective data collected near the end of each 15 minute period. When the subjects moved from sitting in

a warm chamber to sitting in a cold one, their average leg skin temperature was significantly higher when wearing the PCM ski ensemble (31.5 °C, 88.7 °F) than the ensemble without PCMs (30.3 °C, 86.5 °F). The chest, arm, and finger temperatures and subjective responses were not statistically different, probably because subject variability was high and the average heating effect of the PCM ski ensemble was low (about 6 W). There were no significant differences in the skin temperatures and thermal sensations of males wearing the PCM ski ensemble compared to the control during the four remaining exercise/rest periods in the cold. When the subjects were walking at 5.5 MET in the cold environment, they were producing more than five times the amount of heat than they did while sitting (1 MET). This extra body heat did **not** raise their skin temperatures to proportionately higher levels and heat the PCMs so that they would change back to liquid. Instead, the body dissipated the extra heat energy by sweating. When the experiment was over, there was significantly more unevaporated sweat in the PCM ensemble, and the subjects felt significantly more clammy when wearing it during the last exercise period and rest period of the test.

Conclusions

Phase change materials produced a small, temporary heating or cooling effect when garments made of the material went through a step change in temperature. The PCM heating and cooling effects changed body heat loss by an average 2-13 W for the first 15 minutes of the environmental transient, and then the effects were over. The magnitude of the effect increased as the number of garment layers and the amount of body coverage with PCM fabrics increased.

When 16 male subjects moved from a warm to a cold environment, their average leg skin temperature was significantly higher when wearing the PCM ski ensemble as compared to the control. However, their other skin temperatures and their subjective responses were not significantly different during the environmental step change at low activity. There were no significant differences in the skin temperatures and thermal sensations of males wearing the PCM ski ensemble during the four remaining exercise/rest periods in the cold. The effect of PCMs in clothing would probably be maximized if the wearer were repeatedly going through temperature transients or intermittently touching hot or cold objects with PCM gloves.

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Protective equipment against heat and/or fire produced from performant fibres

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Introduction

The effects on health and physical integrity of the persons exposed to risks caused by heat and/or fire are the most serious. This led to paying special attention to this individual protective equipment (IPE) category. In order to assure the protective level suitable for different exposure and intensity levels, there have been created special types of IPE.

This requirement was imposed by the different ways the risks of heat and fire appear, for instance for the heat (various types with specific effects: contact, convective or radiant) and for the fire (short time occasional contact with flame, projection of incandescent or molten metal particles, etc.).

Being used against heat rays and/or against fire, the IPE has fulfilled the following requirements:

- the heat quantity transmitted to the user has to be small enough so as the whole quantity accumulated during the entire period of operation in that part of the body which needs to be protected not to reach the pain's break point or other boundaries that could damage one person's health;
- IPE has to obstruct, if necessary, the liquid or the vapor to penetrate and also has to avoid burns at the contact between the protective layer and the user.

The risk of inflaming the protective clothing can be caused by:

− the occasional contact with the flame;
− high intensity heat rays;
− direct contact with glowing materials.

In order to establish the potential range of use was necessary to emphasize the concrete usage conditions of the IPE against heat and/or fire. We started from the assumption that only a fair evaluation of the accident or rendering sick risks results in choosing and utilizing in high efficiency conditions the IPE.

The analysis of the risks for the working places emphasizes the presence of one type of risks very rare, in most of the cases we are faced with the cumulative action of many types of risk. The most frequent case in this respect is a cumulating of risks determined by the superficial mechanical aggressions as a result of working with pieces endowed with rough surfaces and sharp ribs.

In order to be able to assure an adequate protection, in designing and accomplishing some new IPE-s against heat and fire, it is necessary that we consider these risks.

Experimental part

In order to assure a suitable protection against fire and heat, heat-resisting fibers are used. Heat-resistance of a polymer is commonly characterized by three aspects:

- the level of basic characteristics (physical and chemical);
- to preserve these characteristics in a given temperature area;
- to maintain these characteristics in a certain time period at a given temperature.

In the particular case of heat-resisting fibers destined for thermal IPE, the most important factors are:

- the level of the basic characteristics imposed by the specific domain of usage (mechanical resistance, resistance to chemical agents);
- to preserve the integrity of the surface of the protection textile structure in the case of:
  - short time exposure to an open radiant flux (heat resistance: many more seconds at 1000 °C);
  - flame closeness (heat resistance: many more minutes at 350 °C).

Accomplishment of IPE involves:

- estimation of the dangers and of the risk levels;
- delimitation of the basic characteristics, specific and additional of the textile support;
- designing the textile support taking into account the performance requirements imposed by the domain of usage;
- testing according to the European standards;
- designing and accomplishing the IPE-s in order to obtain the protection, ergonomic and comfort characteristics;
- certification of the IPE.

For the thermal IPE, the textile support is submitted to the most severe requests of fire resistance and temperature, the primary and the most important condition being not to maintain the burning. That's one of the reasons for which in accomplishing the respective woven fabric, some fibers with special characteristics are used, namely inherent inflammable fibers, resistant to different chemical agents, and in the same time with small combustion gas emission, even at carbonizing temperatures.

The Twaron para-aramidic fibers produced by Akzo combine the good processing properties of the high temperatures resistant textile fibers with the high level resistance of the organic fibers (Table 1).

Table 1. Characteristics of Twaron fibers.

Length Density, dtex	1.78
Individual Length, mm	38.5
Tensile Breaking Strength, cN	27.6
Breaking elongation, %	5.3
Tenacity, cN/tex	15.5
Breaking modulus, cN/dtex	290.5

The fibers used for experimentation have been processed on the conventional spinning systems, such achieving 37 tex yarns (Table 2).

Table 2. Performance characteristics of the obtained 100 % Twaron textile support.

Length density (warp and weft), tex	37x2
Weight, g/m^2	294
Breaking resistance, N, warp/weft	5500/4700
Breaking Elongation, %, warp/weft	12/7
Tearing Resistance, N, warp/weft	750/680
Wearing Resistance (00 abrasive) no. of cycles	more than 2000
Water vapor permeability, mg/cm^2 24 h	665
Air permeability, l/m^2 - s	200

Testing the protection performances against heat and/or fire

In order to finalize the usage domain of the IPE-s accomplished from 100 % Twaron woven fabrics, some specific tests have been made (Table 3).

Table 3. The tests that were carried out on 100 % Twaron woven fabrics

Characteristic	Obtained performances	Testing method
Limited flame propagation	Corresponds to 6/2 SR EN 531 and EN 533: – doesn't propagate the flame: post burning time after removing the ignition flame< 1 s; – during the exposure the flame doesn't touch the superior or the vertical margin of the test bar; – doesn't release any molten, burning or burnt rests; – test bars don't get perforated; – medium time of after glowing- 1 s.	6.2.2./SR EN 531 after a perpendicular flame exposure in accordance to SR EN 532
Fire behavior	In accordance to 5.1/SR EN 407, in the initial state and after washing: – medium time of flame's persistence- 0 s; – medium time of residual after glowing- 0 s.	6.3 SR EN 407 + 5.1 SR EN 407
Convection heat resistance	In accordance to 5.3/SR EN 407 Performance level 4 HTI > 18 – time to increase the internal force temperature with 40 °C at a direct flame exposure in a 50 mm distance, caloric flux of about 80 kw/m^2: more than 25 s	Romanian Standard adjusted after 6.5/SR EN 407 + EN 367
Contact heat resistance	In accordance to 5.2/SR EN 407 Performance level 3 – breaking point time: 20 s for a contact temperature (of the plate) of 350 °C	6.4/SR EN 407 + Romanian Standard adjusted after pr. EN 702
Small fluid metal projections	In accordance to 5.5/SR EN 407 Performance level 2 – the number of particles that may lead to a growth of the internal force temperature with 40 °C: 15 min.	6.7/SR EN 407 + EN 348
Large fluid metal projections	In accordance to 5.6/SR EN 407 Performance level 1 – the quantity of melted cast iron that doesn't bring about any flow signs or any changes in the exterior surface of PVC foil	6.8/SR EN 407 + Romanian Standard adjusted after EN 373

Taking into account the very good performances assured by the accomplished textile supports in both protection against heat and/ or fire (guaranteed for the entire period of service because of the maintenance of parameters by using performance Twaron para-aramidic fibers) and in mechanical characteristics with reference to breaking and tearing resistance, the following prototypes were designed and accomplished:

- anticaloric clothing used as fire-proof clothing against convection heat; this clothing is specially designed for works effected near by some important heat sources (low level risk, located heat and / or fire exposure) where short time contact with the open flame, or with incandescent molten metal particles (sparks) is possible, or in the presence of risks caused by superficial mechanical aggressions (medium level risk – abrasion, punch, hanging);
- anticaloric gloves with one finger, accomplished from three layers of textile materials:
  - they are designed for works effected near by important heat sources, medium level, which assure the thermal isolation against contact heat (when handling hot objects with temperature higher than 350 °C);

- they are used against convection heat, against projection of particles or medium quantities of molten cast iron, as well as against short time chance contact with the open flame;
- their main characteristics are: abrasion, punch, tearing and cutting resistance.

The accomplished products, tested and certified in accordance to the law in force satisfy the main security and health requirements, suitable for different usage domains.

Conclusions

- To assure the security and the health is a main concern of the working process, and we have to refer to it when creating the working life, if we want to obtain its maximum efficiency.
- The protection effect of an IPE depends mainly on its structure. In order to achieve the best structure it is required to use performance fibers, which assure quality, multifunctionality and comfort.
- In order to accomplish the woven and/or knitted structures for IPE against thermal and /or mechanical aggressions Twaron para-aramidic fibers can be used.

Acknowledgments

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Dynamics of sweat vapour sorption as the function of physical parameters of textile packets under protective barrier

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Introduction

Protective clothing made from barrier fabrics very often puts a thermal strain on its wearer. This takes mostly place during intensive manual labour (Beckett et al., 1986). Under these conditions, the body begins to intensely perspire, while, during wear of hermetic barrier clothing, only a small quantity of sweat can evaporate from the skin. The effect is a rapid growth in the humidity of the microclimate and the accumulation of moist sweat on the skin.

As proven by many research studies, there is a significant influence of textiles worn near the body on the intensity of heat and sweat removal - a determinant of under-garment microclimatic parameters as well as of a level of discomfort (Umbach, 1980, Umbach Sonderdruk). The phenomenon particularly applies to fabrics worn under protective barrier clothing. When moist sweat appears on the skin, a fabric of under-barrier clothing ought to enable its removal and then its effective absorption. In order to eliminate the sensation of wetness, resulting from moisture sorption, the layer of an under-barrier fabric which adjoins the skin should be made from a raw material characterized by minimal moisture sorption and a structure providing good capillary transport. It is thus advisable to assume that the under-barrier fabric should have a two-layer structure. The first, inner, conductive-diffusive layer should enable the diffusion of water vapour and moisture capillary transport, whereas the second, sorptive one should arrest humidity within its structure.

The purpose of the research work was to characterize an effect of diversely structured textile packets used under the protective barrier on shaping the under-garment microclimate and, consequently, to select the packet optimal for use during intensive physical effort.

Materials and methods

The basic test materials were one-component knitted fabrics made from five different types of textile raw materials, i.e., polyester (PES), polypropylene (PP), cotton (CO), viscose (CV), and wool (WO), manufactured in two stitches: interlock and float special pique. The investigation also encompassed unwoven fabrics containing superabsorbents in the form of fibres and powder. Characteristics of the fabrics produced for the investigation were presented in Table 1. The materials were also tested in two-layer systems: the near-body hydrophobic layer covered with the hydrophilic one.

The dynamics of humidity of the microclimate was examined at the test stand shown in Figure 1 (Zieliński, 1997). The lower part of the chamber contains a porous glass agglomerate, supplied with water and kept at the constant temperature of 30±1 °C, which

simulates the perspiring human skin. Initially, the humidity in the microclimatic zones was equal to approximately 15±2 %. The velocity of water vaporization in the experiment amounted to 0.85 ml/m²·min. The investigation was carried out in the chamber at the constant temperature of 30±1 °C. The packet of the tested materials was placed above the skin surface:

- an under-barrier clothing fabric or system of fabrics,
- the protective barrier (polyamide-polyester fabric coated with PVC).

Table 1. Characteristics of under-barrier fabrics.

Variant	Kind of material	Raw materials	Mass per square meter [g/m²]	Thickness [mm] pressure 0.5 kPa	Water vapour resistance*⁾ [m²·Pa/W]
a_1	knitted fabric - interlock	PES textured	218	1.01	3.9
a_2	knitted fabric - interlock	PP textured	228	1.09	3.8
a_3	knitted fabric - interlock	CO	299	1.42	4.5
a_4	knitted fabric - interlock	CV	277	1.05	3.3
a_5	knitted fabric - interlock	WO	309	1.70	5.8
b_1	knitted fabric – RL float special pique	PES textured	127	1.48	4.6
b_2	knitted fabric – RL float special pique	PP textured	158	1.66	4.7
b_3	knitted fabric – RL float special pique	CO	212	1.41	4.5
b_4	knitted fabric – RL float special pique	CV	182	1.22	3.2
b_5	knitted fabric – RL float special pique	WO	272	2.25	6.9
p	unwoven fabric	PES, PP powder Favor SAB-954	366	1.58	6.3
w	unwoven fabric	PP, CV, fibres Fibersorb 900	94	0.36	2.9

*⁾ according to ISO 11092
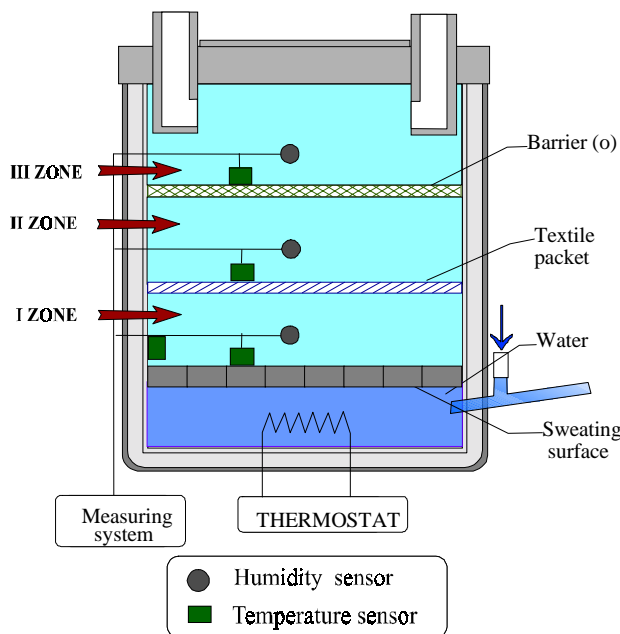
Figure 1. Diagram of the apparatus measuring humidity dynamics of the microclimate.

The layers of the packet divided the under-barrier space into the two zones (I, II) where the humidity of the microclimate was investigated. Besides, the humidity above the barrier (zone III) and temperatures on the surface of each layer of the packet and the 'perspiring skin' were recorded. The hermetic water-steam-tight barrier used in the experiment caused that the humidity in zone III of the microclimate remained constant. Results of the measurements were expressed as graphs illustrating the dynamics of humidity changes in zones I, II and III of the microclimate and the temperature on the surface of the textile packet (Figure 2).
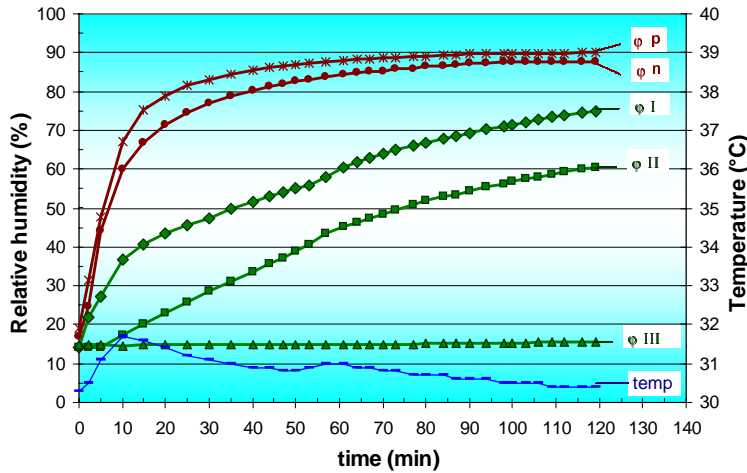
$\phi_I \phi_{II} \phi_{III}$ - humidity in zone I, II and III respectively for the packet: knitted fabric a_4 + barrier
$\phi_p \phi_n$ - humidity in zone I and II respectively for the barrier itself (o)

Figure 2. Results of measurements of dynamics of the microclimate humidity and temperature on the surface of the under-barrier fabric for the packet: viscose knitted fabric (design a_4) + hermetic barrier.

In order to make a comparative analysis of the results of measurements, indices characterizing dynamics of the microclimate were assumed.

The dynamics of humidity growth above the 'perspiring skin' was calculated by means of the formula (Figure 2):

$$Dp = \frac{\int_0^{120} \phi_I(t)dt}{\int_0^{120} \phi_p(t)dt}$$

where:
ϕ_I - humidity in zone I of the microclimate,
ϕ_p - humidity in zone I of the microclimate without the under-barrier fabric,
t - time.

The dynamics of humidity growth above the under-barrier fabric was calculated by means of the following formula (Figure 2):

$$Dn = \frac{\int_0^{120} \phi_{II}(t)dt}{\int_0^{120} \phi_n(t)dt}$$

where:
ϕ_{II} - humidity in zone II of the microclimate,
ϕ_n - humidity in zone II of the microclimate without the under-barrier fabric,
t - time.

Indices D_{p10} and D_{n10}, characterizing the dynamics of humidity growth above the 'perspiring skin' and the under-barrier fabric, were calculated similarly 10 minutes after the beginning of the experiment.

Results

The fabrics were assessed in comparison to the proposed two-layer model designed for use under the protective barrier. The first layer - made from a hydrophobic fabric - should be characterized by high permeability and low absorptivity of water vapour. Therefore, indices D_p and D_n as well as D_{p10} and D_{n10} ought to be high. In this respect, the best properties were shown by the float special pique fabrics manufactured from synthetic fibre textured yarn (b_1, b_2), especially the polyester knitted fabric - design b_1 (D_p and D_n near 1).

The second layer of the under-barrier fabric should show high sweat vapour sorption and, thanks to this quality, be able to reduce humidity of the microclimate near the skin. Therefore, indices D_p and D_n ought to be adequately low. Comparing the raw textiles used for the sorptive layer, a high rating was given to viscose and wool yarn knitted fabrics. The best properties were shown by the interlock wool knitted fabric (D_p=0.62, D_n=0.50), yet it is necessary to add that this design was at the same time characterized by high superficial mass. Bearing in mind the low superficial mass of the unwoven fabric with high-sorptive fibres, one should take note of high water vapour sorption efficiency (D_p=0.76, D_n=0.66).

On the other hand, no direct correlation between the of water vapour resistance and the effect of the fabrics on shaping the under-garment microclimate was observed. It follows that in order to analyse an influence of fabrics worn near the body upon forming the under-barrier microclimate it is necessary to research into the dynamics of humidity for the whole packet of clothing (under-barrier fabric + barrier).

Conclusion

The research work done made it possible to describe the impact of the structure of the fabric packets placed underneath the hermetic protective barrier upon shaping the dynamics of the under-clothing microclimate. Taking into consideration the proposed two-layer fabric model designed for use under the hermetic barrier, it was affirmed that the most suitable materials to be used for the near-body layer are the open-structured pique knitted fabrics made of synthetic fibres. The materials best fitted for the second, sorptive layer are those characterized by the tight structure and made from the raw materials of high water vapour sorption, particularly in the first phase of the experiment - i.e., viscose or wool knitted fabrics, or high-sorptive fibre unwoven fabrics.

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Psycho-physiological mechanisms of thermal and moisture perceptions to the touch of knitted fabrics

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Introduction

Being defined as freedom from pain and discomfort, comfort is a fundamental and universal need of consumers. Meanwhile, closely integrated with human life, comfort of clothing plays an important role in human sensory experience (Hatch, 1993) and for the clothing industry, the final goal is improve the quality of life and the survival of human beings. Many articles in the literature investigated the factors involved in clothing comfort (Lake & Hughes, 1980; Nielsen & Endrusick, 1990; Schneider & Holcombe, 1991; Li et al., 1996,). Thermal and moisture sensations have been widely recognised as the most important factors contributing discomfort sensations. In this paper, we study the psycho-physiological mechanisms of the thermal and moisture sensations by conducting a series of perception trials using knitted fabrics.

Neurophysiological basis of the thermal and moisture sensations

Based on Hensel's research (Hensel, 1981), Li *et al* developed a mathematical equation as following to describe the neurophysiological response of this process:

$$Q(y,t) = K_s T_{sk}(y,t) + k_d \frac{\partial T_{sk}(y,t)}{\partial t} + C \qquad (1)$$

Where $Q(y, t)$ is the pulse output response of the thermoreceptors as a function of time t and at the depth y of the thermoreceptors below the skin surface in impulses. $K_s = -0.72$, $K_d = -50$ and $C=28.1$. The integrals of the thermoreceptor frequency output curves, named as psychosensory intensity (PSI value), were calculated to describe the intensity of the thermal sensations and the stated as equation (2):

$$PSI = \int_0^t Q(y,t)\,dt \qquad (2)$$

To study the psychophysical relationship, the maximal skin temperature change rate (MTC) also defined as:

$$MTC = \frac{\partial T}{\partial t}\Big|_{max} \qquad (3)$$

Experimental

All the tests were carried out in a conditioned laboratory, controlled at 20 °C ±0.5 °C and relative humidity of 63 %±1 %. Fifteen subjects (seven males and eight females, ranging in age from 20 to 41) participated in the trial. Each session consisted of testing two sets of specimens, one for dampness perception and another for coolness perception. A series of fabrics were used in this study and detailed in Table 1. Fabrics were considered at

"equilibrium regain", when the moisture content of fabrics was in equilibrium with the ambient condition. Additional water added to fabrics was termed as "excess moisture", which was expressed as a percentage of fabric weight at equilibrium regain. Three levels of moisture were used: the 0 % (i.e. the "dry" fabric in equilibrium with ambient condition), 4 % and 16 % of excess moisture.

Table 1. Fabrics used in experimental program.

Sample Code	Fiber Content	Fabric Construction	Mass/Unit area g/m2	Thickness at 98 pa pressure mm
K1	Nylon	knitted	90.6	0.27
K2	Darcon	knitted	178.5	0.95
K4	Orlon	knitted	252.0	1.23
K8	30 % Cotton / 70 % Polyester	knitted	200.4	0.62
K9	Cotton	knitted	356.6	0.94
K15	20 % polyester / 70 % wool / 10 % nylon	knitted	454.6	3.06
K16	25 % Cotton / 75 % Polyester	knitted	319.4	1.52
K17	Nylon	knitted	231.4	2.64

The weights of test fabrics were determined prior to the testing after conditioning in the ambient condition for 24 hours. Before test, the desired moisture contents for an individual fabric were introduced by adding water to the fabric to required level of excess moisture. And then stored in individual seal storage bags overnight to make sure they have reached equilibrium at the certain excess moisture. In the trial, non-comparative unbalanced and forced rating scales are used for tester. Subjective scores on coolness and dampness were recorded on two scales, which range from "dry" to "Extremely Damp" and "Slight Warm" to "Cold" respectively. The scales marked with text labels faced to the subjects and the numeral scales faced to the operator on the rear of the ruler. A pointer, which was indicated by a subject on the text scale, provided a corresponding numerical value that was recorded by the operator. Prior to the trial, we fixed two type-T thermocouples on the inner surface of subject's forearm and connected to a portable PC. During the trial, we began to record the temperatures before the fabric was placed on the forearm and then continued to record during the fabric-skin contact.

In the experiment, the arm of subjects was kept static and the operator placed the fabric samples across the subject's forearm. The apparatus for temperature measuring can be shown in Figure 1. Typical skin temperature-changing curve during the fabric contact is shown in Figure 2 and the calculation of measured temperature-changing rate and Q(t) at the skin surface are shown in Figure 3.
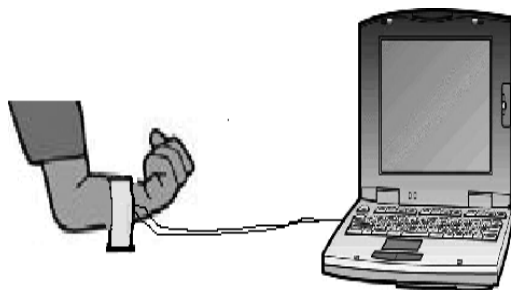
Figure 1. Apparatus for temperature measurement.
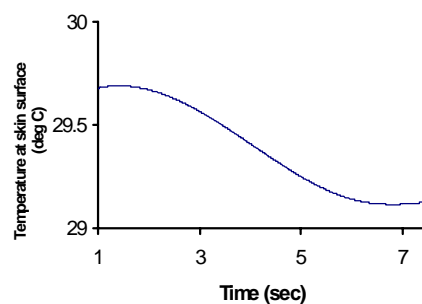
Figure 2. Measured temperature changes at the skin surface.
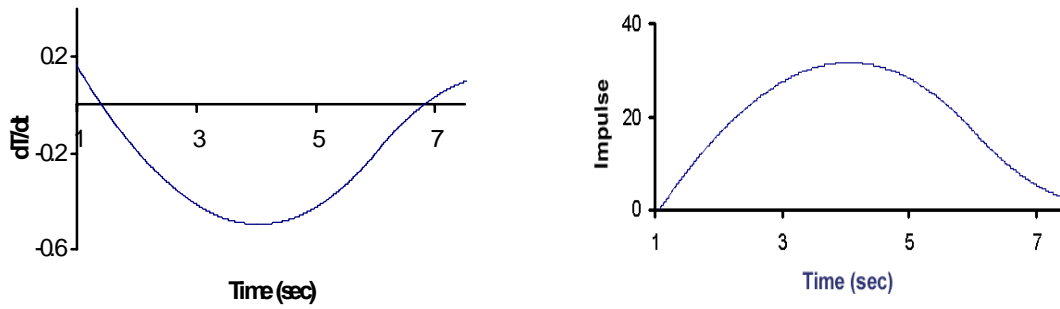
Figure 3. Calculation of temperature change rate and impulse on the skin surface.

Results and discussion

To reduce the influence of individual bias on subjective coolness and dampness judgement, all the subjective perception data had been standardised before the mean calculated and the results are shown in Figure 4. The means of MTC and PSI are shown in Figure 5 too. Both subjective perceptions and psycho-physiological indexes on knitted fabric are highly correlated with the water content in the fabric and increased with it.
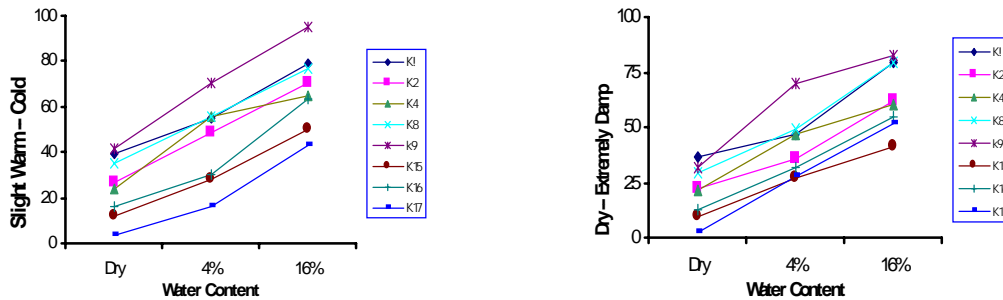
Figure 4. The means of subjective perception on coolness and dampness.
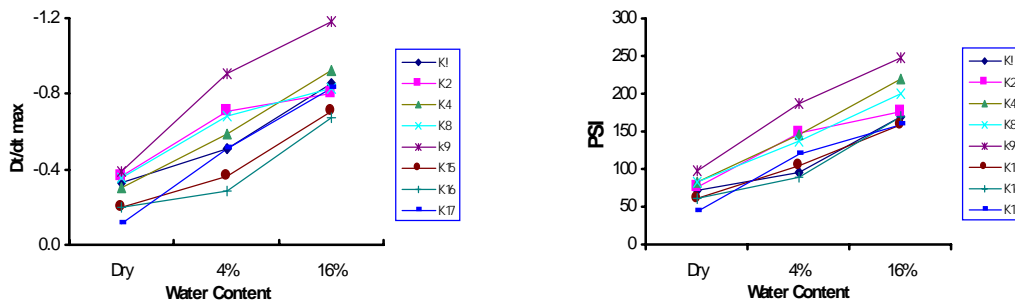
Figure 5. Means of MTC and PSI on the skin surface.

Using the GLM General Factorial and GLM Multivariate methods, we obtained the significance of influence of water content, fibre content on the perception of coolness and dampness, which are shown in Tables 2~4 respectively. As shown in the tables, the level of water content in the fabrics and fibre content have significant influence on the subjective sensations with P<0.001, suggesting that coolness and dampness sensations are not only determined by the level of water content in the fabric, but also the types of fibres in the fabric. Similarly, the objectively measured skin temperature changes and PSI are also significantly influenced by the excess moisture with p<0.001 and fibre content with P<0.002. These results show that both subjective perceptions and the neurophysiological indexes (MTC and PSI) depend on the excess moisture and fibre content, indicating that

the subjective sensations may be determined by the two factors through the neuro-physiological responses of the thermoreceptors.

Table 2. Analysis of variance on subjective coolness ratings.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	164536.0	20	8226.8	22.8	.000
Intercept	740681.7	1	740681.7	2049.1	.000
Water content	107214.7	2	53607.3	148.3	.000
Fiber content	49025.5	6	8170.9	22.6	.000

Table 3. Analysis of variance on subjective dampness ratings.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	153786.0	20	7689.3	16.2	.000
Intercept	609691.6	1	609691.6	1286.0	.000
Water content	102457.6	2	51228.8	108.1	.000
Fiber content	37560.0	6	6260.0	13.2	.000

Table 4. Analysis of variance on objectively measured MTC and PSI.

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	MTC	13.0	20	.7	5.2	.000
	PSI	589910.7	20	29495.5	6.1	.000
Intercept	MTC	78.2	1	78.2	628.8	.000
	PSI	4569584.1	1	4569584.1	943.5	.000
Water content	MTC	8.6	2	4.3	34.6	.000
	PSI	449219.5	2	224609.8	46.4	.000
Fiber content	MTC	3.0	6	.5	4.0	.001
	PSI	130212.8	6	21702.1	4.5	.000

Furthermore, the dampness sensation is highly correlated with the coolness sensation, as shown in Figure 6, suggesting that the perception of temperature and moisture may be determined by the same psycho-physiological mechanisms: the neurophysiological responses of skin thermorecptors to skin temperature changes during the fabric-skin contact.
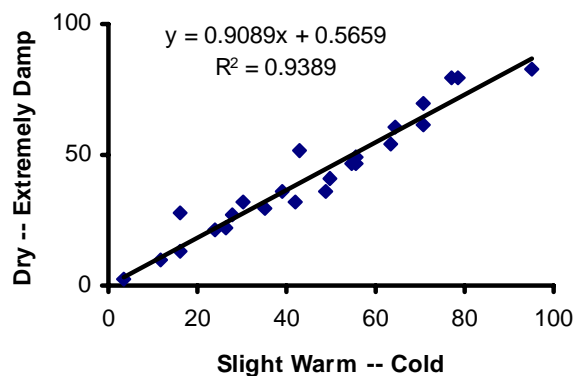
Figure 6. The relationship between coolness and dampness.

The relationships between the subjective perceptions of coolness and dampness the neurophysiological indexes (MTC and PSI) are shown in Figure 7~10. The coolness perception is highly correlated with the PSI and MTC with R^2 of 0.79 to 0.82 respectively, which are significant at level of P<0.001. The linear relationship between the two suggests that the coolness perception be determined by the psycho-physiological mechanism of thermoreceptors' response to the skin temperature changes. Similarly, the dampness perception is also linearly related to MTC and PSI with the R^2 of 0.81 and 0.84 respectively, showing that the same psycho-physiological mechanism determine the subjective perception of moisture in the fabrics. Comparing the results for coolness and dampness sensations, good agreement between the two confirms our assumption that perception of moisture is determined by the same psycho-physiological mechanism as the perception of temperature in the body.
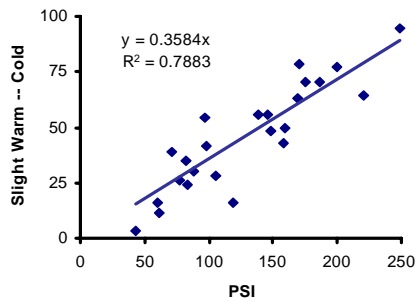
Figure 7. Coolness and PSI.
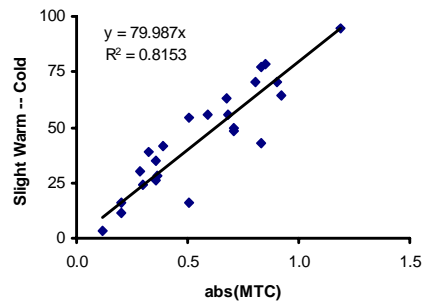
Figure 8. Coolness and MTC.
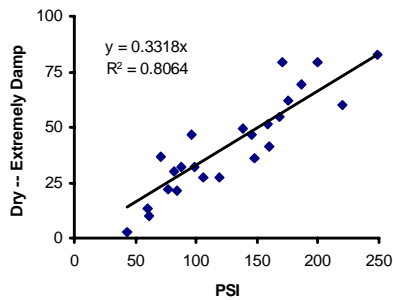
Figure 9. Dampness and PSI.
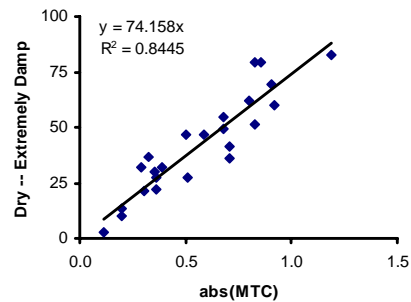
Figure 10. Dampness and MTC.

Conclusions

By conducting a series of psycho-physiological perception trials and measuring the skin temperature changes during the fabric-skin contact process, we found that subjective perception of coolness and dampness is highly correlated with each other and significantly influenced by fabric excess moisture and fibre content. The perception of moisture and temperature is shown determined by the same psycho-physiological mechanism: the neurophysiological responses of thermoreceptors to the skin temperature change during the fabric-skin contact.

Acknowledgement

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Combined effects of fabric moisture absorbancy and air permeability on thermophysiological responses in the warm environments

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Abstract

I talk on combined influences of fabric moisture absorbancy and air permeability in the warm environments. Two kinds of sportswear, i.e., 100 % cotton with moisture regain of 6.1 % and air permeability of 143 ml/square centimeter/second (Type A) and 100 % cotton with moisture regain of 7.0 % and air permeability of 26.8 ml/square centimeter/second (Type B) were prepared. Thickness and mass were controlled as equally as possible. Participants wearing either Type A or Type B performed cycle exercise, which intensity corresponded with 60 % of their maximal oxygen uptake, for 60 min under wind of 1.5 m/s or no wind at an ambient temperature of 30 degree C. Rectal temperature during 60 min exercise was significantly inhibited to increase in Type A compared with Type B under windy condition, while there did not exist any differences in rectal temperature increase under no windy condition between Type A and Type B. This fact suggests that the fabric with high moisture regain plus high air permeability can inhibit an increase of core temperature during exercise and effective evaporative cooling can be accelerated by combined function of fabric high moisture absorbancy and air permeability under light windy condition.

Fibres, textiles and materials for future military protective clothing

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Introduction

The Defence Clothing & Textiles Agency of the Defence Logistics Organisation is responsible for providing all Clothing and Textile items for the U.K Armed Forces. It has tri-service responsibility, in that it covers all requirements for the Royal Navy, the Army and the Royal Airforce (excluding aircrew clothing, and diving clothing for the Navy) (Scott, 2000).

The Research and Technology Group carries out research, development and Quality Assurance for this organisation. A large proportion of the scientific effort involves research on novel materials and clothing systems for the future. One of the main research programmes is entitled "CRUSADER 21" – future integrated combat clothing system (Beyts & Scott, 1999). Another (Core) programme provides underpinning research in the form of background information, new techniques, and computer modelling of high-risk human protection scenarios. A third programme, (Inventive Corporate) involves high-risk, long term, innovative research topics.

Improvements in future military combat clothing

Many of the requirements for future combat and protective clothing are aimed at solving a set of perennial problems. These are:

a. *Improved Protection* - against the natural environment and battlefield threats.
b. *Maintenance of Thermo-physiological comfort* - or survival in extreme conditions.
c. *Improved compatibility* - between and within different components in the clothing assembly.
d. *Reduction in weight and bulk* - especially load carriage systems and ballistic protective clothing.
e. *Integration of Clothing items* - in which the clothing items are considered to be parts of a multi-role system.
f. *Reduction in life cycle costs* - future systems may be more expensive, but may be more effective, durable, may consist of fewer components, and could be recyclable.

Research objectives

The research programme is split into a range of threat-based objectives. The aim is to provide protection of the individual combatant, whilst maintaining full operational effectiveness. The following list approximates to the threat priority order:

1. *The Natural and Operational Environment:* mainly world climatic extremes, but includes sea water, dust, mud, altitude, terrain and vegetation. The operational environment includes protection from low speed impacts, foreign object damage, petrol, oils and lubricants, noise, abrasion, wear, and static electricity.
2. *Ballistic Protection:* against fragmenting munitions, such as bombs, mines and shells, bullets, and other projectiles such as flechettes.
3. *Surface Heat and Blast:* this includes open flames, heat, weapon flash and blast.
4. *Detection, Identification and Recognition:* involves camouflage, concealment and deception against a wide spectrum of surveillance threats.
5. *Biological and Chemical Protection:* against toxic chemicals such as mustard gas, nerve agents, bacteria, viruses, and bio-regulators.
6. *Nuclear and Radiological Protection:* against the effects of nuclear weapons.
7. *Directed Energy Weapons:* mainly battlefield range-finding lasers.
8. *Mobility and Load Carriage:* involves the provision of appropriate footwear, and means of carrying personal loads.
9. *Integration, Interfaces and Design:* deals with all aspects of integrated clothing systems.
10. *Human Factors:* considers such factors as Thermo-Physiological comfort, military performance factors, anthropometry and fit of clothing.

Materials research

It is predicted that concentrating on innovative materials can make significant improvements in military protective clothing in the future. This has led DCTA to consider the use of "smart/reactive" materials for protection.

Smart / reactive materials

These are designed to operate so that the wearer is comfortable and effective during normal duties. When the threat changes, such materials respond and change state in order to oppose the threat, and provide increased protection *just when it is required.*

   Examples are included in the following sections of the paper.

Materials for environmental protection

Thermal Insulation - here the aim is to provide "smart" adjustable insulation in one garment, rather than adding or removing multiple layers. The approaches include *Variable Pile Fabrics* (Patent GB.2,234,705B) or *Inflatable Mesh Systems* (Patent GB.2,242,609B).(Forshaw, 1999) These materials can be erected or inflated to increase thermal insulation when ambient temperatures and activity levels are low. Conversely, they can be collapsed to offer minimal thermal insulation when ambient temperatures are high, or activity is high. A variety of materials are being used in the pile fabrics, including monofilament polyester, core yarns and microfibres to give optimum properties. The inflatable meshes have utilised rubber, PVC and polyurethane films.

   New polyester filling fibres combining the properties of high insulation, low bulk, and high recovery from compression are now available in many forms and are being evaluated.

High Performance Wicking Materials - are being investigated for next-to-skin clothing. A range of purpose designed polyester fibres such as Coolmax®, Thermostat®, and nylon microfibres are being evaluated for their ability to transfer liquid moisture from the skin and dry quickly. They are being examined in a range of knitted fabric constructions. The incorporation of controlled release biocidal treatments to improve hygiene during longer wear periods is under investigation.

Waterproof / Water Vapour Permeable (WVP) Materials - are in wide usage in U.K military foul weather clothing. Development continues to produce the optimum balance of properties for particular uses. Some require high WVP and waterproofness for infantry, Marines and special forces, whereas Navy personnel require high waterproofness with lower WVP for their particular tasks. Cost is a particular current driver for rainwear. Research is also examining the concept of fabrics with "smart pores", which are designed to open when the internal humidity is high (i.e. sweating conditions), and close when humidity is low.

Multi-Role Textiles - are designed to minimise the number of separate clothing items to be carried and maintained. We can currently demonstrate a laminate which combines 8 levels of functionality comprising water proofness, vapour permeability, wind proofness, flame-retardance, non-melting, and camouflaged in the visible, near infra-red and acoustic parts of the spectrum.

Phase Change Materials - are designed to buffer temperature changes in clothing systems by absorbing or releasing latent heat. These are based upon the use of micro-encapsulated waxes in fibres or fabrics. The buffering effects are proving to be rather limited at this stage of development, but promise future improvements (Lennox-Kerr, 1998).

Improved Repellent Finishes - involving new chemistry to covalently bind fluorocarbon chains to textile fibres have achieved some limited success in providing permanent high levels of oil and water repellency for the life of the material.

Materials for ballistic protection

Light weight flexible protection for the individual requires the use of specialist high modulus fibres for body armour. They are also used for light weight composites for helmets. Such fibres combine very high tensile strength with very low elongation at break. They are effective against bomb fragments and low velocity bullets.

Fibres available include ballistic nylon, para aramids (aromatic polyamides) such as *Kevlar*® (Du Pont), and *Twaron*® (Enka). *Kevlar* in particular is available in a variety of continuous filament decitexes and finishes. More recently these have been joined by a new fibre *Zylon*® (Toyobo). This is a PBO fibre (paraphenylene polybenzobis oxazole). Early evaluations show some promise, although the price is currently prohibitive (Payne, 2000).

A range of Ultra High Modulus Poly Ethylene (UHMPE) fibres have been developed in recent years. They are typically Gel Spun Poly-Ethylene (GSPE) fibres with tradenames such as *Dyneema*® (DSM), and *Spectra* ® (Allied Signal). A needle punched felt fabric *Fraglight*® having chopped, randomly laid GSPE fibres, offers a very low density (0.97 g/ml) ballistic pack, albeit with a degree of bulk. The choice of ballistic fibre and fabric depends on ballistic performance, weight, flexibility and cost.

Protection against high velocity bullets and projectiles is provided additionally by ceramic plates, often based upon alumina, or boron carbide for more severe ballistic threats. The plates are limited in size - because of their weight - and are designed to protect vital organs such as the heart.

Fibres for flame and heat protection

Flames, heat and flash threats in operational conditions are deliberate threats to military personnel. Significant R&D efforts are expended in order to provide adequate protection at reasonable cost, and to maintain thermo-physiological comfort.

A limited range of Flame Retardant (FR) fibres and finishes are actually used in UK military clothing, although the number of options available is increasing.

The most widely used FR fibre is *Proban*® treated cotton – hydroxymethyl phosphonium oxide or chloride. Fabrics currently contain up to 30 % of polyester in a blend to improve durability, dimensional stability, and smart appearance. The major user is the Royal Navy, whose working and action clothing on board ship is made from this blend. Certain coveralls used in workshops and dockyards are also supplied in FR treated cotton.

When Naval crews are required to fight fires they currently don a heavy insulative coverall in *Zirpro*® treated wool. There are plans to replace this in the future.

The UK Nuclear, Biological and Chemical (NBC) protective over suit currently has an outer fabric made from a (FR) modacrylic warp and nylon weft. This gives a degree of flash and flame resistance to the wearer.

A wide range of meta aramid fibres now exist. Examples such as Nomex® (Du Pont), Conex® (Teijin), and Kermel® (Rhone-Poulenc) are becoming more widely used, and is largely replacing other current products, such as wool, especially in the fire- fighting sector of the business.

Nomex® is available in a range of blends with Kevlar® para-aramid, some of which contain small percentages of a P140 antistatic fibre for specific applications (Mountford, 2000).

MOD uses some of these variants in Tank Crew clothing, Explosive Ordnance Disposal (EOD) clothing, Aircrew and Special Forces clothing, and is currently worn by submarine crews. The newer variants are being evaluated for uses in future multi-role textiles (para.4.b.4), aircrew clothing, FR underwear, Firefighters ,and specialist protective clothing systems.

MOD civilian fire brigades have also recently trialled turn- out suits in PBI "Gold" fibre (Poly Benz-Imidazole fibre)

Reactive materials for flame and heat protection

One of the main problems with protection is providing sufficient insulation to prevent skin burns whilst maintaining wearer thermal comfort. Multiple layers of clothing and air gaps will provide the required protection. Reactive materials are designed to provide minimal insulation during normal wear, but maximum insulation when the heat threat impinges. The DCTA has examined several novel approaches:

Intumescent treatments - are formulations containing a carbonific source, a catalyst, and a spumificant, or gas blowing agent. These would normally be in the form of thin, low insulation coatings on a lining fabric. When activated by excessive heat or flames the formulation swells instantly to form an inert insulative char, protecting the wearer. Such in-

tumescent treatments are currently being optimised for use in clothing systems (Scott, 1999).

Shaped Memory Alloys - are metals which can assume different shapes when the temperature is changed. In this case we wish to establish a large air gap during the threat phase. This can be achieved by using a coil spring between two fabric layers which adopts a flat conformation during normal operations, but which rapidly forms an extended helical shape when the heat threat arrives. These can increase protection times against 2nd degree skin burns by a factor of between 50 and 85 %, depending on the heat flux and clothing system (Congalton, 1999).

Photochromic Dyes - are colorants which change colour with light intensity. To provide flash protection for the eyes we would ideally envisage an optical eye protector which is perfectly clear under normal conditions, but which instantaneously attains an optical density of at least 3 when nuclear weapon flash occurs. Such systems have shown some promise for this application.

Thermochromic Dyes - are textile colorants which change colour with temperature. In order to provide radiant flash protection, we ideally want to use dyes, which normally exhibit the correct visual camouflage print, but which bleach white instantaneously when the flash arrives. This reflects a proportion of the incident radiant energy. Such dyes will react in nanoseconds, although it is currently difficult to provide the effects in all 4 colours of the UK camouflage print.

Camouflage, concealment and deception

Full spectrum camouflage for combat clothing encompasses the ultra violet, visible, (0.4 to 0.8 micron) near infra red (0.8 to 1.2 micron), and thermal far infra-red (2.0 to 5.6 and 8 to 14 micron) We also desire to defeat surveillance systems operating in the radar and acoustic bands.

Adaptive Camouflage - Camouflage patterns on UK clothing are designed to mimic woodland and desert backgrounds. The natural background changes markedly with the seasons – there being a preponderance of green hues in summer, many of which disappear in winter. To cope with these changes research is examining the use of thermochromic textile dyes that will change colour when triggered by a significant seasonal temperature change. The desired effect must mimic the background vegetation in both the visual and near infra-red parts of the spectrum, as surveillance devices such as Image Intensifiers and low light television can detect contrasts in the near IR.

Thermal Camouflage - Reduction of the human thermal signature is a complex problem. It can be achieved by providing thermally insulating clothing, but this can cause problems with heat stress and discomfort, since the face and hands must also be screened.

An additional approach is to lower the emissivity of the outer materials by applying metallised coatings which also provide the correct visual and near IR properties. Research work is producing interesting solutions to these multi spectral problems.

Selectively permeable materials for chemical protection

Nuclear, Biological and Chemical protective hand and foot wear is currently provided by impermeable rubber gloves and overboots. These can cause skin maceration within a few

hours wear, due to entrapped sweat. A research programme is examining the possibility of providing rubber with selective permeability, which allows perspiration vapour to escape whilst preventing the ingress of toxic chemical warfare agents.

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Woven technical textiles for ballistic protection

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Introduction

All scientific discoveries led the military research results to high modernization limits. Following the path of all scientific achievements a major issue is soldiers total protection, improving survival conditions.

In this respect, one of the textile industry performances is the military protective equipment meant to assure humans normal life conditions during extreme fighting situations.

At research boundaries there are some specific directions such as: strength to ballistic bullets impact and protection in nuclear biological or chemical contaminated field. According to this background the textile research industry takes into account some major requirements:

- physical requirements: durability to prolonged exposure to inclement weather and heavy wear, good tensile and tear strength and abrasion resistance;
- environmental requirements: water repellency, air permeability;
- physiological requirements: low weight, easy to wear, minimum heat stress, air moisture and vapor permeability and comfort;
- battlefield requirements: ballistic protection, flame resistance, resistance to chemical and biological agents, resistance to long range thermal effects of nuclear weapons, good camouflage properties and low noise generation.

Considerations regarding the used yarns for ballistic protection

During the projectile impact with the textile support, specific and complex phenomena take place, phenomena which were not completely explained until now. The ballistic and shell fragment protection is assured by using the woven fabrics with content of yarns characterized through high tenacity, low breaking elongation and a very good capacity of impact energy absorption.

Nowadays, on the market of the ballistic protection equipment are know two types of fibers:

- para–aramide fibers :   Kevlar (Du Pont)
                                     Twaron (AKZO)
                                     Technora (Teijin)
- high tenacity polyethylene fibers : Dyneema (DSM)
                                     Spectra (Allied Signal)

In Table 1 are shown the comparative values of the characteristics determined for different fibers used in manufacturing the ballistic protection equipment.

Table 1. Comparative characteristics for the fibers used in ballistic protection equipment.

Fiber type	Density	Tenacity	Specific modulus	Elongation at break	Sonic velocity
	g/cm3	N/Tex	N/Tex	%	m/s
Polyamide HT	1.14	0.80	5	20.0	2 200
Aramid - ballistic	1.44	2.35	52	3.6	8 200
HP polyethylene	0.97	3.30	101	3.7	10 000

In ballistic protection, the degree and the mechanism of impact energy absorption are very important. For example, the specific modulus and the density determine the velocity of the shock wave propagation into fiber. Moreover, the specific modulus and the sonic velocity in fiber determine the ballistic potential of the textile complex, this becoming more performant as the velocity of sound propagation into fiber is higher.

The capacity of impact energy absorption is determined by the tenacity and elongation of the yarn. It is obvious the fact that this is direct proportional with the two size multiplied. It should be emphasized the fact that woven fabrics with content of para–aramidic or polyethylene yarns are preferred those of polyamide HT, although the capacity of energy absorption is almost similar, because a high breaking elongation determines the increasing of the backface deformation and implicit of the traumatic shock (Figure 1).
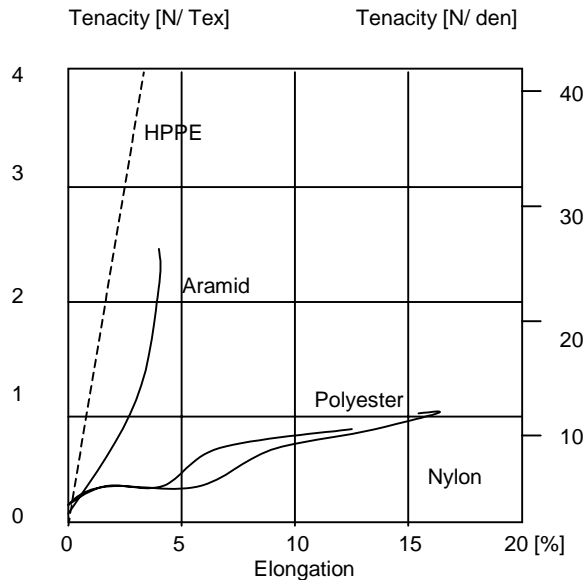
Figure 1. Tenacity vs. elongation for fibers used in ballistic protection.

The studies and researches made until nowadays have shown that approx. 80 % of the dead and the wounded in battle are due to the shell fragments and not to the bullets. For this reason, the military ballistic vests are designed and are tested in order to reduce these looses. For establishing the military ballistic vest performances it is necessary to determine the parameter *ballistic limit velocity*- V_{50}. "The ballistic limit velocity for a material or armour is defined as that velocity for which the probability of penetration of the chosen projectiles is exactly 0.5" (STANAG 2920).

In Figure 2 there are presented the V_{50} values for Kevlar complexes tested according to STANAG 2920 with 9 mm FMJ ammunition.
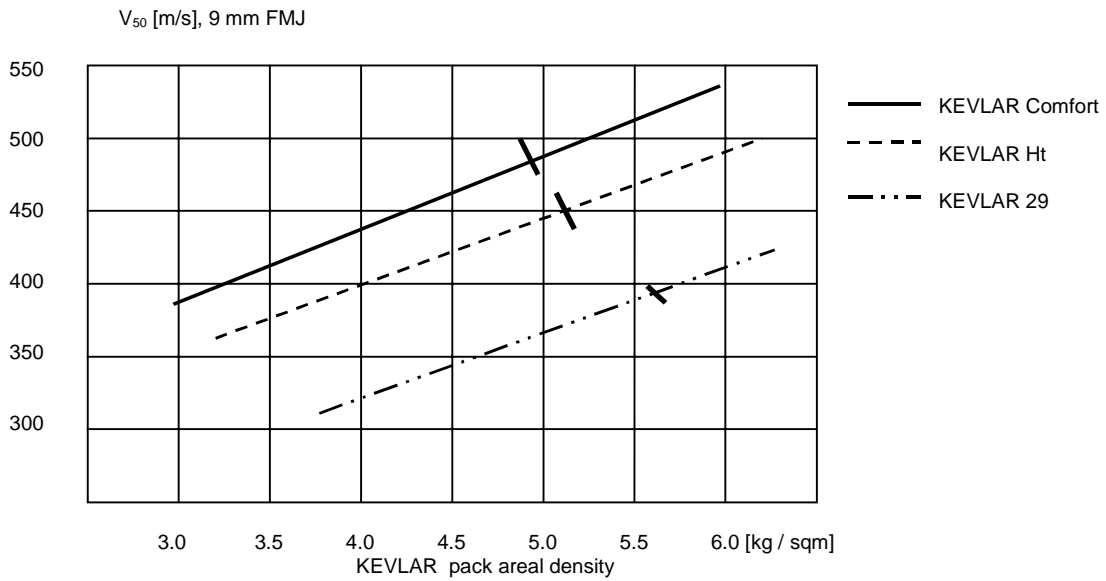
Figure 2. V_{50} vs. pack areal density.

Kevlar Comfort has a 10 % higher ballistic resistance V_{50} compared with Kevlar HT and also, has 35 % higher ballistic resistance V_{50} than Kevlar 29.

The Figure 3 shows V_{50} values for different fabric panels and contrasts the Twaron standard type and Twaron CT (high tenacity) with Twaron CT Microfilament.

In figure 4 there are shown, in comparison, the V_{50} value for HPPE and para–aramidic tested according to STANAG with 1.1 g FSP ammunition.
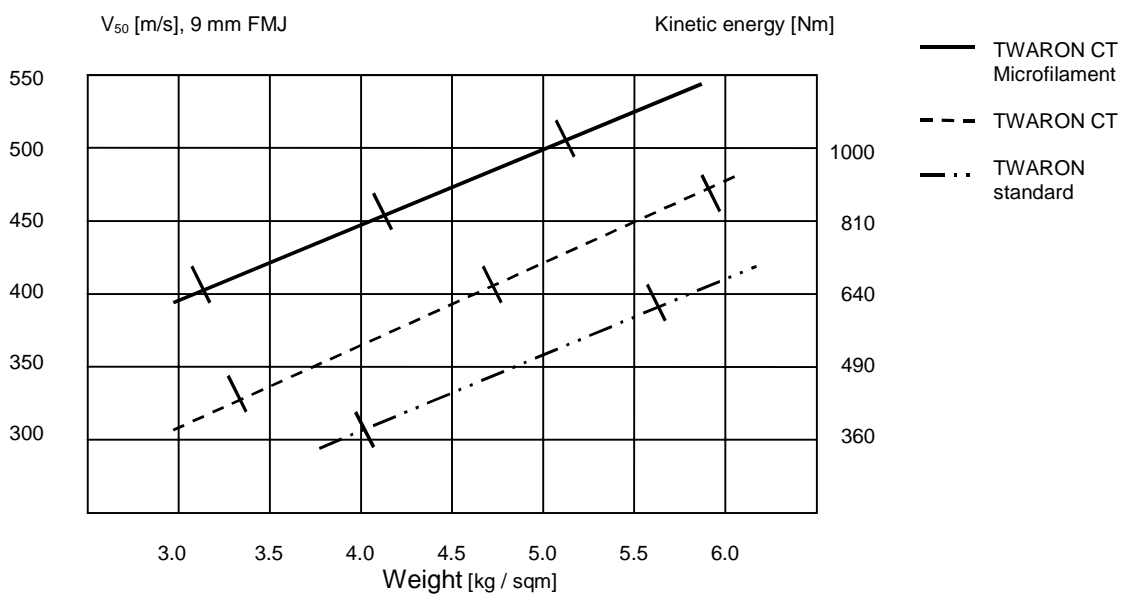
Figure 3. V_{50} and kinetic energy vs. weight. The test has been done according to STANAG 2920 with 9 mm FMJ.
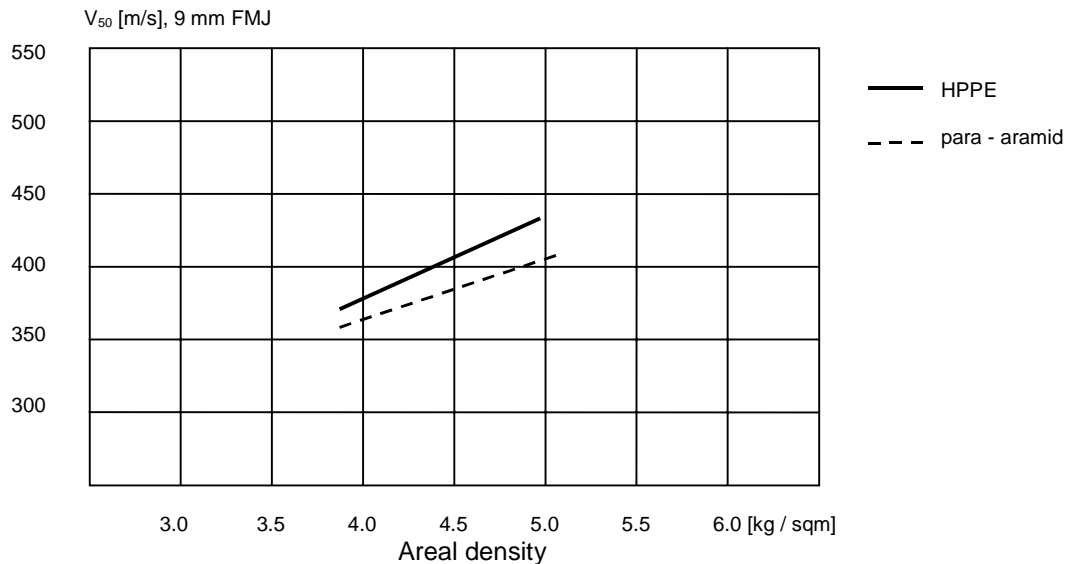
Figure 4. V_{50} values for HPPE and para–aramid.

Own technological experiments for producing ballistic woven fabrics

Taking into account the conditions imposed to ballistic structure, two woven fabrics have been made at The National Research – Development Institute of Textile and Leather, woven fabrics composed of 100 % Kevlar yarn 930 dtex and 220 dtex respectively, whose main characteristics are presented in Table 2.

Table 2. Characteristics of Kevlar yarns used for ballistic woven fabrics.

Characteristics		Symbol	
		VB – 60 – K129	K - 160 - PG
Filament Type		964 C	964 C
Yarn count, warp / weft	dtex	930 / 930	220 / 220
Weight,	g/sqm	216	88
Weave		plain	plain
Tensile strength, warp / weft	daN /5 cm	900 / 900	310 / 310

I have to mention that the woven structure K – 160 PG has been designed according to the requirements imposed in using at the brake parachutes for supersonic airplanes type MIG 29.

The reason of using woven fabric made of 220 dtex yarns, in order to realise armours, had as result the reducing of the weight with about 14 %, assuring at the same time special comfort in normal using conditions.

The two woven fabrics have been tested at Scientific Research Center for N.B.C. Protection Technics from Ministry of National Defence. The ballistic Test Method consisted in sending a projectile to a target (textile support placed in a plastiline block) at 5 meters distance. In these circumstances has been evaluated the diameter of the trauma produced in the plastiline block by deforming the textile suport during the impact.

Ballistic protection for the two supports have been tested according to NIJ 0101.03/87, for the following types of ammunition:

- • 357 Magnum JSP (Jacketed Soft Point);
- 9 X 19 mm FMJ (Full Metal Jacketed).

The results are presented in the Tables 3 and 4.

Table 3. Ballistic performances for VB – 60 – K129 woven fabric.

Ammunition	No. of layers	Weight kg/sqm	Velocity m/s	Strength	Backface deformation mm
9X19 FMJ	18	3.88	360 ± 15	Yes	35
9X19 FMJ				Yes	18
9X19 FMJ				Yes	27
9X19 FMJ				Yes	24
•357 Magnum JSP			400 -425	Yes	25
•357 Magnum JSP				Yes	30
•357 Magnum JSP	17	3.67	400 - 425	Yes	30
•357 Magnum JSP				Yes	30
9X19 FMJ			360 ± 15	Yes	27
9X19 FMJ				Yes	29
9X19 FMJ				Yes	30
9X19 FMJ				Yes	30
9X19 FMJ				Yes	31
9X19 FMJ	16	3.46		No	-

Table 4. Ballistic performances for K – 160 – PG woven fabric.

Ammunition	No. of layers	Weight kg/sqm	Velocity m/s	Strength	Backface deformation mm
9X19 FMJ	34	2.99	360 ± 15	Yes	30
9X19 FMJ				Yes	44
•357 Magnum JSP			400 -425	Yes	50
•357 Magnum JSP				Yes	47
•357 Magnum JSP	32	2.82		Yes	50
9X19 FMJ	28	2.46	360 ± 15	No	-

It can be seen that VB – 60 – K129 woven fabric with 17 layers structure can hold the II Level of ballistic protection, and K – 160 – PG woven fabric with 34 layers can hold the II Level of ballistic protection with backface deformation bigger than 44 mm.

For the VB – 60 – K129 woven fabric has been determined the V_{50} ballistic limit velocity tested according to STANAG with 1.1 g FSP ammunition which is of 570 m/s. The determined V_{50} indicates also a good ballistic resistance to shell fragments.

Conclusions

The construction of the military protective equipment meant to assure humans normal life conditions during extreme fighting situations is one of the textile industry performances.

Taking into account the conditions imposed to ballistic structure, two woven fabrics have been made at The National Research – Development Institute of Textile and Leather, woven fabrics made of 100 % Kevlar yarn 930 dtex and 220 dtex.

The two woven fabrics have been tested at Scientific Research Center for N.B.C. Protection Technics from Ministry of National Defence:

- The 930 dtex woven fabric symbolised VB – 60 – K129 with 17 layers structure can hold the II Level of ballistic protection.
- The 220 dtex woven fabric symbolised K – 160 – PG with 34 layers can hold the II Level of ballistic protection with backface deformation bigger than 44 mm.
- The determined V_{50} for VB – 60 – K129 woven fabric indicates also a good ballistic resistance to shell fragments.

Thermal protective textiles: Correlation between FR properties and static propensity

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Introduction

All clothing is protective to some extent. It is the degree of protection that is important, particularly for those working in hazardous occupations, such as fire fighters, foundry and utility workers. Concern over the health and safety of workers in various industries has stimulated research and development in the area of personal protective clothing. Some of this research was focused on thermal protective clothing, which is designed to extend people's physical and physiological limitations in response to fire and heat exposure. The performance of thermal protective clothing depends on its ability to insulate and to maintain structural integrity when exposed to high heat or flash fires (Raheel et al., 1994). However in certain circumstances, such protective clothing may add to, rather than reduce, the hazard. For example, such clothing may lead to electrostatic discharges (sparks) at low humidities, which can cause explosions in the presence of flammable gases, and lead to the potential for injury and the loss of human life.

In Canada and in some other parts of the world, many industrial workers are required to carry out their duties in very cold and therefore very dry conditions. It has been shown that when worn under such low humidity conditions, clothing made from thermal protective materials, such as aramid or flame-retardant cotton, may generate enough energy during a discharge to ignite a fuel vapour-air mixture (Rizvi et al., 1998).

Ignition of flammable materials due to a human spark is a significant concern in the oil, military, chemical, electronic, and other industries, leading to a considerable amount of research on the charge generation characteristics of various types of textiles used in clothing. Many cases have been documented (Scott, 1981; Crow, 1991) where charges generated on an object reach the level at which the resistance of the air-gap between the object and a conductor at a lower potential breaks down, producing a spark. The most serious effect of an electrostatic discharge (ESD) is its ability to ignite flammable gases, vapours, or powders, resulting in fires and explosions and the possible loss of human life. For example, the average individual walking across a non-conductive floor or sliding off a car seat can generate discharge potentials up to 15 kV at low humidity (Matisoff, 1986; Rizvi et al., 1995). Wilson (1977/78) showed that the minimum ignition energy (MIE) of coal gas and air is 0.03 mJ. The MIE required to ignite methane and air in a closed chamber by a spark between a finger and an earthed electrode has been measured at 1.1 mJ (Tolson, 1980), and as low as 0.5 mJ (Crugnola & Robinson, 1959).

The purpose of this research was to study both the flame resistance (FR) properties and the electrostatic propensity of different thermal protective textile materials, and determine if the electrostatic propensity is influenced by the degree of FR protection. Of a major concern was to determine if an increase in thermal protection could cause an increase in the electrostatic propensity of thermal protective textile materials.

Methods

FR properties were evaluated in terms of char length (mm) and thermal protective performance (kW · s/m^2) following CAN/CGSB 4.2 Method No 27.1, Flame Resistance – Vertical Burning Test, and ASTM Method D 4108 –Test Method for Thermal Protective Performance of Materials on Clothing by Open-Flame Method, respectively.

The electrostatic propensity of the materials was evaluated in terms of surface peak potential (V) and charge decay rate to 10 % of the initial charge (V/s) following a modified method of the UA ESD Test System, which has been described by Gonzalez et al. (In press). The modification to the UA ESD Test System involves the use of a movable specimen holder. At the end of the charging process, the specimen holder is moved under a sensor head connected to a static voltmeter[1], which is then connected to a flatbed recorder[2] and a digital oscilloscope[3]. The oscilloscope is set in roll mode and used in combination with WaveStar® version 2.0 software for data acquisition. Both the voltmeter and recorder are activated immediately after placing specimen under the sensor head to measure and record peak potential and charge decay from the fabric surface.

Thermal stable and FR finished fabrics were tested, including FR cotton, meta-aramid, meta-aramid/carbon, meta-aramid/FR viscose, para-aramid, and para-aramid/PBI (Table 1). Specimens for flammability tests were conditioned according to their respective standard method; those for electrostatic tests were prepared following CAN/CGSB-4.2 Method 15, non-fibrous materials on textiles, and conditioned at 0 % relative humidity (RH) by drying specimens out at 105 °C for an hour, cooling them off inside a dessicator, and then storing the specimens in sealed polyethylene bags until testing.

Table 1. Fabrics used in the experiment.

Code	Fibre Content	Weave	Fabric Count (Yarns/cm)	Fabric Mass (g/m2)
01	FR cotton	Twill	35 x 19	320
02	Meta-aramid	Plain	32 x 30	203
03	Meta-aramid/carbon	Twill	30 x 24	251
04	Meta-aramid/FR viscose	Twill	32 x 21	264
05	Para-aramid	Plain	11 x 11	208
06	Para-aramid/PBI	Plain	32 x 18	182

Using commercially available, SPSS® version 10.0 software, the following statistical analyses were performed, with the level of significance for testing hypothesis set at $p < 0.05$.

1) One-way ANOVA (analysis of variance), to test the null hypothesis (H_{01}) that there was no significant difference in char length, thermal protective performance (TPP), surface peak potential and decay rate among different thermal protective fabrics.
2) Pearson's correlation coefficient, to test the null hypothesis (H_{02}) that there was no significant correlation among char length, TPP, surface peak potential, and charge decay rate.

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[1] Electro-Tech System, Inc. model 105
[2] Cole-Parmer flatbed recorder model 08376 with a millivolt/volt module model 8376-65
[3] Tektronix model TDS 340A

Results and discussion

The null hypothesis H_{01} was rejected; One-way ANOVA found a significant main effect of fabric on all measured variables, indicating that there were significant differences. Duncan's multiple range test results for each dependent variable (Table 2) imply that these parameters measured from different fabrics differ significantly (p <.05) from each other, although there are some homogeneous subsets.

Table 2. Analysis of variance: Char length, TPP, peak potential and charge decay rate.

Fabric	TPP		Char Length		Peak Potential		Decay Rate	
	Mean	S. D.	Mean	S. D.	Mean	S. D.	Mean	S. D.
FR cotton	8.43[a]	0.15	8.20[e]	1.23	2304[c,d]	291.1	0.42[a]	0.11
Para-aramid	10.90[b]	0.18	0.90[a]	0.21	2942[e]	268.9	0.64[a]	0.20
Para-aramid/PBI	11.21[c]	0.29	3.35[b]	0.88	985[b]	186.7	5.21[b]	3.67
Meta-aramid	11.46[c]	0.37	5.44[c]	1.84	2606[d,e]	161.9	0.21[a]	0.11
Aramid/FR viscose	11.96[d]	0.29	6.26[c,d]	1.05	1921[c]	140.6	18.65[c]	5.18
Aramid/carbon	14.34[e]	0.53	6.70[d]	0.79	141[a]	11.5	0.09[a]	0.02

[a,b,etc] In each column, means with the same letter superscript indicate homogeneous subsets (highest and lowest means are no significantly different) when subjected to Duncan's multiple range test (p <.05).

To test the null hypothesis H_{02}, Pearson's correlation analysis was performed between FR and electrostatic parameters (Table 3). Correlations between peak potential and either char length or TPP were significant; thus, the null hypothesis was rejected for these three parameters. Figure 1 graphically shows the relationship between thermal protective performance and the surface peak potential.

Table 3. Correlations (R) between char length and TPP, with peak potential and decay rate.

Parameter	Peak Potential	Decay Rate
Char length	-.300*	.107
TPP	-.613*	.115

[*]Correlation is significant at the .05 level (2-tailed)

Conclusions

The main purpose of this study was to determine whether the electrostatic propensity was affected by the degree of FR protection of thermal protective fabrics. A vertical burning test was used to assess the resistance of a series of fabrics to burning, and the TPP test was used to rate the same textile materials for thermal resistance and insulation. In addition, the amount of surface static charge generated by tribo-electrification and its subsequent dissipation was evaluated by ESD testing. Different properties and characteristics of the fibres such as polymer chemical composition and polymer structure are at work during flammability tests. Surface charge generation depends to a large extent on the nature of the material rubbed and other external factors; while charge dissipation depends on the geometric, dielectric and resistivity conditions of the material and surrounding environment.

Results from this investigation suggest that surface peak potential increases as the thermal protection performance decreases, although these changes occur at different rates. Since both parameters are highly dependent on the polymer structure, it implies that changes in polymer structure for improving FR protection may cause variations in the material's propensity to be tribo-charged.
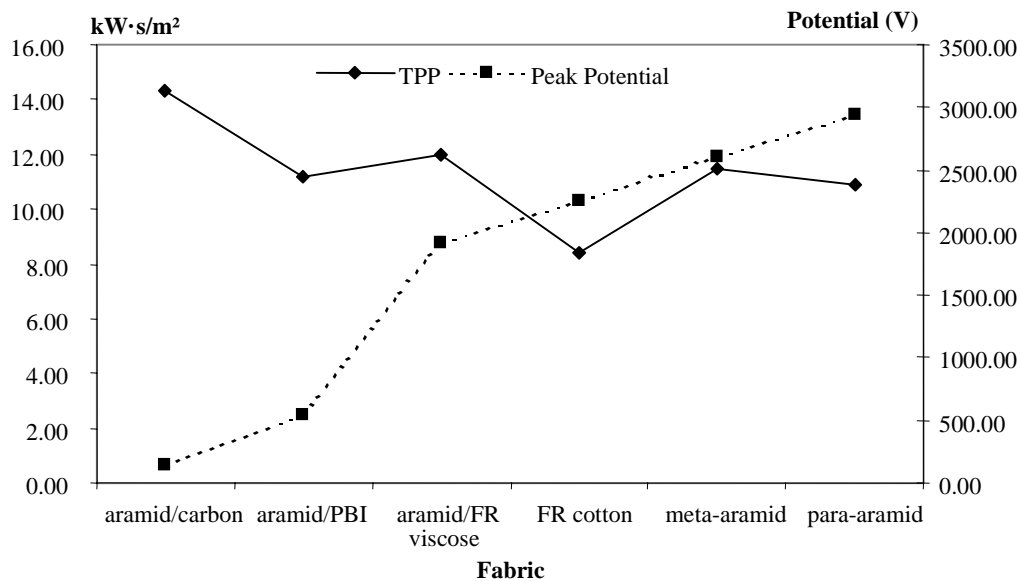
Figure 1. Correlation between thermal protective performance and surface peak potential.

Further work is therefore needed to determine how much influence the polymer's structure has on both thermal protective performance and the generation of static charge.

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Testing and evaluation of electrostatic behaviour of electric inhomogeneous textiles with core-conductive fibers

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Introduction

The energy of electrostatic discharges from charged textile materials can exceed the minimum ignition energy of flammable gas- air atmospheres. To avoid the risk of explosion for persons working in such environments, besides other measurements the textile materials for this aims incorporate conductive components (Holme et al., 1998; IEC 61340-1, 2000).

The test method (EN 1149-1, 1995) for the evaluation of the surface resistance is often not suitable, especially in the case of modern textiles with highly conductive fibers in core –matrix –structure. Materials of this kind are able to dissipate static electricity by several physical mechanisms (Löbel, 1995, 1987; Holdstock, 1996):

- Dissipation by homogeneous conductivity of material components: time constant of the decay is dependent on the surface resistivity
- Dissipation owing to polarisation effects in polymer material: initial decay effect with time constant in the range 10 - 100 ms;
- Induction field and shielding effect of this caused by the presence of highly conductive fibres (metal or carbon) in the fabric: time constant for generation of shielding effects after induction charging is practically zero (range µs … ns) because of the high conductivity of the metal or carbon components;
- Neutralisation of charges by corona discharging from the fibres within the fabric.

All of these mechanisms require a specific test method.

Methods

The STFI developed so called *induction decay-method* (Löbel, 1995, Löbel & Haase, 1995).

This method allows all of the above processes to be observed if they are present in a fabric specimen. The principle of the test method is shown in Figure 1 (see also Holme, 1998; EU-Project No. SMT4-CT96-2079, 2000).

It is based on placing a circular field electrode (diameter 70 mm) directly below an earthed specimen but not in contact with it (distance 4 mm). This electrode delivers a momentary(within 30 µs) 1,2 kV-step from a piezo-electric generator. The resulting electric field induces a quickly initial charge of opposite polarity on the conductive specimen. The test specimen is clamped in a circular, earthed holder (diameter 300 mm). The field screening and decay-effects of the fabric is monitored by circular field-measuring probe (diameter 30 mm) above the sample. The field strength is measured via a two-channel charge amplifier connected to a two-channel high speed recorder (ASTRO-Med Inc. Type DASH IV).
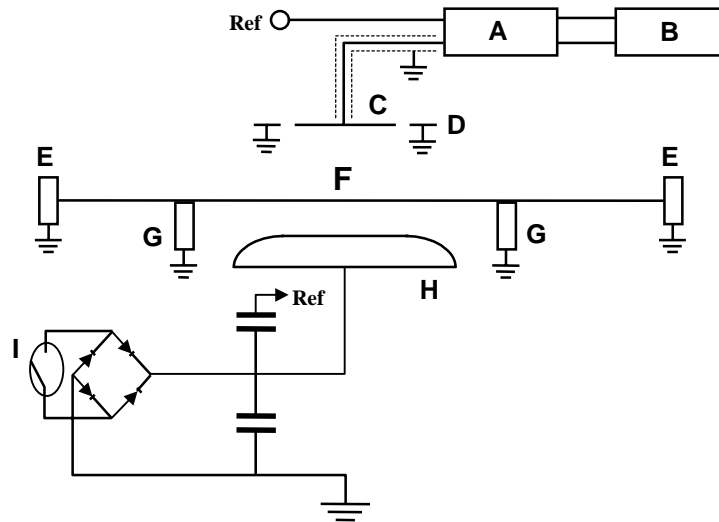
Figure 1. Schematic outline of induction method.
Key:

A Charge amplifier	B Recording device	C Field-measuring probe
D Guard ring	E Specimen clamping ring	F Test specimen
G Support ring	H Field-electrode	I Voltage generator

Results and discussion

The typical charging and charge decay profiles of the different types of material are summarised in Figure 2.
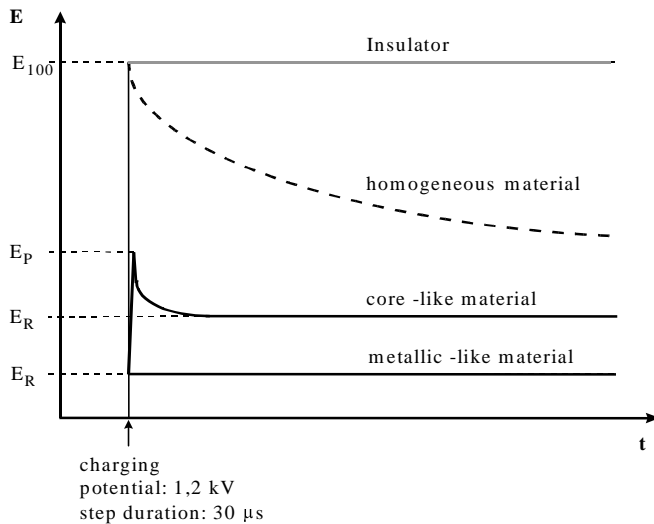
Figure 2. Charge decay profiles of different materials.
Key:

E field signal on the field probe as a function of time

E_{100} initial field signal on the field probe

E_{50} field signal on the field probe after 50 % decay

t time (it be used two time scales: 0,00005s/mm recorder paper; 0,04 s / mm)

t_{50} half decay time, i.e. time to reach E_{50}

R resistance

C capacitance of measuring device (14 pF)

E_{P} field signal on the field probe at maximum of "core peak"

E_{R} field signal on the field probe at minimum of core peak, i.e. where the residual field of the high conductivity component transitions to the second, long decay time component

From the measured decay curves E = E(t) several parameters - besides of the charge decay time -can be evaluated depending of type of the specimen conductivity:
Resistance R for homogeneous materials (long time decay):

$$R = \cdot \frac{t_{50}}{C \cdot \ln \frac{E_{100}}{E_{50}}}$$

Equivalent resistance R_i for inhomogeneous materials with core conductivity (short time decay):

$$R_i = \frac{t}{C \cdot \ln \left[\frac{E_{100} - E_R}{E_P - E_R} \right]}$$

Electrostatic shielding value S:

$$S = 1 - \frac{E_R}{E_{100}}$$

S depends substantially on the distribution and grid density of the conductive fibres within a fabric. When the grid density is high, i.e. the spacing between conductive fibres is small, then $E_R/E_0 \rightarrow 0$ and the value $S \rightarrow 1$.

Table 1 shows typical test results for characteristic specimens (details see EU-Project (2000)).

Table 1. Typical test results for characteristic specimens.

sample	typ	fibre material	high con-ductive material	EN1149-1 spec. surface resistance (Ohm/sq)	Ri short time decay (Ohm)	R long time decay (Ohm/sq)	t_{50} short time decay (s)	t_{50} long time decay (s)	S
PPC17	hom.	CO FR	-	2.1E+12		2.2E+12	-	0.6	-
PPC18	metal	Aramid	1 % steel f.	1.1E+05	<<1.0E+06	>1.0E+13	<0.01	>50	0.61
PPC19	hom.	Aramid/ Visk FR	-	5.6E+12		3.2E+12	-	0.84	-
PPC20	hom.	Aramid	-	>1.0E+13		>1.0E+13	-	>50	-
PPC23	core	Aramid	2 % C-core	>1.0E+13	1.4E+06	>1.0E+13	<0.01	>50	0.86
PPC25	core	Aramid/ Visc FR	3 % C-core	1.5E+12	1.1E+06	1.0E+12	<0.01	0.5	0.91
PPC41	core	PES 5x5 grid	trilobal core fiber	>1.0E+13	1.2E+06	>1.0E+13	<0.01	>10	0.76
PPC42	core	PES 20 mm stripe	trilobal core fiber	>1.0E+13	1.0E+06	>1.0E+13	(<0.01)	>10	0.21
PPC43	core	PES 10x10grid	trilobal core fiber	>1.0E+13	1.0E+06	>1.0E+13	<0.01	>10	0.68
PPC44	core	PES 10 mm stripe	trilobal core fiber	>1.0E+13	1.4E+06	>1.0E+13	<0.01	>10	0.6

The specimens with core conductive fibers have a equivalent resistance in the range of 10^6 Ohm and decay -time <0.01 s. The antistatic quality is good.

Conclusion

For testing antistatic behaviour of electric inhomogeneous textiles with core – high conductive fibers, resistance measurements are unhelpful. Testing must be based on charge/discharge principles. Frictional charging is the most realistic but is difficult to reproduce and does not allow the short-term effects to evaluate. Corona charging likewise does not allow the short-term effects to evaluate. The inductive method generally very good discriminates between samples of all typs of conductivity. Short time effects can be evaluated. The method is involved in preparation of the European Standard EN 1149-3.

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Features of electric arc accidents in Finland 1996-1999

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Introduction

An electric arc is an electric current, which passes from one electrode to another through hot ionised gas. The temperature of an electric arc burning in the air can be 6000 ° – 20000 °C. About half of the energy of an electric arc is consumed by heating the air, the equipment, walls and other structures, as well as ionising the air. Depending on the material of the electrode, 5-20 % of the energy of an electric arc is used for melting and vaporising the electrodes. The rest of the energy mainly evaporates into the environment as radiant heat (Martikainen, 1978).

The amount of energy that is released in an electric arc affects essentially the extent of the damages. Electric arc energy less than 0.5 MJ can be considered harmless, while energy greater than 0.5 MJ is dangerous, and energy greater than 4 MJ causes a great risk of serious bodily injury. The magnitude of electric arc energy is characteristically 0.4-5 MJ in the low voltage range, and 3-120 MJ on high voltage. Burn injuries from an electric arc are mainly caused by the radiant heat and splashes of molten metal. Some of the gases that are formed as combustion products of the electric arc are toxic. The fumes of the vaporised electrode materials are the most dangerous ones of these. The phenomenon includes a loud noise caused by rapid expansion of the air, and a brilliant flash of light, which can cause a temporary eye injury. (Askaner, 1972; Martikainen, 1978; Meyer, 1960; Pälli, 1988)

Nominal voltages below 1000 V are generally called low voltage. Nominal voltages between 1 and 100 kV are referred to as high voltage. In high voltage switchgear, the voltage in an electric arc short-circuit is relatively small compared to the supply voltage. In the low voltage range, electric arc voltage is of the same magnitude as the nominal voltage. (Martikainen, 1978)

In Finland, since 1986, clothing used in work involving a hazard of electric arc, has had to be made of a flame-retardant material. After the European Union directive of personal protective equipment came into in force 1995, all protective clothing used in electrical work must be CE labelled. CENELEC CLC/TC78 is preparing a standard test method for materials and garments used in work entailing risk from exposure to an electric arc. (Centre of electrical inspection, 1986; CLC/TC 78, 2000)

The aim of this study is to investigate the characteristics of electric arc accidents that have happened to electricians, in order to obtain information on the present risk level. We examined the type of electrical equipment, electric arc current, as well as the clothing worn by the workers, damage of the clothing, and the seriousness of the workers' injuries.

Methods

The study material consisted of electric arc accidents that occurred to electricians in Finland from 1996 to June 1999. Two official registers were used to collect the informa-

tion on the accidents. Only occupational accidents were included in the study. In 1996-1999, 40 electric arc accidents had been recorded. Altogether 171 electrical accidents have been reported to the Safety Technology Authority of Finland during the same period.

We contacted the employers of electric arc accident victims and asked whether they would like to participate in the study. We interviewed of 25 electric arc accident victims or employers' safety delegates using a questionnaire. The purpose of the interviews was to find out features of the electrical installations involved in the accidents, as well as the type of the clothing and damage to the clothing that was worn by the electricians in the accident situation. We also recorded the seriousness of their injuries.

The damage to the clothing was evaluated by dividing them into three categories.

1. Minor damage: There was no visible damage at all; or fabric became sooty; it was dotted by splashes of molten metal; or it become brittle after laundering
2. Moderate damage :   The fabric hardened but did not break open, got small holes from splashes of molten metal
3. Significant damage: The fabric melted, burned or hardened and broke open in the accident

Results

Electrical equipment

In several cases, the electric arc was ignited when a tool touched live parts. Some accidents occurred when a peeled or a broken cable touched live parts. Other reasons for the ignition of an electric arc were faulty equipment, installation or operation. Over two-thirds of the electric arc accidents took place in low voltage installations. On the average, the duration of the electric arc was estimated to be 0.5 s. The short-circuit current varied from 0.1 to 50 kA.

In 11 accidents, the branch of activity was the production or distribution of energy. Eight of the interviewed electricians worked in electrical installation enterprises. Accidents occurred also in the forest industry, the metal industry, shipbuilding, and several other branches. Every third accident happened to a subcontractor's employee.

Burn injuries

Third degree burn injuries were at least 2.5 times as common in high voltage accidents as in low voltage accidents. Third degree burn injuries occurred in at least 43 % of the high voltage electric arc accidents. In the low voltage accidents, 11 % of the accident victims got third degree burns. About three-quarters of the victims got burn injuries on their hands. Nearly every second accident caused facial damage.

Half of the interviewed electricians had worn flame-retardant protective clothing when the accident took place. Unexpectedly, the seriousness of the burn injuries was not directly connected to flame retardancy of the clothing material. Instead, the seriousness of the injuries correlated to the damage to the clothing. The clothing was significantly damaged in 75 % of the cases in which the victims got third degree burn. When the injuries were first or second degree burns, the clothing was only slightly damaged in 50 % of the cases (Figure 1).
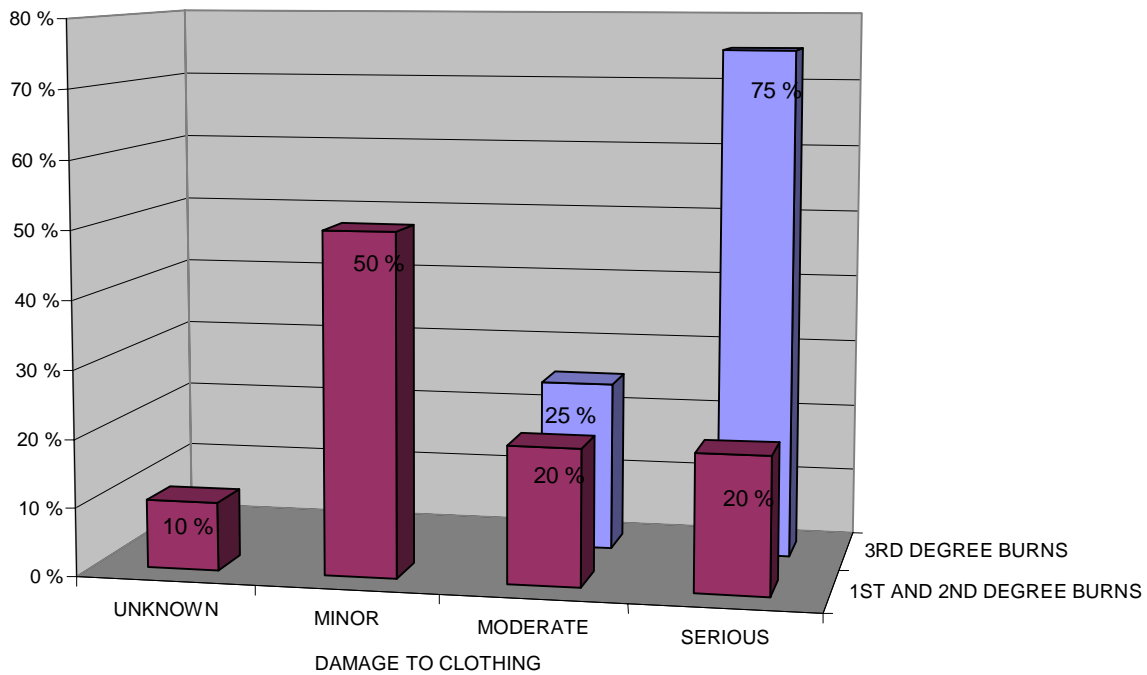
Figure 1. Damage to the clothing and burn injuries in electric arc accidents.

In most low voltage accidents, the damage to the clothing was minor, while in high voltage accidents the clothing got severe damage in 50 % of the cases. Both flame-retardant and untreated garments had damages in all three categories.

Discussion

The material of this study might consist of accidents that are more serious than the average. The Safety Technology Authority of Finland estimates that a large percentage of electric arc accidents, as well as many other accidents, remains unreported. However, serious accidents are always investigated and reported.

The injuries caused by an electric arc were more serious when they took place in high voltage installations, than they were in low voltage installations. The circumstances varied greatly in the studied accidents. When the energy of an electric arc is high enough, the clothing is destroyed regardless of its material, and serious burn injuries are caused.

In the CENELEC draft, a 400 V supply voltage, 0.5 s duration time for an electric arc is and 4 and 7 kA currents are given as test parameters for electric arc testing of flame-retardant clothing. These parameters are in line with our observations, and represent average real life electric arc accidents reasonably well.

Half of the interviewed electricians used flame-retardant protective clothing. One third used other work clothing and the rest wore regular clothing. The work was often carried out in the immediate proximity of live electric parts without following live working procedures. A tool falling on or touching live parts was a typical cause of igniting of an electric arc. Using appropriate tools could diminish the accident hazard. Many of the accidents happened to very experienced workers.

Conclusions

Most of the investigated electric arc accidents took place in low voltage installations, while accidents in high voltage installations were more serious. Third degree burns were at least 2.5 times as common in high voltage accidents as in low voltage accidents. The damage to the clothing was directly proportional to the seriousness of the injuries. Because the circumstances of the accidents varied greatly, both flame-retardant and untreated clothing were damaged to diverse degrees.

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Electric arc testing with heat flux measurement for FR clothing materials

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Introduction

Protective clothing used in work involving a hazard of electric arc should be CE-labelled in accordance with the European Union directive on personal protective equipment. As of yet, there is no harmonised standard, which would explain the requirements of the directive. CENELEC CLC/TC 78 is preparing a standard test method for materials and garments used in electrical work. Various European countries have had their own methods for electric arc testing, and research work on the workers' exposure to electric arc, and testing of clothing materials have been carried out for example at Manitoba University, Canada, and by AMYS, Spain. (King et al., 1988 and 1992; AMYS 1998)

   The aim of this study was to perform electric arc testing of flame-retardant fabrics, utilising two different test methods. In addition, the rise in temperature underneath the fabric sample was recorded. We evaluated the thermal performance of the fabrics by calculating the heat flux through the samples, and compared it to the Stoll curve (Stoll, Chianta, 1969). We also assessed the relation of the changes in the materials to the heat flux peak value.

Material and method

The test methods used were based on the Swedish EBR test and the CENELEC draft test. The test equipment was constructed according to these test method instructions, respectively (CLC/TC 78, 2000; EBR, 1997). With the EBR method, we used 11 and 13-kA test currents. We performed the tests with the CENELEC method using mostly 4-kA current. In the CENELEC method, the use of a plaster testbox intensifies the effect of the electric arc, and thus a lower test current can be used. For each test, we combined a temperature measurement modified from the IEC standard proposal test method A, arrangement of two-sensor panels (IEC/ TC78, 1999). There were two calorimeters on a test panel, each consisting of four K-type thermoelements connected to a thin copper plate. In addition to this, there were two thermistors on each test panel. An IR detector was used to obtain a measurement of the fabric's surface temperature. Total heat flux from the electric arc was measured by exposing the temperature- measuring equipment to an electric arc without any fabric between the sensor panel and the ignition source.

   The tested samples consisted of single and double layer fabrics. The outer layer was always flame-retardant (FR). The single layer test samples include cotton (CO), cotton and polyester blends (CO/PES) and aramid (AR). We tested two different weight classes of each material type. The outer layer fabrics of two layer samples were FR cotton, FR polyester (PES), and a cotton and polyester blend (Tables 1 and 2).

Table 1. Tested single layer materials.

Material no.	Composition	Construction	Weight (g/m²)	Thickness (mm)	Test
1	FR 100% CO	Satin	320	0.68	CENELEC, EBR
2	FR 100% CO	Twill	175	0.43	CENELEC
3	FR 75% CO, 25 % PES	Twill	340	0.72	CENELEC
4	FR 70% CO, 30 % PES	Twill	240	0.44	CENELEC
5	100% AR	Twill	260	0.51	CENELEC
6	100% AR	Twill	165	0.39	EBR

Table 2. Tested double layer materials.

Material no.	Composition	Construction	Weight (g/m²)	Thickness (mm)	Test
7	Outer: FR 100% CO	Twill	175	0.43	CENELEC
	Under: FR 100% CO	Plain	180	0.42	
8	Outer: FR 100% PES	Twill	230	0.51	CENELEC
	Under: FR 100% CO	Plain	190	0.41	
9	Outer: FR 100% CO	Satin	320	0.68	CENELEC
	Under: 100% CO	Plain	180	0.42	
10	Outer: FR 75% CO, 25 % PES	Twill	340	0.72	CENELEC
	Under: 100% CO	Plain	180	0.42	

When tested with the CENELEC method, the fabrics were conditioned for at last 24 h in an atmosphere with a temperature of 20 ± 2 °C and relative humidity 65 ± 5 %. The samples used in the EBR test were not conditioned. No prewashing was done. All tests were conducted outdoors under a shelter. The ambient temperature was about 10 °C when the tests with the EBR method were performed. When testing with the CENELEC method, the temperature was around 0 °C. At the beginning of each test, the calorimeters were approximately at ambient temperature.

Results

The total heat flux from the electric arc was measured without a fabric sample. The total heat flux was 265 kW/m² in the EBR test and 261 kW/m² in the CENELEC test. All the tested single-layer fabrics would pass class 1 in the CENELEC test, which, according to the test criteria, does not allow holes greater than 5 mm in any direction. The maximum heat flux value of the Stoll curve is 50 kW/m²; exceeding this value indicates the onset of a second-degree burn injury. The maximum heat flux value for material 1 in CENELEC test was 71 kW/m². For material 2, the maximum heat flux was 97 kW/m². With the EBR method, the maximum heat flux for material 1 was 49 kW/m². Comparing these results indicates a second-degree burn injury would occur in the two former cases but not in the last. However, charring of the fabric was more severe in the test sample tested by the EBR method. Maximum value of heat flux for material 3 was 55 kW/m² and for material 4, it was 77 kW/m².

The maximum heat flux value in the EBR test for material 6 was 73 kW/m². The maximum heat flux value in CENELEC test for material 5 was 53 kW/m². The difference in the results is mainly due to the different weight of the fabrics. Surprisingly, the typical colour change of aramid fabrics was significantly slighter in the samples tested with the CENELEC method.

The heat flux for double layer fabrics 7, 8, 9 and 10 was below the Stoll curve. The peak value of the heat flux greatly depended on the weight of the fabric. The heavier the

fabric, the lower was the heat flux peak value measured. Even sample 8 with a 100 % polyester outer layer, which melted completely from the exposed area, conformed to this pattern.

HEAT FLUX (kW/m2)
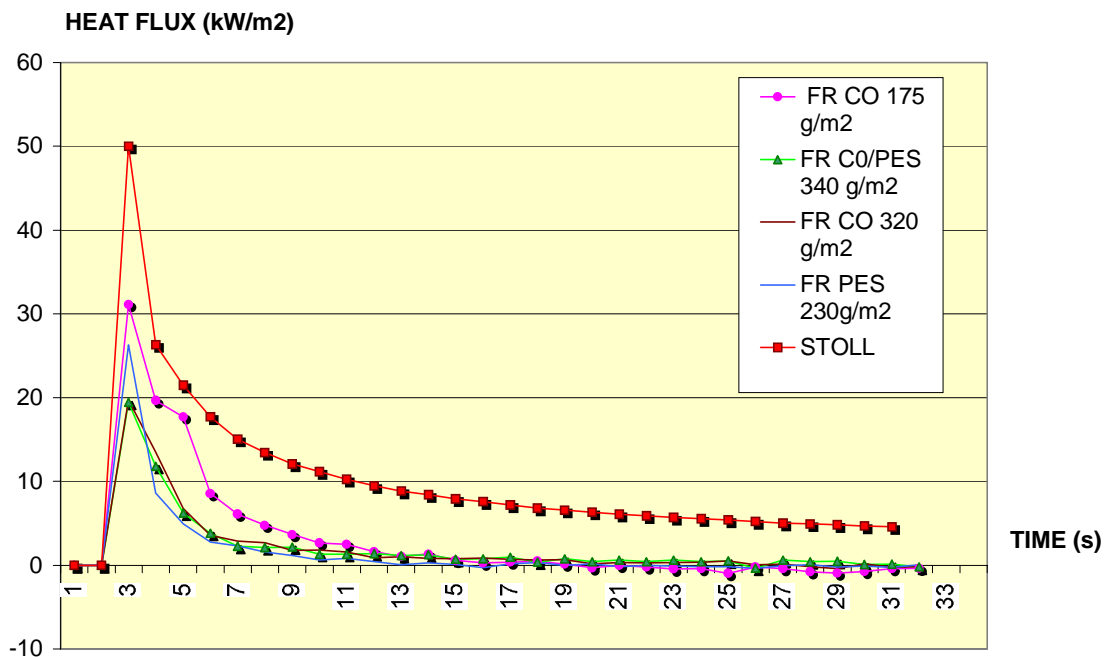
Figure 1. Heat flux curves for two-layer fabric combinations.

Discussion

The formation of holes in the outer material seems to have a relatively minor effect on the actual heat flux through a test sample consisting of two FR fabric layers. However, the heat flux through a fabric could in some cases be significant even when the fabric is unbroken. This is the case particularly with lightweight FR fabrics. This suggests that the integrity of the fabric alone would not be a sufficient criterion for deciding which materials should be recommended for the protective clothing of electricians.

Because the total heat flux values of the two test methods are in a very limited range compared to the inherent variation in an electric arc, we concluded that it is relevant to compare the results of the tests performed with these methods and test currents. In the CENELEC test, the colour of test samples turned dull and muted compared to samples tested with the EBR test, and compared to garments that have been worn in an actual electric arc accident. It is possible that some plasterdust gets comes from the testbox. Together with the vapours from electrode materials which condense on the surface of the fabric, the dust forms a layer that may reduce the material changes in this test.

All testing was performed in ambient temperature and humidity conditions, which makes it difficult to compare the results to tests performed at some other temperature. However, the results are valid for material comparisons.

Burning was observed in the test-box in virtually every test performed. Presumably the molten electrode material had ignited the plaster, because holes were visible in the test-boxes. The burning times in the box varied from less than second to a few seconds. The energy, which is released in the burning process in the testbox, is probably negligible compared to the energy of an electric arc. While its influence can be observed in the heat flux curve, its effect on the test result remains negligible.

Conclusions

We performed electric arc testing on flame-retardant fabrics. In the CENELEC method, the use of a plaster testbox intensifies the effect of the electric arc. We found that the 4-kA CENELEC test and 11-kA EBR test are comparable in terms of total heat flux. However, the fabric changes in the CENELEC test were lesser, while the heat flux values were higher for samples of the same material. All single-layer samples of the presented selection of FR fabrics pass class 1 (4-kA) according to the CENELEC method test criteria. The heat flux for each combination sample was below the Stoll curve. The thicker and heavier the fabric combination, the lower was the heat flux peak value observed.

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Needs for research for protective clothing standards

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Introduction

After the adoption of the New Approach and Directive 89/686/EEC for Personal Protective Devices (PPE) CEN committees prepare about 300 standards or draft standards. This work has been done in a very short time period and the quality of the standards has not been always good. There has been no time enough to conduct necessary pre- or co-normative research on the working conditions where the use of special protective clothing is needed. The validation of the standardized test methods has not been possible and numerous interlaboratory tests should be done and new better methods developed.

Research needs for protective clothing standards

Research on the foreseeable use conditions

The basis for the standardization of special work clothing is the knowledge about the foreseeable use conditions, about the risks against which the clothing shall give protection as well as the physiological and environmental factors. Based on this clarification, it is evaluated, which essential safety and health requirements of the directive are relevant and should be taken into account in the drafting of the standard.

Unfortunately in many cases the requirements for the clothing are given on the basis of the existing products on the market, not on the basis of a carefully conducted risk analysis.

The requirements for the clothing should be based on reliable data produced by research. There are many good research reports, but unfortunately these are not always taken into account.

The standards specify normally several protection levels. The relationship of these protection levels and the existing risk levels are difficult or even impossible to understand. The number of performance levels should relate to the different risk levels in foreseeable conditions of use. In many standards the existing products are classified, not the risk levels. Due to the uncertainty of the measurements, the classes may overlap.

A systematic procedure in the drafting of a standard shall be followed. The first step shall be reliable data, which can only be produced by the research.

Ergonomic requirements

The first part of the essential safety and health requirements contains mainly requirements related to the ergonomic properties of the devices. There are only few test methods, which can be used when the conformity of the product with the directive is assessed.

The human tolerance values against different kind of mechanical, physiological and physical and chemical threats are not available. For instance protective clothing used in

various sport activities are mostly protecting against mechanical impacts or abrasion towards different part of the body. A general database for these limit values is missing and such data shall be produced.

The test methods try normally to simulate the accident situation. All different possible cases can not be simulated. A reliable test method giving clear pass/fail limit should be given for each requirement. A global horizontal harmonization of the methods is needed. The prerequisite for this harmonization is the research on suitable and reliable test methods and validation of those by interlaboratory testing and research co-operation

The overall uncertainty of the measurements is found to be big. During the standardization process, all major sources of the uncertainty should be identified and pre- and co-normative research is needed during the whole drafting period.

Optimum level of protection

The Directive 89/686/EEC requires that PPE be designed to provide the highest possible level of protection. The "highest possible level" is explained in other clauses of Annex II of the directive.

It is required that the protection level be only so high that the wearer can use the equipment in foreseeable conditions of use without excessive discomfort or stress. The aim is to get the maximum benefit from the use of PPE taking into account its protection efficiency and wearer acceptance.

The standards are prepared considering this basic principle and present technological possibilities. The problem is that this optimum level is very difficult to specify when only few research results are available from the real use situations. The realistic practical performance test shall be created on the basis of the field studies. For the time being the practical performance tests are only existing possibility to assess the different properties connected to the ergonomics or usability of the clothing.

Chemical safety

The horizontal question, how to specify the requirements for the chemical safety of the materials used in the design of the clothing, is still open. The risk determination of various chemicals, which may come into contact with the skin of the user, is expensive and time consuming. Possibilities for a better practical solution should be clarified.

Conclusions

Research to support the standardization work is needed. When the existing standards are revised, the work shall be based on more reliable data on work conditions, physiological and other relevant factors. The main problem is that the same persons who are responsible for the standardization work are also busy with certification or testing of the protective clothing. The compulsory interlaboratory tests shall also be done. The time for the basic and applied research needed is normally not existing. The situation can be improved through increased co-operation of the research institutes. There should be also more financial support.

A new structure of Ergonomic Standards for PPE – Proposal from Kommission Arbeitsschutz und Normung – KAN (Commission for Occupational Health and Safety and Standardization)

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Introduction

Ergonomic aspects are important for good product design for personal protective equip-ment (PPE), because PPE - which is designed to protect people – is in close contact with the body. It is therefore important that PPE does not affect the comfort of the user or his physical abilities more then is absolutely necessary. PPE should be for example not to heavy and should reduce as little as possible the mobility and dexterity of the user.

The European Directive 89/686/EEC demands, in its safety and health requirements, the ergonomic design of PPE. But at the moment, the harmonised European Standards for PPE do not reflect ergonomic aspects sufficiently. It is important to note that it is generally difficult to specify ergonomic parameters and suitable test methods in PPE standardization because it is not easy to establish objective ergonomic requirements.

One important step towards solving this problem was the establishment of a joint working group within the European Technical Committee for Ergonomics (CEN/TC 122 JWG 9). The joint proposal from KAN (Commission for Occupational Health and Safety and Standardization in Germany) and the German standards committee for Ergonomics within DIN for a new structure of ergonomics standardization might be a next step.

The legal situation in Europe: product requirements versus requirements concerning the health and safety at the workplace

Directives based on Article 95 are mainly concerned with the free movement of products in the European Union or the European Economic Area. The target group includes manu-facturers, distributors, public authorities and notified bodies. Such directives normally contain basic health and safety requirements with respect to the products, regulations on conformity assessment, testing and certification and regulations on market surveillance. The aim of the directives is total harmonisation. Therefor the directives must be trans-ferred into national law by the member states without any changes.

Because the "essential health and safety requirements" in the Directives are kept quite general, the European Commission intends to supplement these requirements with har-monised European Standards. Although the use of harmonised European Standards is not obligatory for the manufacturer it bears great advantages. When the manufacturer applies these standards, it will be presumed that his products are in conformity with the essential health and safety requirements of the Directives. Therefore, harmonised European Standards play an important role in the harmonisation concept of the European

Commission. Product standards developed under these product related directives may contain fixed requirements and limit values if those are considered necessary.

Directives based on Article 137 are aimed at the improvement of the safety and health of workers at work. The target group of these Directives includes employers, employees and supervising authorities. The Directives contain company regulations and regulations with respect to the workplace and the work environment. They contain minimum requirements, and the Member States are obliged to transfer at least these minimum requirements into national law. But the member states are free to define completing and more stringent provisions in their national law. Harmonised standards are not intended to further specify the requirements of these Directives. But they might be helpful to define terminology or measuring procedures.

In no case should these standards contain requirements or limit values, because these might conflict with national legal requirements.

The new concept of ergonomic standards

The concept takes the legal situation into account and will lead to a hierarchical structure of ergonomic standards and thus to more clarity. This is positive for the users of the standards as well as for the experts developing ergonomic standards. In addition, the concept will help to avoid the development of standards conflicting with existing national legal regulations on health and safety at the work place.

The new concept certainly wants to influence the structure of future standards. This does not mean however, that existing standards now have to be replaced by new standards in conformity with the new concept. If the concept is generally accepted, it is advisable to adapt the existing standards during their periodical revisions.

Many of the existing CEN and ISO standards in ergonomics are already now fitting into the new concept just as if they were designed accordingly. In many cases, this adoption could merely consist in adding a few new headlines and rearranging the existing contents under these new headlines.

The concept envisages three levels of standards (Table 1). There is the first level of basic standards the second level of generic standards and the third level of product standards. This concept is to a certain degree comparable with the CEN standardization concept under the Machinery Directive.

Table 1. Proposed concept for ergonomics standards

Type of standard	Content	
	Product requirements (Art. 95)	*Design of the working environment (Art. 137)*
Basic **(B)**	Principles and methods to describe human factors	
Generic **(G)**	Product groups **(GP)**	Work systems **(GW)**
Product **(P)**	Integration of data from B and GP in specific product standards	

Basic standards

Basic standards (B) should contain principles and methods to describe human factors such as

- terminology

- human characteristics (e.g. anthropometric data, human forces, stress/strain)
- measuring and evaluation
- general design principles for standards on ergonomics.

This means that basic standards should describe principles and methods independent of the design of products or work. An example for a basic standard is prEN 979 "Basic list of definitions of human body dimensions for technical design". The document provides a basic list of anthropometric measurements for use in the establishment of common comparative definitions of population groups.

Generic standards

The generic standards (G) must be divided into two groups:

- Those standards dealing with product groups (P) and
- those standards dealing with work systems (W).

In *generic standards for product groups* those parts of the basic standards which are relevant for the product group under consideration are used. These standards may contain quantitative and qualitative ergonomic requirements, they can deal with measuring and test methods and they could contain guides for the application of generic product standards. In many cases it would be useful if basic data described in basic standards was repeated in these generic standards for product groups.
   Typical examples for generic product standards are the standards developed in CEN/TC 122 JWG 9 for the field of personal protective equipment (PPE):

– WI "Personal Protective Equipment - Ergonomic principles - Part 3: Biomechanical characteristics"
– WI "Personal Protective Equipment - Ergonomic principles - Part 4: Thermal characteristics",
– WI "Personal Protective Equipment - Ergonomic principles - Part 6: Sensory factors".

Generic Product standards on special ergonomic aspects, for example PPE-related data on problems such as "sweating" or "skin contact" do not yet exist. Therefore, TC 159 "Hearing protection" itself specified the ergonomic requirements in product standards. On the basis of the new concept, we would suggest to standardize these data in a generic standard.

Generic standards for work systems should contain those elements from the basic standards, which are relevant for the work system under consideration. The standards should contain qualitative design information for work systems without setting limits. This is very important since work systems usually describe the situation at the workplace, which is regulated by national law. Generic standards for work systems may also include a description of measuring methods, which can be used in the different cases. For the special field of PPE, there are no standards.

Product standards

Product standards of the third level should not be developed in Technical Committees dealing with ergonomics. Usually, these product standards are developed in TCs, which are specialised in the technical field the product belongs to. Ergonomic data from Basic standards and generic product standards should be integrated in specific product standards. But at that point it is extremely important that the experts in ergonomics contribute

to the development of product standards by offering generic product group standards to other Technical Committees. It does not make much sense if for example an expert group standardizing earth moving machines develops at the same time detailed ergonomic requirements for this type of machinery. This should be done by experts of ergonomics on the level of generic product standards. The standards organisations play an important role by informing the different Technical Committees about the existence of generic product standards containing details on ergonomics.

Examples for product standards are:

– EN 340 "Protective Clothing – General requirements". EN 340 specifies general requirements for protective clothing such as ergonomics, the size system and marking. But at the moment, there are some problems concerning the quantification of ergonomic parameters. Ergonomic requirements are specified in the form of recommendation. It has shown in practice that specifying ergonomic parameters objectively is generally extremely difficult.
– EN 420 "General requirements for gloves" specifies design principles and requirements concerning the possible effects of protective materials on the skin (ph value, chromium(VI) content) and comfort (size, water vapour permeability). The requirements concerning the possible effects of protective materials on the skin should be standardized in a generic product standard, too.

In the field of article 137 of the EC Treaty, no product standards are developed.

Conclusion

The proposed concept would not mean that existing PPE standards have to be pressed into a bureaucratic pattern. It is much rather intended to consider the structure during the revision of standards. The existing PPE standards are to a large extent already in conformity with the proposed structure.

KAN sees a need for the documents of CEN/TC 122 JWG 9 to be completed. These mostly belong to the group of generic product standards. What is also needed is the development of guidelines for PPE TCs on how to use generic product standards when drafting product standards.

When ergonomic aspects of a general nature are already specified at the level of PPE product standards, these aspects should be included in GP standards if not partly in basic standards. This would make these aspects available to standardizers when drafting other PPE product standards.

What should furthermore be done is check, during the revision of a standard, whether an adaptation of the product standard to the requirements of the relevant GP standard is necessary.

For this kind of work, close cooperation between the PPE TCs and CEN/TC 122 JWG 9 is necessary.

Main non-conformities of protective clothing detected in the Spanish market

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Introduction

The European Directive 89/686/EEC lays down the obligation for each Member State to survey that the PPE placed in its market comply with the provisions of the Directive, specially that they do not endanger the health and safety of people when used for its intended purpose. In Spain, the Ministry of Industry, in order to effectively fulfil this obligation, and in the exercise of the competence conferred on him by the Spanish legislation, has been carrying out since 1994 annual campaigns for the surveillance of PPE in the Spanish Market, with the collaboration of the Centro Nacional de Medios de Protección, centre of the Spanish National Institute for Occupational Safety and Health specialised on PPE. These control campaigns have reached through all these years a wide variety of PPE, including protective clothing (comprising clothing and gloves) against mechanical, thermal, chemical and electrical hazards.

Methodology

In the course of each annual campaign a number of commercial premises (in most cases specialised shops and superstores) distributed all around Spain were visited. Among the models of PPE available in each store a certain number of them were randomly selected and purchased. For each selected model, the number of purchased units depended on the checks to be carried out to that type of PPE. These checks consisted basically of:

- ❑ Existence and correctness of the CE marking.
- ❑ Existence and completeness, in accordance with Annex II, art. 1.4 of the PPE Directive, of the instructions for use provided with the equipment. A great importance was attached to this point since the safety of a PPE can only be assessed in relation to its intended use according to the manufacturer's instructions.
- ❑ Compliance with the most representative health and safety requirements, verified by testing in accordance with the applicable European harmonised standards.

Table 1. Distribution of the inspected models depending on the type of clothing.

Mec. and therm. gloves	Thermal clothing	Chemical gloves	Chemical clothing	Electrical gloves
55 %	13 %	18 %	4 %	10 %

Table 2. Distribution of the inspected models depending on the origin.

Spain	Other EU countries	Other countries	Unknown origin
42 %	33 %	7 %	18 %

In the 6 campaigns already concluded 136 different models of protective clothing have been inspected, implying the purchase and testing of around 600 units. Tables 1 and 2

show the distribution of these 136 models depending on the type of protective clothing and on the origin of the manufacturer (not necessarily coincident with the country where the equipment is manufactured). The great majority of the models coming from non-EU countries and those of unknown origin (most of them later known to come from third countries) were purchased in superstores, where they are usually commercialised.

Results

In the first campaign, in 1994, the protective clothing presented a very high level of non-compliance with the Directive. This situation improved continuously and at a good rate till 1997, and then the level of compliance became stabilised. Two clearly different periods may therefore be considered, 1994-96 and 1997-99, with the following results:
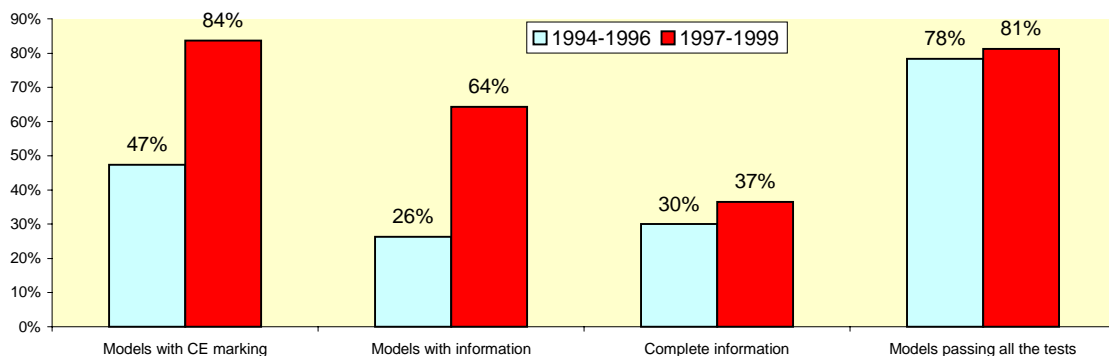
Figure 1. Protective clothing: levels of compliance with the requirements of the PPE Directive.

The rate of complete information is referred to the number of models with instructions. For the detailed analysis of the results that follows, and in order to simplify and make it easier to draw conclusions, we will start from the following considerations:

- ❑ Three large groups of protective clothing will be considered: gloves and clothing against mechanical and thermal hazards, gloves and clothing against chemical hazards, and electrical insulating gloves. The reason for this is the homogeneity observed in each of these groups as regards the type and rate of non-conformities.
- ❑ Only the results obtained in the period 1997-1999 are presented and analysed, since these are the results that reflect the present situation of the protective clothing.
- ❑ For the analysis of the results according to the origin of the models, two large groups are considered: the EU models and the rest of the models. The reason is the similarity of the results offered by the models coming from Spain and from the rest of the EU, and the difference with the results offered by the other ones.

Protective clothing against mechanical and thermal hazards

As shown in Figure 2, the main detected problem relates to the manufacturer's instruction for use: a considerable percentage of the models did not bring any instructions at all or these were incomplete. The most frequently missing information are the levels of protection and limits of use (in fact the most important information for a safe use of the product), followed by the information about the manufacturer and the certifying body, and the significance of the markings affixed on the equipment. This lack of information about the levels of protection implied that in many cases only the minimal levels of performance laid down in the standards (usually easy to pass) were verified. This fact may

have helped for the very high rate of compliance with the tests obtained, mainly in the case of the non-EU models where the said information was very often missing.
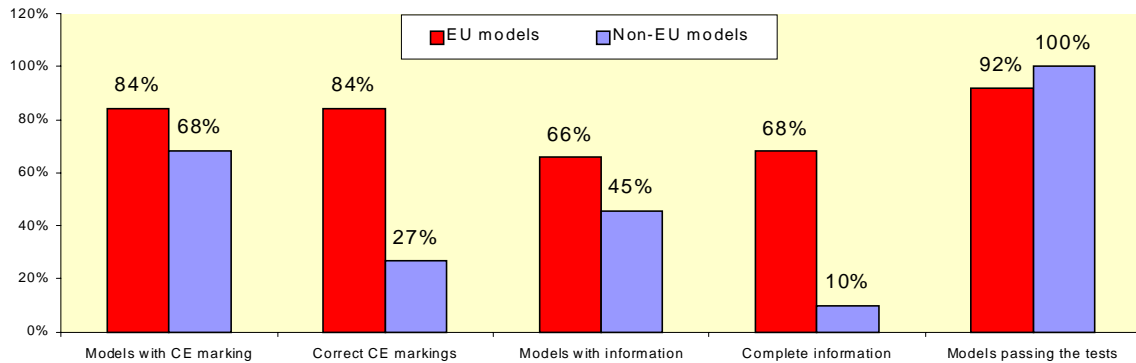
Figure 2. Results for the models of protective clothing against mechanical and thermal hazards.

As regards the CE marking, the most common defect is the affixing of the two digits of the year and the number of the certifying body, and this is partly due to the amendments of the Directive in relation to the marking. Finally, it is necessary to highlight the difference between the results of the EU and non-EU models, much worse for the latter.

Protective clothing against chemical hazards
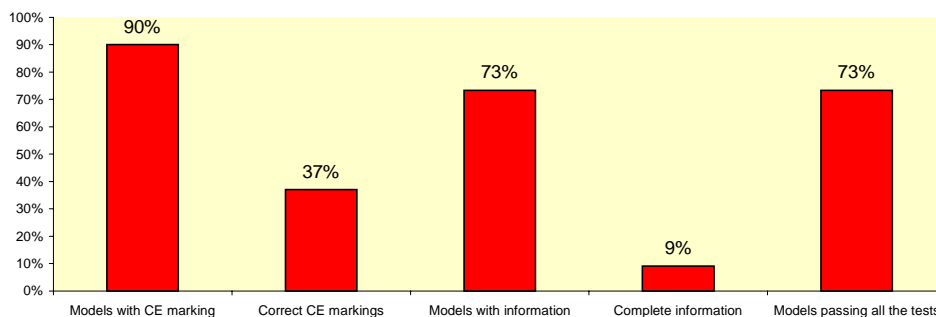
Figure 3. Results for the models of protective clothing against chemical hazards.

Practically all the inspected models come from the EU. As shown in Figure 3, important levels of non-compliance have been detected for the 3 verified aspects of the Directive:

CE marking: It is rather a question of classification of the chemical gloves as PPE of category 2 or 3, what implies different CE marking. While some EU countries, including Spain, interpret the Directive so that chemical gloves (except those of category 1 for protection against minimal risks) belong all to category 3, other EU countries consider that they may be included either in category 2 or 3.

Information: We have on the one hand equipment that only bring an address or a telephone number where to obtain information and on the other equipment with incomplete instructions for use. The most often missing information are again the levels of protection and limits of use (mainly the resistance to permeation of chemicals), followed by the information about the manufacturer and certifying body, the obsolescence, and the cleaning and servicing instructions.

Tests: The tests presenting the highest rate of failure are the permeation test and the jet test (only for type 3 clothing). In the permeation test according to EN 374-3 (which not always could be carried out due to the lack of information) differences of up to 5 levels were detected between the results obtained and the values indicated in the manufacturer's instructions. As regards the jet test according to EN 463, the different interpretation about the incidence angle of the jet may lead the equipment to pass or fail the test.

Electrical insulating gloves
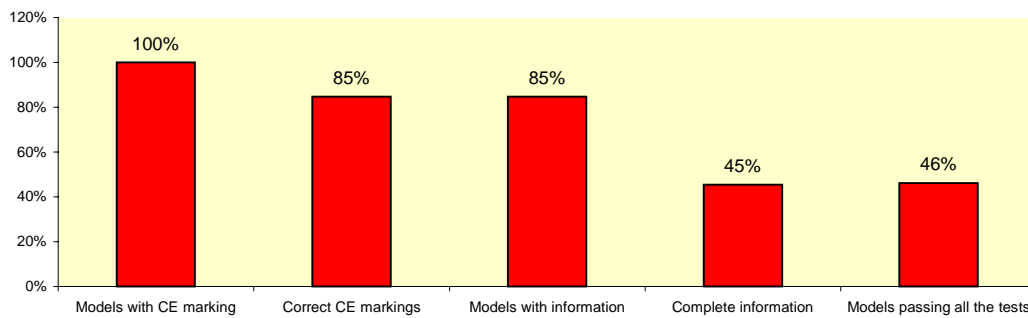
Figure 4. Results for the models of electrical insulating gloves.

All the inspected models come from the EU. It is worrying the high percentage of models failing some of the tests, in all cases electrical tests (proof and withstanding voltage tests according to EN 60903). Another general problem, not shown in the graph, is the absence of the additional marking requested for this PPE in the Directive (annex II, art. 3.8), and the bad quality of the marking (60 % of the models failed the durability test of EN 60903).

Conclusions

- The evolution of the results along the successive campaigns proves the effectiveness of this type of market surveillance, especially when we take into account that the inspections insisted on the equipment and tests which offered the worst results in previous campaigns
- The present levels of non-compliance make it advisable the maintenance of the surveillance intensity with the aim of protecting the users and preventing unfair competition. It should be increased the control of the equipment coming from third countries usually commercialised in superstores.
- It is necessary a better control of the manufacturing process by the manufacturers, so as to ensure the homogeneity of production and the conformity with the certified type. Furthermore, it is surprising that the level of non-compliance with the tests for the whole of the PPE is similar in the case of PPE of category 2 and 3, despite the fact that the latter are required to undergo a periodic quality control by a Notified Body. This result questions to what extent this requirement is being fulfilled and, when that is the case, if that external control is being effective.
- The different European forums devoted to PPE, such as the Standing Committee 89/392, the ADCO Group, the Co-ordination of Notified Bodies, etc., must act quickly to solve the problems of interpretation of the Directive and the harmonised standards detected in the market surveillance, which create confusion among the different parties involved: manufacturers, distributors, users, etc.

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Directive 89/686/CEE *on the approximation of the laws of the Member States relating to personal protective equipment (PPE), and its amendments.*

Evaluating the cutting resistance of protective clothing materials

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Basic principles of a cut test method

To cut through a material, it is necessary to slide a cutting component or cutting probe (blade, knife), applying a given force to cross the material. The higher the force necessary to cut through the material, the higher the cut resistance will be. To determine the cut resistance level, the first criterion is that the cutting probe should have a controlled quality so that the results obtained with different cutting probes are reproducible. The second criterion is that the test apparatus be reliable and produce a constant normal force throughout the test at the point of contact of the cutting probe with the sample material. It is also necessary to have a valid test procedure that allows cutting probe sharpness to be controlled.

Forces involved in a cutting test

Most standardized cutting test methods use a blade (circular or straight blade) that slides on the sample materials to be cut through, when a given force is applied. The following forces are present in a cutting process: a normal force F_N, which is applied at the blade-material point of contact; a frictional force F_F, which develops when the blade slides and penetrates the material; the resultant cutting force F_R, which is the resultant vector of F_N and F_F.

Figure 1. Example of forces involved in a cutting process.

Figure 1a represents the case of a material where the coefficient of friction F_F is much higher than F_N, which is typical of some rubber materials. Figure 1b represents the case of a material for which F_N is higher than F_F, which is typical for knitted fiber materials such as Spectra® and Kevlar®. The magnitude of these forces, which differ from material to material, are important when selecting the right test method for evaluating the cut resistance of protective materials.

Some of the test methods included in the standards (ASTM, 1997; ISO13997, 1998; EN 388, 1994) will be presented here.

Cutting test method EN 388

The test method described in EN 388 uses a round blade that has a diameter of 45 mm. The test apparatus described in EN 388 standard consists of a pivoting arm fixed at one extremity through a pivot to the motor. At the other extremity of the arm, the blade is attached at the bottom, with the weight installed directly on the blade. A weight of 5 N is used for the cutting test. At the bottom is the straight sample holder, 90 mm in length with 5 slots, each 5 mm wide. The blade slides into the slots on the material, driven by a motor describing simultaneously an alternative horizontal movement and rotating in the direction opposite its movement. The sample material is fixed on a conductive material. When the blade comes in contact with the conductive material, the test stops and a counter indicates the number of cycles the blade has made to achieve cut-through. A cotton reference material is used to control blade sharpness. A test is performed on the control material before and after a test on the sample material. Thus, the test sequence is repeated five times. The material's cut resistance is determined by the following equation:

$$i_n = \frac{(\overline{C}_n - T_n)}{\overline{C}_n}$$

where i_n is the index for a given test sequence; $\overline{C}_n$ is the average value for the number of blade cycles for the cotton reference material measured before and after the test on the sample material; and T_n represents the number of blade cycles for the sample material.

This test method works well for materials having a low cut resistance level. However, for high cut resistant materials, significant blade sharpness degradation is observed. The results presented in Table 1 are a typical example of this.

Table 1. Cutting test results for Spectra glove material.

Blade	C_n	T_n	C_n
2	0.8	50 (without cut)	25.5
"	25.5	50-200 (without cut)	24.4
"	27.3	200-400 (without cut)	27.2
"	27.2	400-558	28.1

These results represent a test performed with a Spectra glove where cut-through was obtained after 558 cycles. After 50 cycles without cut-through, the test was stopped and the blade sharpness was verified with the cotton control material. Initially, the number of cycles on the control material was 0.8 cycles, whereas after the test on the sample material, the test on the control material was 25.5 cycles. This result demonstrated that blade sharpness degrades before material cut-through. Standard EN 388 specifies that when the number of cycles on the control material tested after testing the sample material is higher than 3, the blade should be replaced with a new one. The test was continued in spite of the fact that blade sharpness had already degraded. Blade sharpness was verified with the control material after 200 and 400 cycles without cut-through and the results show no significant changes after the blade degradation detected after 50 cycles.

Advantages: Easy to use, Compact
Disadvantages: Limited to materials of low cut resistance and without abrasive surfaces

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Load vs distance concept

At the end of the 1980's, a new concept to evaluate the cut resistance of fabrics was developed. It considers the relationship between the load applied to the material-blade point of contact and the blade displacement needed to cut through the material. The basic principle for a test apparatus complying with this concept is that the normal force applied should remain constant throughout the test and that the blade displacement to cut through the material should be measured precisely (Lara et al., 1996). In the study, blade degradation was characterized. Figure 2 shows the effect on blade edge sharpness of repetitive tests on a Neoprene sample material. For example, a new blade cuts through the material at approximately 2 mm when a normal force of 3.92 N is applied. Under the same experimental conditions, its takes approximately 15 mm after reusing the blade for 40 tests and 23 mm after 70 tests. Figure 2 shows how blade edge degradation increases regularly with the number of tests. For this reason, it is recommended that a new blade be used for each cutting test. Furthermore, a procedure to control blade sharpness using Neoprene 1.57 mm thick from Fairprene was proposed.
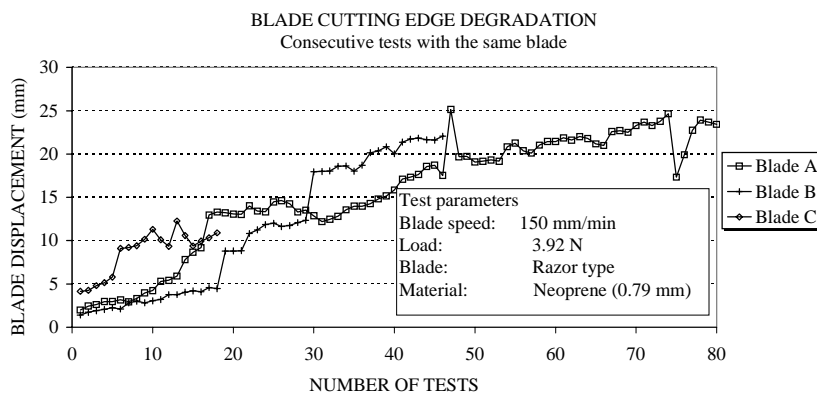
Figure 2. Consecutive tests performed with blades A (80 tests), B (46 tests) and C (18 tests).

In the same study, a procedure to perform the cutting tests was developed. It considers using a straight blade 70 mm long[4], and testing a material with at least three different loads, with five tests at each load. Typical curve results are presented in Figure 3. The higher the load applied, the lower the blade displacement will be to cut through the material. A conductive material is placed directly under the tested material. When cut-through is achieved, the blade comes in contact with the conductive material and the test automatically stops. The blade displacement is precisely measured with an LVDT to 0.1 mm.
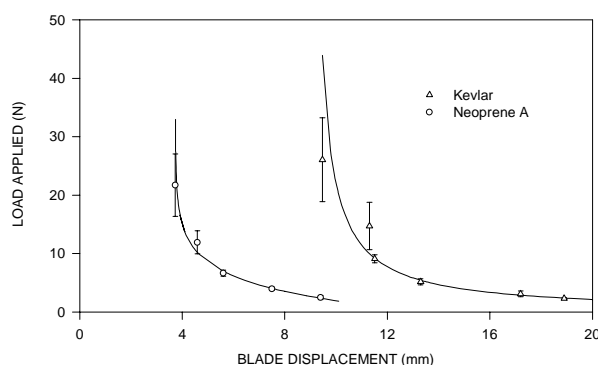
Figure 3. Typical results obtained with cutting test prototype using the load vs distance concept with Neoprene and Kevlar materials.

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[4] American Safety Razor Company, Stauton, VA 24402-0500, model number 88-0121

The curves presented in Figure 3 show that a decreasing exponential relationship exists between the load applied and the blade distance to cut through the material. This type of curve is typical for each material and is used to determine the cut resistance level.

ASTM F 1790 cutting test method

Figure 4a is a schematic representation of the ASTM cutting test method. It consists of a motor-driven balance arm holding the blade, which moves vertically with a sinusoidal speed. The force is applied normally to the blade at the blade-material contact point. Weights installed on the platen on the horizontal arm result in twice the normal force applied on the blade before a test (static mode). This is due to the 2:1 ratio of the arms, as illustrated in the figure. However, when the blade moves down (dynamic mode), the frictional force developed when the blade slides and penetrates the material pushes the mechanism down, which results in an increased cutting force equal to $\vec{F}_N + \vec{F}_F$. For the same reason, when the blade goes up, the cutting resultant force is $\vec{F}_N - \vec{F}_F$, which results in a lower cut resistance value. The higher the frictional coefficient, the higher the error will be in the cutting results obtained with this test apparatus.

The use of this test apparatus is limited to materials with very low frictional coefficients and no thicker than 3 mm. Before performing a test, the equilibrium of the test apparatus should be verified. This equilibrium is quite difficult to verify.

a)   **b)**
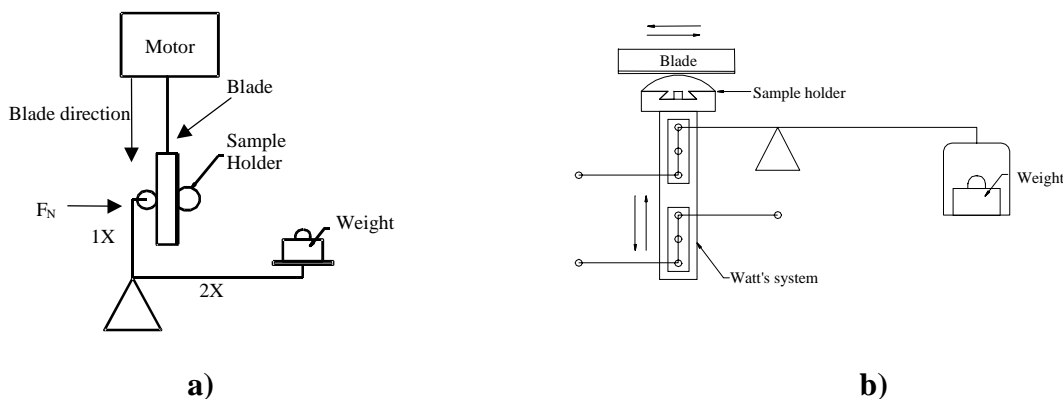
Figure 4. Schematic representation of ASTM F 1790 (a) and ISO 13997 Cut Test Methods (b)

ISO 13997 cutting test method

Figure 4b is a schematic representation of the cut test apparatus in standard ISO 13997. In this test method, the blade slides horizontally at a controlled rate. The force at the material-blade point of contact is applied normally to the blade through a double Watt's mechanism. This mechanism ensures that the sample holder has a precise vertical movement. As shown in Figure 4b, the arm lengths have a ratio of 2:1 so that the weight installed on the platen results in twice the normal force applied directly on the sample holder. This test apparatus is sensitive to 0.02 N, is easy to operate, and the equilibrium of its mechanism is easy to establish before a cutting test. The particular Watt's mechanism used on this apparatus ensures that equilibrium is reached even if the level arm is not in a perfect horizontal position. It also ensures that materials up to 20 mm thick can be tested without introducing errors into the test results. Furthermore, the mechanism used eliminates the problems caused by frictional forces. Details on the design of the test apparatus were recently published (Massé et al., 1997).

Table 3. Main differences between ISO 13997 and ASTM F 1790 cutting test methods.

ISO 13997	ASTM F 1790
Normal force constant	Normal force variable and a function of the material's coefficient of friction
Blade speed constant	Blade speed sinusoidal
Cut resistance calculated at 20 mm blade displacement	Cut resistance calculated at 25 mm blade displacement
Sample installation: the sample is placed on the double phase tape in direct contact with the conductive material	Sample installation: the sample is placed on the double phase tape. The blade should cut through the sample material and the double phase tape to contact the conductive material
Correction for blade sharpness as follows: $C = 20/l$ (l is the cutting stroke on neoprene at 5 N)	Correction for blade sharpness as follows: $C = 25/l$ (l is cutting stroke on neoprene at 400 g)

Because of the differences in the test apparatus and procedures, the results obtained with the ISO 13997 and ASTM F 1790 cutting test methods cannot be compared. Differences between the results obtained with both test methods are smaller for materials with negligible coefficients of friction, and significant differences are expected for materials with high coefficients of friction.

Conclusions

The load vs distance concept is emerging as the more valuable approach for measuring cut resistance. It is important that the normal force applied between the blade and the material to cut-through remain constant throughout the test. The use of instruments where this basic principle is not respected will result in erroneous results and incorrect information about material cut resistance. Furthermore, this incorrect information could affect the development of new and better-performing materials.

Progress in the development of a test method to evaluate material cut resistance has been slow because of the complexity of the cutting phenomenon. The development of test methods based on the load vs distance concept have open possibilities for developing knowledge on the breaking mechanism by using instrumented apparatus to measure the forces developed during cut-through. A better understanding of the contribution of these forces will be helpful in the development of improved materials with higher cut resistance.

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Testing materials against small hot metal drops - Development of a new test method

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Finnish Institute of Occupational Health

Introduction

There is a diversity of conditions in which splashes of molten metal may come into contact with garments used by welders.

The current test method for determining the behaviour of materials on impact of small splashes of molten metal is presented in EN 348:1992. This method measures the insulation of the material when drops weighing 0.50 g fall on the same point at a velocity of 20 drops per minute. A steel rod is melted in the flame of an oxyacetylene welding torch, and the molten drops are guided through a funnel made of polytetrafluoroethylene onto the fabric attached to a sensor support block. The number of drops required to raise the temperature of the sensor by 40 K is measured (EN 348:1992). The method is quite complicated because of many variables which are difficult to adjust and calibrate. Factors related to the formation of a molten metal drop are difficult to control, as are the heat transfer phenomena occurring during drop travel, and its subsequent collision with the test specimen. The large spread in the results obtained from three separate interlaboratory trials indicated that there is a need to develop this test method further. Also individual laboratories experience difficulties in reproducing their results.

The aim is this paper is to describe the development process of a new method with better accuracy. The method should give satisfactory repeatability between different laboratories, and give still a realistic view of the protection performance of the material used for welders' protective clothing or gloves. The method should be based on the measurement of parameters which can be calibrated and are traceable.

Method

Different types of alternative test methods were sought and the problem was simplified to trying to find methods with clear measurable parameters. Already during the interlaboratory trials according to EN 348, some laboratories were looking for an alternative test method. The following test methods were considered:

1. Contact heat test method in accordance with EN 702 (EN 702:1994)
2. Repeated short contact.
   In this method the number of hot contacts, contact-heat element (900 °), needed to raise the temperature by 20 Kelvin was counted under the sample.
3. Hot ball test method
3.1 One hot ball.
   In this method a hot steel ball is projected at a point on a horizontally placed test specimen, and the time needed for a 40 °C temperature rise is measured. Changes, e.g. holes, adhering of the drop to the fabric, ignition, are recorded.

3.2 Several balls.

In this method several hot balls are heated by induction and dropped protected on the sample as in EN 348. The number of balls which raise the temperature under the sample to 40 Kelvin is counted.

4. Field trials

Parallel with the material tests described above, garments, made of the same fabrics as tested in the laboratories, were given for field trial in a shipyard. The welders evaluated the properties of the garments by filling out a questionnaire on insulation against small splashes, the adhering of the drops in the folds of the fabric or on the fabric, ignition of the fabric. The results of field trials were compared with the inter-laboratory test results according to EN 348 and to alternative test methods.

Seven different materials were used for testing. Table 1 summarizes the fabrics used for different interlaboratory trials. The garments for the field trials were made of fabrics 1, 2 and 4.

Repeatability and reproducibility was calculated in accordance with ISO 5725-2 (ISO 5725-2:1994).

Table 1. Materials for interlaboratory trials.

Sample	Material	Thickness (mm)	Weight (g/m²)
1	Pyrovatex 100 % CO, satin	1.17	470
2	CO/PES, 2/2 twill	0.70	380
3a	Proban 100 % CO, twill	0.78	360
3b	100% Aramid	0.70	265
4	Proban 100 % CO, satin	0.71	330
5	100 % CO	0.74	310
6	FR 100 % CO	1.06	440

Results

The results of the hot ball test method correlated well with the results of the EN 348 method, and also with the welders' experiences of the fabrics in normal use (Table 2).

Table 2. Protection against welding drops.

Method	Fabric 1	Fabric 2	Fabric 4
Impact of molten drops (EN 348)	18-36 (27.4)	11-21 (15.3)	11-22 (16.8)
Repeated hot contacts	13.3	16.9	15.7
Hot ball test (time measured)	13.1 s	5.7 s	6.5 s
Welders' subjective experiences:			
1) Insulation	2.33 new	1 new	1.67 new
	2.43 used	2 used	2.3 used
2) Nonadherence	3 new	1 new	2.67 new
	2.43 used	1.83 used	2.43 used

3=good, 2=moderate, 1= poor

Prototype 1

In June 1998 after three interlaboratory trials with EN 348, and after considering alternative test methods, the decision was made in CEN TC 162/WG 2 to build the test apparatus in one laboratory and to circulate it to other laboratories.

The equipment was based on suitable parts of the current EN 348. It consisted of:

- A funnel, made of heat-insulating material which directs a steel ball onto the specimen; the drop guide according to EN 348 was used
- An oven as a heat source, capable of maintaining the steel ball at a temperature of 900±20 °C. The ball was heated in an oven in a cone. When the temperature of the steel ball was 750±20 °C it was guided onto the sample from the cone.
- A steel ball weighing 0.5 g with diameter of 4.2 mm
- A timer, capable of measuring the elapsed time

Results were obtained from seven laboratories. The variation between the laboratories was considerable. There was also variation within one laboratory. This was anticipated. The testing needs many manual operations and practising is necessary in order to perform the tests successfully. On the other hand, the results from some of the laboratories were very similar. Figures 1 and 2 show the repeatability (r) and reproducibility (R) for materials 1, 2 and 5. For material 3b r was 3.56, and R 18.2 of the results of all laboratories. For the results of selected laboratories, r was 2.28, and R 1.49. For material no 4, r was 6.41 and 1.62, and R 18.05 and 3.05, respectively.

Prototype 2

The reasons for the great variation in the results were analysed, and the improvements tested at the FIOH. Some parts of the equipment were modified by FIOH and distributed to voluntary laboratories in 1999 with new samples and work instructions, including a video presentation. The modified parts were the cone, the sensor, the sensor support block, the solenoid with an electrical switch, and the lowest part of the drop guide. The tested materials were nos. 1, 2 and 5 from the previous trial, and also tighter FR cotton material (no. 6, in Table 1).

The repeatability and reproducibility with the second prototype apparatus are shown in Figures 1 and 2 for materials 1, 2 and 5. For material 6, r was 1.6 and R was 2.97.
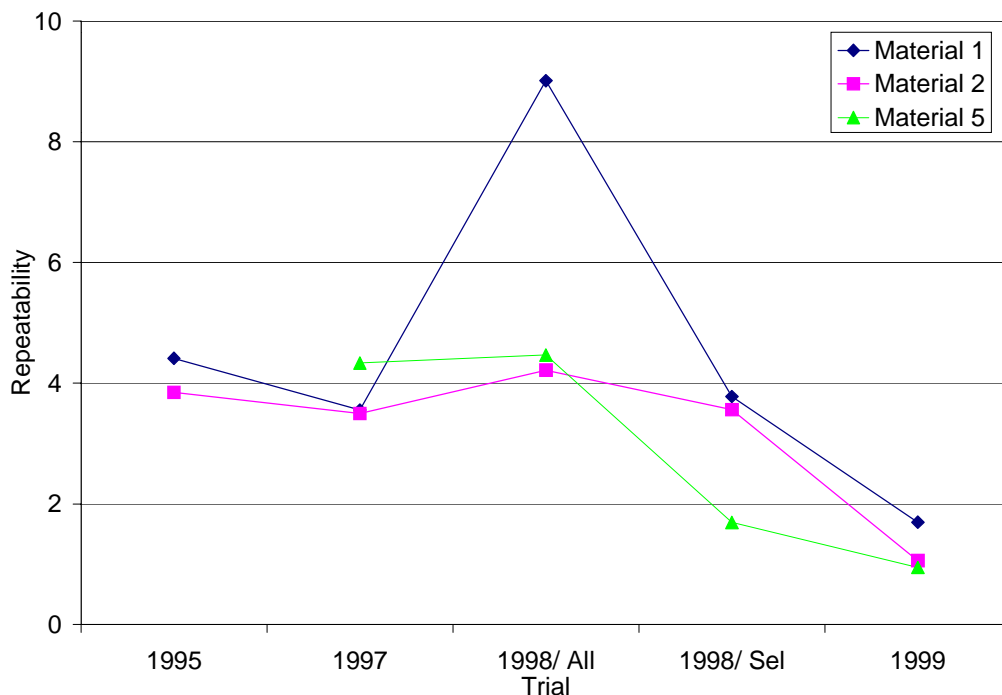
Figure 1. The development of repeatability.
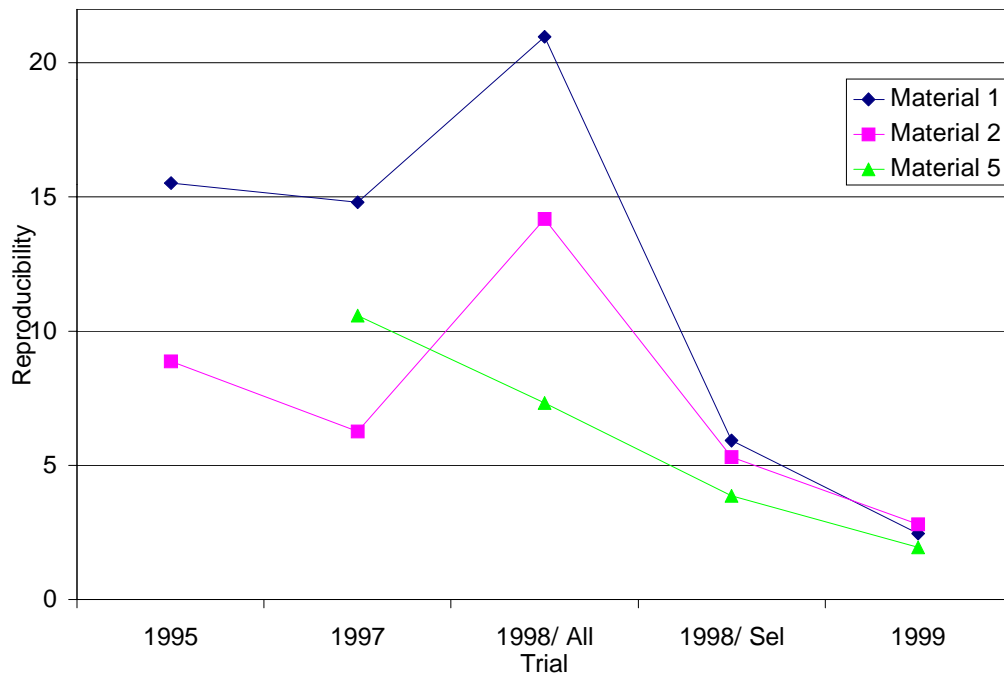
Figure 2. The development of reproducibility.

Figures 1 and 2 show that the repeatability and reproducibility of the test results from the first trial with EN 348 in 1995 to the trial with the second prototype hot ball test method in 1999 have improved remarkably.

Conclusion

The proposed method is based on normal parameters which are easy to trace and calibrate, i.e. temperature and time. Until now, only very traditional fabrics used for welders' garments are tested. Tests with additional fabrics used for welders' clothing and gloves (leather, Kevlar knit and new CO and viscose blend fabrics with aramid and other new fibres) are going on to see how this method screens out different types of fabrics.

Totally 12 European laboratories have participated in the trials in some phases (four labs to all trials) The work has been conducted in laboratories as additional work without any supporting money. The laboratories have only paid for the basic material and the construction work cost of the new equipment for the co-ordinating laboratory. This shows that testing houses really want to find ways to carry out the tests in a reliable and reproducible manner. This also shows that the development is a long process.

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Revision of test methods: Better screening of PPE materials against liquid pesticides

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Introduction

Use of appropriate Personal Protective Equipment (PPE) is recommended while handling pesticides. Currently three test methods are proposed or used as national/international standards to measure repellency, penetration and/or retention properties of PPE materials against liquid pesticide formulations. A previous study indicated that the three test methods used to measure performance of textile materials against liquid pesticides produced significantly different results (Shaw et al., 1999). These variations are primarily due to the differences in approach in the development of the test methods. The gutter test (EN 368) was developed to measure fabric performance against splashes or accidental liquid spillage. The atomizer method (BBA –3-3/2 German guideline) was designed to measure the performance of textile materials against atomized liquid pesticide typically used for field spraying. Whereas, the pipette method (proposed ASTM method) was designed to measure the performance of textile materials against known volumes of liquid pesticides (concentrate and field strength). The objective of this study was to revise the three test methods such that the results reported were a true indication of the performance of textile materials against liquid pesticides applied under various exposure conditions in agriculture.

Methods

Atrazine (46 % a.i., flowable liquid) diluted to 0.23 % a.i. was used for all three test methods. Physical characteristics of the six fabrics are given in Table 1.

Table 1. Physical characteristics of the fabrics

Code	Fiber Content	Fabric weight (g/m^2)	Fabric construction	Yarn count (yarns/cm)	Water repellency (range 0-6)	Comments
A	polyethylene	72	nonwoven*	NA	3	nonporous material
B	cotton	277	twill weave	44 x 23	6	fluorochemical finish
C	polypropylene	61	nonwoven	NA	3	Proshield 1®
D	cotton/polyester	245	twill weave	40 x 25	0.5	
E	cotton/polyester	248	twill weave	41 x 26	0	Fabric D washed
F	cotton	127	plain weave	56 x 28	0	---

Note: *nonwoven with polyethylene film laminated to the face of the fabric (Tyvek®QC)

Gutter test

The gutter test was modified to allow additional contact time between the pesticide and test specimen. This was achieved by changing the angle of the incline and/or the rate and pressure at which the pesticide was applied. Based on the preliminary test results, three modifications (45º, 10 mL in 10 sec. was used for the previous study) were selected:

1. 45º incline, 10 mL applied in 2 min 50 s as drip (high incline, low rate and thus no pressure)
2. 10º incline, 10 mL applied in 10 s (low incline, high rate and thus with pressure)
3. 10º incline, 10 mL applied in 2 min 50 s as drip (low incline, low rate and thus no pressure)

The following procedure was used for the gutter test modifications:

*   The fabric specimen (top layer) and Benchkote paper (collector layer) were weighed separately and then clipped to the gutter.
*   A syringe was used to apply 10 mL of the pesticide formulation to the surface of the fabric.
*   Pesticide runoff was collected in a pre-weighed beaker placed at the bottom of the gutter.
*   A cover was then held against the fabric surface to ensure contact with the collector layer.
*   Both layers were separated and weighed. Amount of liquid in the fabric layer was used to measure pesticide retention and that in the collector layer to measure penetration. The liquid collected in the beaker was used to measure repellency. Total amount applied was calculated by adding the repellency, pesticide retention, and penetration values for each fabric specimen. Results were reported as a percentage of amount applied.

Pipette test

The pipette test was modified to measure fabric performance against two levels of contamination. For lower level 0.1 mL and for higher level 0.2 mL of liquid pesticide was used. The revisions were based on tests conducted using different volumes and concentrations.

The following procedure was used for both levels of contamination:

*   Test assembly consisted of 8x8 cm fabric specimen (top layer) and 8x8 cm Benchkote Plus paper (collector layer) held together between two 10x10 cm Plexiglas plates – a base plate and a cover plate with a 6x6 cm opening in the center.
*   A pipettor with a disposable tip was used to apply the pesticide as a single drop to the center of the fabric specimen.
*   After 10 min., a second Benchkote Plus paper was placed between the fabric and the cover plate to measure repellency. After another two minutes, the three layers were separated and extracted. Each layer was extracted twice in 50 mL of acetone in an orbital shaker for 30 minutes at 200 rotations per minute. The two aliquots were combined and analyzed using a gas chromatograph with a N/P detector.
*   Pesticide extracted from the paper placed on top of the fabric was used to measure repellency. The amount extracted from the fabric was used to measure pesticide retention and that in the collector layer to measure penetration. For this study the

amount applied was calculated by adding the amount extracted from each layer. Results were reported as percentages of amount applied.

Atomizer test

Preliminary tests were conducted to determine factors that would enable the atomizer to apply higher volumes and/or concentrations of the liquid pesticide. Syringe needles with different inner diameter were used. Based on the preliminary test results, 2 mL of the pesticide was atomized. Of the 2 mL applied, approximately 0.5 mL to 0.6 mL was deposited on the surface of the fabric specimen. The following procedure was used for the atomizer test.

- Test assembly consisted of 8x8 cm fabric specimen (top layer) and 8x8 cm Benchkote Plus paper (collector layer) held together between two circular metal plates – a base plate and a cover plate with 7 cm diameter opening in the center.
- The test assembly was enclosed in a cylindrical test chamber with a suction device and an atomizer.
- A syringe was used to dispense 2 mL of the pesticide under 300-hPa air pressure into the test chamber. The fabric specimen was exposed to the atomized spray in the chamber for 3 min. The test assembly was then removed from the chamber and placed under the fume hood for 30 min.
- The layers were separated for extraction. The liquid on the surface of the fabric specimen was extracted with the specimen.
- An orbital shaker was used to extract the fabric specimen and the collector layer in acetonitrile for 30 minutes at 200 rotations per minute. They were extracted once in 20 mL and then twice in 15 mL. The three aliquots were combined and analyzed using HPLC.
- The amount extracted from the collector layer was used to measure penetration. Repellency and pesticide retention were not measured for this method. Amount applied was calculated by adding the amount extracted from the fabric and collector layer. Penetration was calculated as a percentage of the amount applied.

Results and discussion

Percent repellency

Percent repellency was measured for gutter and pipette tests. The mean values for Fabric A ranged from 92.7 % to 99.6 % and for Fabric B from 85 % to 99.5 %. Fabric A had a polyethylene film on the surface and Fabric B had a fluorochemical finish that resulted in higher repellency values for both fabrics. For the gutter tests, the low angle of incline and low rate at which the pesticide was applied affected the repellency values for Fabrics C, D and F. Percentage of repellency was reduced drastically due to increased contact time between the liquid and the fabric. These results indicate that the lower angle and rate may be better suited to measure the repellency. There was minimal or no measurable percent repellency for Fabrics C, D, E, and F using the pipette method. For Fabric C, a previous test conducted using the same conditions had measurable percent repellency. The differences were due to the variation in the nonwoven fabric.

Percent pesticide retained

The amount extracted from the fabric specimen is reported as pesticide retained. This may be pesticide on the surface, or within the fabric structure. Percent pesticide retained was measured for the pipette and gutter tests. The results ranged from 0.5 % to 6.7 % for fabric A and 0.8 % to 13.7 % for fabric B. For Fabrics C, D and E, most of the pesticide was retained by the fabric when 0.1 mL was applied using the pipette method. The percent pesticide retained by the material was lower for 0.2 mL as the liquid holding capacity of the fabric had been reached and so the pesticide penetrated through the fabric.
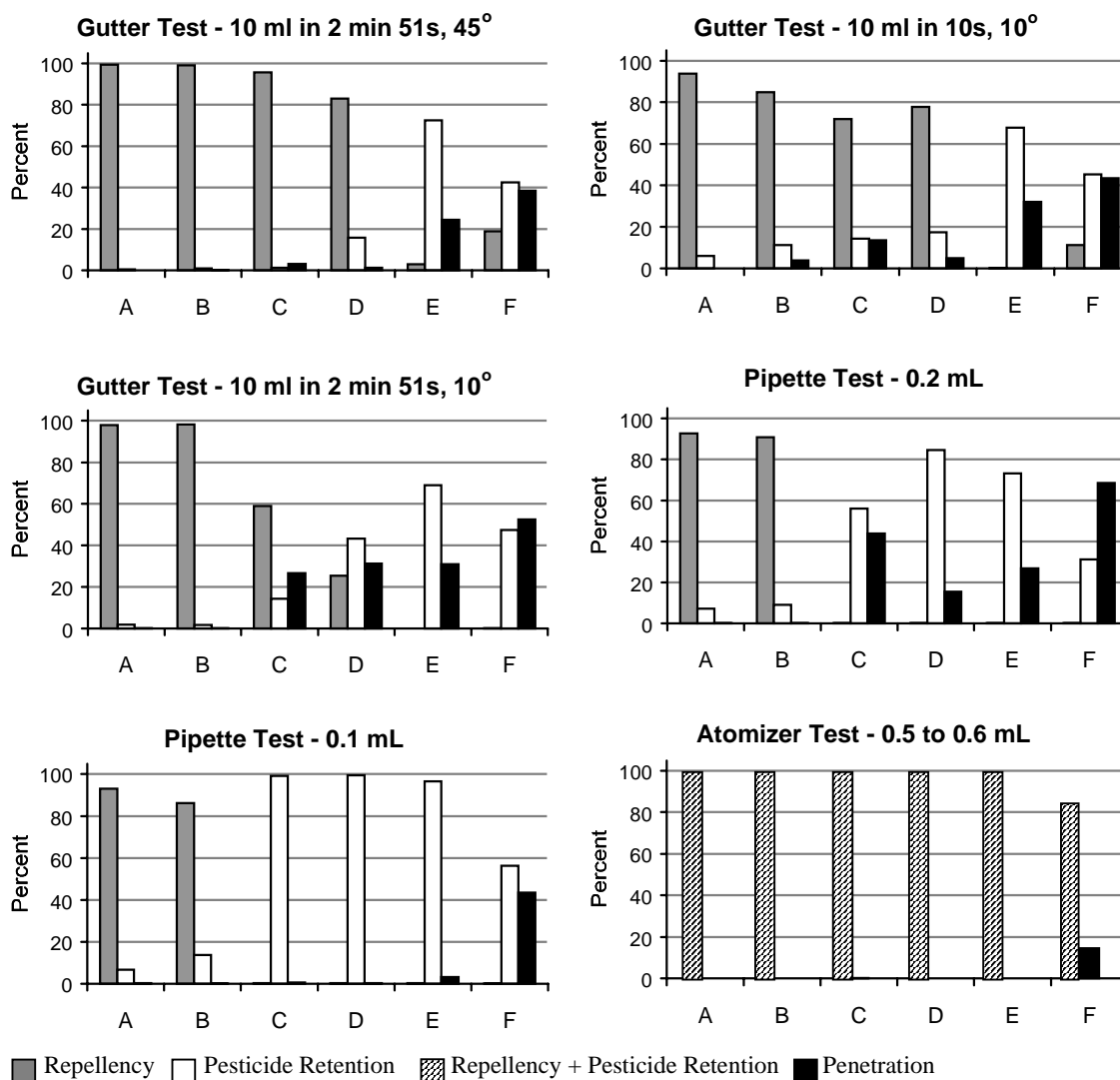
Figure 1. Means for repellency, pesticide retention and penetration for fabrics using different test methods (repellency and pesticide retention was measured as one value for atomizer test).

Percent penetration

Pesticide penetration was measured for all tests. Fabric F had the maximum penetration using all test methods. There was minimal or no penetration through Fabrics A and B with the exception for fabric B (3.8 %) when the pesticide was applied at a higher rate at 10° incline. For the pipette method, the percent penetration increased with the increase in volume applied to Fabrics C, D, E, and F. This, as mentioned previously, was because the holding capacity of these materials had been reached. For atomizer test, 0.24 % penetrated through Fabric C, 14.5 % through Fabric F, and no measurable amount through the

other four fabrics. As in the case of 0.1 mL pipette method, the holding capacity of Fabrics C, D and F had not been reached. As repellency is not measured for the atomizer test, reduced penetration due to repellency could not be differentiated from amount retained by the fabric. The differences in the penetration data for the atomizer and pipette tests were due to the size and distribution of the droplets on the material.

Conclusion

Test method selection should be based on the pesticide exposure conditions to which the PPE materials will be subjected. Gutter test with lower angle and rate and pipette method with higher contamination level are more suitable to evaluate PPE materials against high exposure with dilute formulations e.g., conditions where there may be equipment leakage and/or rubbing against contaminated foliage in addition contamination due to spray drift. The atomizer method is suitable for measuring the penetration through materials when there is low contamination only due to fine droplets.

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A new British standard: The assessment of heat strain for workers wearing personal protective equipment

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Introduction

In many industrial situations workers are required to wear personal protective equipment (PPE) to protect against hazards. Although offering protection, it is recognised that some forms of PPE may increase the risk of heat strain. Methods for estimating potential heat stress include the WBGT index (BS EN 27243) and Required Sweat Rate index (BS EN 12515) (see Parsons, 1999). However, these methods assume that the clothing worn is water vapour permeable; the WBGT index also assumes it is relatively light. Since most forms of PPE either have a higher insulative value than that assumed or are not water vapour permeable, these standards cannot be accurately applied when PPE is worn. A British standard (BS) was developed to allow interpretation of these standards for workers wearing PPE. This paper outlines the development and contents of the BS (to be published as BS 7963: 2000) and its application.

Development of the British standard

A detailed work programme was undertaken to obtain information relevant to the BS. The research comprised of a literature review and discussion with experts to provide relevant information; two questionnaire surveys of potential users of the BS (PPE manufacturers and health and safety experts) to identify their needs and current use of thermal standards; and limited validation of the BS using physiological data from work situations and experiments (see Hanson, 1999). The research was overseen by a steering group appointed by BSI subcommittee PH/9/1. The draft BS was circulated for public comment in May 1998, discussed at the UK Clothing Science Group meeting in June 1998 and amended based on comments received during this consultative process. The remainder of this paper outlines the contents of the BS. It covers the effect of PPE on heat balance, and the application of methods to interpret existing thermal standards to take account of PPE.

Content of the British standard: the effect of PPE on heat balance

The heat balance equation can be expressed as: $M - W = C_{res} + E_{res} + C + E + R + K + S$
    The effect of PPE on heat balance can be summarised in these terms:

- Metabolic rate (M) can be increased due to the weight of the PPE or the restrictions it imposes on the wearer's movements.
- Convection and evaporation in the respiratory tract (Cres + Eres) can be affected by the temperature and humidity of the air breathed, e.g. through BA.
- Convection (C) and conduction from the skin (K) can be affected by the amount of the body covered by PPE and by its thermal insulation properties.

- Evaporation from the skin (E) can be affected by the amount of the body covered by PPE, by its thermal insulation properties, and by its evaporative resistance.
- Radiation from the skin (R) can be affected by the amount of the body covered by PPE. In environments where there is a high radiant load, heat may be gained by the body.
- There can be a heat load through chemical activity of PPE (e.g. closed circuit BA).

W is the mechanical work done by the body during the physical activity and S is heat storage in the body. If heat storage exceeds heat loss, heat strain will occur.

The specific guidance in the BS concerning how PPE may affect these factors, is summarised briefly below. Full guidance is contained within the BS. In assessing the risk of heat stress when wearing PPE, the environment (e.g. temperature, humidity, air velocity), metabolic rate and individual factors (e.g. acclimatisation) obviously need to be considered in relation to the PPE worn.

The effect of PPE on metabolic rate

PPE can increase the wearer's metabolic rate due to its weight or the restrictions it imposes on movement. This impact will depend on activity, and will be greater at higher metabolic rates. Typical increases in metabolic rate when PPE is worn, based on experimental data, are shown in Table 1 below. These increases should be added to the metabolic rate estimated for the activity being undertaken (see BS EN 28996: 1994). Where a combination of items is worn, the increase in metabolic rate due to each form of PPE should be added to the metabolic rate for the activity being undertaken.

Table 1. Estimated increases in metabolic rate (M) due to wearing PPE.

| PPE item | Increase in M due to wearing PPE ($W \cdot m^{-2}$) | | | | |
	Resting	Low M	Mod. M	High M	V. high M
Safety shoes / short boots	0	5	10	15	20
Safety boots (long)	0	10	20	30	40
Respirator (low/moderate performance, e.g. P1, P2)	5	10	20	30	40
Respirator (high performance, e.g. P3)	5	20	40	60	80
Self-contained breathing apparatus	10	30	60	95	125
Light, water vapour permeable chemical coverall (e.g. disposable)	5	10	20	30	40
Chemical protective water vapour impermeable ensemble (e.g. PVC) with hood, gloves and boots	10	25	50	80	100
Highly insulating, water vapour semi-permeable ensemble (e.g. firefighters' gear)	15	35	75	115	155

The thermal insulation of the material covering the body

Thermal insulation values (I_{cl}) for clothing ensembles are given in BS ISO 9920: 1995. Few values are given for different forms of PPE, but where these are available they have been included in the BS.

The evaporative resistance of the material covering the body

The evaporative resistance (R_T) of material is a significant factor in heat stress, but is often not quantified. Materials with low evaporative resistance will allow evaporation of sweat through them, and thus reduce heat stress. However, where evaporative resistance

is high, a condensation-evaporation cycle can develop within the garment, allowing some cooling.

Closure of garments to the body

'The pumping effect' (ventilation of the garment caused by the wearer's movement) will provide some cooling, dependent on activity. At metabolic rates below 100 $W.m^{-2}$ thermal insulation of clothing should be reduced by 10 %; at metabolic rates above this it should be reduced by 20 %. These reductions in thermal insulation should not be applied to garments that are sealed to the body, since they provide limited potential for this effect. PPE which compresses the ensemble (e.g. harnesses, belts) also reduces the potential for this effect; the reduction in thermal insulation should not be applied if this type of PPE is worn.

The proportion of the body covered by PPE

Heat stress will be affected by the amount of the body that is covered by PPE. Based on data from BS ISO 9920: 1995, the proportion of the body covered by PPE was estimated. Where several garments, that overlap are worn, the extent of overlap is considered.

The effect of respiratory protective equipment

A supply of compressed air (open circuit BA, airlines) may provide some cooling to the body, primarily through convective heat loss and evaporation of water from the lungs. With an air line, some air can be vented into the suit and provide additional (evaporative and convective) cooling. In contrast, closed circuit BA usually delivers warmer air with high humidities, and this may result in some heat gain. However, wearing BA will increase the metabolic rate and reduce the movement of air within the garment (the pumping effect) and thus the potential for cooling. On balance, the net effect of air delivered from a cylinder worn on the body can be to increase heat stress, while the net effect of air provided by an airline can be to decrease heat stress.

Table 2. Correction factors to be applied to BS EN 27243:1994 WBGT reference values when PPE is worn (from ACGIH, 1990)

Clothing type	Thermal insulation (clo)	Correction factor for WBGT (°C)
Summer work uniform	0.6	0
Cotton coveralls	1.0	-2
Winter work uniform	1.4	-4
Water barrier, water vapour permeable ensemble	1.2	-6 [a]
Water vapour impermeable ensemble (fully encapsulating suit, hood, gloves, boots)	1.2	-10 [a, b]

[a] Because these WBGT correction factors were derived from experimental data, it is not necessary to increase metabolic rate due to these items of clothing. If PPE *in addition to that listed* is worn (e.g. BA) the metabolic rate should be increased to take account of only these additional items.
[b] Use the WBGT reference value for 'no sensible air movement' with this correction factor. Also, when a water vapour impermeable ensemble is worn, the ambient dry bulb temperature is more important in determining heat stress than the wet bulb temperature as sweat cannot be evaporated into the environment. In effect, the dry bulb temperature replaces the WBGT.

Content of the British standard: Application to existing thermal standards

BS EN 27243: 1994, WBGT index

BE EN 27243: 1994 provides limit values for the WBGT above which action should be taken to reduce the risk of heat stress. To interpret this for workers wearing PPE, the normal data required for this standard should be collected. Two additional steps should be taken to account for the PPE: firstly, apply a correction to metabolic rate due to PPE (see Table 1), if required; secondly, if the worker is not wearing a 'standard working garment' (see BS EN 27243:1994), apply a correction to the WBGT limit values, see Table 2.

The correction factor for PPE should be applied to the WBGT limit value. Any measured WBGT value above this will require action to reduce the risk of heat stress.

BS EN 12515: 1997, Calculation of required sweat rate

BS EN 12515 provides a more detailed method for assessing thermal stress, taking account of the thermal environment, clothing worn and the work undertaken. It includes a computer program which calculates the sweat evaporation rate required for thermal balance. This requires information about: duration of exposure; dry bulb air temperature; globe temperature; psychometric wet bulb temperature; air velocity; metabolic rate; proportion of the body exposed to environment; and thermal insulation of clothing.

PPE can affect the metabolic rate, proportion of the body exposed to the environment and clothing thermal insulation (including the pumping effect). Based on the guidance in this BS these input variables can be adjusted directly to take account of the PPE.

The effects of water vapour impermeable PPE also need to be accounted for. When such clothing is worn, the potential to evaporate sweat into the environment will be negligible. Therefore, the wet bulb temperature (water vapour pressure) is not relevant to potential heat loss; it should be set to equal the measured dry bulb temperature. Also, air velocity will have only a limited effect on the amount of heat lost from the body. The air velocity input should be set to 0.1 ms^{-1} to reflect this limited potential for heat loss.

Respiratory protective equipment will affect inspired air temperature. The variable for inspired air temperature in the BASIC program should be altered to 45 [EC] if closed circuit BA is worn; 25 [EC], if open circuit BA is worn; and to the dry bulb temperature if a filter which does not chemically react with the inspired or expired air is used.

The BS provides guidance on the impact of PPE on heat strain, and methods for interpreting existing heat stress standards for workers wearing these garment. Three worked examples using the methods described above for BS EN 27243 and BS EN 12515 are given in the Annex of the BS.

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Assessment of the scientific validity of ISO 7933/EN 12515

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Introduction

Ergonomic standards such as ISO 7933 and ISO 9920 are based on a number of assumptions that do not adhere to conventional thermodynamic principles, e.g. the concept of a thick layer of stationary air on the outermost surface of the garment and such air layer being opaque to low frequency radiation, or which are contrary to common experience, e.g. the change in clo value due to wearing gloves is effectively nil yet personal experience in cold weather is that gloves do make a substantial difference.

European Standards for high performance protective clothing will shortly be published. To meet the performance requirements of these new standards clothing may be manufactured from fabrics which have poorer air and water vapour permeability and which are better sealed to the wearer's body than many current garments. These new garments may therefore have greater potential than current garments for creating or exacerbating heat strain. ISO 7933 has been adopted as EN 12515, and may therefore be used to assess the potential for protective clothing to generate heat strain, e.g. EN 12515 has been incorporated into a draft UK standard for such assessment, BS 7963:2000.

It is therefore essential that the scientific validity of ISO 7933/EN 12515 be assessed.

Methodology

In assessing the scientific validity of ISO 7933/EN 12515 it is useful to compare the relevant heat transfer equations described in basic thermodynamics with those used in the ISO/EN standards. The text referred to hereinafter is that from EN 12515:1997.

The simplest situation for quantifying heat transfer between the body and the environment is where the inner surface of the clothing is in contact with the skin. If such contact does not occur heat is transferred between the skin and the inner surface of the clothing by natural convection, forced convection caused by pumping of the in-garment microclimate generated by movement of the body and/or radiation.

Sensible heat transfer between the body and the environment through impermeable clothing sealed to the wearer's body and not in contact with external surfaces occurs by: heat transfer between the skin and the inner surface of the clothing by physical contact, radiation or natural or forced convection; heat transfer through the clothing by conduction; heat transfer between the outer surface of the clothing and the environment by convection and radiation, i.e. algebraically, conduction = convection + radiation.

That is, for clothing in contact with the skin, the steady-state net sensible heat transfer by convection and radiation in still air is given by:

$$k_c(t_{sk} - t_{so}) = h_c(t_{so} - t_a) + \varepsilon \, p[(t_{so} + 273)^4 - (t_r + 273)^4] \, 5.7 \times 10^{-8}$$

where: k_c thermal conductivity of clothing
         t_{sk} skin temperature
         t_{so} clothing outer surface temperature
         h_c convection coefficient
         t_a dry bulb air temperature
         ε radiant absorbency of outermost surface
         p posture correction
         t_r mean radiant temperature

Note: if $t_r \gg t_a$ then t_{so} can exceed t_a because the surface gains more energy by radiation than it loses by convection.

h_c for natural convection can be calculated in a stepwise fashion.

1)   The Grashof number, $Gr, = g\beta \, (t_{so} - t_a)L^3/ \nu^2$

where: g gravitational acceleration
         β $1/[273 + 0.5(t_{so} + t_a)]$
         L Characteristic (vertical) length
         ν kinematic viscosity at $0.5(t_{so} + t_a)$

2) $h_c = k_a C(Gr.Pr)^a/L$

where: k_a thermal conductivity of air
            $C = 0.59$ and $a = 0.25$ for $Gr.Pr$ in range 10^4-10^9, fluid flow in the boundary layer is laminar
            $C = 0.13$ and $a = 0.33$ for $Gr.Pr > 10^9$, fluid flow in the boundary layer is turbulent
         Pr Prandtl number at $0.5(t_{so} + t_a)$

The above equations can be easily solved by successive approximation.

Assessment of validity of ISO 7933/EN 12515

The validity of the above equations for heat transfer between the body and the environment can be assessed for a thermal manikin as specified in ISO 9920 (1995). Assuming the manikin is 1.7 m tall, has a surface area of 1.8 m², a mean skin temperature of 33 ℃, ε = 0.95 and a posture factor of 0.77 and is in a thermal environment where $t_a = t_r = 25$ ℃, the mean heat loss is 25 W/m² convective and 37 W/m² radiative, midway between the overall specified limits of 40-80 W/m². Note that flow in the boundary layer is turbulent, i.e. h_c varies as $(t_{so} - t_a)^{0.33}$.

The above equations differ critically from those adopted in EN 12515.

1) Equations (4), convection, and (5), radiation, in EN 12515 are based on the difference between t_{sk} and t_a and t_r rather than between t_{so} and t_a and t_r respectively. As fluid flow in the boundary is generally turbulent so that the temperature difference is raised to the power 1.33 for convection and to the power 4 of the absolute temperature for radiation, the error of assuming t_{sk} rather than t_{so} as the basis for temperature differences cannot be corrected for by altering the values of the linear coefficients in the equations unless within a limited range of applicability. The range of such applicability is currently unspecified.

2) Equation A.3 for convective heat transfer assumes laminar flow rather than turbulent flow. However, for other than minimal temperature differences between t_{so} and t_a flow in the boundary layer is turbulent. Consequently h_c should vary as $(t_{so}-t_a)^{0.33}$ rather than as $(t_{so}-t_a)^{0.25}$ as in EN 12515. As above, the difference between $(t_{so}-t_a)^{1.33}$ rather than $(t_{so}-t_a)^{1.25}$, for other than small temperature differences cannot be corrected for by altering the value of the linear coefficient unless within a limited range of applicability. The range of such applicability is currently unspecified.

3) Equation A.7 for radiant heat transfer is based on the absorbency/emissivity of skin. For radiative heat transfer between an effectively fully clothed body and the environment the only radiative transfer between the skin and the environment will occur from uncovered skin, e.g. the hands or face. For a body which is effectively completely clothed, the relevant radiant absorbency/emissivity is therefore that of the clothing outer surface(s). Equation A.7 is therefore invalid for fully clothed bodies. However, radiation between the skin and the environment can be important for uncovered skin and between the skin and the inner surfaces of the clothing can be important in some situations.

4) From the form of Equations 4, 5 and A.8 heat transfer by convection and radiation must both be either positive or negative, i.e., EN 12515 cannot accommodate situations where $t_r \gg t_a$ such that $t_{so} > t_a$. However, when wearing a garment with a conductivity of 5 W/m²/K and an ε of 0.95 in a t_a of 50 ℃, convective heat transfer becomes negative when $t_r > 63$ ℃. Such conditions are commonly encountered by workers such as restaurant chefs, asbestos strippers, welders and fire-fighters.

5) EN 12515 uses clo values derived on the basis of the assumption that there is a thick layer of stationary air attached to the outermost surface of the garment. Authors such as Havenith (1999) describe a clothing material as having "a still air layer attached to its outer surface" up to 6 mm thick. From the above application of basic thermodynamic principles to a thermal manikin there is no need to postulate a thick stationary air layer adhering to the surface of the manikin as assumed in ISO 9920 and ISO 7933/EN 12515.

The assumption of a thick stationary air layer may be based on a failure to understand that although the boundary may be a number of mm thick, there is significant air movement within the boundary layer and that within the boundary layer there is a very thin layer of stationary fluid adjacent to the surface through which energy eventually transferred by convection must initially be conducted.

In EN 12515 it is further assumed that the stagnant air layer affects radiant transfer. If a thick stagnant air layer was present, such an air layer would be effectively transparent to radiant energy of the frequencies of interest and therefore would not affect radiative heat

transfer. The radiative transfer calculated from ISO 7933/EN 12515 is therefore likely to be underestimated. This could be critical in high radiant energy situations.

Conclusion

By comparison with the principles of basic thermodynamics, the scientific basis of ISO 7933/EN 12515 is faulty. However, the standard may be applicable through a limited, presently undefined, range of conditions.

A thorough scientific review of the standard is therefore required.

Until completion of the review and replacement by a scientifically valid standard, the limits of applicability of ISO 7933/EN 12515 should be clearly stated.

Such scientific review should be extended to all other standards in which clo values derived from tests based on the assumptions of a thick stationary boundary layer and/or heat transfer being driven by the differences between skin temperature and ambient dry bulb or radiant temperatures, e.g. ISO 9920:1995.

Such review should ensure that all assumptions on which the standards are based and all individual steps within the standards are scientifically valid and not simply balanced to match observations over a limited, unspecified, range of conditions.

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The influence of the number of thermal layers on the clothing insulation of a cold-protective ensemble

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Introduction

Clothing is essential for wellbeing and performance in cold climate. The thermal properties of the clothing are especially important. The required thermal insulation in a specific environmental condition can be predicted by use of the IREQ (Insulation REQuired) method, described in ISO document ISO/TR-11079, Evaluation of cold environments - Determination of required clothing insulation (IREQ) (ISO/TR-11079, 1993). The method is used for assessment of cold work environments and to provide recommendations of clothing insulation for specific cold exposures. If possible, work clothing with an insulation value that is equivalent to the IREQ value is of course preferred, both from the employers and the employee's view. However, sometimes the predicted insulation value, IREQ, is not achieved by the actual work clothing. Then, a time limit for the cold exposure (DLE, Duration Limited Exposure) may be calculated to prevent the worker to cool unacceptably. The thermal insulation of a clothing ensemble can be measured with a thermal manikin (ENV-342, 1998) or estimated according to the international ergonomics standard ISO 9920, "Ergonomics of the thermal environment - Estimation of the thermal insulation and evaporative resistance of clothing ensemble" (ISO-9920, 1993). Thermal manikin measurements of clothing insulation are relatively costly and are limited to certain test laboratories. To compose a clothing ensemble with appropriate insulation for certain conditions an alternative method is to use tables of garments in the standard ISO 9920, annex 2. The estimation method is discussed in another paper presented in this conference (Gavhed et al., 2000).

The standard includes a number of tables, which provide the thermal insulation of clothing ensembles with specified garments, as well as the insulation of single garments. Additionally, the type and weight of the ensembles and garments are described in the tables. The basic thermal insulation of single garments (I_{clu}) can be summated to form the basic insulation (I_{cl}) of a whole clothing ensemble. The values of I_{clu} and I_{cl} in the tables ISO 9920 are obtained from measurements on thermal manikins.

In cold environments more than one layer of thermal underwear is commonly used. Thermal underwear is usually made out of knitted fabrics. Numerous pockets of air (air is a very good insulator) are trapped between the fibres in the fabric. In addition to reduction of the air layers between clothing layers, the fibres in knitted garments may be compressed when worn in tight fitting multiple layers. If compressed, the air volume inside the knit would be reduced and, concurrently, the insulation. Addition of thermal layers to an ensemble is therefore not likely to have a simple additive effect on the thermal insulation of the whole ensemble, i.e. the sum of I_{clu} of single garments may differ from the measured basic insulation, I_{cl}. The influence of the number of clothing layers on the insulation of clothing ensembles has not been systematically investigated.

The purpose of the study was to investigate the resulting thermal insulation of clothing ensembles with different numbers of thermal underwear and the relative contribution of the underwear to the insulation of a whole cold-protection clothing ensemble.

Methods

The total insulation (clothing + boundary air layer insulation) of different combinations of garments was measured on a standing thermal manikin. The basic insulation (I_{cl}, the insulation of the clothing and the intrinsic air layers without the outer surface air layer insulation) was calculated from the total insulation according to ENV 342 (ENV 342, 1998). Seven pieces of clothing, sweaters, pants and coveralls were combined in different numbers of layers (1-6 layers). The sweaters and pants were manufactured from Ullfrotte Original™ (Ullfrotte AB, Sweden) "U", a terry material which is knitted from wool and synthetic fibres. Three qualities of Ullfrotte™ were tested (Table 1). The garments were thermal sweaters with turtle neck and long back (fabric qualities U2, U4 and U6, Table 1), thermal pants (U2 and U4, Table 1), a coverall with thin polyester lining (CLI) and a heavy insulated coverall with polyester filling (CHI). The outer layer of the coveralls had low air permeability. One to five thermal sweaters/jackets and one to two thermal pants combinations were measured alone, and combined with CHI and CLI, respectively. All garments were measured with gloves and double pairs of thick socks. The air velocity was < 0.3 m/s during the measurements.

Table 1. Description of the fabric materials.

Code	Mass/area (g/m^2)	Fibre materials
U2	200	60 % wool, 25 % polyester, 15 % polyamide
U4	400	70 % wool, 18 % polyamide, 12 % aramide
U6	600	70 % wool, 18 % polyamide, 12 % aramide

Results and discussion

The measured basic insulation values (I_{cl}) of the ensembles are given in Figure 1. The resulting I_{cl} of two layers of knitted underwear was not purely the sum of I_{cl} of the two knitted clothing layers measured and worn as single layers. The sum of I_{cl} for U2 sweater/ U2 pants and U4 sweater /U4 pants was 0.29 clo higher than I_{cl} of the combination of U2+U4 sweaters/U2+U4 pants, which corresponded to 22 % of the insulation of the single layers added together (Figure 1). 1 clo = 0.155 m^2·°C/W. Similarly, the sum of I_{cl} for U6 sweaters /U4 pants and U2+U4 sweaters/U2+U4 pants was 0.48 clo higher than I_{cl} of the combination of U2+U4+U6 sweaters /U2+U4 pants, which corresponded to 31 % of the insulation of the single layers added together (Figure 1). Further, combination U2+U4+U6 sweaters /U2+U4 pants insulated even less than the sum of I_{cl} for U2 sweater/U2 pants and U4 sweater/U4 pants, although one more sweater was worn in the combination. Havenith et al reported 15 % reduction of the insulation of two layers when worn under a coverall in comparison to worn without coverall (Havenith et al., 1990)

I_{cl} of the ensemble with U4 sweater+pants and the ensemble with U6 sweater/U4 pants as single layer were similar (Figure 1). The weight of U6 was higher than U4, but the thickness did not differ much (about 0.5 mm). Thus, probably about the same amount of air was trapped in both fabric qualities. The thickness is correlated with insulation, but is certainly not the only determinant for insulation.
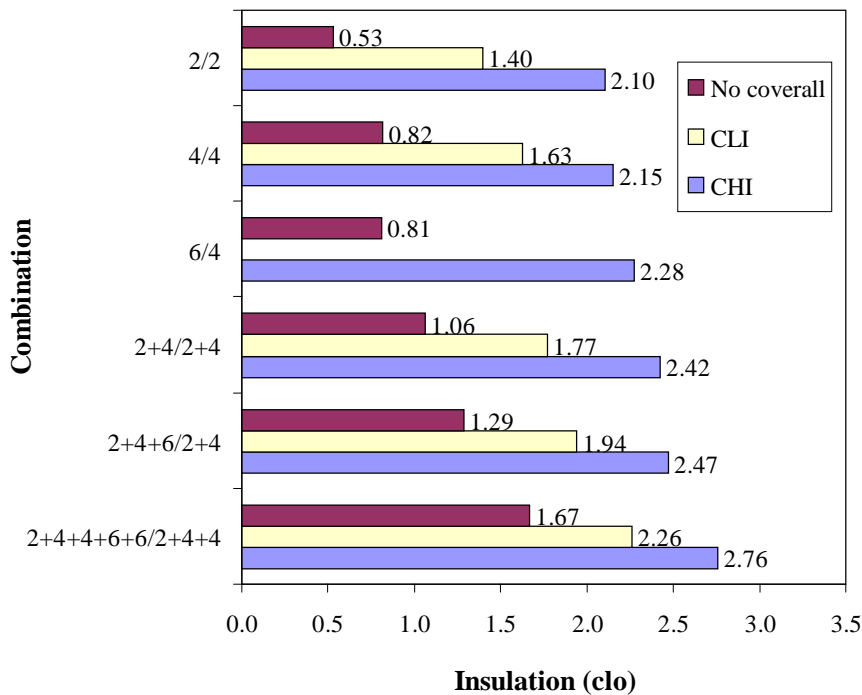
Figure 1. Insulation in different combinations of thermal underwear and coveralls together with standard gloves and socks. For explanation of the codes, see Methods. The code before the slash in the y-axis labels denotes the tested quality of the sweater and the code after the slash denotes the tested quality of the pants.

A third layer worn under CHI on the upper body barely contributed to I_{cl}, only by 0.05 clo, compared with two layers. A corresponding relevant table value would be about 0.30 clo. Under CLI, the contribution to I_{cl} was slightly larger, 0.14 clo (Figure 1). The small contribution to I_{cl} of the ensemble was probably because the clothing and air layers under the shell were probably slightly compressed especially when three layers were worn. The compression was probably larger in the thick coverall. The coveralls had normal fit for the manikin body and the knitted garments were of the same size, fitting the manikin body. However, as the number of layers increased, the garments, which were put on top of other layers stretched more. In addition to compression, the stretching may have reduced the insulation of the garment in comparison to being the innermost layer.

During standing the convection along the skin and clothing surfaces inside the outer shell was rather limited. However, when the body moves, the clothing is ventilated and air flows through the openings of the clothing, known as the "pumping effect". Air may also be exchanged through air permeable fabrics. Pumping during walking and wind reduces the insulation of a multi-layer clothing ensemble by up to 70 % (Havenith et al., 1990, Nilsson et al., 1998). The influence by the number of clothing layers on insulation is most likely otherwise during walking (Havenith et al., 1990) and wind than during standing. Therefore studies of the influence of air velocity and body movements on the insulation of the above combinations are planned.

The effect on the insulation of clothing ensembles with multiple layers of compression and stretching of fabrics has obviously not been taken into consideration in the standard method, probably partly because most ensembles in the tables are indoor clothing ensembles. Thus, the insulation of multi-layer clothing ensembles risks to be overestimated by summation for standing (Gavhed et al., 2000). The estimated value of I_{cl} is for example used for calculations of Duration Limited Exposure, DLE (ISO/TR-11079, 1993). The assessment of DLE, and other climate indices may thus be inaccurate if summated table values are used without correction. For example, according to IREQ, the clothing

ensemble with U2+U4+U6 sweaters /U2+U4 pants and CHI (I_{cl} 2.47 clo), would not allow thermal comfort at standing for eight hours below +8 °C. At -10 °C, the DLE for maximal allowed cooling in this clothing is 85 min. If the I_{cl} of the single layers were summated, I_{cl} of the combined ensemble would be overestimated by at least 0.48 clo according to this study. The corresponding DLE would then be one hour longer, 145 min.

To improve the insulation of an ensemble by adding a layer, the garments must be large enough. Otherwise, the garments may be compressed and stretched. Then, the insulation will not increase proportionally to the insulation of added garments. Further, different fibres and knitting structures may collapse under pressure easier than others. The insulation would probably reduce more at compression of thermal underwear made from soft fibres and knits with high loft.

Conclusions

The basic insulation of knitted wear combined in layers were 22-31 % lower than I_{cl} of the sum of the garments in single layer.

The insulation values of multi-layered clothing ensembles of this kind would be overestimated by summation of the I_{clu} of individual garments. Overestimation leads to wrong recommendations of cold-protective clothing or working time limits, at least during standing, but probably also during physical activity.

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Thermal insulation of multi-layer clothing ensembles measured on a thermal manikin and estimated by six individuals using the summation method in ISO 9920

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Introduction

The thermal insulation of a clothing ensemble can be measured with a thermal manikin (ENV-342, 1998) or estimated according to the international ergonomics standard ISO 9920, "Ergonomics of the thermal environment - Estimation of the thermal insulation and evaporative resistance of clothing ensemble" (ISO-9920, 1993). Estimation is commonly used, since thermal manikin measurements are more costly and time consuming. In the standard there are tables of thermal insulation both for a number of specific clothing ensembles (annex 1) and separate tables for single garments (annex 2). The tables in annex 2 contain information about the insulation of the garments, fabrics of the garment, type of garment and weight. The insulation values of single garments are summated to provide an estimate of the insulation of a whole clothing ensemble.

The thermal insulation of clothing is used in assessment of the thermal environment of workers. The measurement of clothing insulation is restricted to certain test laboratories, why estimation is the most used method at thermal environment assessments. Estimates of the insulation of a clothing ensemble by summation of garments may naturally differ between individuals. Deviations from the actual value are probably higher when more garments are included in the ensemble.

The tables are based on measurements with thermal manikins mainly before 1985 (McCullough et al., 1985, Olesen and Nielsen, 1983). Most garments in ISO 9920 are sleepwear, daily wear or industrial work wear. Some types of clothing are not well represented, such as heavy insulated outdoor wear, boots, gloves and headgear. A large part of the measurements on garments were originally done as a complement for assessment of the thermal indoor environment (ISO-EN-7730, 1995) and thus rather few garments in the tables are for cold protection. Further, new materials have been developed since the tables were completed. For the practitioner it can be difficult to estimate the insulation of clothing ensembles comprising pieces of clothing or types of garments that are not found in the tables.

The purpose of this study was to investigate i) the error of the estimate of the insulation of cold-protective clothing ensembles comprising two or more clothing layers and ii) the interrater reliability of the estimate.

Methods

21 pieces of clothing (two coveralls, sweaters, thermal pants, t-shirt, socks, gloves, hood and helmet) were combined into seven clothing ensembles (Table 1). The ensembles were used at mast work in Sweden in winter. The thermal insulation of the ensembles

was measured with a standing thermal manikin at < 0.2 m/s. The basic insulation was calculated from the total insulation (clothing + boundary air layer insulation) according to ENV 342 (ENV 342, 1998). Six individuals ("raters") were instructed how to use the tables in ISO 9920, annex 2. They were asked to estimate the basic insulation of the garments (I_{clu}), which constituted the measured clothing ensembles. The basic insulation of the whole ensemble was estimated by summation of the I_{clu} of the single garments according to the ISO standard.

Table 1. Description of the garments and the seven clothing ensembles measured. Besides the garments in the table, all clothing ensembles comprised cotton briefs, gloves, thick boot socks, hood and safety helmet. Ullfrotte[TM] terry knit (Ullfrotte AB, Sweden) "thin": 60 % wool/ 40 % synthetic fibres, "medium" and "thick": 70 % wool/ 30 % synthetic fibres.

Garment, type	Material	Clothing ensemble						
		A	B	C	D	E	F	G
Long-legged underpants	Ullfrotte, thin	x	x	x	x	x		
Long-legged underpants	Ullfrotte, medium thickness						x	x
Thermal underpants	Fibre pile							x
Thermal undershirt	Ullfrotte, thin	x	x	x		x		
Thermal undershirt	Ullfrotte, medium thickness	x			x			
T-shirt	Cotton				x		x	
Sweater	Cotton		x		x	x		x
Jacket	Fibre pile							x
Coverall, outdoor	Multi-component					x	x	x
Coverall, heavy insulated	Multi-component with filling	x	x	x	x			
Socks	Ullfrotte, thin	x	x			x	x	x
Socks	Ullfrotte, medium thickness		x		x	x	x	x
Socks	Ullfrotte, thick			x				
Socks	Synthetic			x	x			
Socks	Fibre pile	x						

Results and discussion

Five out of six raters underestimated the basic insulation (I_{cl}) of most clothing ensembles. The maximal deviation of the estimated basic thermal insulation (I_{cl}EST) from the measured basic thermal insulation (I_{cl}MEAS) was 67 % (underestimation). I_{cl}MEAS of four ensembles was underestimated by on average 15 %, one ensemble was overestimated by on average 10 % and the average I_{cl}EST of two ensembles were similar to I_{cl}MEAS (Table 2). One rater systematically overestimated I_{cl}MEAS. In contrast to the other raters, this rater used the fabric of the garment as a determinator for the insulation estimate. Body surface area covered and fabric thickness are the most important determinators for thermal insulation of garments (Afanasieva, 1977), but not fabric material (McCullough et al., 1985). I_{cl}EST by the two raters without experience deviated more from I_{cl}MEAS (average difference 0.5 clo) than estimates done by the four more experienced raters (< 0.3 clo). McCullough et al (1985) concluded that the estimates of the insulation of clothing ensembles made by a group of educated raters were unacceptably inaccurate.

Table 2. Measured, I_{cl}MEAS, and estimated basic insulation, I_{cl}EST, by six raters (1 clo=0.155 m^2°C/W). U="Ullfrotte™ terry knit, C=cotton, F=fibre pile, HIC=heavy insulated coverall, NFC=coverall without filling. SD=standard deviation of the mean.

Ensemble code	Layers on the torso, *Material/ type*	Layers on the lower body, *Material/ type*	I MEAS (clo)	I_{cl}EST average (clo)	SD	Minimum	Maximum
A	3, *U,U,HIC*	2 *U,HIC*	2.35	2.08	0.53	1.55	3.07
B	3, *U,C,HIC*	2 *U,HIC*	2.35	2.00	0.45	1.55	2.86
C	2, *U,HIC*	2 *U,HIC*	2.34	1.79	0.48	1.25	2.69
D	4, *C,U,U,HIC*	2 *U,HIC*	2.35	2.19	0.48	1.75	3.13
E	3, *U,U,NFC*	3 *U,U,NFC*	1.74	1.72	0.18	1.41	1.94
F	3, *C,U,NFC*	2 *U,NFC*	1.70	1.73	0.23	1.37	2.07
G	3, *C,F,NFC*	2 *F,NFC*	1.87	2.06	0.24	1.68	2.28

The measured basic insulation may have been somewhat underestimated since the area surface enlargement factor (f_{cl}) was not taken into account. According to equations presented by McCullough et al (McCullough et al., 1985) f_{cl} may be 1.7 for multilayer ensembles. The estimated value for ensembles A-F would then be even more distant from I_{cl}MEAS, while I_{cl}EST for ensemble G would be closer to I_{cl}MEAS.

The insulation of the ensemble with only one layer on the upper and lower body beneath HIC (ensemble C) seemed to be most difficult to estimate correctly. This may partly be explained by the properties of the clothing ensemble. HIC was heavy insulated, the outer material was made of tight weave and the air permeability was low. About the same amount of air was probably trapped inside the outer shell regardless of the clothing beneath this shell. The air contributed to the total intrinsic (basic) insulation. The insulating air layers between the clothing layers beneath the outer shell are not accounted for in the estimation method. When there were more layers than one beneath the shell, the insulation of these garments was added to the insulation of the whole ensemble. The insulation of the air, which was not taken into account in the estimate, was then "replaced" by the insulation of the garments. Similarly, McCullough, et al (1985) observed that the number of garments, but also the type of clothing influenced the accuracy of the estimate. An additional explanation of the discrepancy between I_{cl}MEAS and I_{cl}EST is that a similar coverall as the one in the study could not be found among the tables.

The smaller garments (helmet, gloves, socks and hood) gave the highest variability among raters, coefficient of variation 23-73 %. This was probably due to the lower absolute insulation value, which made a small over- or underestimation of the absolute value relatively large, and to the fact that I_{clu} of helmets and hood were not found in the tables, while the gloves were only represented by one type and value. Further, the I_{clu} of the insulated coverall showed an average deviation of 59 % of the mean. The large variation was mainly due to the same reason as for the smaller garments, that a similar coverall to the one used in the study could not be found in the tables of ISO 9920.

The raters commented that the tables were not well organised and that many garments were lacking in the tables, e g heavy insulated coverall and boots.

I_{cl}MEAS was measured at standing at low air velocity. The estimate of insulation is adequate for this condition. However, with body movements, air will move beneath the clothing and through openings (pumping effect), which causes the insulation to decrease. The reduction of thermal insulation depends on factors such as the air permeability of the garment and openings of the clothing. The thermal insulation of a multi-layer clothing ensemble in dry conditions can be reduced by about 30 % during walking (Nilsson et al., 1992). The relationship between the number of layers, type of clothing material and in-

sulation needs further study to provide better estimations of insulation of multi-layer clothing ensembles.

The estimated value of I_{cl} derived from the tables in the standard ISO 9920 is, for example, used for calculations of Duration Limited Exposure, DLE (ISO/TR-11079, 1993) to limit work time if the cold protection is not sufficient for the conditions at work. The estimates with the highest error in this study (+0.72 clo and -1.1 clo, respectively), would render a calculated DLE for standing at -10 °C in calm air, which is about 40 minutes longer and about 30 min shorter than the actual DLE, respectively. These values correspond to 50-90 % of the DLE based on I_{cl}MEAS. Further, the underestimation by 1.1 clo would limit work to less than an hour at the same conditions according to DLE, while the working time with I_{cl}MEAS would be thermally comfortable for more than eight hours.

Conclusions

The estimations of insulation were more accurate for the ensembles with lower insulation with only one layer beneath the outer shell than with higher insulation and multiple layers. The raters considered the tables to be complicated to use. Experience to do insulation estimations tended to improve the estimate.

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Effect of the number, thickness and washing of socks on the thermal insulation of feet

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Introduction

An effective way to increase the insulation on feet is to add socks. However, the effect of adding new layers on feet has not been studied enough. There is limited data on insulation of socks and their combination with footwear. In this study 4 types of socks with different fabric thickness and 3 types of footwear were tested on a thermal foot model to study the effect of the number, thickness and washing on the thermal insulation of feet.

Methods

Four types of socks, manufactured by Ullfrotté (Table 1) were tested separately and in combination with the others. Some socks were tested in combination with 3 types of footwear (Table 2). The cotton sock, and boots AS and WS were used in thermal foot measurements earlier (Kuklane et al., 1997; Kuklane et al., 1998; Kuklane et al., 1999b; Kuklane et al., 1999c).

Table 1. Sock types, measured on thermal foot model.

Sock	Manufacturer	Material	Material weight (g/m^2)	Weight of a sock (g)
Cotton		70 % cotton, 30 % polyester		20
2	Ullfrotté	60 % wool, 40 % polyamide	200	21
4	Ullfrotté	65 % wool, 35 % polyamide	400	39
6	Ullfrotté	60 % wool, 40 % polyamide	600	53
8	Ullfrotté	85 % wool, 15 % polyamide	800	77

Table 2. Boot types, measured on thermal foot model.

Boot	Manufacturer	Material	Weight (g)
AS	Arbesko, Sweden	Leather	801
SS	Steitz Secura, Germany	GoreTex	827
WS	Arbesko, Sweden	Impregnated leather, Thinsulate, nylon fur	815

The thermal foot model has 8 zones (toes, sole, heel, mid-foot, ankle, lower calf, mid-calf and a guard zone) that are controlled separately by a computer program. At a constant ambient temperature (in this study 6.0±0.5 °C, air velocity <0.2 m/s) a certain power is needed to keep the foot surface temperature constant (in this study 34.0±0.1 °C). The supplied power is directly related to the heat losses from the foot. From the temperature gradient and the heat losses it is possible to calculate the insulation for each zone or whole foot.

The insulation was defined as the total insulation of the foot zones (toes, sole, heel, mid-foot) and ankle zone. All insulation values, given in the paper, include the air layer

insulation. The air layer insulation (0.108 m^2°C/W) was measured earlier (Kuklane et al., 1999a).
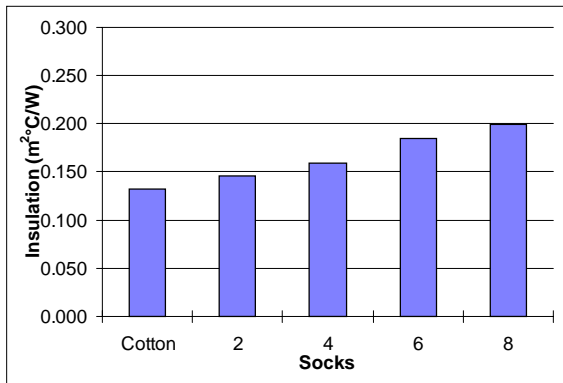

Figure 1. Insulation of single socks.
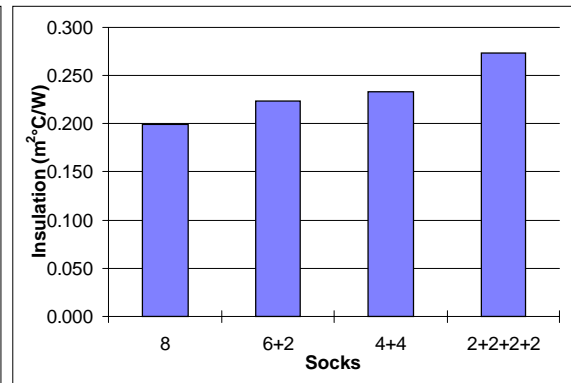
Figure 2. Insulation of sock combinations giving the total material weight 800 g/m^2.
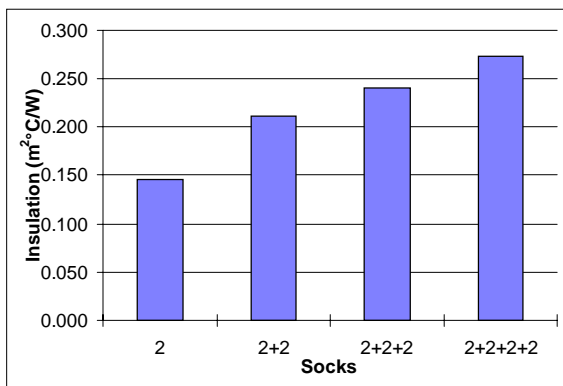
Figure 3. Effect of sock layers on the insulation on the example of the thinnest sock.
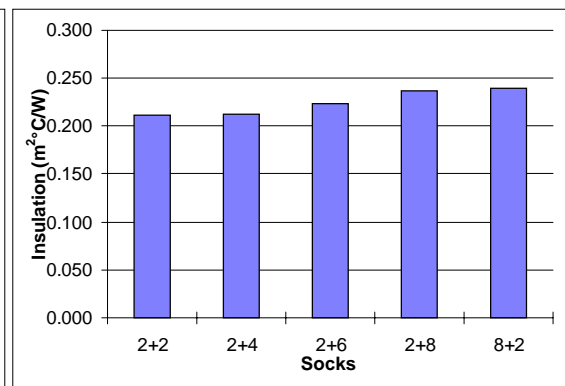
Figure 4. Effect of adding one thin sock to every type and the effect of having it inside or outside.
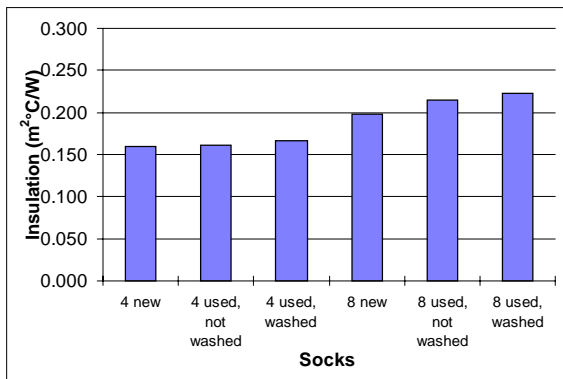
Figure 5. Effect of the use and washing.
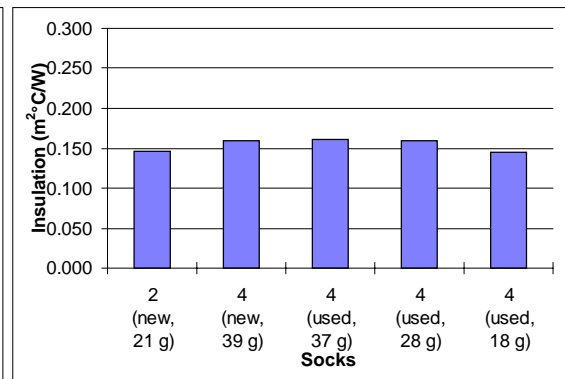
Figure 6. The effect of wear.

Results and discussion

There is a clear difference between socks with various material thickness/weight (Figure 1). By combining different socks to the same material weight the effect of layers becomes obvious (Figure 2). The effect of layers is even clearer if one compares Figures 1 and 3. Adding one layer of thin sock to each sock type increases more noticeably the insulation of thinner socks (Figure 4) and the difference between the insulation provided by different sock types decreases (Figures 1 and 4).

Figure 5 shows the effect of use and washing. The slightly higher insulation of washed socks could be related to the properties of wool fibres that become more loose with washing thus increasing material thickness and trapping more air. With use, dirt and compression diminish this effect. Such behaviour of wool fibres could also explain, why a cotton sock of the same weight has slightly lower insulation than a woollen one (Figure 1).

Figure 6 shows, how the insulation reduces with the loss of material on the example of a sock material of 400 g/m^2 and in comparison with a sock material of 200 g/m^2. A used sock had higher insulation than a new one after washing. This could be related to the loosening of the wool fibres. When the material had become more worn out, the insulation decreased. However, when the sock had lost the loose wool fibres and the material had reduced to the weight of a thinner sock, then the insulation had decreased accordingly.

Similar effect of layers can also be observed in the case of footwear in Figure 7. It shows clearly that higher insulation of the footwear is related to lower gain of insulation corresponding to the added socks. It means that the well insulated footwear traps air relatively well and adding socks could even press out some air. However, the sock layers would gain importance during sweating as moisture transport and absorption media, thus contributing to better comfort. This question should be studied further.
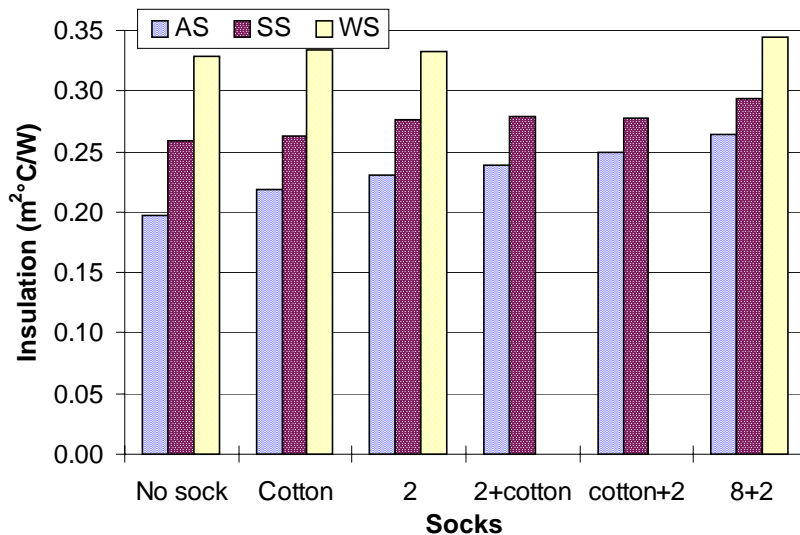
Figure 7. Insulation of the footwear without and in the combination with socks.

Conclusions

- It is more effective to use several layers for higher insulation.
- Thin layers give relatively higher insulation gain than thick socks with the same number of layers.
- Washing increases the insulation of woollen socks to a certain extent. However, each use and washing reduces the amount of material in the sock and in long run the insulation will decrease.
- Footwear insulation increases with added socks. The effect of insulation gain is bigger in footwear with lower insulation.

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Methods for cold protective clothing evaluation

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Introduction

For evaluation of the protection requirements in cold environments it is suggested that thermal insulation values from a moving thermal manikin (ENV 342) can be used to match requirements specified by the IREQ-method (ISO/TR-11079, 1993). It is known from prior work (Olesen et al, 1982; McCullough & Hong 1992; Nilsson et al, 1997) that the clothing insulation can be reduced by wind and body movements by up to 70 % from the value measured on a standing thermal manikin.

This paper deals with the assessment of the effects of wind and walking movements on insulation reductions of clothing and how it can be used for evaluation of work clothing with a modified IREQ-method.

Figure 1. After ten years' construction work, the Øresund Bridge will open to traffic on Saturday, July 1 2000.

Materials and methods

The thermal manikin used is one in the TORE-series that has been described earlier (Hänel, 1983; Nilsson et al, 1992). The power transmission, in the walking apparatus, has been made with pneumatic cylinders, which gives a simple and durable construction with a minimum of mechanical components. The manikin surface sensors and the air temperature sensors were calibrated prior to the tests (ASL F25, Uncertainty: ± 0.015 °C, Pentronic, Sweden).

Three different types of cold protective clothing were investigated. They will be used by the Swedish police force on the Øresund bridge between Sweden and Denmark. The ensembles have a total insulation of up to 5.0 clo (ENV 342:1998) and an air

permeability of 8 l/m²s. The ensembles comprised (A) an outer layer consisting of an insulative jacket and trousers, (B) an insulative overall and (C) jacket and trousers on top of the overall.

The walking speed of the manikin was set to 0 (standing) and 0.8 m/s at an average wind speed, over a cross section of the wind tunnel in front of the manikin, of 0.38 ± 0.07 m/s (Low Velocity Transducer 54R10, Uncertainty: ± 0.02 m/s, Dantec, Denmark).

Figure 2. Pictures of TORE dressed in the different clothing combinations used in the investigation (A to the left and C to the right).

A. Winter overall $I_{cl} = 0.344$ m²K/W

B. Jacket and trousers $I_{cl} = 0.378$ m²K/W

C. Overall as well as jacket and trousers on top. $I_{cl} = 0.458$ m²K/W

Insulation reduction $(I_{t,r}/I_t)$ as a function of air permeability $(p, \text{l/m}^2\text{s})$, wind speed $(v, \text{m/s})$ and walking speed $(w, \text{m/s})$ is calculated with (Nilsson et. al, 2000):

$$I_{t,r}/I_t = 0.54 \cdot e^{(-0.15 \cdot v - 0.22 \cdot w)} \cdot p^{0.075} - 0.06 \cdot \ln(p) + 0.5 \qquad (1)$$

The equation for air layer reduction is produced from (1) by inserting $p = 10000$ l/m²s and $I_a = 0.085$ m²K/W. The equation then becomes:

$$I_{a,r} = 0.092 \cdot e^{(-0.15 \cdot v - 0.22 \cdot w)} - 0.0045 \qquad (2)$$

Using the relationship below from ENV 342, equation 4 is derived. In all the following calculations $f_{cl} = 1$ is used in consequence of ENV 342, although this can be modified in the future:

$$I_{cl,r} = I_{t,r} - I_{a,r} \quad (A.3) \quad \text{ENV342} \qquad (3)$$

This way of calculating the basic clothing insulation by not taking into account the clothing area factor is questioned. The increase in clothing area is in the region of 30 to 70 % for heavy winter clothing. The value of $I_{cl,r}$ will be underestimated.

$$I_{cl} = \frac{I_{cl,r} + (0.092 \cdot e^{(-0.15 \cdot v - 0.22 \cdot w)} - 0.0045)}{(0.54 \cdot e^{(-0.15 \cdot v - 0.22 \cdot w)} \cdot p^{0.075} - 0.06 \cdot \ln(p) + 0.5)} - 0.085 \qquad (4)$$

$$h_c = \frac{1}{I_a} - h_r \qquad (5)$$

The reduction of the air layer is calculated with equation 2, the $I_{cl,r}/I_{cl}$ correction is now calculated with equation 4. The convective heat transfer coefficient is produced with

equation 5. The equations 2, 4 and 5 replace corresponding equations in ISO TR 11079 for the calculation of IREQ.

Results

The results of the analysis of 8 different conditions on the bridge are shown in Table 1. Weather information, provided by The Øresund Link Consortium, shows that the temperature at Drogden very seldom is below -5 °C during the coldest month. Wind speed data from the same location show values that very seldom exceeds 15 m/s. Relative humidity most of the time is around 80 to 90 %. Two metabolic rates are used for the calculations (EN 28 996:1993) - 100 W/m^2 (Low metabolic rate) and 165 W/m^2 (Moderate metabolic rate).

Table 1. IREQ calculations with wind, permeability and walk reductions made with the new equations.

	Low metabolic rate				Moderate metabolic rate			
M (W/m^2)	100	100	100	100	165	165	165	165
t_a (°C)	5	5	-5	-5	5	5	-5	-5
t_r (°C)	5	5	-5	-5	5	5	-5	-5
p (l/m^{2}s)	8	8	8	8	8	8	8	8
w (m/s)	0	0	0	0	0.8	0.8	0.8	0.8
v (m/s)	5.0	15.0	5.0	15.0	5.0	15.0	5.0	15.0
rh %	85	85	85	85	85	85	85	85
I_{cl}- available	*0.458*	*0.458*	*0.458*	*0.458*	*0.458*	*0.458*	*0.458*	*0.458*
IREQ (m^{2}K/W)	**0.298**	**0.332**	**0.416**	**0.451**	**0.168**	**0.197**	**0.241**	**0.269**
I_{cl}- needed	*0.415*	*0.679*	*0.591*	*0.946*	*0.235*	*0.380*	*0.351*	*0.548*
DLE *(hours)*	*>8.0*	*1.1*	*1.8*	*0.5*	*>8.0*	*>8.0*	*>8.0*	*1.7*

The low metabolic rate is presumed to correspond to a standing activity and the moderate metabolic rate to conditions with light movements. The corrections in IREQ (neutral, $I_{cl,r}$) are now depending on the prevailing wind, permeability and walking conditions.

Discussion

The clothing insulation is strongly affected by wind and to some extent by body movements. The combined effect of body movements and wind increases the heat loss from the human body. A reduction of the clothing is consequently needed.

At the most severe situation in table 1 (-5 °C and 15 m/s) the evaluation suggests a work duration (exposure time) for half an hour - if standing still. The time limit prevents body cooling to unacceptably low levels. With the higher activity this time can be increased to approximately one and a half hour. Another possibility is, of course, to increase the insulation at these extreme cases. On the other hand is it recommendable to decrease the insulation, e.g. by taking of the jacket, if the temperature goes up to 5 °C or if the wind decreases to 5 m/s.

More investigations have to be made with the clothing area reduction factor f_{cl} for multilayer winter clothing at high wind speeds and during movements. Special consideration has to be made concerning the fact that the wind sometimes is compressing the clothing material and consequently reducing area increase.

Conclusions

The new set of equations makes it possible to calculate the insulation reduction due to activity and wind for most winter work clothing, if the static clothing insulation is known from the manufacturer or manikin measurements.

The analysis provides an overall assessment of the protective value of the three ensembles, that can be used as a guideline for organisation and performance of work during extreme weather conditions. It is necessary to emphasise that the final adjustment of clothing must be made by the user according to his or her situation, requirements and preferences.

To validate the relationships measurements on subjects exposed to real conditions on the bridge would be valuable.

Acknowledgements

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Research on typical medical work clothing on humans and on a thermal manikin

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Introduction

Many models and indices for predicting comfort or thermal stress make use of the value of the insulation of the clothing worn in a specific situation. Normally, this insulation value is unknown and has to be determined usually on humans, but more often on thermal manikins. For the same clothing ensemble the insulation value determined on humans was generally found to be lower than the corresponding value determined on a manikin, with no satisfactory explanation of the observed differences. Our ultimate objective is to confirm and test this effect. The present work – thermal insulation measurements of medical work clothing using a thermal manikin compared to measurements on humans – is only the initial phase in the realisation of this task. We would also like to look at those results from the point of view of ergonomics and show how they can be used to determine the parameters of the working environment in which medical personnel in that clothing will be at thermal comfort.

Methods

Garments

Three clothing ensembles were selected for this study:

Ensemble A - shoes, socks; underwear, briefs and a shirt (cotton); surgical ensemble (cotton-like nonwoven with hydrophic viscose fibres, material square metre weight [sq]=65 g/m^2±7, good permeability of air and water vapour).

Ensemble B - Ensemble A plus a surgical apron (hygienic foil-covered two-layer nonwoven made of fibres and polypropylene foil, material square metre weight [sq]=45 g/m^2±2), not permeable to any liquids).

Ensemble C - Ensemble A plus a surgical apron (thermoplastic two-layer hygienic nonwoven made of propylene fibres and hydrophilic viscose fibres, material square metre weight [sq]=35 g/m^2±2, good permeability of air).

The ensembles were chosen as typical medical work clothing, made according to WHO recommendations and the requirements of ISO 9001 and EN 49000.

Thermal manikin

Clothing insulation of the tested ensembles was determined using a thermal manikin type TM3 (made in cooperation with the Thermal Insulation Laboratory, Technical University of Denmark). The measurements were performed according to ISO 9920.

Posture and movements

One posture and one movement type were tested: rest in standing posture.

Wind

One wind condition was tested: no wind (air speed ≤ 0.1 m/s). That is why all the experiments were performed in a climatic chamber.

Experimental procedure

Manikin - I_a, I_T test: The experiments were carried out in a climatic chamber in which air (T_a) and mean radiant temperature (T_r) were maintained to within 0.1 °C. Relative humidity was kept constant at 40±5 % and air velocity at 0.1±0.03 ms^{-1}. Two series of experiments were performed.

In series I (nude manikin), I_a dependence was determined for various values of ($T_{ms} - T_o$) and for various values of H. There was a total of 12 experimental sessions. Each session lasted about 4 hours.

In series II (clothed manikin), I_T insulation was determined for the clothing ensembles (A, B, C) selected for this study. During the experiments the operating temperature in the climatic chamber was kept constant at 23.5±0.1 °C. There was a total of 15 experimental sessions. Each session lasted about 4 hours. During this period all measurements were performed every second and recorded as minute averages. The measurements were also continuously displayed graphically, enabling an easy check of the steady situation.

Humans – I_a, I_T test: Seven healthy male subjects (Table 1) volunteered for these experiments. The studies on humans are conducted for the same clothing ensembles (A, B, C), in exactly the same conditions as for the studies with the manikin (rest standing posture, practically identical thermal load conditions). Subjects began the test at a mean skin temperature of 33 ± 0.5 °C (comfort).

Table 1. Physical characteristics of subjects

Subjects	Body weight (kg)	Height (m)	A_D* (m^2)	Age (years)
AS	70	1.72	1.82	23
JT	65	1.79	1.82	27
TT	71	1.72	1.83	29
PR	67	1.73	1.79	23
KK	77	1.74	1.91	23
AK	81	1.79	1.99	26
ML	80	1.77	1.97	22
Mean	73.0	1.75	1.87	25

*A_D Hardy and DuBois Body area.

A measurement session in the climatic chamber lasted for 120 minutes. There was a total of 28 experimental sessions.

Maximal oxygen uptake in the subjects was calculated by the indirect method of Astrad-Ryhming. Metabolic heat production was calculated from oxygen consumption. Oxygen content and the respiratory quotient were measured with a Beckman analyser. Rectal temperature and mean skin temperature were measured with the accuracy of 0.15 °C using standard thermocouples, and recorded on a 15-channel Ellab point recorder.

Mean skin temperature was calculated in accordance with the 8-point Hardy and DuBois formula; heart rate – by counting QRS of the EKG. The body and clothes were weighed before and after the experimental period (accuracy ± 5 g).

Physical basic and derived parameters were measured according to ISO 7726. All these measurements and calculations were carried out every 5 min.

Calculations

Insulation (manikin): Total insulation, I_T (in $m^2 \cdot °C/W$), is the insulation from the surface of the manikin to the environment, including the effect of the increased surface area, f_{cl}, and the resistance on the surface of the manikin, I_a.

$$I_T = \frac{\overline{T}_{cms} - T_o}{H}$$

where: T_{cms} =mean manikin surface temperature, in °C; T_o =operating temperature, in °C; H=heat loss from clothed thermal manikin, in W/m^2.

Surface air insulation (I_a) and effective clothing insulation (I_{cle}) can be similarly calculated:

$$I_a = \frac{\overline{T}_{nms} - T_o}{H} \qquad\qquad I_{cle} = \frac{\overline{T}_{cms} - T_o}{H} - I_a$$

Insulation (humans): During the relative steady states of body temperatures observed at the end of our experiments, $(C+R)_{sk}$ is determined from the heat balance equation: $(C+R)_{sk} = M - E - E_{res} - C_{res} - S$, where M is metabolic rate, E is evaporative heat loss rate, E_{res}, C_{res} are evaporative and convective respiratory heat rates respectively, S is heat storage rate, all in $W \cdot m^{-2}$.

Total clothing insulation I_T and effective insulation I_{cle} (all in $m^2 \cdot °C/W$) can be similarly calculated:

$$I_T = \frac{\overline{T}_{sk} - T_o}{M - E - E_{res} - C_{res} - S} \qquad\qquad I_{cle} = \frac{\overline{T}_{sk} - T_o}{M - E - E_{res} - C_{res} - S} - I_a$$

where I_a – resistance at the surface of the clothed body $I_a = 1/(h_c + h_r)$ determined from experiments in "nude" conditions (briefs and shoes).

The measurements and calculations were performed according to ISO 9920.

Results from the point of view of ergonomics: Assuming typical activities, typical environmental parameters and knowing thermal clothing insulation (ensemble A and C) for surgeons in the operating theatre, operating temperatures at which medical personnel will be at thermal comfort were estimated on the basis of heat balance and comfort defined with the PMV index.

Statistics: A statistical package STATGRAPHIC and analysis of variance were used to determine the effects of the parameters under investigation on insulation values. Two-Sample Analysis and ANOVA were used to test differences between separate levels of significant parameters. A significance level of α=0.05 was accepted.

Results and discussion

The results of the manikin and humans measurements are presented in Table 2. The insulation of the surface air layer of the manikin/humans is 0.78 clo.

Table 2. Mean values and standard deviations of total (I_T) and effective (I_{cle}) thermal clothing insulation calculated for each experimental session (three ensembles measured on the standing manikin and standing **subjects** at air velocity ≤ 0.1 m/s). The differences between the average values (**subjects**, manikin) for ensembles A and B are statistically significant (Two-Sample Analysis, s.l.=0.02÷0.03).

Ensemble	I_T		I_{cle}	
	(m^2K/W)	**(clo)**	**(m^2K/W)**	**(clo)**
A	0.206 ± 0.001	1.33 ± 0.01	0.084 ± 0.001	0.54 ± 0.01
	0.25 ± 0.03	**1.6 ± 0.2**	**0.13 ± 0.03**	**0.8 ± 0.2**
B	0.218 ± 0.002	1.40 ± 0.01	0.096 ± 0.002	0.62 ± 0.01
	0.25 ± 0.03	**1.6 ± 0.2**	**0.13 ± 0.03**	**0.8 ± 0.2**
C	0.269 ± 0.001	1.73 ± 0.01	0.147 ± 0.001	0.95 ± 0.01
	0.28 ± 0.05	**1.8 ± 0.3**	**0.16 ± 0.05**	**1.0 ± 0.3**

Manikin

The relative measurement error of clothing thermal insulation (I_T) treated as an error of the complex value is approximately 3 %. The partial input of particular measured values is as follows: operating temperature measurement error (T_o) – 56 %, manikin surface temperature (T_{ms}) – 35 % and heat loss from manikin surface (H) – 9 %. The relative error assessed on the basis of the measurements does not exceed 2 %. Thus, the role of the climatic chamber is important for these measurements. The number of necessary measurements assessed on the basis of the average variance of results for estimate precision of 0.01 clo is n≅11, and for 0.02 clo it is n≅3. Therefore, for testing clothing in practice it is sufficient to repeat measurements three times for one tested ensemble. The differences between the average values for ensembles are statistically significant (ANOVA, F=1000).

Humans

The relative measurement error of clothing thermal insulation (I_T) treated as an error of the complex value is approximately 6 %. The partial input of particular measured values is as follows: metabolic heat production error (M) – 52 %, skin temperature (T_{sk}) – 24 %, operating temperature (T_o) –16 % and evaporative respiratory heat rate (E_{res}) – 6 %. The relative error assessed on the basis of the measurements changes from 12 % to18 %. The number of necessary measurements assessed on the basis of the average variance of results for estimate precision of 0.02 clo is n≅600, and for 0.2 clo it is n≅8. That is why, in order to increase precision of the measurements of thermal insulation on humans, the precision of the measurements of metabolic rate and skin temperature should be increased, with the same number of measurements. The differences between the average values for ensembles are not statistically significant.

Humans/manikin – comparisons

To make a correct comparison possible, the conditions of the experiment were chosen such that a manikin, which cannot sweat or move and which is made to stand, was compared to a standing human at rest in thermoneutral conditions (a limited amount of excreted sweat). For this experimental condition for the same clothing ensemble, the insulation value determined on humans was generally found to be slightly higher than the corresponding value determined on the manikin (it was 13 %). This difference can additionally increase after diffusion evaporation through the skin has been considered in calculating thermal insulation of the clothing.

Clothing insulation-point of view of ergonomics

Ergonomic conditions (thermal comfort) for medical personnel is determined by limit values for operating temperature: Ensemble A (20 °C$\leq T_o \leq$24 °C); Ensemble C (16 °C$\leq T_o \leq$20 °C).

Conclusions

To summarise, it is risky to draw general conclusions from measurements on the three garments tested in one set of thermal load conditions of our experiment. However, the measurements show clearly that:

1. for the same clothing ensemble, the insulation value determined on humans was generally found to be slightly higher than the corresponding value determined on a manikin,
2. taking diffusion evaporation into consideration can additionally increase this difference,
3. a thermal manikin makes it possible to determine thermal clothing insulations a few times more precisely compared to measurements performed on humans,
4. greater precision in determining thermal clothing insulations on humans can be achieved by making measurements of oxygen consumption more precise and – to a lesser degree – by making measurements of skin temperature more precise.

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Comparative evaluation of the methods for determining thermal insulation of clothing ensemble on a manikin and person

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Introduction

According to the European standard ENV 342-97 (ENV 342, 1997) the heat-shielding parameter of an ensemble for protection against cold, called the resultant total thermal insulation (I_{tr}, ºCm^2/W) is determined with a heated physical model (manikin). This adequately reflects the conditions of heat exchange with the environment. According to the Russian standard GOST R12.4.185-99 (Standart R 12.4.185-99, 1999) thermal insulation of an ensemble for protection against cold is determined directly on a person. Undoubtedly each of these methods has both advantages, and disadvantages (Higenbottam et al., 1997). A comparison of the methods would be useful from positions of mutual use of the data with the purposes of manufacturing clothes with proper heat-shielding parameters.

Methods

Four clothing ensembles (I-IV) were used for determination of their thermal insulation on a manikin (ENV 342, 1997) and on a person (Standart R 12.4.185-99, 1999). The ensembles included a jacket and trousers, having various thickness of thermal insulation. As top and lining the fabric "Pertex" was used and Thinsulate™ manufactured by the company 3M was used as thermal insulation.

A volunteer (man in the age of 40 years, surface of a body is equal to 1.8 m^2) and a manikin were dressed in a cotton linen, half-woolen sports costume, cotton and half-woolen socks, heated jacket and trousers, helmet, mittens, heated boots.

Before the experiment according to (Standart R 12.4.185-99, 1999) the volunteer, wearing an ensemble of "indoor" clothes, sat within 30 minutes in a comfortable microclimate: air temperature (t_a) 23.0±0.5 ºC, relative humidity 40±5 % and air velocity (V) less than 0.1 m/s. The sensors for measurement of "dry" heat flow (q, W/m^2) and skin temperature (t_s, ºC) (Nilsson, 1997) were placed on the skin surface to the following locations: forehead, chest, back, stomach, waist, shoulder, back of the hand, upper and bottom of a hip, shin, and back of the foot. The subject donned the clothing ensemble (jacket, trousers, helmet, mittens, footwear) and entered the climatic chamber. Air temperature was kept at 8.0±0.5 ºC. The value of t_a was selected so as to provide the subject with comfort.

The tests were repeated three times in a relatively calm air. The volunteer was standing in the climatic chamber for 60 minutes. The values of t_s and q were registered with a periodicity of 5 minutes. On the bases of local values of t_s and q were calculated the average

weighted skin temperature (t_{aws}) and the "dry" heat flow (Afanasieva, 1977, Afanasieva, 1994).

The thermal insulation of the ensembles, determined on the person, was calculated according to the equations 1-3 (Table 1).

Table 1. The equations used for calculation of a thermal insulation of clothing ensembles, I_e, ºC·m²/W, by results of tests on the person (1 - 3) and the manikin (4 - 5).

Nr.	Equation	Note
1	$I_e = (t_{aws} - t_a)/q_{aws} \Rightarrow [(\Sigma f_i \cdot t_{si}) - t_a]/\Sigma f_i \cdot q_i \Rightarrow$ $\Rightarrow [(\Sigma f_i \cdot t_{si}) - t_a] \cdot A/\Sigma Q_{ci}$	GOST 12.4.185-99 SSBT
2	$I_e = \Sigma f_i \cdot R_i \Rightarrow \Sigma f_i \cdot [(t_{si} - t_a)/q_i] \Rightarrow$ $\Rightarrow \Sigma f_i \cdot [(t_{si} - t_a) \cdot a_i /Q_{ci}] \{ºC·m²/W\}$	ENV 342-1997
3	$I_e = 1/\Sigma f_i \cdot K_i \Rightarrow 1/\Sigma f_i \cdot [q_i/(t_{si} - t_a)]$	GOST 12.4.185-99 SSBT
4	$I_{tr} = [(\Sigma f_i \cdot T_{si}) - T_a]/\Sigma H_{ci} \Rightarrow$ $I_{tr} = [(\Sigma f_i \cdot t_{si} - t_a)] \cdot A/\Sigma Q_{ci} \{ºC·m²/W\}$	PrEN 342: 1995
5	$I_{tr} = \Sigma f_i \cdot [(T_{si} - T_a) \cdot a_i/H_{ci}] \{K·m²/W\} \Rightarrow$ $\Rightarrow I_{tr} = \Sigma f_i \cdot [(t_{si} - t_a) \cdot a_i /Q_{ci}] \{ºC·m²/W\}$	ENV 342-1997

Where:

f_i - factor of area of a section of a manikin or human body part; $f_i = a_i/A$;

a_i - area of surface of a section of a manikin or human body part, m²;

A - common area of surface of a manikin or human body, m²;

$T_{si} = t_{si}$ - local temperature of a surface of a section of a manikin or human body part, ºC;

$T_a = t_a$ – air temperature, ºC;

H_{ci} - local power of heating of a section of a manikin, W;

q_i - density of a "dry" heat flow of a site of a human body, W/m²;

Q_{ci} - heat flow of a site of a human body surface (manikin), W;

K_i - heat transfer coefficient, W/ºC·m².

The change of a thermal insulation of the clothing ensemble under influence of wind and walking of the person was determined on the bases of the empirical equation obtained before (Afanasieva, 1977, Afanasieva, 1994) with reference to the given sort of clothing (jacket and trousers):

$$C = (0.07 \cdot B + 2.0) \cdot V + 5,$$

where:

C - lowering the I_s value, %;

B - air permeability of a package of clothing materials, dm³/m²·s;

V - Wind speed, m/s.

The above described clothing ensembles were investigated also according to (prEN 342, 1995; ENV 342, 1997) on a manikin. The conditions for the standing manikin were the following: air temperatures of 10.6±0.2 ºC or 5.1±0.3 ºC and air velocity <0.2 m/s, and at t_a=4.1±0.1 ºC and V=1 m/s. The conditions for the moving manikin were the following: walking 0.8 m/s (2.8 km/h), t_a=4.8±0.1 ºC and V<0.2 m/s, and ta = 4.2 ºC and V=1 m/s.

The calculation of the resultant thermal insulation (I_{tr}) of the clothing ensemble by the results of the tests on the manikin were conducted according to the equations 4 (prEN 342, 1995) and 5 (prEN 342, 1995; ENV 342, 1997) (Table 1). The equations 1-3 and 4-5 are identical in their heat physical meaning.

Table 2. Thermal insulation of a clothing ensembles [I_e, °C·m^2/W (clo) *].

Ensemble number	Average weighted thickness of material package, δ, cm	On the person			On the manikin	
		Equation, on which was calculated I_e				
		1	2	3	4	5
I	4.49	0.750	0.808	0.749	0.704	0.928
		(4.87)	(5.21)	(4.83)	(4.5)	(6.0)
II	3.47	0.648	0.676	0.647	0.636	0.839
		(4.18)	(4.36)	(4.18)	(4.1)	(5.4)
III	2.23	0.557	0.581	0.557	0.555	0.660
		(3.59)	(3.75)	(3.59)	(3.58)	(4.30)
IV	1.28	0.519	0.535	0.519	0.548	0.667
		(3.35)	(3.45)	(3.35)	(3.5)	(4.40)

* 1 clo = 0.155 °C·m^2/W;

Results and discussion

The values of thermal insulation of the clothing ensembles calculated by various ways according to the test results from a person and a manikin are given in Table 2. According to the data, the value of I_e calculated with a person by the equations 1 and 3 are practically identical (difference 0-0.7 %); and those calculated by the equations 1 and 2 differ by 3-6 %. The difference between values of I_e and I_{tr} defined by the tests on the person and the manikin and calculated according to the equations 1, 3 and 4 are within the limits of 3-6 %; the differences in values defined by the equations 2 and 5, 1 and 5 are more essential (12-22 %; 15.6-22.8 %).

Thus, the analysis of obtained data indicates that the difference in values of a thermal insulation of a clothing ensembles measured on a person and a manikin "at rest" under relatively calm air are defined by the way of their calculation. The least differences are observed with calculations according to the equations 1 and 3 (Standart R 12.4.185-99, 1999) and 4 (prEN 342, 1995); the greatest - by the equations 1 and 5 (ENV 342, 1997). Accordingly, a conclusion can be made, that for determining of heat-shielding properties of clothing ensembles the various methods (studies on the person and manikin) can be used.

However, only when the equations 1 (or 3) and 4 (respectively for the person and manikin standing still) are used for the calculation of a thermal insulation of clothing ensembles, the statistical differences are minimal.

The studies carried out under conditions of wind and walking have shown that under influence of these factors a greater reduction of the thermal insulation of a clothing ensemble is observed when testing them on a manikin than on a person. The thermal insulation of an ensemble during walking under the effect of wind was reduced 32.6 % and 10 %, respectively.

The most relevant values of a thermal insulation of clothing ensembles are obtained by calculation according to the equations 1 (Standart R 12.4.185-99, 1999) and 4 (prEN 342, 1995).

The essential differences in values of thermal insulation of a clothing ensemble obtained under the effect of wind and walking on the person and the manikin suggest that additional studies on the influence of these factors are carried with allowance for variation in its construction and thermo-physical parameters of materials.

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Evaporative resistance of various clothing ensembles measured on standing and walking manikin

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Introduction

Evaporative heat loss (E) and evaporative resistance of air layer and clothing (R_t) are important components of human heat balance models (Wenger 1972). They can be estimated according to ISO standard (ISO 7933). However, measured values for E and R_t obtained with thermal manikins are rare (Blazejczyk & Holmér 2000, McCullough et al. 1989, Meinander 1994, Kuklane & Holmér 1998, Liu & Holmér 1995, Tamura et al. 1994). The purpose of the paper is to present the results of experimental studies of evaporation rate (dm) and evaporative resistance (R_t) with a sweating manikin when wearing various clothing ensembles in different ambient conditions.

Materials and methods

The measurements were made in climatic chamber. Air temperature is regulated from 0 up to 35 °C. However, air humidity depends on air moisture outside the chamber. Air movement is generated by 3 wind turbines and can be regulated precisely from 0.2 to about 2 m s^{-1}. At "no wind" conditions an air motion of 0.1 m s^{-1} was assumed. The humidity in the chamber was determined by psychrometric measurements. Three pairs of thermometers (dry and wet bulb) - located on the altitude of 30, 130 and 180 cm over the floor - were used.

A standard thermal, moveable manikin (TORE) was used as the anthropometric model for the sweating system. The manikin has 17 separately controlled segments. For the wet measurements the whole manikin was covered with thin plastic foil to protect temperature sensors and heated wires against water infiltration. The skin surface was simulated using a tight fitting, cotton, long underwear. Feet and hands were dressed in thin socks and gloves.

The water supply system consisted of a GILSON ® peristaltic pump Minipuls 3, which supplied water simultaneously through 8 PVC tubes. The water was distributed to 6, left side segments of the manikin (upper arm, lower arm, hand, thigh, calf and foot). Special Y-shaped devices multiplied the number of watered points on the skin surface (up to about 20). The other segments of the manikin were kept dry. The volume of water supplied was settled at a level similar to evaporation observed in subjects at the same ambient conditions. We have excluded the problem of water dripping and the wettedness of skin was relatively constant during every run of the experiment (36-46 % of total water capacity of skin textile). The MENEX model was used for simulations (Blazejczyk 1994).

The water loss from the skin surface was observed on the nude manikin as well as under two types of clothing: tennis (T-shirt+shorts+socks) - basic I_{cl} of 0.32 clo and standard (long sleeve shirt+trousers+socks) -I_{cl} of 0.59 clo. The tests were made on stationary

and walking ($v' = 0.8$ m s^{-1}) manikin as well as at two wind speeds (v): 0.1 and 1.0 m s^{-1}. The studied combinations of ambient conditions are shown in Table 1.

Table 1. The studied ambient conditions.

Ta (°C)	vp_a (kPa)	RH (%)	v (m s^{-1})	v' (m s^{-1})
20	0.9-1.3	40-55	0.1 & 1.0	0.0 & 0.8
27	1.1-1.5	30-45	0.1 & 1.0	0.0 & 0.8
34	1.4-1.9	25-40	0.1 & 1.0	0.0 & 0.8

The I_{cl} values for standing manikin in still air were assumed as refereed insulation of examined ensembles. However, clothing insulation observed on dry manikin in various combinations of wind and walk is shown in Table 2.

Table 2. Clothing insulation at various combinations of wind and walk.

Clothing ensemble	Air movement conditions			
	v=0, v'=0	v=1, v'=0	v=0, v'=0.8	v=1, v'=0.8
tennis	0.324	0.133	0.116	0.130
standard	0.593	0.492	0.418	0.426

v and v' in m s^{-1}

Total evaporative resistance (R_t in kPa m^2 W^{-1}) was calculated as follows:

$$R_t = \frac{(vp_s - vp_a) \cdot A}{\lambda \cdot \frac{dm}{dt}}$$

where: dt - time rate (in seconds), dm - rate of water evaporated (in grams), λ - latent heat of vaporisation (= 2426 J), A - studied area (m^2), vp_s - vapour pressure on the surface (kPa), vp_a - air vapour pressure (kPa).

The total evaporative resistance consists of vapour resistance of boundary air layer (R_a) and vapour resistance of clothing (R_{cl}). The R_t calculated for nude manikin is equal to R_a values. Thus, clothing evaporative resistance (R_{cl}) can be determined.

Results

The water loss from the manikin (dm) decreased according to the rise in basic insulation of clothing ensembles. The trend is observed at all combinations of ambient conditions and varied from about -40 g per hour for an increase in insulation of 1 clo at an air temperature of 20 °C up to -55 g per hour - at T_a of 34 °C (Figure 1).

Evaporative resistance of clothing ensembles (R_{cl}) were derived from R_t values calculated for clothed and nude manikin. It clearly depends on air and/or manikin movement as well as on basic insulation of clothing. The biggest R_{cl} was found in still air (0.006 kPa m^2 W^{-1} for standard and 0.0025 kPa m^2 W^{-1} for tennis clothing). Air and/or manikin movement reduced R_{cl} values to about 0.0005 - 0.0015 kPa m^2 W^{-1} (Figure 2). The biggest differences in R_{cl} for standard and tennis clothing were noticed at still air on standing manikin. Considerably high were also differences in R_{cl} between compared clothing ensembles at air temperature of 34 °C.
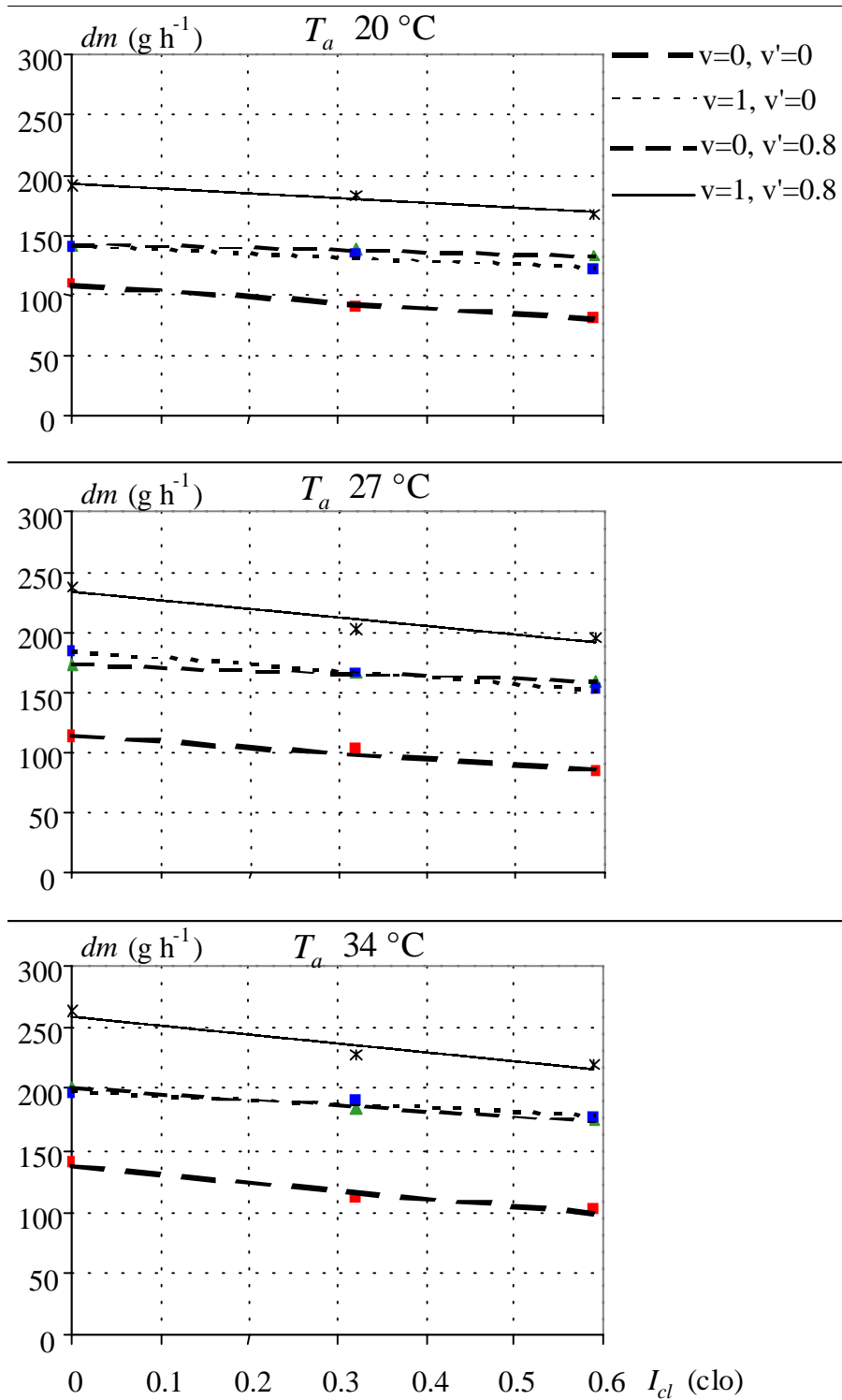
Figure 1. Evaporation rate (*dm*) as function of clothing insulation (I_{cl}) at various air temperature (T_a) and air movement/walking (*v, v'*).

Conclusions

1. The trends in *dm* in relation to clothing insulation have negative values, i.e. increase in I_{cl} reduces amount of water evaporated from the manikin surface.
2. Evaporative resistance of clothing (R_{cl}) was highest in still air on standing manikin. The air and/or manikin movement reduces R_{cl} values to about 40 % for tennis and about 20 % for standard clothing.

3. The probable reasons of R_{cl} reduction due to air movement around the manikin is the increased convection in microclimate and boundary layers by wind and movements.

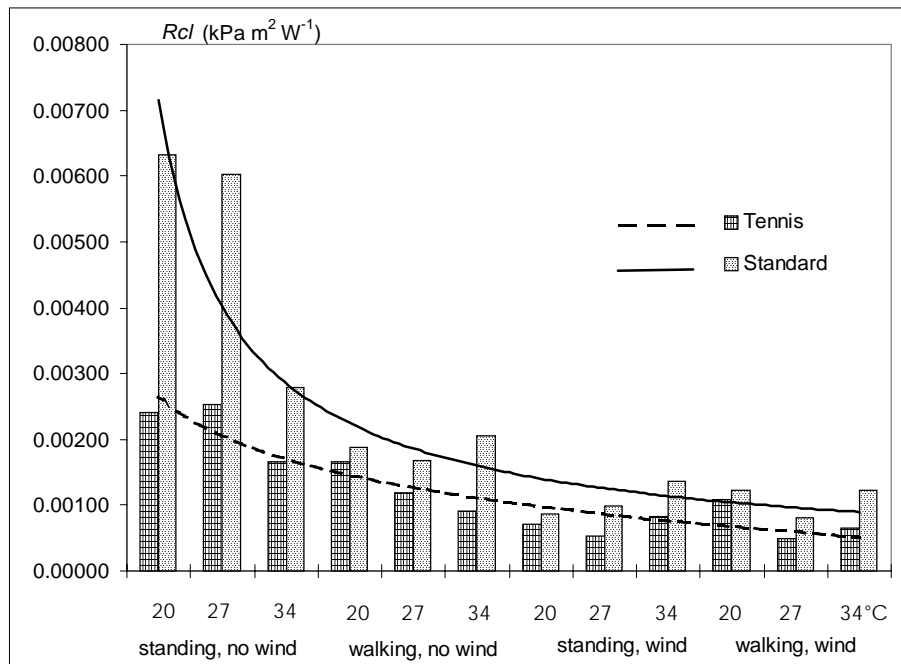**Figure 2.** Evaporative resistance of clothing ensembles at various combinations of air temperature (20, 27 and 34 °C) and air movement on standing and walking manikin.

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Rain tightness of protective clothing – Prenormative interlaboratory tests using a manikin

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Introduction

Current European and national standardisation of protective clothing against foul weather requires water-tightness tests for materials and seams only, as for these items, appropriate test standards and extensive test experience are available. In addition to material testing, standards should require testing of the complete garments in order to verify their rain tightness. In order to achieve this aim, a test standard to determine the rain tightness of garments has yet to be developed.

In recent years, test institutes have applied various rain test methods in the context of research activities, product development and quality assurance in the framework of production control measures. These test methods need to be compared by interlaboratory tests involving various test institutes in order to prepare the ground for the development of a European standard for a rain test. This paper outlines different rain test methods, explains the methodology applied for the interlaboratory tests and presents their essential results.

The tests were conducted in the framework of a research project carried out jointly by EMPA (Swiss Federal Laboratories for Materials Testing and Research), St. Gallen, Switzerland, and ZS (Centre for Safety Engineering), Erkrath, Germany.

Rain test methods

In order to check the rain tightness of garments, three different rain test methods are used in Europe, which will be briefly described in the following. They mainly differ in the way in which the artificial rain is produced and the type of manikin.

Rain test with drop nozzles (Method 1)

In order to produce the artificial rain (approx. 450 l/hm²), a tub containing drop nozzles spaced 3.4 cm apart is fixed approx. 10 m above a manikin dressed with the test clothing. The diameter of the water droplets of approx. 4 mm complies with EN 29865 (rain-shower test for textile fabrics). An anthropometric manikin made of synthetic material is used for testing. In order to visually check and inspect the test clothing for any signs of water penetration after the exposure to artificial rain, the manikin is dressed with a detection undershirt made of material with high water absorbing qualities, such as cotton. In addition, several sensors are fixed on different parts of the manikin in order to collect information on when and where during the rain shower test wet areas occur.

Rain test with full cone nozzle (Method 2)

The artificial rain (approx. 100 l/hm²) is produced by a full cone nozzle (with a spray angle of 90°), which is placed approx. 6 m above a manikin and sprays out the water droplets to obtain a diameter of approx. 0.5 mm. The protective clothing against foul weather is worn by an inflatable manikin, so that almost the entire inner face of the test garments, such as a jacket or a pair of trousers, comes into contact with the inflatable manikin. The manikin used for this rain test method is also dressed with a (cotton) detection undershirt, which, where appropriate, is provided with humidity sensors.

Rain method with drop-spray-nozzles (Method 3)

The manikin is positioned in the centre between four vertical tubes containing several nozzles which are placed at a defined height. The nozzles produce bow-shaped drop sprays (droplet diameter approx. 1 mm), wetting the test clothing from the sides. In addition, the test clothing is wetted from behind by drop-spray-nozzles placed above the manikin's head. The intensity of the artificial rain is approx. 240 l/hm². Humidity sensors are fixed at the manikin, which is also dressed with a cotton detection undershirt. The dimensions of the rain test device are approximately 1 m x 1 m x 2.5 m.

In the following, some meteorological data on the amount of precipitation and droplet size will be given, which will allow you to compare the artificial rain as generated by these three methods with natural rain.

Amount of precipitation: The mean amount of precipitation in many places in Central Europe varies between approx. 500 and 1000 l/m² per year. Heavy rainfall is called a cloudburst if a particularly intensive rain of at least 1 l/min m² falls for a very short period of time. During such a cloudburst, an essential part of the annual precipitation in Central Europe can come down within one hour. In other parts of the world, e.g. in tropical regions, values may exceed 300 l/hm² in special cases.

Type of droplets: The following types of droplets can be distinguished:

a) cloud drops   – diameter less than 0.1 mm   – drop velocity < 0.25 m/sec.
b) drizzle   – diameter 0.1 to 0.5 mm   – drop velocity 0.2 to 2 m/sec.
c) rain drops   – diameter 0.5 to approx. 5 mm   – drop velocity 2 to 9 m/sec.

These data show that all three rain methods correspond to a cloudburst with small or large rain drops. As the rain test method with drop nozzles involves a large droplet mass m and a high drop velocity v, the kinetic drop energy ($E = 0.5 \, mv^2$) is accordingly much higher than the values obtained when using the other methods. This has to be taken into account when comparing the test results.

How the tests were made

Three different test jackets were used for comparison:

a) green jacket   – approx.   990 g   – PUR coating   – without hood
b) blue jacket   – approx. 1000 g   – micro fibres   – without hood
c) red jacket   – approx.   480 g   – double layer laminate – with a hood sewn onto it.

In order to be able to ascertain whether the test results obtained for the three rain methods used show significant differences, the rain test methods applied should neither lead to a dry nor to a completely wet detection underwear. This is why, e.g. for testing the green and the blue jacket, their non-watertight collar seams as well as the head of the

manikin were covered with a plastic bag in order to protect the jackets against excessive water penetration during the tests.

The comparison tests on the three jackets were carried out by five test institutes. At each test institute, the individual jackets were tested twice in accordance with one or more rain test method(s). After the tests, the position of visible wet areas as produced by a leakage in the test jackets was entered into diagrams. In addition, the test jackets and the detection underwear were weighed in their wet and dry condition and the results recorded.

Test results

The essential test results as achieved by the test institutes involved were analysed by means of figures and tables (see Table 1). The results came from a total of 42 rain tests, each carried out for a period of 1 h (without preliminary and additional tests).

Table 1. Summary of wet areas detected.

Test institute	Method	Test	Test jacket		
			green	blue	red
A	1	1	- -	- -	-
		2	- -	-	-
B	2	1	-	+[1]	-
		2	-	+	-
C	3	1	-	+[1]	-
		2	-	+[1]	-
D	3	1	-	+	-
		2	-	+	-
E	1	1	- -	- -	-
		2	- -	- -	-
E	2	1	-	+	-
		2	-	+	-
E	3	1	-	+	-
		2	-	+	-

+   no wet area   -   large wet area or several wet areas
+[1]   only a small wet area   - -   very large wet area (> 50 % of the total jacket surface)

Some essential conclusions drawn from the results of the tests using the three rain methods:

- For one test jacket, the size of the wet area that resulted from water penetration varied depending on the rain method used. The rain tests showed the following sequence in terms of increasing wet spots on the jackets under test:
  - red, blue, green jacket for the rain method with drop nozzles;
  - blue, green, red jacket for the two other rain methods.

  The material of the blue and the green jacket proved not to be sufficiently tight when exposed to large rain drops with high kinetic energy as produced in the rain tests with drop nozzles. When exposed to smaller rain drops, the blue and the green jacket only showed much smaller wet areas or none at all. Because the red jacket was not water-tight, testing carried out on this item led to wet areas on the detection undershirt, regardless of the rain method used.
- The tests generally showed a greater need for the material in the upper region of the jackets, especially in the shoulder area, to be water proof when the tests were carried out with the rain method with drop nozzles rather than with one of the other methods.

The rain tightness of the shoulder area is of particular importance e.g. for protective clothing against foul weather for use on construction sites, since the shoulder area is prominent when rain exposure is concerned. Fabrication flaws such as can be found in seams and the design of fasteners in the lower part of the jacket can be more easily detected in the rain test with full cone nozzle or with lateral drop-spray-nozzles than in the rain test with drop nozzles. A notice indicating such deficiencies may be useful when work has to be carried out under special marginal conditions (e.g. implying the use of water jets).

– For the evaluation of rain tests as carried out on jackets, it is useful to use sensors to get information on when and where wet areas occur as well as data on the water absorption of the detection underwear and the test jacket (see Table 2). The water absorption of the detection underwear and the test jacket should in general be as low as possible. The water absorbed by a test jacket, which is e.g. provided with outer pockets or made of multi-layered material, can amount to more than 500 g (disadvantage: increase in weight and prolonged drying times).

– For the first time ever, the comparison tests allowed, for all three test methods, preliminary information to be gained on the repeatability of the test results. The test results show that for each of the three rain methods, the same sequence could be established for the water tightness of the jackets under test, when the tests were repeated by the same institute or carried out by another. In addition, the occurrence of wet areas was generally quite similar. In order to increase the repeatability of the rain test results, it is necessary – in view of the number of influencing parameters that have to be taken account of in the test specifications – to establish detailed specifications of the test device (e.g. rain and manikin characteristics), the test procedure (e.g. positioning of the manikin), the recording of the test and evaluation of test results.

Table 2. Examples of water absorption of jackets (ja) and detection underwear (de).

Garment	Water absorption [g]		
	Method 1	Method 2	Method 3
ja - green	611	105	270
de	429	-	47
ja - blue	452	40	57
de	120	-	16
ja - red	208	65	74
de	72	-	22

The test results achieved from the present investigation form the basis for discussions and decision-making in the process of standardising a rain test method. A work item for the development of a European standard is already in preparation, so that a generally available European test basis will be specified in the near future.

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Development of the research and technology group flammability manikin systems

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Introduction

The Research and Technology (R&T) Group is responsible for research and development programmes aimed at optimising the performance of textile equipment used by United Kingdom military forces.

These programmes are actively investigating the following important aspects of military equipment.

- Durability.
- Comfort.
- Protection from the environment.
- Protection from battlefield hazards.

Providing the military with the best available materials is essential to ensure they can carry out their duties in the most effective way possible. However, it is also important to minimise the physiological burden imposed by the equipment. R&T Group is leading programmes of work which use smart and responsive materials which allow protection to be provided when required, whilst keeping the physiological burden to a minimum during normal use.

The flame and heat protection programme

One of R&T Groups major items of work is the optimisation of flame and heat protection.

UK military carry out many varied tasks in a wide range of environments. The range of threats from flame and heat are correspondingly varied and can include very simple threats like waste paper basket and fuel spillage fires as well as very complex and severe threats like explosive thermal pulses and Naval below decks fire-fighting.

Personnel can be adequately protected from simple threats by provision of flame retardant working dress for military users or CE marked personal protective equipment for civilians working as contractors on military bases.

Complex threats can only be adequately dealt with using well designed and, in many cases, specifically developed equipment; the key properties being protection from the clearly identified range of risks and compatibility and design of each item of a protective ensemble.

Testing for flame and heat protection

As well as the range of threats being complex and varied, the number of test methods available are also bewildering in their variety. Over recent years, R&T Group have obtained a world class range of apparatus allowing us to characterise important aspects of flame and heat protection relevant to the military environment.

This apparatus range allows us to measure the properties of materials, starting with sample sizes of a few tenths of a gram right through to the whole ensemble of equipment, and includes the following test methods:

- Differential Scanning Calorimeter, Thermo-mechanical and Thermo-gravimetric analysis.
- Resistance to convective and radiative heat sources.
- Resistance to small ignition source.
- Cone calorimetry.
- Flammability manikin.

The flammability manikin has been in use for the last five years and during this time many hundreds of clothing ensembles have been tested. A great deal of useful information has been produced allowing many improvements in protective clothing to be made available to the user.

Why was the flammability manikin developed?

Manikins have been used for many years by R&T Group. Their usefulness was first identified during simulated nuclear thermal exposures in New Mexico, in a series of tests carried out by the US military in which we co-operated. Deploying instrumented steel manikins produced much useful information relating to the measures necessary to protect men in the open from these very severe events.

Development of a laboratory based full body manikin was completed in 1995, which gave us the capability to measure protection when using a less severe challenge than the nuclear pulse. The system was designed to measure two important performance characteristics; the effect of fit and design of equipment on protection and the protective properties different types of textile material.

Features of the manikin system

The system is made up of an instrumented manikin, an array of burners and a computerised data acquisition system.

The manikin is constructed from reinforced polyester resin and is instrumented using 10 mm diameter copper disc calorimeters, set flush with the surface of the manikin.

K type thermocouples are welded onto the inside of the copper discs that measure the temperature of the calorimeter. The manikin is jointed at the neck, shoulders, elbows, wrists, hips, knees and ankles, allowing the manikin to be posed into various positions adding an extra dimension to the range of test conditions available.

The manikin is surrounded by an array of thirty propane cup burners that engulf the manikin in flame, with the energy delivered to the surface being, on average, 75 kW/m^2. Simple manual controls are used at present to pilot and run these burners, fed by four

large propane cylinders, connected in series to allow an even pressure to be delivered throughout the length of any exposure.

Information from the 120 calorimeters over the surface of the manikin is collected by a computerised data acquisition system. One reading is taken per second from each calorimeter. On completion of an exposure, a unique programme, designed specifically for this system, is used to calculate the number of calorimeters that reached the equivalent of first, second and third degree burn. Also the most severely damaged sensor and the earliest time that each of the levels of burn injury was reached is calculated. All the results are presented in the form of an injury curve, a pictogram of damaged sites and the injury values along with other relevant test parameters such as exposure duration and a description of the ensemble.

What is the manikin used for?

The manikin produces results that allow two major aspects of performance to be assessed;

- The effect of garment design.
- The effect of material design.

Exposure of complex ensembles of protective equipment regularly shows up weaknesses in design, for example a very costly flame protective garment will be of little use if parts of the garment trim are ignitable. This type f failure of performance is obvious when manikin testing is carried out, but can be very easy to overlook if only looking at the performance of component materials.

A disadvantage to testing ensembles on the whole body manikin was found to be that it is impossible to realistically dress the manikin with equipment worn about the head and neck, such as headovers, helmets and respiratory protection. This is due to wiring leaving the manikin via a loom attached to the neck and a hook in the top of the head, which supports the weight of the manikin.

Development of the instrumented head form

Due both to the problems described above and the increasing importance of measuring the performance of head protection, particularly for the Royal Navy, we embarked on the development of an instrumented manikin head. The main features of this system were;

- An increased density of calorimeters over the head surface (30 in total, compared to only 18 on the full body system).
- Supported in a way which allows head protective equipment to be donned realistically, without cutting seams or drilling holes.
- For the first time, protective garments for the head can be tested in a situation representative of real-life.

The burner and data acquisition systems are fundamentally the same as for the whole body. The results are presented on a specially adapted pictogram, mapping damaged areas of the head, consequently equipment and material design weaknesses can be accurately identified and corrected and the effect these corrections have on the performance can be measured realistically.

Areas of use for the instrumented head form

As well as identification of optimised head protection for Royal Navy fire-fighters, we are now in a position to offer this innovative new test apparatus for other purposes, namely;

- An optional additional method to support draft European Standards of performance for fire-fighters head protection.
- A commercial facility available to equipment designers to assist in the complex decision making processes involved in measuring the relative performance of the many types of protective clothing currently on the market.
- A design tool for aiding in the optimisation of the available performance of equipment.

We currently have an extensive programme of testing underway to characterise the protective capabilities of new and used in-service military equipment. This programme will, for the first time, make available a comprehensive body of data: This can be used to assist in the risk taking approach which is becoming increasingly necessary when purchasing protective equipment when faced with shrinking budgets. Also it can be used to help to build the confidence of the user in the performance of his equipment – their life and future well being depend on the ability o their equipment to protect them and it is essential that this factor remains uppermost in the designers mind.

Summary

Research and Technology Group's international reputation as designers of military textiles is based on our unbiased and objective assessment of the performance of a huge range of equipment. We are able to back up our assessment work with unrivalled measurement facilities. In the case of flame and heat protection, the full body manikin is now complemented by the world's first head form, a unique piece of equipment that has already proved to be an invaluable tool for our design team.

It is our intention to extend the use of our flammability measurement apparatus to allow it to be exploited commercially. The addition of the head form in particular will become an accepted additional test method to help civilian designers and users decide what equipment is most appropriate for their end use.

Thermal properties of protective gloves measured with a sweating hand

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Introduction

The protective gloves form an important part of the personal protection of a worker. The gloves protect the hands against cold, heat, chemicals, mechanical threats, radiation, etc. An unrestricted performance of the hands is essential for many working tasks, and the need for finger dexterity is often in conflict with the need for protection of the hands. From the thermal balance point of view the hands react differently from the central body parts, cooling rapidly in cold conditions and being an area with high heat loss and sweating in the warm conditions.

The thermal comfort of the hands is essential for the general work efficiency and safety. This is not generally considered in the choice and classification of protective gloves. In the European standards for protective gloves, the general requirement standard EN 420 states that "Where practicable, protective gloves shall allow water vapour transmission" and gives a recommended value of 2 mg/cm² for leather gloves, tested according to the leather standard IUP 15. EN 420 also states that "Where the protection level of the glove inhibits or excludes water vapour transmission, then the glove shall be designed to reduce the effect of perspiration as much as possible". The water absorption of leather gloves should be at least 8 mg/cm²·8 h. In the standard for protective gloves against cold, EN 511, the thermal resistance is determined using a thermal hand model, in which however the influence of sweating on the thermal insulation and comfort is not considered.

Methodology

A sweating hand was constructed for the measurement of simultaneous heat and moisture transmission through gloves. The same basic principle was used for the construction as in our previous instruments, the sweating cylinder, foot and manikin (Meinander, 1992). The hand surface is divided into 10 heating sections, which are separately controlled (5 fingers, palm, knuckle, wrist, 2 lower arm sections). Liquid water is supplied to 30 sweat glands underneath the skin material, where it evaporates. Figure 1 shows the sweating hand with some of the sweat glands, photographed before the application of the skin material.

In the first test series with the sweating hand the thermal insulation and water vapour transmission properties of a set of different types of protective gloves were measured. The gloves were acquired from Finnish producers and importers, and are listed in Table 1.

The measurements were performed in the climatic chamber, where the temperature was set to –15 °C. First a dry test was done, duration 2 hours, and directly after that the sweating 200 g/m²·h was turned on, duration 3 hours. The gloves were conditioned in 65 % RH / 20 °C for 24 hours before the tests, and weighed before and directly after the

tests. The parts of the lower arm, which were not covered by the glove, were insulated with a thick woollen knit and a quilted fabric. Two replications of each test were done.
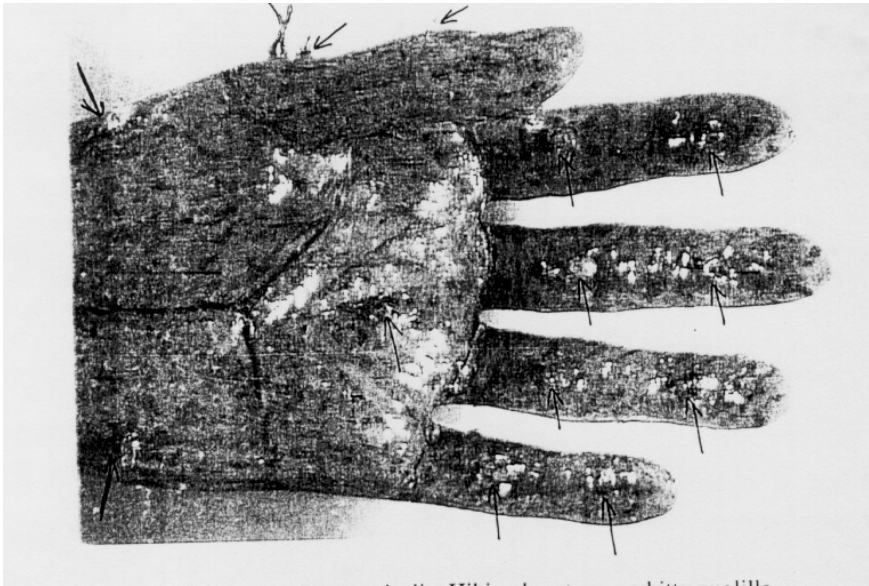

Figure 1. The sweating hand without skin material. Some of the sweat glands are indicated with arrows.

Table 1. Tested gloves

Sample no	Product	Type
1	M150	cold protection
2	M3202	cold protection
3	3040	heat protection
4	TKK 36 NC	heat protection
5	JokaOiler	chemical protection
6	JokaTop	chemical protection
7	JokaTherm	chemical protection + thermal insulation

Results

Each test gives the following set of results:

– a summary table with the results at the end of the test (set values, total condensation, total heat supply, heat of evaporation, thermal insulation (mean and local), weight increase in gloves)
– graphs of water supply / condensation / evaporation, local temperatures, local heat supply values, and local thermal insulation values during the tests.

Most important are the thermal insulation in dry and sweating conditions, and the evaporation and condensation of water, which are shown in Figures 2 and 3.

Discussion

The dry thermal insulation R_c of all the tested gloves is somewhat on the same level, between 0,35 and 0,40 m²·°C/W, Figure 2. Even the chemical protective gloves have fairly high insulation values, due to their loose design. The decrease in thermal insulation

after the sweating test is between 0,069 and 0,118 units, being smallest for the cold protective glove #2 and largest for the chemical protective glove #5.
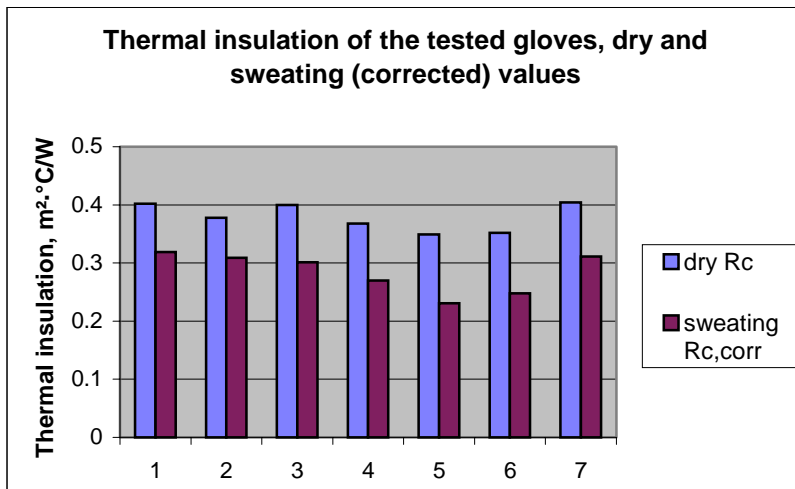

Figure 2. Thermal insulation values of the tested gloves in the end of the dry and the sweating tests.
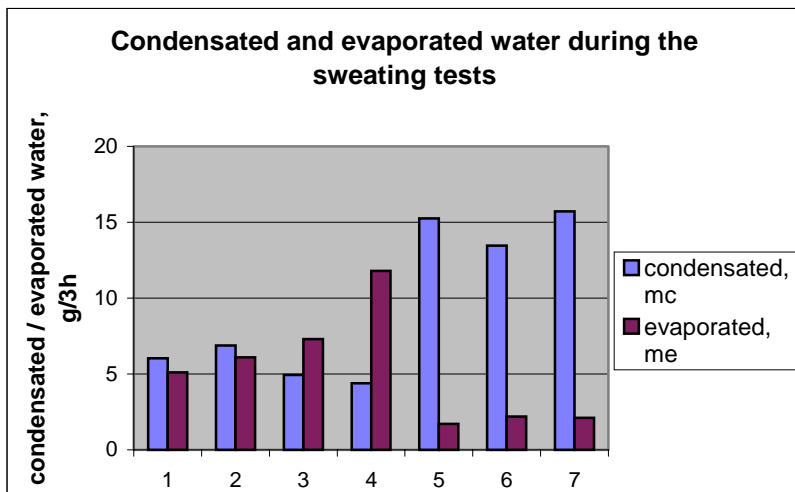

Figure 3. Measured water condensation and evaporation values in the sweating tests.

The supplied amount of water during the 3 hour test is 22,8 g (the sweating area is 0,038 m²). A part of the water is transmitted as water vapour through the glove to the environment, transmitting heat of evaporation; a part evaporates but recondensates to liquid water in the glove; and a part remains as liquid water in the skin material of the hand. A high evaporation and a low condensation are always aimed at. The heat protective glove #4 has the highest evaporation, 11,8 g or 52 % of the supplied water. The chemical protective gloves #5, #6 and #7 have the lowest evaporation values, 1,7 g or 8 %, 2,2 g or 10 % and 2,1 g or 9 %, respectively. However, for impermeable gloves it could have been expected that no evaporation at all can take place, and it can be assumed that the water vapour in this case is transferred through the opening of the glove.

The tests were performed in a low temperature, which caused a relatively low water vapour transmission even in those gloves which do not have a moisture barrier. Based on earlier studies of protective clothing ensembles it can be assumed that in a higher environment temperature, the difference between "breathable" and "non-breathable" gloves would be even more significant.

Conclusions

Within this limited project it was shown that the thermal comfort properties (thermal insulation and water vapour transmission) of protective gloves can be assessed using a sweating thermal hand. Differences between different types of gloves can be defined, which should be important information for the development and choice of gloves for specific wear situations.

Acknowledgements

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Manual performance after gripping cold surfaces with and without gloves

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Introduction

Manual performance is a combination of many kinds of abilities that require, for instance, good tactile sensitivity, hand dexterity, force capability and motor co-ordination etc. and these skills are all influenced by hand cooling. Previous studies mainly focused on the influence of hand cooling during cold air exposure (Mackworth, 1953; Morton et al., 1960; Tanaka et al., 1983; Rogers et al., 1984; Daanen, 1993; Geng et al., 1997) or immersion in the cold water (Provins et al., 1960; Bensel et al., 1974) on the manual performance. In practise, workers often use bare hands or gloved hands to grip cold surfaces. Cold contacts with bare hand or insufficient protective hand wear add to hand cooling when gripping, thereby reducing the manual performance in cold operations. In addition, a risk of cold injury through gripping the cold surface exists. The present study concerns hand cooling response and the subsequent manual performance after gripping different cold rods with bare hands and gloved hands in the cold.

Methods

Ten subjects (5 females and 5 males) age 22 - 35 years, weight 56-90 kg without any history of peripheral vascular disease or cold injury volunteered in the experiments. The instruction and explanation of the experiment were given to the subjects. Subjects were allowed to discontinue the performance of the experiment whenever they felt uncomfortable in the cold situation. All subjects were right-handed and non-smokers.

   Two types of industrial gloves were selected for the experiment. Their characteristics are described in Table 1.The selection of protective gloves against cold was based on the contact cold materials at various cold temperatures.

Table 1. Gloves used in the experiment.

Glove type	Insulation (m² °C/W)	Thickness (mm)	Weight (g)	Material	Usage in the test
1	0.06	1.00	15.00	Cotton and Rubber	Gripping Al, steel and stone rods at –10 °C; gripping nylon rod at –10 and –20 °C
2	0.12	2.70	59.40	Leather (pig) and Cotton	Gripping nylon rod at –20 °C; gripping Al and steel rods at –10 and –20 °C;

   Experiments were carried out in a cold climatic chamber at various cold ambient temperatures, which were adjusted from –20 to -10 °C to equilibrate with the surface temperature of the rods tested. Four rods with size ∅ 40×400 mm of different materials (steel, aluminium, stone and nylon) were selected as the gripping objects. Their thermal

properties are listed in Table 2. The rods were mounted in a counter balance system to support a constant weight of 0.5 kg for gripping force. Thermocouples were used to measure hand/finger-cold surface interface contact temperature (T_C).

Two standard instruments, namely, Semmes-Weinstein filaments for the pressure tactile sensitivity and O'Connor model 32021 for the finger dexterity, were utilised to evaluate and analyse the manual performance after gripping the cold rods.

Table 2. Materials used for gripping cold contact.

Material	Thermal conductivity, λ, ($Wm^{-1}K^{-1}$)	Specific heat, C, ($J kg^{-1}K^{-1}$)	Density, ρ, ($10^3 kg m^{-3}$)	Penetration coefficient ($J m^{-2} s^{-1/2} K^{-1}$)
Nylon-6	0.34	1484.00	1.20	778.12
Stone	2.07	750.00	2.80	2084.95
Steel	14.80	461.00	7.75	7271.64
Aluminium	180.00	900.00	2.77	21183.48

Experiments were carried out under combined conditions of different materials and surface temperature. Pilot studies had been performed to determine optimum experimental procedure. During gripping with or without gloves, the T_C was measured on the palm side (under index finger) of the dominant hand. The duration of gripping depended on either extensive pain or the contact temperature (stopped when $T_C < 1$ °C). The subject was asked to rest between trails in order to fully re-warm at room temperature (~ +20 °C). Also, each subject was asked to perform the manual tasks after gripping. The pressure tactile sensitivity test was performed using Semmes-Weinstein filaments, which touched on the palm side (under index and little fingers and pad of the middle finger). In the experiment, the subject gave the actual response within 3 seconds without seeing. The filament's size 2.36 represents that a press force of 15 mg was used as the lightest force in all tests (Tomancik, 1987). For the finger dexterity, the subject was required to fill the first line with 3 pins per hole from left to right as quickly as possible. As a result, the time needed to complete the task and number of mistakes (incorrect pins were filled or fell down) were recorded. To avoid a cold injury during gripping the cold metallic surfaces at –10 °C, the cooled hands were treated immediately by supervisor's warm hand. This could influence the results of the manual performance tests.

Results and discussion

Hand cooling on cold rods with or without gloves

Figure 1 shows the contact temperature at the end of gripping the cold metallic and non-metallic rods without or with gloves. It is seen that the hand cooling is related to both the material of the rod, ambient temperature as well as type of gloving. As shown in Figure 1a, significant temperature differences (at 95 % LSD Intervals) appeared for the case of without or with gloves and for the case of glove type when gripping the metallic rods at –10 °C. Clearly, a thicker glove with higher thermal insulation value (type 2) gives a higher T_C (>21 °C), compared to a thinner glove (Type 1) (<14 °C) or no glove (<9 °C). Gloves lead to a decreased rate of heat transfer from hand to the cold surface during gripping (Table 1). In addition, Figure 1b shows a significant glove effect on the T_C at the end of gripping the cold nylon rod at –20 °C. The T_C was significantly lower at the end of gripping without gloves. This emphasises that hands must be protected with gloves during gripping non-metallic materials like nylon at cold temperature of –20 °C and

lower. However, there exists no statistically variation on the T_C between glove types 1 and 2 in this case.

It is noticed that the variation of the T_C appeared to be significantly related to the presence of hand protection. Averaged for all conditions, the presence of a glove increased hand contact temperature by 4-10 °C for gripping the cold rods, compared to bare hand.
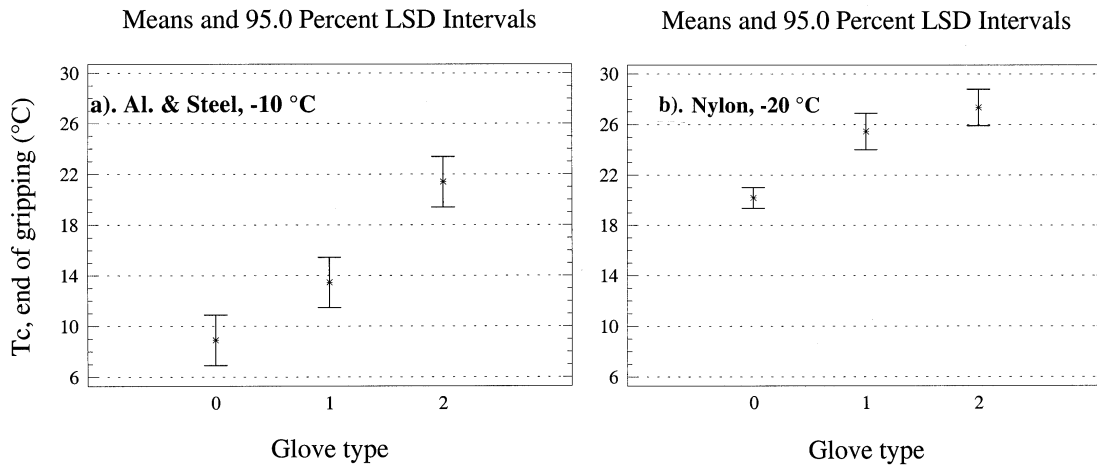

Figure 1. Mean T_C at the end of gripping different cold rods with bare hand (0), gloves (1) and (2): a) for aluminium and steel at-10 °C and b) for nylon at –20 °C.

Manual performance after gripping the cold surfaces

The manual performance (SWP sensitivity and O'Connor fingers dexterity) after gripping with and without gloves at –10 °C is shown in Figure 2. It is obvious that manual performance after gripping the cold non-metallic rods with gloves was better than with bare hand. Type of glove also has a significant effect on the manual performance for the case of gripping the cold metallic rods. Hands after using glove 2 with higher thermal insulation value give a subsequent better performance. The resultant differences that are due to the hand cooling after gripping the cold rods with or without protective hand wear to varying degrees. It is known that the hand cooling reduces the dexterity due to the influence of cold on muscles and joints of finger/hand (Havenith, et al., 1995). Finger dexterity decreased sharply when the finger skin temperature fell below 15 °C has been found by some earlier studies (LeBlanc, 1956; Daanen, 1993). Also, the loss of tactile sensitivity of fingers/hands at cold environment may be attributed to changes in the properties of the skin or to the effects on biochemical processes at nerve or receptor level (Geng, et al., 1997). The results reflect that glove 1 with lower thermal insulation value was ineffective to protect the hand during gripping the cold metals at –10 °C, but it seems satisfactory for the case of gripping on the non-metallic rods even at –20 °C (Figure1b).

Conclusions

- Hand contact cooling was affected both by type of material and their surface temperature as well as by the use of the protective hand wear. It is suggested that hands must be protected with gloves during gripping metallic materials at -10 °C or lower and while gripping non-metallic materials like nylon at temperatures of –20 °C and lower.
- A significant hand cooling after gripping cold rods with bare hands or with insufficient protective hand wear caused a significant decrease in manual performance.
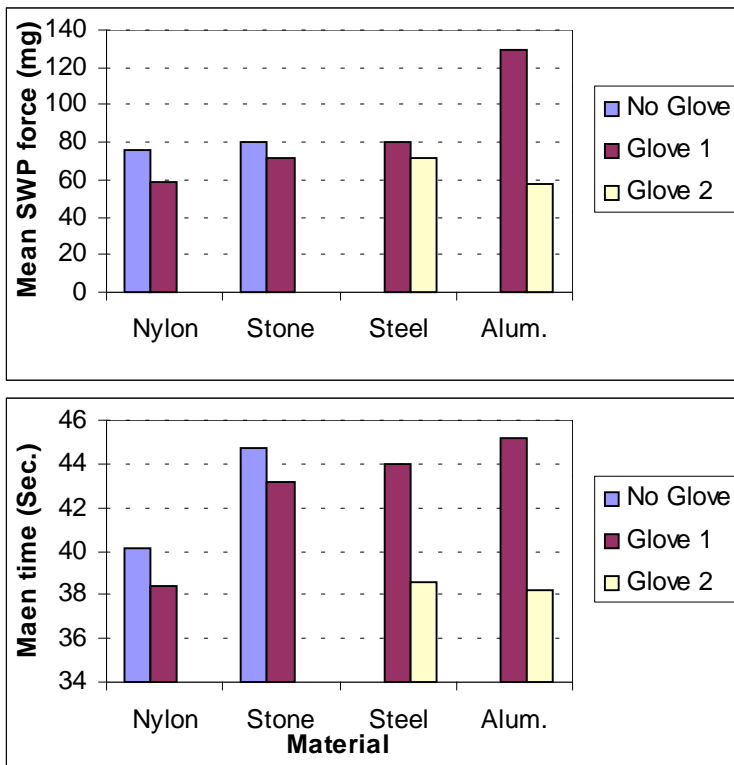
Figure 2. Effects of gripping material type on the SWP sensitivity and O'Connor fingers dexterity after hand gripping with and without gloves at –10 ℃.

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Cold protective gloves in meat processing industry - product development and selection

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Background

One of the major problems in food industry is cooling of hands causing discomfort, accidents and further health problems. Workers in the cooled factories face many health risks due to repetitive manual work, cold environment, draught and moisture. Griefahn et al (1996) have presented evidence that working in moderately cold working places may constitute a health risk e.g. symptoms of white finger disease. Upper limb overuse symptoms are common in the meat processing industry (Viikari-Juntura et al, 1991). There is not so many studies concerning the development of gloves in this field of industry even though the effect of thin gloves has been known to be very important on cooling (Havenith et al, 1992).

The main aim of this project was to test and develop gloves to decrease cold induced discomfort and hand cooling among the workers and test the meaning of clothing on finger temperatures.

Material and methods

Workers in various departments used several different types of gloves. Cool or cold environment (0-10 °C) as well as cold and wet products were common for all the workers. In the prestudy 11 workers were interviewed concerning gloves used today.

Six different kind of commercial or self-developed knitted gloves were tested, measured and evaluated by measurements and interviews of users. Materials tested were: PES (100 % polyester), CO/PES (50/50 cotton/polyester), CO/PAN (50/50 cotton/acrylic), CO (100 % cotton), Polycolon® (100 % polypropylene), Thermastat® (100 % polyester; hollow fibre). 19 workers tested the new materials; 10 in an elimination test for all six materials and 9 for the best two. Most common used gloves were two-layer system: rubber glove with knitted underglove. Because thicker gloves than used today were not possible, different materials to decrease sensation of cold and moisture were tested. Conductive and convective (prEN 511) thermal insulation were measured in laboratory. Also the cooling of hands were measured by the field tests. The overall heat balance of the workers was also assessed by the measurements and guidelines for protective clothing were revised. The project was conducted in co-operation with glove manufacturers, which provided the new type of gloves for the companies.

Results

In the prestudy (n=1117) 90 % of workers reported about harmful cooling of hands and fingers. 40 % informed about pain experienced in hands. So the hand protection against cooling is very important.

Workers in the case companies were interviewed in purpose to clear up how the present gloves function in those cold conditions. Results from the interview are presented in Table 1.

Table 1. Results from the interview of the workers relating to the used cold protective gloves in the case companies.

Question	Answer (%) (n=11)	
	yes	no
Do you suffer from hand cooling during work?	100	0
Do you suffer from moisture in gloves?	91	9
Do the gloves fit?	55	45
Does your manual dexterity remain while wearing gloves?	45	55

In the physical measurements of contact cooling the differences between the materials and gloves were maximally 3 °C in 25 min test period. Contact cooling of tested materials is presented in Figure 1. Materials were tested as dry and moist with weight of 0.1 kg.
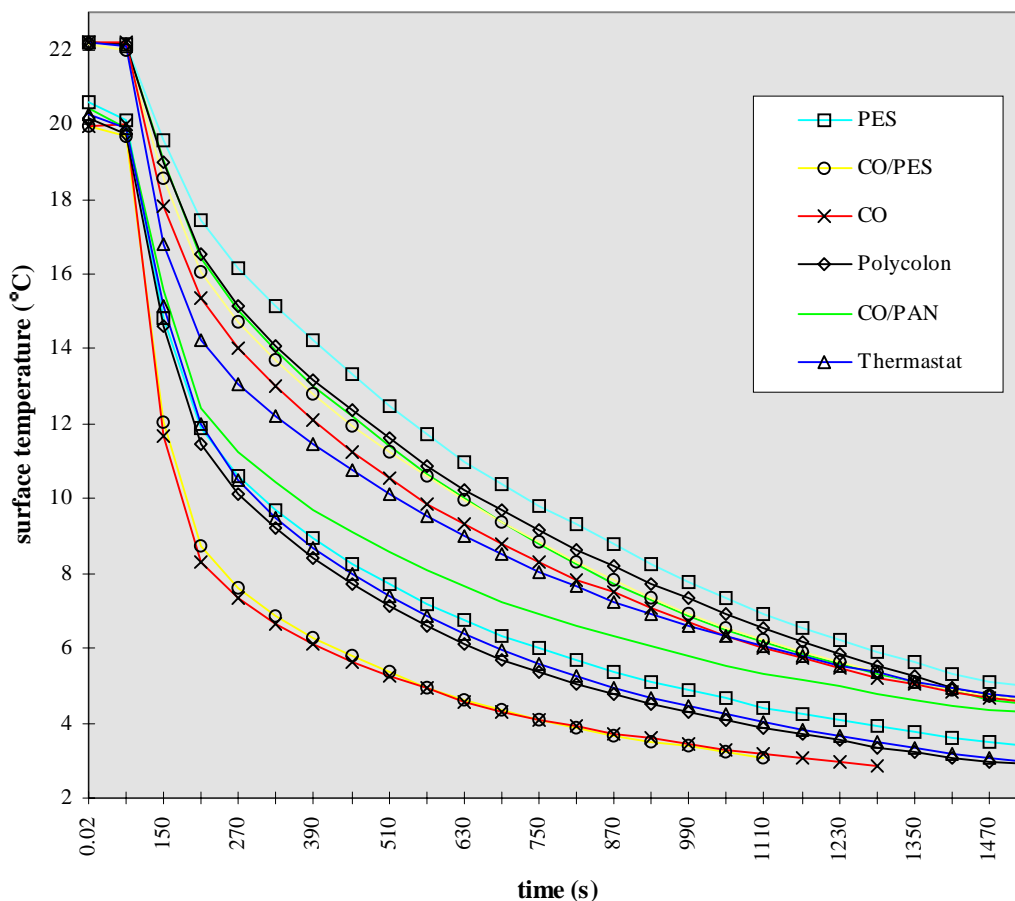

Figure 1. Contact cooling for tested dry (beginning temperature 22 °C) and moist (beginning temperature 20 °C) materials.

Different materials' possible differences in convective insulation were tested with four new kind of glove materials. Test results are presented in Figure 2. Convective insulation of the tested materials did not differ greatly from each other, but when much thicker gloves were tested for comparison the range of variation was larger, 0.051-0.110 m^2K/W.

The differences in insulation of the gloves in the field measurements were similar to the laboratory tests even though the conditions varied to some degree in every test.
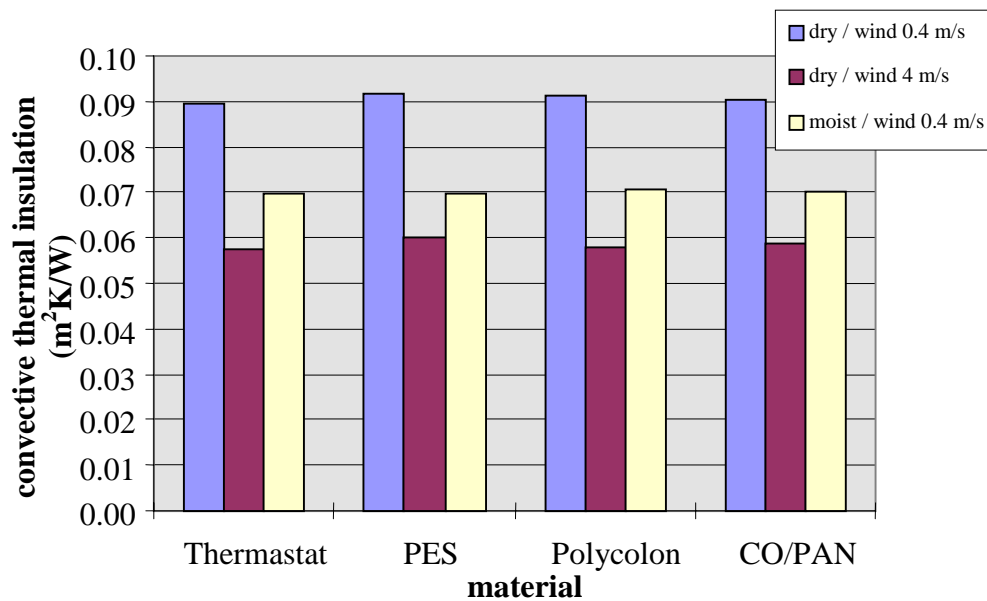
Figure 2. Convective cooling for dry and moist materials (wind 0.4 m/s or 4 m/s).

By combining the results from laboratory and field tests four and later two superior materials were chosen to be further tested in the companies. Material based on polypropylene and thermastat were found to be better than the other tested materials according to the measurements and questionnaires.

Results of interview concerning comparison of the old and the two best glove materials are presented in Table 2. Comparing Polycolon and Thermastat, all the workers preferred Polycolon. Because Polycolon as a moist transferring material was better than other tested materials it shows the meaning of moisture on cold sensation.

Table 2. Results from the interview concerning comparison of the old and the two best glove materials.

| Material | Answears (%) (n=9) | | |
	better than the old one	no difference	worse than the old one
Polycolon	89	11	0
Thermastat	67	22	11

The use of additional clothing, down vest (0.5 clo), made the finger skin temperatures either 4-5 °C higher or the cooling of the fingers became slower.

In conclusion, by combining the test results from laboratory tests and from comparison field tests done by workers in the case companies, best materials are in superiority order: Polycolon, Thermastat, CO/PAN, PES.

Discussion

The present study confirms the earlier findings (Griefahn et al, 1996; Viikari-Juntura et al, 1991; Havenith et al, 1992) by showing a high prevalence of complaints of fingers in moderately cold food processing industry. Workers' cooling is a marked problem in the cold food processing industry and causes unpleasant cold sensations, pain and numbness of fingers and hands.

In this study the cooling by convection, conduction and subjective sensations of cooling with different gloves were measured. In conclusion, the differences between tested

materials and gloves were quite small but distinct. The effect of thickness of the material was small compared to the effect of material itself. In the other hand increasing the thickness of glove wasn't possible because decreasing manual dexterity. Wetness of gloves wasn't so big problem as informed beforehand measured as amount of water in glove. However it effected very much on cold sensations, but with the moisture transferring material situation became much better.

The results in different tests were along the same line and the subjective evaluations supported the measurement results.

Also the meaning of body clothing insulation on finger temperature was clear according to the field measurements and that should be taken care better than nowadays.

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Protective gloves against mechanical and thermal risks

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Introduction

A significant part in preventing professional diseases and work accidents is held by protective gloves which have to respond to the following requirements:

- a perfect conception, without faults
- comfort in wear
- adapted the purpose of wearing
- made of which should provide protection to all parameters involved in the specific safety field

The choice of a solution concerning the accomplishing of protective g1oves involves knowing the risks, the properties of the fabrics their behaviour under risk conditions.

The poster will present the results of researches concerning:

- the risk levels depending on the fields of utilisation
- designing and accomplishing the woven structures meant for protective gloves
- protective gloves against mechanical and thermal risks

The textile structures have been accomplished by using fibres with performant characteristics, such as

- Twaron para-aramidic fibres
- Kermel polyamid-imidic fibres

Criteria

Essential criterion is to protect the human life. Other criteria are:

- damages and level of risk assessments
- limits of the main characteristics, specific and additional properties
- establishing the criteria of fiber selection
- designing the textiles depending on the performance demands of end-uses
- testing in conformity to European standards
- designing and accomplishing the individual protective clothing
- IPC certifying

General requirements for designing and accomplishing:

- terms of choosing textile raw materials
- elements of designing
- technological solutions

The other requirements are:

- Requirements for environmental resistance
- Requirements for designing
- Requirements for an efficient marketing

Caloric protective gloves "CALOR TW"

Structure

Layers:

- exterior: 100% twaron fabric
- intermediary: 100% kermel nonwoven
- interior: 100% viscose FR

Utilization fields:

- glass and ceramic industry
- metallurgic industry

Characteristics

Mechanical risks:

- Abrasion resistance: > 4000 cycles, 3rd performance level (SR EN 388)
- Blade cut resistance: cut index >2.5, 2nd performance level (SR EN 388).

Thermal risks resistance:

- behaviour to fire: after-flame time 0 s, after-glow time 0 s (after 15 s fire exposure), 4th performance level (SR EN 407);
- contact heat resistance: break point time 20 s (350 °C contact temperature), 3rd performance level (SR EN 407);
- convection heat resistance: increasing time* 36 s (HTI>18 s), 4th performance level (SR EN 531).

*time to increase internal layer temperature with 40 °C, at direct flame,caloric flux of 80 kW/ sqm

Knitted protective gloves

Structure

Layers:

- exterior: 100% twaron knit
- interior: 100% viscose FR

Utilization fields:

- glass and ceramic industry
- machine -building industry
- physic - mechanical laboratories

Characteristics

Mechanical risks:

- Abrasion resistance: > 100 cycles, 3rd performance level (SR EN 388).
- Tear strength: >380 N, 4th performance level (SR EN 388).

Thermal risks:

- heat resistance   250 °C, 6 s;
- contact temperature   100 °C, 15 s.

A case study on the selection and development of cut resistant protective gloves for household appliance assembly industries

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Introduction

Statistics of the Quebec Occupational Health and Safety Board demonstrated that in the metal and electrical appliances industries, close to 30 % of injuries are to the hands (Commission de la santé et de la sécurité du travail du Québec, 1999). Most injuries are cuts, punctures and lacerations caused by tools, metal pieces, small screws and wire manipulations. These industries are characterized by rapid working operations and the high level of dexterity needed to perform the assembly operations. A test method to evaluate the cut resistance of materials used in protective clothing was recently developed and has been adopted as ISO Standard 13997 (ISO 13997, 1998). To evaluate dexterity when using gloves, laboratory test methods exist (Bensel, 1993; Robinette et al., 1986; Johnson & Sleeper, 1986; Plumber et al., 1985). However, to our knowledge, no study exists that attempts to correlate the laboratory results and the workers' perception of dexterity in real working situations. The goal of this study was to select or develop a protective glove for household appliance assembly operations that provides good dexterity and has a good cut resistance.

Methodology

This study had two major parts: I) Identifying the characteristics of a glove adapted to the type of work performed by assembly line workers; II) Selecting or developing a glove that fulfills the requirements identified in the first part of the study

Identifying the characteristics of the protective gloves

A   Primary analysis. The goal of this part of the study was to establish the main requirements for a protective glove acceptable to workers, by analyzing the long-term injury register, by systematic questioning of workers, and by observing real operations in the field. A household appliance manufacturing company collaborated on this study.

B   Detailed analysis. After the first analysis of the information extracted, a detailed analysis was carried out on the hand injuries that occurred in a two-month period. For this, a detailed questionnaire specifically prepared for this study was used to obtain the workers' description of the accident within two days of its occurrence, so that they would clearly remember what had happened. One hundred and forty accidents involving 93 workers were analyzed. This step in the study enabled us to assess the level of risk and the workstation on the assembly line with the highest risk of injury.

Analysis of workstations. The operational modes and working positions on the assembly lines for the workstations identified as the highest risk were systematically observed and filmed. This identified the risk of cut injuries and the dexterity level required to perform this work. The reasons for using protective gloves or not were identified as well. The workers' opinions of the desired characteristics for protective gloves were also obtained. The identified characteristics for the protective gloves were the following;

– cut resistant
– allow operations needing good dexterity
– good adhesion to metal pieces contaminated with oil or grease
– glove material must have a capacity to absorb oil or grease.

Selecting or developing a glove

Glove distributors and manufacturers were asked to propose protective gloves with the above mentioned characteristics. Thirty gloves were proposed and tested for cut resistance using standard test method ISO 13997, and for dexterity using an in-house method simulating field operations involving the handling of screws and wires.

Results

From the thirty gloves proposed, twelve gloves were selected for more detailed tests. Results of these tests are presented in Table 1. Furthermore, the glove manufacturer that participated in this project agreed to develop two prototypes with the above-mentioned desired characteristics, which are also presented in the same table. Cut resistance values reported in Table 1 represent the force necessary to cut through a material with a 20-mm blade displacement. Dexterity values are a subjective classification from 1 (low dexterity) to 5 (very good dexterity).

Table 1. Preliminary cut resistance and dexterity results.

Gloves (commercial products)	Material	Cut resistance F (g)	Dexterity
1- Jomac 1814	Kevlar/nitrile	1 043	4.5
2- Jomac 1805 NBC	Kevlar/cotton/ nitrile	1 268	4.0
3- Jomac 1800 NPC	Kevlar/cotton/Nitrile	1 131	3.5
4- Levitt GKVL20AR-100	Kevlar	1 324	3.0
5- Dupont Golden Needles	Kevlar	1 232	3.0
6- Superior Gloves S13K	Kevlar	774	4.0
7- Superior Gloves LL100	Cotton	528	4.5
8- Superior Gloves SSL-C13G	Kevlar/leather	700	4.5
9- Superior Gloves	Cotton	556	4.5
10- Superior Gloves	Cotton/rubber	472	4.5
11- Ansell-Edmont 47-200	Cotton/Nitrile	418	4.0
12- Ansell-Edmont 72-025	Spectra	1 269	4.5
Glove prototypes			
Superior Gloves Prototype 1	Kevlar/cotton/lycra	616	4.5
Superior Gloves Prototype 2	Spectra/cotton/lycra	1 050	4.5

As a result of these series of tests to select the best candidates, only three gloves from the commercial products were selected. These were glove numbers 1, 2 and 3, because they best met the desired specifications. Also, the two prototypes prepared by the glove manufacturer that participated in this project were selected. These gloves were used for

field testing. Workers tested each glove for one week on a voluntary basis. The gloves were identified by a number and associated with a worker, which allowed a controlled follow-up of the field testing. A specially developed protocol included a questionnaire on the workers' dexterity, comfort and durability perceptions after they finished the test. The questionnaire included the following information: how easy it was to handle screws, tools, metal parts, wires, etc.; an evaluation of comfort, glove fit, thermal comfort, grip, skin irritation, etc.; perception of cutting resistance; and an overall assessment. Table 2 presents the results of worker perception of dexterity and comfort. The marks for the answers were as follows:

- a positive answer +1
- a negative answer -1

The numbers reported in the table represent the average of the answers for all items in the questionnaire for all workers participating in the field testing and for each glove. Gloves are represented by the number given in Table 1.

The results in this table show that prototype 2 was the glove most appreciated by the workers for dexterity and comfort. Glove 3 was the least appreciated.

Table 3 presents the durability results for the gloves tested. They were obtained by calculating the time the worker used the glove before deciding to replace it with a new one. The results represent an average glove durability in relation to the gloves used prior to this project.

The results in this table show that all gloves except glove 3 are more durable than the gloves used at the time this project was started. The most durable glove was Prototype 2, with an average durability 13 times longer than the previous glove.

Table 2. Results of field testing of gloves for dexterity and comfort.

Gloves	Dexterity	Comfort
Prototype 1 (Kevlar-cotton-lycra)	0.30	0.35
Glove 1 (Kevlar)	0.24	0.25
Glove 2 (Kevlar-cotton)	0.43	0.35
Prototype 2 (Spectra-cotton-lycra)	0.86	0.64
Glove 3 (Kevlar)	-0.6	-0.38

Table 3. Durability ratio between the gloves tested in this project and the gloves used prior to this project.

	Prototype 1	Glove 1	Glove 2	Prototype 2	Glove 3
Durability ratio	2 to 16 times longer	2 to 8 times longer	2 to 16 times longer	1.5 to 80 times longer	Not available
Average	6.2	3.5	6.1	13.1	
Number of workers who answered this question	9	9	13	19	3

Table 4. Overall worker assessment of the protective gloves.

Rating	Prototype 1	Glove 1	Glove 2	Prototype 2	Glove 3
Unacceptable	0	0	0	0	3
Poor	2	2	3	0	0
Average	2	3	5	0	1
Good	4	3	4	9	0
Very good	1	1	1	10	0
Number of workers answering the questionnaire	9	9	13	19	4

Table 4 present the results of the overall worker assessment of glove quality based on the characteristics that the gloves should have, namely cut resistance, dexterity, durability, grip and comfort necessary for this type of work.

The results in this table show that Prototype 2 stands out from all the other gloves tested, with 9/19 workers finding the gloves good, and 10/19 finding them very good. This glove is made of knitted on Spectra™, Lycra and cotton fibers. Spectra™ is a cut-resistant material, Lycra provides elasticity to obtain a good glove fit, and cotton provides the capacity to absorb oils and greases, which is important for a good grip. Furthermore, to improve the grip, PVC dots are placed on the glove palm.

Conclusion

This study demonstrated that no commercially available glove was adapted to the type of work performed in electrical household appliance assembly operations. As a result of this study, a new protective glove was developed that meets the specifications established in the first part of this study, namely good cut resistance, grip and dexterity. The results also demonstrated that the gloves are well accepted by the workers, which is essential in ensuring that they will be worn. This new glove is commercially available, and it has been demonstrated that it is useful for other types of work operations, such as mirror manufacturing and cutting, and any kind of glass or metal operations requiring good dexterity.

An approach has been developed in this study for assessing the characteristics that gloves must have for working operations. Furthermore, the study combined the expertise of researchers, a glove manufacturer and users in developing, in an iterative exchange, a new glove adapted to the workers.

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Issues and challenges in chemical protective clothing

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Introduction

Significant advances have been made in the field of chemical protective clothing. These advances have included new materials offering tremendous improvements in chemical resistance and the development of several standards covering a range of clothing applications. The industry is now maturing but faces new issues and challenges particularly with regard to overuse of permeation data and human factor considerations.

Historical progression of chemical protective clothing

Starting in the 1970's, the primary materials used in chemical protective clothing were elastomers such as Neoprene rubber or thermoplastics represented by polyvinyl chloride. With the evolution of emergency response teams and the greater awareness of toxic effects from skin exposure to chemicals in the early 1980's, the need for broader chemical resistance became important. This trend coincided with the first use of permeation testing to demonstrate the barrier effectiveness of clothing materials. Many material suppliers and clothing manufacturers then began working on new materials with increased chemical resistance. Some of the early developments included chlorinated polyethylene, improved versions of polyvinyl chloride, and new laminates such as Viton/butyl rubber. While these materials provided greater resistance, they were usually susceptible to permeation by one or more classes of chemicals.

The first successes for broad-based chemical resistant materials were made in the offering of Teflon products and multilayer films. In the United States, ChemFab Corporation applied material technology used in weather-resistant radar covers to clothing material. At nearly the same time, solubility theory of "like dissolves like" was applied to the construction of multilayered plastic films to achieve what is known today as the 4H material used in gloves. Both materials were able to provide broad resistance to a number of chemical classes. However, the ChemFab product was relatively expensive and the multilayer plastic laminates did not have the elongation and other properties normally associated with rubber to allow three-dimension hand forms required for good glove hand function.

The establishment of inexpensive plastic film technology led to further development of alternative clothing and glove materials. The introduction of inexpensive nonwoven fabrics as substrate materials created a new class of lightweight, limited uses clothing products. With specific engineering, these materials were developed to provide the desired range of chemical resistance and physical strength. Permeation resistance became an increasingly important factor in chemical protective clothing selection.

As limited use fabrics gained importance, a different type of material development was undertaken. These materials were not permeation-resistant, but were designed to prevent the penetration of liquid splashes. While liquid splash protective clothing had been avail-

able for many years, primarily in the form of polyvinyl chloride rainwear, this new group of materials offered something different – breathability or water vapour transport. The use of microporous film technology was adapted from filter applications to clothing, by laminating microporous films to nonwoven or woven textile fabrics. To demonstrate the appropriate barrier technology, penetration tests were developed that involved a determination that gross amounts of liquid did not pass through the materials.

Key issues and challenges

The history of the chemical protective clothing market appears to have met the original industry goals in producing materials that have broad chemical resistance at the molecular level. The market has also provided alternatives for offering varying levels of performance to different types of exposure. In Europe, a type classification system for chemical protective clothing has been established that creates a hierarchy of protection from the most extreme hazards to the less innocuous chemical exposures. Despite these achievements, there remain key issues and challenges that remain unaddressed. These include:

- overuse or inappropriate use of permeation data
- distinguishing between limited use and reusable products
- lack of attention to ergonomic issues in clothing design
- protection from multiple hazards

Use of permeation data

The permeation breakthrough time has become the standard measurement by which end users judge material barrier performance. Breakthrough times are now used to classify material chemical resistance and determine product acceptance. A material with good chemical resistance is one that has no reported breakthrough or high breakthrough times against a battery of different chemicals.

Implicit in the term breakthrough time is the prevention of any exposure to a given chemical, but in reality, the breakthrough time represents a threshold equal to a specific permeation rate where some chemical passes through the material. With the exception of a few chemicals, the amount of acceptable chemical permeation is generally unknown, as permissible dermal exposure limits are not set in industry as they are for respiratory protection. Presumably, the indication of "no breakthrough" is perceived as appropriate for any clothing (or glove) use up to the breakthrough time. Consequently, any information related to the permeation rate (if reported) is neglected and not applied to clothing use decisions as it would be for the analogous selection of respirators.

The majority of permeation testing is conducted with neat organic liquids or concentrated inorganic acids, bases, and salts. Most testing against gases is performed with the gas challenge at 100 % concentration. In the majority of circumstances, this testing represents a "worst case" exposure with liquid or gas at full "strength" continuously in contact with the clothing over the duration of exposure. In most work situations, employees attempt to minimise their exposure and in some cases are instructed to exit the work area and remove clothing when contaminated. Under these circumstances, it would appear that permeation testing includes a large safety factor.

There are also arguments that permeation testing does take into consideration workplace factors. For example, permeation testing is performed at ambient temperatures (21 °C in Europe and 25 °C in North America) and does not account for changes in the mate-

rials introduced by wear (abrasion and flexing). Many temperatures may occur at elevated temperatures. Furthermore, materials in contact with the body will be raised to temperatures near the skin, some 10 degrees warmer than the test temperature. Given the temperature dependence of permeation, increased permeation could be expected. In addition, permeation testing is performed on static samples that do not take into account changes in material resistance produced by wear.

Despite the limitations of permeation test data, the information provided by testing is useful if properly applied. Concerns arise when permeation data are used for situations where the type of barrier performance is not consistent with the clothing design or function. For example, the use of permeation data for a clothing item with non-sealed seams against a volatile chemical with known skin absorption points to misuse of the data and perhaps the selection of the wrong type of clothing. Similarly, applying permeation data for clothing products where the main intent is to keep liquid off the wearer's skin does not make sense and could result in overprotecting the individual.

Limited use versus reusable clothing

The trend towards limited use or disposable products has attempted to offer an economic alternative and convenience for an end user. However, this trend has also raised the question as to the appropriate reasons for replacing clothing and acceptable levels of durability. In the marketplace, the distinction between reusable and disposable clothing is based on the purchase price of the clothing. This approach fails to take into account other important factors.

Decisions for deciding between reusable and limited use clothing should take into account the clothing life cycle cost, the durability of the clothing, and the ease and effectiveness of decontamination. Purchase cost is insufficient for comparing clothing. Costs associated with the maintenance and care of clothing, such as those involved in cleaning, testing, storing, and disposing of clothing must also be considered. Durability is another important factor but is more difficult to assess. Material physical properties such as breaking strength, tear strength, abrasion resistance, and flex fatigue are typically used for evaluating material durability, but may not determine the durability of the overall clothing. Furthermore, different end uses will dictate different levels of clothing durability. The ease of decontamination is also a difficult clothing attribute to assess. Determining effective decontamination requires destructive evaluation of the clothing, but a material with good surface chemical resistance is less likely to be affected when compared to a material that might readily absorb chemicals. In addition, when the chemical contaminants and exposure circumstances are well understood, organisations can have greater confidence in ensuring acceptable decontamination.

Ergonomic issues

Improvements in clothing design have not kept pace with the advances in material technology. The industry now has tests for evaluating the integrity of clothing for exposure to different type of chemical exposure, whether as vapours, liquids, or particles. These tests create the need for interfaces and other design features that restrict wearer movement and reduce comfort. In some cases, ill-fitting and uncomfortable clothing actually creates hazards in the form of reduced vision, tripping hazards, and heat stress. Gloves, footwear, respirators, and other equipment may be incompatible with selected garments. The limited availability of clothing sizes and lack of form-fitting designs create poor fit for end users. Tape is often used to incorporate sizing adjustments and seal off interfaces.

Clearly, design improvements must be sought that provide a reasonable balance between protection and wearer function and comfort.

Another aspect of clothing comfort can be affected by clothing design and material choices. Overspecification of clothing, particularly in using clothing with more protection than is needed may create more of a hazard to the wearer than the exposure to the chemicals present. In particular, if the chemical hazards are not severe, the situation is well characterised, and experience shows exposure is not likely, a lower level of clothing can be selected. For example, breathable penetration-resistant fabrics can be used in place of coated, non-breathable fabrics in a "splash" (liquid-resistant) suit for chemicals that pose no dermal vapour exposure hazards. Table 1 shows a hierarchy of clothing performance based on both clothing integrity and material barrier performance.

Table 1. Hierarchy of chemical protective clothing performance.

Type of protection	Needed garment integrity	Needed material barrier performance
Vapour-protective	Gas-tight	Permeation resistance
Liquid-protective with vapour dermal hazard	Gas-tight	Permeation resistance or penetration resistance
Liquid protective	Jet-tight	Penetration resistance
Splash protective	Spray-tight	Repellence
Particle protective	Particle-tight	Particle hold-out

Protective clothing against multiple hazards

The increasing specialisation of clothing and applications where special protection is needed has grown. For example, while emergency response teams engage in hazardous materials incidents, it is often impossible to segregate different hazards in the incidents they respond to. The most common dual incident is having clothing that offers flash fire protection in combination with chemical protection. Most products must achieve this protection by employing aluminised clothing over chemical suits. This practice increases the bulk of clothing on the wear and requires the sacrifice of a relatively expensive outer-suit. Another example exists for clothing used for abrasive blasting involving harmful skin-toxic particle debris. Special reinforcements of this clothing are necessary to provide the combination of clothing abrasion and particle holdout. Continued improvement of protective clothing designs and materials are necessary for identifying the optimum balance of attributes for appropriate levels of protection.

Conclusions

Chemical protective clothing is not the final solution in avoiding chemical exposure. Nevertheless, advances in chemical protective clothing have enabled relatively high levels of protection to end users in many applications. Continued improvement of chemical protective clothing and attention to the issues addressed in this paper will further allow end user additional protection with balanced consideration of comfort, function and other ergonomic needs.

Sweat effects on adsorptive capacity of carbon-containing flannel

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Introduction

Permeable chemical protective suit (PCPS) protect against toxic gases (vapors) mostly depends on activated carbon on PCPS. Because activated carbon on PCPS is contaminated by human sweat in hot environment, adsorptive capacity for toxic gases is reduced. Sweat effects on adsorptive capacity of chinese carbon-containing flannel were studied. Carbon-containing flannel, inner layer of chinese permeable chemical protective suit, is made of flame-resistance cotton flannel, one surface of it is finished with oil-repellent agent, and the other surface finished with the emulsion of activated carbon and polyacrylate.

Methods

Determination of adsorption isotherm

Determination by Head-Space Gas Chromatograph (HS-GC), its apparatus is shown in Figure 1.
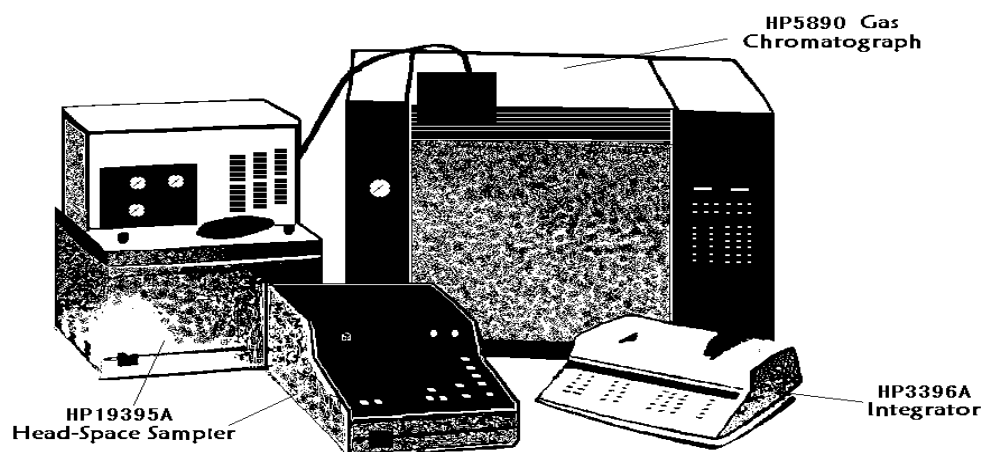

Figure 1. Head-Space gas chromatograph system.

Adsorbate: carbon tetrachloride(CCl_4)

Adsorbent: treated and untreated carbon-containing flannel with sweat and its individual constituents

Adsorption equilibrium time: more than 48 hours, enough to static adsorption equilibrium.

Determination of breakthrough curve

A schematic of the apparatus for the study of dynamic adsorption of carbon-containing flannel is shown in Figure 2.
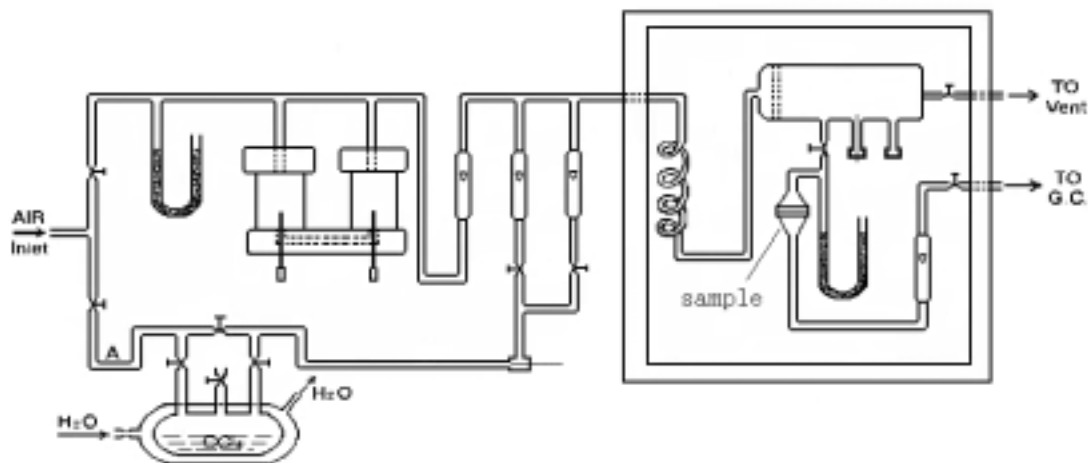

Figure 2. Schematic of vapor test apparatus.

Experimental conditions:
Temperature: 20 ℃
Relative humidity: 50 %
Test agent: CCl_4
Inlet concentration of test agent: 0.05~0.20 mg/l
Specific velocity of air flow: 2.5~10.0 cm/min

Results and discussion

The effects of sweat and its individual constituents on static adsorptive capacity of carbon-containing flannel

The effects of the principal constituents of sweat on CCl_4 static adsorption capacity of carbon-containing flannel were determined. The data shown in Figure 3 indicate that organic constituents of sweat poison carbon-containing flannel most severely, lactic acid and amino acid are most severe in inhibiting total amount of CCl_4 adsorbed and reduce static adsorption capacity of carbon-containing flannel by 24.29 % and 21.37 % with respect to conditioned material. Glucose treatment, surprisingly enhances static adsorption capacity by 8.45 %.
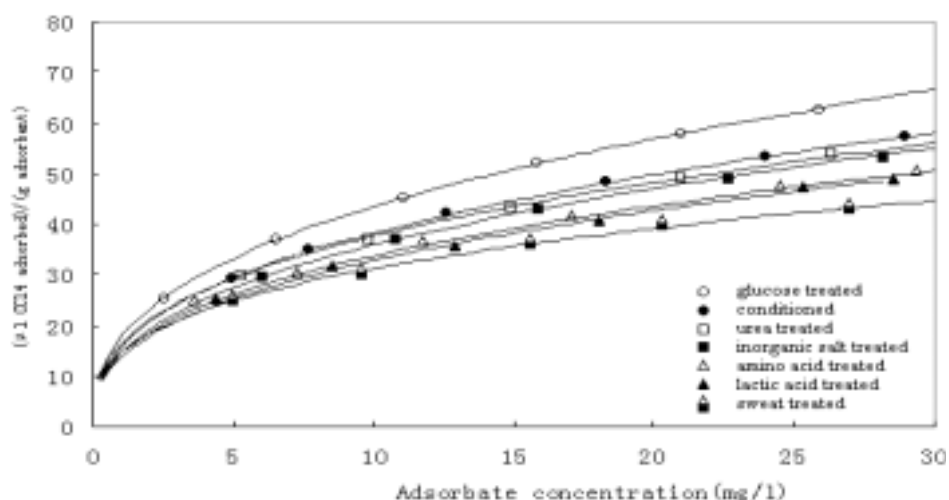
Figure 3: Adsorption isotherm of CCl_4 on treated and untreated carbon-containing flannel at 42 °C.

Table 1. Comparison of static adsorption capacity.

	a (•l/g)						
	conditioned	sweat	lactic acid	amino acid	inorganic salt	glucose	urea
$C_b/C_s=0.175$	57.97	43.38	43.89	45.58	57.00	62.87	55.92
Degradation percent (%)		-25.17	-24.29	-21.37	-1.67	8.45	-2.05

Protection time analysis

Table 2. Comparison of protection time.

Condition			$t_{0.1}$(min)			
C (mg/l)	V(cm/min)	W(mg/cm²)	conditioned	sweat	lactic acid	amino acid
2.45	5	8.45	28.64	19.74	21.37	23.63
Degradation percent (%)				-31.08	-25.38	-17.49

Table 2 shows that protection time of carbon-containing flannel contaminated by human sweat is seriously decreased to about 31.08 %.

Adsorption rate constant

In our laboratory, 54 breakthrough curves of treated and untreated carbon-containing flannel were measured. Adsorptive rate constant k_{ads} can be calculated with Wheeler's equation, its value as follows:

Table 3. Comparison of adsorption rate constant.

treatment mode	conditioned	sweat	lactic acid	amino acid
$k_{ads} \cdot V^{-0.5}$	1.06	1.46	2.38	2.15

Above-mentioned table shown, the effects of sweat and its individual constituents on adsorption rate of carbon-containing flannel are just a little.

Conclusions

The experimental results show that organic constituents of sweat are mainly responsible for poisoning action, lactic acid and amino acid are most severe in inhibiting total amount of CCl_4 adsorbed and reduce static adsorption capacity of carbon-containing flannel by 24.29 % and 21.37 % with respect to conditioned material. Protection time of CCl_4 on carbon-containing flannel is decreased to about 31.08 %, the effects of sweat and its individual constituents on adsorption rate of carbon-containing flannel are just a little. The cause on protection time of carbon-containing flannel decreased is in sweat reducing its static adsorption capacity.

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Dynamic elongation test to evaluate the chemical resistance of protective clothing materials

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Introduction

To evaluate the resistance of a protective material to chemicals, standardized permeation test methods are generally used. These techniques determine quantitatively the permeation of the chemical through the material by measuring the amount of chemical vapors that reach the inside face of the tested material and then evaporate. The breakthrough times and permeation rates can thus be determined. These values characterize the resistance of a material to a chemical. The higher the breakthrough time, which usually corresponds to a low permeation rate, the higher the material's resistance to the chemical. To obtain reliable permeation results, the chemical must be sufficiently volatile to be detectable when breakthrough occurs. However, this method does not allow non-volatile (e.g., chemicals with boiling points of 160 °C or higher) or water insoluble chemicals (e.g., pesticides) to be investigated. Despite the work that has been done to develop a method to evaluate a material's chemical resistance to non-volatile chemicals, no reliable test is currently available (Ehnholt et al, 1988; Bromwich, 1997).

In this paper we describe a new test method to characterize the chemical resistance of protective materials by measuring the changes in length of a piece of polymeric membrane immersed in the chemical liquid which is followed over time in a specially designed cell. This method is suitable for characterizing the chemical resistance of protective materials to chemicals of low volatility. Furthermore, the elongation data can also be used to obtain solubility parameters as demonstrated in this paper.
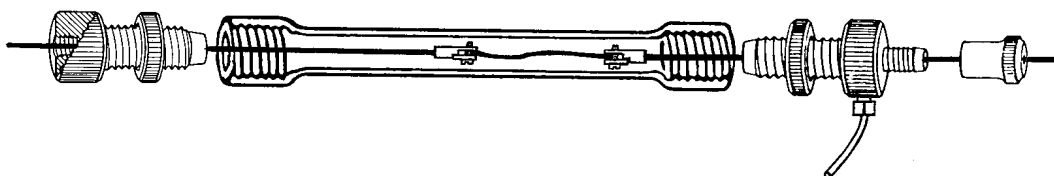

Figure 1. Schematic representation of the elongation test cell.

Description of the dynamic elongation test

Dynamic elongation tests are carried out by placing a rectangular piece of the sample material, 50 mm long x 4 mm wide, in a glass filter column (Ace-Glass Michel-Miller) containing the solvent (see Figure 1). This cell is 150 mm long x 8 mm inner diameter and closed at both ends (# 7 adapter injection port ACE-thread). A Michel-Miller Teflon® injection port adapter is used at each end. The sample is held in place by two small 10

mm x 5 mm metallic sheets attached at the ends of the rods. One rod is fixed while the other can be moved to keep the polymeric band fully extended during the swelling experiment. Care must be taken to avoid stretching the material.

To start the experiment, the solvent is introduced into the cell through the opening in one of the stoppers placed in one end of the cell. Air in the cell is evacuated through the opening in the other end of the cell. The holes into the Teflon® injection port are enlarged to allow easy movement of the rod inside the cell when the material swells, and also to allow free air and solvent circulation. The membrane sample is completely immersed in the solvent, thus allowing the solvent to diffuse into the entire sample surface. The timer is started as soon as the solvent comes in contact with the polymeric membrane. By measuring the displacement of the mobile rod used to keep the sample extended, the change in length of the sample is followed over time with a precise caliper (millimeter square graph paper can also be used). The initial reference point of the rod corresponds to the extended material without any solvent.
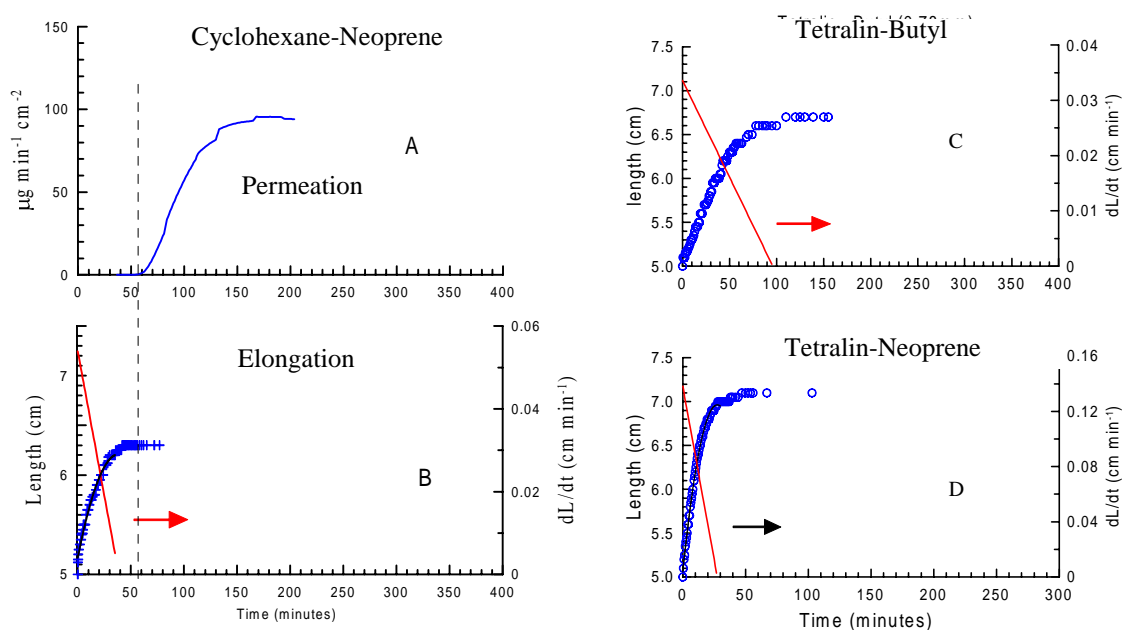

Figure 2. Curves A and B are a comparison of results obtained with the ASTM F 739 permeation test and the dynamic elongation test on a neoprene glove material with cyclohexane. Curves C and D represent the dynamic elongation tests performed with tetralin on butyl and neoprene glove materials, respectively.

Results and discussion

Figures 2A and 2B show a comparison of the results obtained with a volatile solvent, cyclohexane, and a neoprene glove material using the ASTM F 739 standard permeation test and the dynamic elongation test. Figure 2A shows that breakthrough occurs at close to 50 minutes. Figure 2B shows that maximum material elongation is reached at close to 40 minutes, which is a shorter time than the observed breakthrough time with the permeation test. This is because in the elongation test, the material's overall surface is in contact with the solvent, whereas in the permeation test, only one of the surfaces is in contact with the chemical. A derivative value dL/dt curve, calculated using a second order polynomial that fitted the results obtained from the first part of the experiment to the time just before the plateau is reached, is represented on the same figure. The dL/dt values extrapolated to 0 correspond to the time where the plateau of the dynamic elonga-

tion curve is obtained. This value was compared to breakthrough values obtained with the permeation tests. Some examples are presented in Table 1.

Curves C and D show the results obtained with the dynamic elongation test with a low volatility solvent, tetralin (b.p. 207.2 °C) tested with butyl and neoprene. These curves show that for butyl, it takes close to 100 minutes to reach the maximum elongation, while for neoprene, the maximum is reached in close to 30 minutes. This demonstrates that the solvent penetrates neoprene faster, so that this material has a lower resistance than butyl to tetralin.

Table 1 shows some examples of results obtained with the permeation and dynamic elongation tests. Breakthrough times obtained with the ASTM permeation test method are compared to the extrapolated dL/dt values as described above. These results demonstrate that breakthrough time and extrapolated dL/dt values are comparable. This means that the chemical resistance of protective clothing materials can be determined with the dynamic elongation test method. The principal advantage of the dynamic elongation test is that the results are not affected by chemical volatility or by detector sensitivity, which is the main problem with permeation test methods.

Table 1. Comparison of breakthrough times obtained with the ASTM permeation test and extrapolated dL/dt values obtained from the dynamic elongation test.

Solvent	Material/Company	Elongation Min	ASTM Min
Acetone	Neoprene/Fairprene	9	7.2 [a]
			12 [b]
			9.5 [c]
Cyclohexane	Neoprene/Ansell-Edmont 29-870	40	57 [d]
m-Cresol	Neoprene Ansell-Edmont 29-870	220	245 [d]
Nitrobenzene	Neoprene/Fairprene	22	22 [d]

[a]ASTM Standard Test Method for Resistance of Protective Clothing Materials to Permeation by Liquid or Gases under Conditions of Continuous Contact F 739-96.
[b]J. Lara Report IRSST R-104 La résistance des gants aux mélanges de produits chimiques, 1995.
[c]D. Bromwich The validation of a permeation cell for testing chemical protective clothing, American Industrial Hygiene Association Journal, 59:842-851, 1998.
[d]K. Forsberg, L.H. Keith, Instant Gloves+ CPC Database, 1999.

Hansen solubility parameters calculated from elongation data

The solubility of an organic solvent into a polymeric material has been associated with the resistance of the protective material to chemicals. The higher the solubility of the solvent into the protective material, the lower the resistance of the protective material to the chemical. Solubility parameters have therefore been used to predict the resistance of protective materials to chemicals, and consequently, to select the best skin protection.

The solubility of an organic solvent into polymers is well described by the use of Hansen three-dimensional (3-D) parameters (Hansen, 1967). From Hildebrand (Hildebrand & Scott, 1950), the solubility parameters for a volatile solvent are represented by the square root of the cohesive energy density $\delta = (E_v/V)^{1/2}$, where E is the vaporization energy, and V, the molar volume. The 3-D solubility concept considers the contribution of three components to the total cohesive energy, namely dispersion, dipole-dipole, and hydrogen bonding forces. The square of the total solubility parameter is represented by the sum of the squares of the Hansen parameters as follows:

$$\delta^2 = \delta_D^2 + \delta_P^2 + \delta_H^2 \tag{1}$$

where subscripts *D, P and H* refer to partial solubilities corresponding to dispersion, dipole-dipole, and hydrogen bonding forces respectively.

If the 3-D Hansen solubility parameters for a polymer and a solvent are known, equation 2 (Hansen and Skaarup, 1967) can be used to determine the degree of solubility of the solvent into the polymer.

$$A = [4(\delta_D^P - \delta_D^S)^2 + (\delta_P^P - \delta_P^S)^2 + (\delta_H^P - \delta_H^S)]^{1/2} \qquad (2)$$

Indices P and S in the equation refer to the solubility values for the polymer and solvent respectively. The smaller the A value, the greater the solubility of the solvent into the polymer, and consequently, the lower the resistance of the protective material to the chemical.

Hansen 3-D solubility parameters have been published for close to 700 solvents (Hansen, 1999). For polymers, solubility parameters can be experimentally obtained from data on solvent-polymer solubilities (polymer swelling or weight changes) using a battery of solvents with a broad range of 3-D Hansen parameters. In the recent studies of Zellers et al. (1996) different methods were compared to determine the Hansen parameter extracted from the experimental data.

In this paper, we report data obtained from the elongation test with a battery of 50 solvents for butyl, nitrile, neoprene, latex, and Viton® glove materials. The inverse value for maximum material elongation replaces the A value in equation 2. Thus, $1/\Delta L = A$. Using SOLO software, iterative calculations were performed to obtain the best values for the partial 3-D solubility parameters for the five commercial gloves. These values are compared to those reported by Zellers et al. (1996). The results are presented in Table 2.

Table 2. Comparison of Polymer 3-D solubility parameters determined with three different methods by Zellers et al 1996 and from the elongation data from this study.

Butyl	Graphic Method	Weighted Average[*]	Regression[*]	This study Regression
δ_d	19.7	17.1	18.4	17.5
δ_p	3.5	2.1	- 5.0	2.7
δ_h	3.6	2.6	- 0.8	3.7
Nitrile				
δ_d	16.9	17.3	18.9	17.1
δ_p	9.7	8.2	8.6	8.0
δ_h	8.6	6.2	6.0	7.2
Neoprene				
δ_d	17.0 (6.3-13)	17.5	19.4	17.5
δ_p	9.3	4.8	3.6	4.9
δ_h	7.6	4.7	4.2	5.5
Latex				
δ_d	17.0	17.2	18.4	17.7
δ_p	6.0	2.9	- 3.7	3.8
δ_h	5.2	3.4	1.4	3.7
Viton				
δ_d		17.0		17.0
δ_p		10.3		8.7
δ_h		6.1		8.2

Zellers studied two methods for determining the 3-D solubility parameters as alternatives to the standard graphical method. With one of the methods, the solubility parameters are determined from the weighted average of the solubility parameters of the solvents, where the weighting factor is the product of the solvent molar volume and the

fractional uptake of the solvent measured by immersion testing. In the other method, Zellers uses a multiple non-linear regression to estimate the 3-D solubility parameters. These two methods are presented as better alternatives to the arbitrary graphical solution. The results presented in Table 2 demonstrate that the calculated 3-D solubility parameter values for the five commercial products compare well to the ones obtained by Zellers using the weighted average method.

Conclusion

The study demonstrated that the chemical resistance of materials to low volatility solvents can be easily characterized by the dynamic elongation test method. This technique can be used with solvents where standard techniques based on the analysis of solvents that vaporize after breaking through the membrane cannot be applied. Furthermore, the results obtained from the elongation test can be used to calculate the Hansen 3-D solubility parameters. These values can be used to estimate the resistance of the polymeric materials used in protective clothing to chemical attack.

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Physiological strain and wear comfort while wearing a chemical protective suit with breathing apparatus inside and outside the suit in summer and in winter

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Introduction

Rescue work while an impermeable chemical protective suit (CPS) is being worn is physically and psychologically one of the most demanding tasks for a fire fighter. The use of CPS in operational work may impose even greater physiological strain in fire fighters than the use of turnout suit when entering into smoke-filled enclosures, which is well documented (Ilmarinen et al., 1994; 1997; 1998). Most studies on the effects of an impermeable chemical, gas or NBC protective clothing are conducted under controlled laboratory conditions at temperate or hot environment using test protocols which are very far from real operational rescue work. The effects of CPS under cool or cold conditions are much less studied (Smolander et al., 1984; Cortili et al., 1996; Rissanen 1998).

The purpose of the present study was to investigate the physiological responses in fire fighters while wearing an impermeable chemical protective suit with self-contained breathing apparatus (SCBA) outside and inside the suit during a simulated chemical accident at an outdoor processing plant both in summer and winter. Additionally, we attempted to find out the effects on the work performance, the wear comfort and function of the suit systems at work.

Methods

The voluntary *subjects* comprised 8 experienced healthy male fire-fighting trainers with an average age of 38.6 (31-44) years, height of 183.5 (178-190) cm, weight of 88.3 (72-110) kg, body fat of 14.6 (9.2-18.9) %, body surface area of 2.1 (1.9-2.3) m^2, BMI of 26.2 (22.6-31.9), and $\dot{V}O_2$max of 51.6 (46-60) ml/kg·min^{-1}.

Chemical protective equipment system (CPES) consisted of pants, cotton underwear with long sleeves and legs, polyester fleece sweat shirt and trousers, wool underhood, wool socks, cotton undergloves, helmet and an impermeable CPS. Two *types of the CPS* were studied: The SCBA (Dräger PA 90/6 l, approx. 16 kg) was carried either outside (SuitA) or inside (SuitB) the CPS. The material of both CPS was butyl rubber. SuitA weighted 5.5 kg and SuitB 7.8 kg. Correspondingly, air flow rate of air supply to CPS were 4 l/min and 2 l/min. The total mass of the CPES averaged 25,5 kg for SuitA system and 27 kg for SuitB system.

Experimental procedure and measurements: The test protocol was developed to reproduce situations encountered in an actual chemical accident. The drill was conducted outdoors in the rescue training area of the Finnish Emergency Services College in Kuopio at air temperature ranging from 13 to 20 °C in summer and from -11 to -20 °C in winter. The work task was 'sealing the leak in the flange in a chemical processing simulator'. The

drill was divided into two consecutive work sessions (WS) with a 20-min rest between the sessions for body cooling (partly doffing the CPS for ventilation of underclothing), drinking *ad libitum* and chancing the air container. In order to perform the demanded task the fire fighters have to walk and search, carry a pressurized hose (length of 80 m, weight of 96 kg) climb stairs and ladders, carry two 35 kg heavy cans about 100 m, seal the flunge and finally decontaminate themselves. The drill was performed in fire fighter pairs with their own speed. The CPS system was randomized for each pair.

The *performance time* was recorded. *Physiological* registration included heart rate (HR), rectal (T_{re}) and skin temperatures (T_{sk}) sweat loss and blood pressure (BP). The change in heat storage for heat exposure time was calculated from changes in mean body temperature using 0.97 Wh/kg·°C for specific heat of the body. *Subjective ratings* of perceived exertion and thermal comfort were requested and a questionnaire on the wear comfort and function of CPS at work was fulfilled. The measuring and evaluation methods are published elsewhere (Ilmarinen & Lindholm, 2000).

The protocol was approved by the Institutional Ethics Committee and the written informed consent of the subjects was obtained before the experimental sessions. The test drill was terminated if one of the following criteria was met: 1) emptying of the air container 2) $T_{re} \geq 39.5°C$ with subjective signs of severe discomfort or fatigue, chest pain or intense muscle pain, and 3) objective signs of exhaustion and exertional dyspnea or dizziness.

Statistics. Means ±SD, ranges and medians were used for description of the data and non-parametric tests were used to calculate differences between test conditions. The < 0.05 level of probability was accepted as significant.

Results and discussion

All test drills were completed. The average performance times for all the drills are in Figure 1. The interindividual variation in performance times was only some minutes. In summer the average performance time for SuitB (38 min) was significantly longer than for SuitA (24 min). In winter the difference between the suit systems was smaller (7 min) but still significant. Snow, partly even ice covered the ground and ladders, which hampered movements thus lengthening the time to complete the task with both suit systems. The difference between summer and winter was significant only for SuitA.
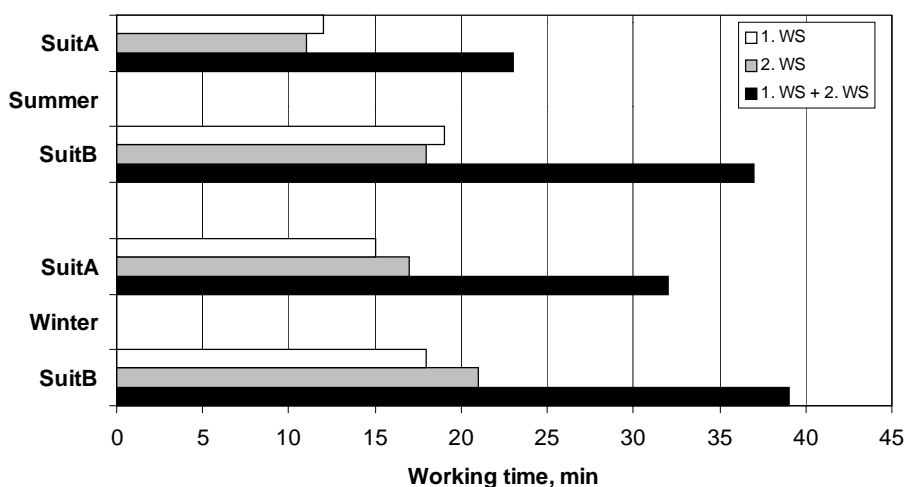

Figure 1. Average performance times for the WSs and completed drills while wearing CPS with SCBA outside SuitA and inside SuitB.

The higher work speed for SuitA resulted in higher average ventilation rates of 80 l/min in summer and 70 l/min in winter than corresponding average ventilation rates for SuitB being 65 l/min both in summer and winter. The differences were not significant.

After rapid increase from the beginning of work HR fluctuated at the near submaximal level during the WSs. The higher work speed in summer also resulted in considerably higher HR levels than in winter. The highest values were measured by using SuitB. On average, median HR (including both WSs and rest) was in summer 131 bpm for SuitA and 145 bpm for SuitB, and correspondingly, in winter 118 bpm and 126 bpm. The average peak HR in summer was 163 (149-173) bpm for SuitA and 168 (136-188) bpm for SuitB. In winter the respective values were 153 (135-173) bpm and 161 (148-178) bpm. The circulatory load was expressed as a time fraction of HR >75% of the individual maximal HR ($HR_{75\%}$). In summer $HR_{75\%}$ was on average 21 (9-37) % of total working time for SuitA and 37 (3-54) % for SuitB. The difference was statistically significant. In winter the time fractions were 13 (1-31) % and 24 (11-33) %. The difference was not significant.

There were no differences in systolic *BP* between the suits or between the seasons. Diastolic *BP* was higher for both suits in winter than in summer but the difference was not significant.

Individual variation in T_{re} responses was considerable. At the start of working T_{re} ranged from 36.2 °C to 37.7 °C. In summer the work resulted in average 0.8 °C increase in T_{re} regardless of the suit system. In winter the average increase was 0.2 °C for SuitA and 0.4 °C for SuitB.

Average $\overline{T}_{sk}$ for SuitB fluctuated during the drill in all conditions at higher levels than for SuitA, on average but the difference between the suits was not significant. Median values for $\overline{T}_{sk}$ (including both WSs and rest) averaged 33.9 °C for SuitA and 34.7 °C for SuitB, and correspondingly, in winter 31.6 °C and 32.0 °C.

The individual rates of heat storage varied in summer from 16 to 41 W/m^2 and in winter from -4 to 23 W/m^2 which resulted greater heat gain in SuitB both in summer and winter (Figure 2). The difference was significant only in summer. In winter the heat gain was significantly smaller for both suit systems than in summer.

No significant differences were found in sweat rates between the suit systems. However, the average sweat rates for both suit systems were significantly greater in summer than in winter being of 657(463-912) g/h·m^{-2} and of 233 (72-461) g/h·m^{-2} for SuitA and correspondingly, 558 (430-898) g/h·m^{-2} and 305(157-453) g/h·m^{-2} for SuitB.
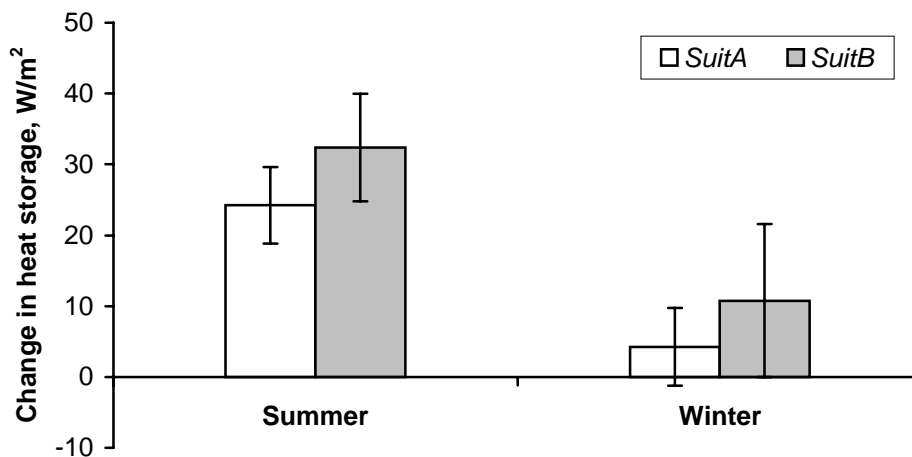

Figure 2. Mean (±SD) changes in body heat storage in summer and in winter while wearing CPS with SCBA outside SuitA and inside SuitB.

Donning and doffing SuitB without help was impossible for experienced fire fighters contrary to SuitA, which everyone managed to don themselves. Restricted movement and especially the loss of vision caused by the misting of the visor imposed an additional stress for the wearer by using SuitB and the work was perceived as being 'hard' both in summer and winter, on average. Some fire fighters perceived the physical work as being 'very very hard'. Correspondingly, physical work by using SuitA was reported 'somewhat hard', on average. Only some fire fighters reported 'hard'. In summer SuitB was considered significantly warmer and significantly more uncomfortable than Suit A. Also in winter SuitB was significantly warmer. There was no difference in average ratings of skin wettedness between the suits but the individual variation was considerable. The skin was felt to be form 'clammy' to 'wet' in summer and from 'nearly dry' to 'wet' in winter.

Conclusions

The results indicate longer performance time, significantly greater thermal and cardio-vascular strain as well as more intense subjective discomfort in fire fighters both in summer and winter while working dressed in fully encapsulating impermeable CPS with SCBA worn inside the suit. The performance of fire fighters and the success of rescue operations are adversely affected by all these facts.

Based on the results it is concluded that a CPS with SCBA worn outside the suit is a more ergonomic, safer and more suitable personal protective clothing for use in Nordic climatic conditions.

Acknowledgements

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Performance criteria for PPE in agri- and horticulture

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Introduction

At their working places farmers are affected by various kinds of load which result from the ambient conditions (climate) and the work process itself e.g. by emitting noise or airborne contaminants. These can be gases or particles, which form a risk potential for the farmers' health and welfare by possibly harmful substances like pesticides. Also the biological content of aerosols – germs, bacteria, and fungi – must be taken into account.

All possible loads have to be kept on low levels minimizing risk. If load can't be reduced means of protection have to be taken at least PPE (personal protective equipment) at the end of the chain of labour protection. According to the EU directive 89/686 EWG all PPE components on the European Market have to be labelled and certified that means that the equipment has to be tested with standard procedures and graded by given requirements on the performance. Those requirements will be derived from kind and situation of exposure time and level. Limit values can be given by national or international responsibilities. After a risk assessment defining necessary values of protection in agri- and horticulture additional questions of performance must be answered e.g. thermal comfort, prize and acceptance by the farmers and their environment. Here the situation is quite different to industrial conditions for the use of PPE, which is mostly understood as a mean for accidental prevention. In the following performance criteria for PPE in agriculture will be given for particular cases of load and protection. Outgoing from the example of risk assessment in pesticide (plant protection products, PPP) use it will be shown how these requirements will be stated.

Methodology / Application of PPE

Food and agricultural non-food production is characterised by various kinds of working places. It is to distinguish between work indoor e.g. in livestock-buildings or greenhouses and outdoor stationary or mobile that means on propelled harvesters or tractors with / without mountings. Apart from climate particular stress factors result from particular work and requires specific means of protection. Table 1 gives an overview about PPE and examples of its application in agriculture, prescribed in Germany (accident prevention regulation, 2000).

A special case form airborne contaminants in agri- and horticulture, which include possible risks by accidents and by long termed effects. Particles and gases may influence farmers health and welfare by dermal or respiratory uptake. Gases are to consider during mixing manure, handling silage and during gas application for conservation, or controlling pests. Particles emitted in livestock-buildings or in field operations like harvesting influence mostly respiration by their possible allergic potential (Hinz et al., 1990).

Table 1. PPE and examples of application in agriculture.

PPE protecting	work field
respiration	use of pesticides, disinfectants, work in dusty atmosphere
head	handling with lifted goods, operating on trees
foot	handling agric. mobiles, contact with claw and hoof animals
eye and face	work with saws and cutter, handling chemicals
hearing	work on non capsulated mobiles, with motor saw, feeding pigs
hand	work with saws cutter, handling chemicals
body	work with motor saws, handling chemicals, pesticide application

Table 2. Main sources of airborne contaminants in agri- and horticulture.

source	contaminant	effect
manure	gas	respiratory
silage, bio-gas	gas	respiratory
greenhouse	aerosol / gas	respiratory / dermal
animal house	aerosol / dust	respiratory / dermal
field operating	dust	respiratory
plant protection	aerosol / gas / dust	respiratory / dermal

A higher risk potential will be given by the use of chemicals – disinfectants and especially pesticides. These are signed according to the hazardous substances ordinance (1986) if they are high-toxic (T^+), toxic (T), caustic, harmful or irritating. The distribution of pesticides in Germany is given in Figure 1 and shows, that the ratio of risky pesticides is much lower than normally expected, only 6 % of the pesticides are classified with T^+ or T which will be used mostly for rodenticides.
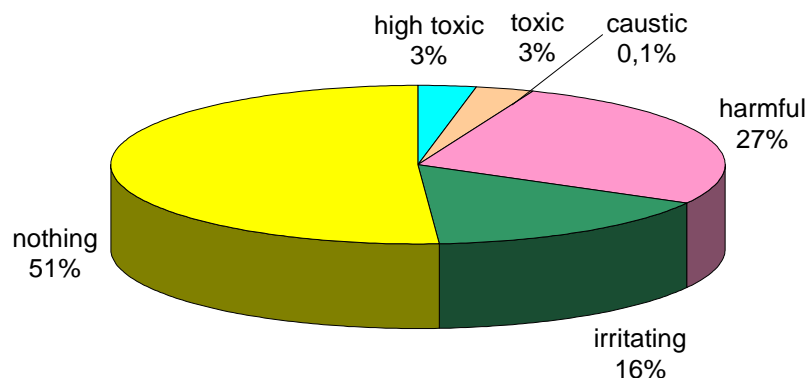

Figure 1. Distribution of pesticides regarding to possible effects to men.

But the influence of those possibly hazardous substances is only one factor load together and must be seen with exposure level and time. Because of a probably remaining portion of risk for all pesticides which shall be distributed in Germany a special risk assessment has to be presented to the body of authorisation. For this purpose a risk management model has been developed which is discussed to be a European harmonized model at the present time (Lundehn et al., 1992). Depart from the more simple idea of accident prevention this model shows some peculiarity e.g. by the introduction of dose effect functions instead of the break through criteria. The main idea of the model is the calculation of exposure whereby all kinds of work and possible ways of uptake are to consider: undiluted pesticide while mixing and loading - short termed, the process of application - long termed and additional possible jobs of maintenance on the field, before and after spraying. The oral, respiratory and the dermal path of uptake must be determined. So calculated over all exposure must be compared with a relevant toxicological limit value which results from special tests and will be prescribed mostly by national

authority. In case of pesticides this value is the acceptable operator exposure level (AOEL) which is required by an EU directive. In case that the ratio of calculated exposure and the AOEL is greater one, means of load reduction e.g. using other procedures of application or less harmful agents or PPE are to be fixed. One key point of the model is the commitment of reduction factors to maximum allowable values of penetration through the protective material. These values are given in Table 3 with e.g. 5 % for suits and 1 % for gloves.

Table 3. Reductions coefficients of performance of PPE.

protective mean	reduction dermal	coefficient inhalation
universal protective gloves (plant protection)	0.01	
standard protective garment (plant protective) and sturdy footwear	0.05	
protective clothing against chemicals; type 1	0	
broad-brimmed headgear of sturdy fabric	0.5	
hood and visor	0.05	
particle filtering half-mask FF2-SL or half-mask with particle filter P2	0.8	0.08
half-mask with combination filter AIP2	0.8	0.02

Plant protection products are only authorized, if the calculated exposure is tolerable for instance by use of PPE. In case of severe special kinds of exposure e.g. while application in greenhouses or in stock protection (fumigation) high protecting suits of type 1 chemical protective clothing may be required.

Besides of the performance requirements of protection more measures are requested for gloves and especially suits, which will be used while handling pesticides. Looking to the long time job of spraying thermal comfort is an important factor. To ensure it water vapour resistance must not pass over a maximum a value, just like the mechanical properties. One really important point concerning the acceptance of these PPE by the farmer is the design and the colour of the equipment. It must be taken into account that the work is in the outdoor area, which is mostly used for vacation of the town people. Means which may represent high degree of protection by view will never been worn in sensitive regions of fruit production or vineyards. These criteria of performance are given in Table 4.

Table 4. Additional criteria of performance of PPE.

criterion	measure	limit value
strength	tensile strength	longitudinal 600 N cross 400 N
	tear resistance	25 N
thermal comfort	water vapour resistance	20 m^2Pa/W
acceptance	design, colour, prize availability	

Depending on the load PPE will be worn in agri-horticulture for the different types of work as given in Table 1. According to the EU directive those means have to been tested by standard procedures of harmonized standards so far available. In other cases national norms or guidelines are to use e.g. as done in Germany with the BBA guideline for PPE in plant protection (BBA, 1993). Table 5 shows the network of existing standards of testing various parameters of PPE performance.

Table 5. CEN standards for testing performance of PPE.

performance property	test method standard
respiration	EN 136, EN 140, EN 146, 147, 149
eye/face protection	EN 166
foot protection	EN 345
hearing	EN 352, EN 458
hand protection	EN 374, EN 388, EN 381 - 7
body	EN 340, EN 465, EN 470, draft DIN 32780 – 300, prENISO 13982 – 2, EN 468, EN 463, EN 368, EN 369

Conclusion

Many working places in agriculture and horticulture effect farmers' health and welfare in various kinds of load. Examples are mechanical or heat stress as well the exposure by airborne contaminants, which may harm or irritate skin or breathing. In such cases the possible risks have to be limited by reducing load or by the use of different types of PPE protecting head, foot, body or respiration. This equipment must be tested and certified according the EU directive 89/686 EWG using CEN standard so far available. In other cases national standards or guidelines may be used as done in Germany with the definition of PPE to protect the applicator of plant protection products (PPP). At the present time a work item in CEN is defined to introduce the test procedure as a European standard.

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Limits of recycling in protective apparel

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Recycling has grown significantly during the last 10 years in Europe. Different companies have created technologies and established commercial supply chains for collecting and so-called "recycling" or "regenerating" fibres and aramids in particular. Globally speaking this is a positive initiative. DuPont is committed to sustainable growth as a matter of fundamental policy and supports reasonable activities in this area.

Our own DuPont Engineering Fibres group is working to introduce a special program to collect and recycle aramid waste (which can occur in processing textiles or at the end of the useful life of garments). Our aim is reliable quality of the resulting fiber products and finished articles that may be achieved. Together with our partners, several interesting opportunities for utilization of recycled para-aramid fibers have been identified. These applications do not require the high level of performance of original (virgin) KEVLAR® brand fibre and can accept a significant variation of properties.

It is clear that, after recycling, the properties of the regenerated fibres vary significantly more when compared to original fibres. Variability includes cut length, impurities in the bale, but also fundamental strength, modulus, cut resistance, heat performance properties, etc.

The virtues of WELL CONTROLLED recycling of aramids can be easily understood and are generally accepted as responsible good business practice.

DuPont would like to invite the market to join in an industry-wide consensus to apply reasonable discipline in the collection, recycling and processing of "second life" fibre. We all need to stop the use of 'recycled' or 'regenerated' aramid products in applications which are critical for human life and nature, such as ballistic and stab resistant vests and other armor, protective apparel, and safety equipment.
We strongly believe and have evidence that improper use in these fields could lead to serious accidents, injuries and human suffering.

Unfortunately, nowadays, a visitor to fairs related to protective apparel will easily find several stands with gloves and garments produced from so-called 'regenerated aramid'. There are several problems in allowing the existing situation to go on or grow.

1. End-users are not informed that these products are made of 'regenerated' aramids and hence cause dangerous differences in performance.
2. Some manufacturers even disguise the fact by using the terminology of virgin fibre marketing, misrepresenting their offering by fraudulent use of trademarks and fibre brand names.
3. Workers and specifiers do not know or understand the difference in performance between 'regenerated' and original (virgin) aramid fibres in products made out of them and generally trust 'regenerated' product as much as they trust virgin fibres.
4. Safety engineers put themselves, and the people they are responsible for, at risk. For even if the product will pass the relevant European Norms, nobody can guarantee that properties do not vary significantly from one individual item or garment to another. This could lead to serious accidents.

5. The much lower cost and price of products made out of 'regenerated' aramids reduces significantly the perceived value of products made out of virgin aramid fibres. The failure of "regenerated" products is ascribed to the "virgin" as well, because nobody so far is asking about differences in performance as soon as it is stated: "Made of 'aramid' fibre".
6. Beyond the waste aramid problem there are other examples of cheating in the market. People sell yellow cotton gloves under the name KEVLAR®, DuPont's registered trademark and brand, hoping to avoid a court case they may use 1 g of aramid sewing thread, for example. You can imagine how many possibilities for cheating, imitating and copying one can have with the un-controlled use of regenerated fibres.

You can probably cite more examples of the problem.

But even with above 6 examples, we consider the existing situation with 'recycled' aramids as very dangerous for the PPE market, the workforce and the general consumer. DuPont are undertaking immediate action in the marketplace and in the legal arena.

DuPont already started, together with our partners, to establish its own chain of collecting and recycling KEVLAR® brand fibres and other aramids.

– We will control strictly where recycled aramids end up.
– We are putting in place an intensive campaign to inform safety engineers throughout Europe about the hazards associated with waste in safety products.
– We will publish, with the agreement of companies negatively affected by un-controlled products, real cases of accidents, which resulted in injuries.
– We are pursuing before the court of law those unprincipled enough to mislead the public through the unqualified and un-authorized use of our trade names.
– We also invite you to support our efforts in managing a proper use of high-value recycled aramids and avoid their misuse in safety applications.

Protective clothing and survival at sea

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Introduction

During the past 50 years, the increase in maritime and intercontinental air traffic and the introduction of helicopter transport to offshore oil platforms have increased the risk of being exposed to accidental immersion in cold water, while a sharper focus on occupational health and safety has brought this matter to more general attention. Offshore oil workers, fish-farm workers, fishermen and military personnel are all, through their occupations, at risk of falling into the water. A wide variety of protective clothing and equipment has therefore had to be designed to meet the range of requirements of these user groups. The area of survival at sea is a multidisciplinary, bringing together expert from a wide variety of fields including policy-making, manufacturing, industry and science. In order to ensure the best possible performance of protective clothing and equipment, a better understanding of the impact of cold water on human physiological responses is essential. In the following paragraphs, hypothermia and other critical events during accidental immersion in cold water are briefly reviewed. The importance of maintaining heat balance during exposure to cold water is discussed in terms of thermodynamic laws and physiology. The design and development of personal protective clothing and equipment for aircrew are also discussed in order to illustrate the difficulty of reconciling thermal protection in water with other user requirements.

When the Titanic sank in 1912, 1498 people lost their lives. All deaths were attributed to drowning and there was no mention of hypothermia in reports of the disaster. Even though the importance of heat loss from the body when immersed in cold water has been known since the work of Lefèvre at the end of the last century (Lefèvre., 1898), not until after the Second World War did it become clear that cold was also a major cause of death after shipwrecks (Keatinge, 1969). The large number of ships and aircraft lost at sea forced the authorities of the countries at war to develop methods of protecting crews against cold water immersion. Research was done on designing protective equipment and on determining survival time in relation to water temperature. Much research during this period focused on the body insulation factor and how it is influenced by body measures. Using the US Navy's well-documented information on shipwrecks between 1942 and 1945, Molnar (1946) was the first to publish a tolerance curve based on the temperature in the water and the total time of immersion. His research also revealed wide individual variations in the length of time that people could survive in the water. In the course of the past 10 years a number of mathematical models that estimate human survival time under various conditions have been outlined. Such models are useful, but must be viewed with caution since reliable data concerning deep hypothermia are unavailable (Tikusis, 1997). Data obtained from case reports of accidental immersion can only provide *a posteriori* proof of the value of protective equipment. It is therefore necessary to assess the process of heat exchange between the body and its environment by studying both general physiological reactions and individual variations in the study of tolerance to cold-water immersion. Recently, much research on accidents at sea has focused not only on the

cooling of the body, but also on secondary physiological responses associated with immersion in cold water (Tipton, 1989). When accidents occur, the chances of survival are critically dependent on the performance of protective equipment, including protective clothing and buoyancy devices. Although protective equipment has indeed saved lives, there are numerous reports of equipment malfunctioning during emergency situations. A recent example is the Sleipner accident off the coast of Norway, in which 16 of the 88 passengers of a high-speed ferry lost their lives. The surviving passengers reported serious problems in donning life-vests, and the rafts carried on board were not functional.

This emphasises that there is still much to be done to improve safety when immersion accidents occur.

Direct effects of the cold; hypothermia

The innate protection mechanisms of the human body against a cold environment are very limited. This is explained physiologically by the fact that man is a homeothermic organism and that our thermoregulatory system is optimised to maintain a deep body temperature of around 37 °C. In contrast, reptiles and amphibians are able to tolerate large fluctuations in their body temperature, avoiding freezing by behavioural avoidance or physiological adaptation (Withers, 1992). Some mammals and birds utilise a regulated lowering of the body temperature to lower their daily energy expenditure. A human being can tolerate a variation of only about 4 °C in deep body temperature without impairment of his physical and mental performance. Any greater change in body temperature will affect cellular structures, enzyme systems and a wide range of temperature-dependent chemical reactions that occur in the body (Åstrand & Rodahl, 1986).

Hypothermia is defined as a condition in which the deep body temperature falls below 35 °C. It usually occurs accidentally, but can also be induced deliberately as part of a therapeutic regime, e.g. open heart surgery. There are three physiologically distinct types of accidental hypothermia; immersion hypothermia, exhaustion hypothermia and urban hypothermia. Immersion hypothermia is the type we must consider in accidents at sea, and it includes the most severe cold stress.

This hypothermia is generally divided into three distinct types according to the degree of body cooling; mild (body temperature of 34-35 °C), moderate (body temperature of 30-34 °C) and deep hypothermia (body temperature < 30 °C). Mild hypothermia is characterised by changes in peripheral resistance due to vasoconstriction, thermogenic shivering and tachycardia (Lexow, 1989). The victim is usually conscious and responsive. Peripheral vasoconstriction leads to an increase in central blood volume, which in turn induces diuresis. This cold diuresis is mediated through hormonal responses (e.g. antidiuretic hormone, atrial natriuretic peptide, aldosterone) that reduce the reabsorption of water and sodium by the kidneys (Vander et al., 1994, Ganong, 1997). As a consequence of cold diuresis and the redistribution of water from vascular space to extracellular space, the hypothermic victim will often be dehydrated (Popovic, 1974). Thermogenic shivering is normally most intense at 35 °C and causes a three- to five-fold increase in heat production.

At moderate hypothermia shivering gradually decreases and heat production declines. The victim's consciousness is clouded and there is increased muscular rigidity with the result that muscular co-ordination is impaired (Bristow, 1984). The cold affects the myocardial conduction system, inducing gradual cardiac slowing. Below 32 °C central body temperature cardiac arrhythmia develops and ventricular fibrillation may occur if the

heart is irritated (Bristow, 1984). There is a gradual fall in blood pressure because of bradycardia and a fall in peripheral vascular resistance.

Deep hypothermia is a life-threatening condition. The victim is usually comatose, the skin is pale and the pupils are dilated and unresponsive to light. There is pronounced bradycardia and at 18-20 °C the heart usually stops. Respiration and pulse are difficult to register below 20 °C deep body temperature, and it is impossible to measure blood pressure. However, due to a decrease in the metabolic rate, the oxygen requirements of the brain are greatly lowered, which implies that hypothermia actually offers some protection against hypoxia.

Indirect effects of the cold

Hypothermia is not always the direct cause of death, but may it induce other lethal effects. Immediately after immersion in cold water, a so-called "cold-shock response" is induced. Tipton (1989) has excellently reviewed this response. The "cold shock" is defined as the range of the initial responses when the victim falls into cold water, including cardiovascular and respiratory disturbances that may cause drowning and other fatal effects. The "cold shock response" is probably responsible for the majority of the 400-1000 open-water deaths that occur annually in the UK (ROSPA, 1988).

The cardiovascular responses include tachycardia, increased cardiac output and peripheral vasoconstriction (reduced peripheral bloodflow). As a result of both cardiac and vascular responses there is a dramatic increase in the blood pressure of the victim. The rapid increase in cardiac output and blood pressure increases the workload of the heart. This may cause greater ventricular irritability, cardiac irregularities and on rare occasions ventricular fibrillation (Tipton, 1989). The respiratory responses of cold shock are a greater threat to survival than the initial cardiovascular responses to cold water immersion. The sudden decrease in cutaneous temperature when exposed to cold water induces an inspiratory gasp reflex followed by hyperventilation (Mekjavic et al. 1987). Hyperventilation causes respiratory alkalosis and hypocapnia, but the most dangerous consequence is that the victim is not able to control his breathing. This, together with the powerful discomfort of the cold, which causes the victim to swim very clumsily, is believed to be one of the major causative factors in the mechanisms of cold-water swimming failure (Golden & Hardcastle, 1982). It has been demonstrated that even good swimmers are not able to swim for more than a few minutes in cold water (Golden & Hardcastle, 1982). The maximum breath-holding times for normally clothed individuals are reduced to less than 10 sec when exposed to cold water (Tipton & Vincent, 1989). A reduction of as much as 30-60 % in maximal breath-holding time has been reported (Hayward et al., 1984). This is extremely critical if the immersion occurs in choppy water or includes submersion from a ditched helicopter or a vehicle. The loss of both breath-holding time and voluntarily control over breathing increases the chances of aspirating water and drowning.

Victims of accidental immersion may collapse and die during the process of rescue or shortly afterwards. Several hypotheses exist regarding the cause of this phenomenon. Deaths have been attributed to an after-drop in observed core body temperature following removal from cold water. However, Golden & Hervey (1981) found no after-drop in the temperature of the central venous blood of pigs after cold water immersion. As an alternative hypothesis they suggested that in the hypothermic individual, the loss of the hydrostatic assistance to circulation (up to 30 % of cardiac output) on removal from the water may lead to the collapse of arterial pressure and, as a consequence, cerebral ische-

mia, coronary insufficiency and myocardial hypoxia (Golden & Hervey, 1981). These effects can be counteracted by lifting victims from the water in a horizontal position.

Thermal balance when exposed to cold water

The above sections have emphasised the importance of maintaining body temperature in humans in order to avoid the lethal effects of cold. The time that elapses before critical lower body temperatures are reached is dependent on the rate of heat loss. This in turn is dependent on the insulation factor provided by clothing and body fat together with environmental factors such as wind, waves, water and air temperature. Heat exchange between the body and the cold water follows the normal laws of thermodynamics. To keep the body in heat balance, heat production and heat gain must equal heat loss, according to the equation $M + R + C + K + S + E = 0$ (where M is metabolic heat production, R is radiation, C is heat loss by convection, K is heat loss by conduction, S is stored body heat and E is evaporative heat loss). Evaporative heat loss is of no significance in water, so total heat loss is determined by radiation, convection and conduction. Heat production can be increased in two ways; either involuntarily by shivering or voluntarily by muscular exercise. It is generally acknowledged that the rate of body cooling in cold water is increased by physical activity, which increases heat loss more than heat production (Keatinge, 1984). Physical activity increases blood flow in the extremities, reducing the internal insulation and thereby increasing convective heat loss (Hayward & Eckerson, 1984). However, leg exercise has been shown to be beneficial in maintaining heat balance during cold water immersion when subjects are wearing insulated survival suits (Reinertsen et al., 1993). Physical activity should therefore be considered as a means of improving endurance when protective equipment and procedures for survival at sea are being designed.

Convective heat loss from the body rises during cold-water immersion, since water has a heat-removing capacity 20 times as high as that of air. Heat loss is dependent on the temperature difference between the skin and the environment, and this in turn is largely dependent on insulation. Circulatory adjustment by vasoconstriction increases the body's insulation by shunting the blood from the peripheral vessels to the core of the body, keeping the central temperature high (Veicsteinas et al., 1982). Once vasoconstriction has set in, the ability to maintain body temperature is largely dependent on the thickness of the subcutaneous fat layer (Hayward & Keatinge, 1981). A thin person will lose heat to the surroundings faster than a fat person. A thin person will thus become hypothermic faster, while a fat person will be able to stabilise his body temperature better. Fat is also an advantage in cold-water immersion because it provides buoyancy. Another important determinant of heat loss is the ratio of surface area to mass. Therefore, as shown by Sloan & Keatinge (1973), children are at greater risk of hypothermia than adults because of their relatively high ratio of surface area to mass. Last but not at least, the impacts of environmental factors are significant in determining heat loss from the body. It has been demonstrated that accidental immersion in rough seas is associated with significantly shorter survival times than have been estimated from calm-water studies (Steinman et al., 1987). This is of importance in the work of developing test methods and standards for protective clothing.

Development of protective equipment; the compromise between different user requirements

The above discussion has demonstrated that the subject of survival at sea is truly complex. The basic principle is that the development and design of protective equipment should focus on all the potential hazards discussed in connection with cold-water immersion. To protect victims from the many different hazards, it is likely that more than one type of equipment will be required. To mention just a few: a survival suit should provide sufficient insulation to prevent the lethal effects of accidental hypothermia and attenuate the cold-shock response by reducing the rate of fall in skin temperature and prevent leakage. Gloves should protect the hands and ensure that the victim is able to swim and clamber on board a dinghy. Life jackets or other buoyancy aids should prevent deaths from initial respiratory responses by keeping the victim's head above water. Emergency underwater breathing apparatus would be advantageous when escaping from a ditched helicopter, by preventing inhalation of water. However, these protection requirements often interfere with performance and comfort requirements, complicating the process of development of protective equipment.

One example of this is the difficulty of reconciling good thermal protection in water with other functional requirements associated with flying. In the Royal Norwegian Air Force, wearing a survival suit is compulsory if the water temperature is below 10 °C. Aircrew personnel in Norway's northernmost squadrons are required to use a survival suit all year round because they are operating in areas where the water temperature may be as low as 0 °C. These suits are designed to extend survival time in case of cold-water immersion, and are therefore made of a material that has low water permeability and provides good thermal insulation. Paradoxically, this leads to a situation in which aircrew are subjected to considerable thermal stress during flight, with possible negative effects on cognitive abilities and mental performance. The survival suit must be compatible with the wearing of other aeronautical equipment and must not hinder flight control operations by restricting movement. If an accident does occur, the survival suit must have good mobility and low buoyancy, thereby facilitating escape from aircraft that may float upside down. In the water, dinghies will help keeping the victim afloat and offer some thermal protection. In the worst-case scenarios, victims may be unable to enter the dinghy and survival suits must keep them alive for up to 12 hours under conditions in which waves continuously wash over them. Finally, important requirements such as fire retarding properties, maintenance and cost must be taken into consideration. It is understandable that producing protective equipment that fulfils all these requirements will necessarily be a compromise. In view of the functional requirements in a working situation, the thermal protection offered by an acceptable suit in water will necessarily be limited. The testing programme should include an analysis of all critical phases in which the equipment might be used. First, procedures for testing personal protective equipment must include an analysis of its usability in the aircraft as well as of the thermal condition of the aircrew during flight. Secondly, the analysis of thermal protection in water must focus on procedures to maintain thermal balance under the environmental conditions against which it is intended to provide protection, and the duration required for such protection.

A questionnaire of Sea-King personnel at five helicopter squadrons in Norway showed that pilots and crewmembers have quite different priorities to the survival suit. All personnel categories put highest priority on safety for eventual emergency situations. Comparing the other requirements for the working situation, thermal comfort was most important for pilots, while flight engineers put a higher priority on keeping the suit clean. The rescue men were most concerned with maximum freedom of movement, while sys-

tem navigators put highest priority on thermal comfort of the feet. The differing priorities of pilots and crewmembers reflect their different working tasks. This emphasizes the importance of involving the end users in order to acquire a better understanding of the working environment and the problems experienced. The method of involving the end-users when developing protective clothing will also be applicable in other user groups that have quite different requirements. For example, thermal protective aids for ferry passengers should focus on the importance of easy donning of the life west's. Offshore oil workers are easy to localize and may not need protection for a very long time. Protective clothing for fish farmers should give a better protection for the sudden exposure to cold water, than long time immersion to cold water. In contrast, fishermen require a survival suit that will only be used in case of an emergency, and should protect against cold water immersion for several hours.

In conclusion, the development and testing of protective equipment should focus on all hazardous responses resulting from cold water immersion and take into consideration the operational requirements of the user.

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Current and future standards of survival suits and diving suits

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International standards for survival suits was first included in the International Maritime Organizations Resolution A.689(17) on Life Saving Appliances, which covered two types of survival suits: insulated suits and uninsulated suits, both of a dry suit type.

The insulated suit are commonly referred to as a 6-hour suit, a name which has arrived from the thermal testing of suits requiring a test of 6 hours in cold water (<2 °C). The uninsulated suit is accordingly referred to as a 1-hour suit, as this type of suit is thermally tested for 1 hour.

Recently the IMO Regulations has been expanded, and now include a third suit, an anti-exposure suit, which can be considered as a work suit with specific integrated survival functions. With regards to thermal properties the requirements for the anti-exposure suit are identical to those for the IMO-uninsulated suits.

The necessity of such life saving appliances onboard commercial sea going vessels have been demonstrated in numerous sea accidents, in which such suits have saved a large number of human lives, in particular in the fisheries.

However, recent accidents with passenger transporting ships have given clear indications that the number of survival suits onboard should be sufficient, also for the passengers, not only for the crew as the situation is today. This is particularly important for sea activities in northern areas and in cold water, where the standard IMO-lifejacket is insufficient to provide any thermal protection of significance.

As a consequence of this realisation the Norwegian Maritime Directorate are proposing a standard for a passenger survival suit which would fulfil the requirement for an improved thermal protective aid (TPA) which is a standard life saving appliances in liferafts and lifeboats. The Norwegian Maritime Directorate is proposing this standard to be implemented in the IMO Regulations for life saving appliances. This would be an addition to the thermal protective lifejacket which was presented at the Subcommittee on Ship Design and Equipment in 1999.

The Norwegian Maritime Directorate has further suggested to differenciate the requirement for personal life saving appliances based upon the water temperatures where the ship or vessel is active.

The proposal is as follows:

In the 1990's the initiative was taken to prepare an European standard for immersion suits. During the work this has developed to become a joint EN and ISO standard, which covers two types of immersion suits:

> Constant wear suits, and
> Abandonment suits

The requirements including safety for these two suits are presently covered in two documents:

> prEN ISO 15027-1 (Constant wear suits), and
> prEN ISO 15027-2 (Abandonment suits)

The test requirements and test methods for these suits are presented in a third document:

       prEN ISO 15027-3

These three documents are currently submitted to the formal vote among the CEN member countries.

The constant wear suit presented by prEN ISO 15027-1 also cover the helicopter transit suit.

However, in 1999 the Civil Aviation Authorities in the countries with offshore activities in the North Sea (UK, Netherlands, Denmark and Norway) started the preparation of a joint standard for helicopter transit suits. The prEN ISO 15027-1 represent the basis for this new standard, as it outlines the minimum requirements for such suits.

The Working Group for the Civil Aviation Authorities have prepared a draft standard for "Helicopter Crew and Passenger Immersion Suits".

This Joint Technical Standard Order gives the requirement which immersion suits for use on helicopters operating to or from helidecks located in a hostile sea area (as defined in JAR-OPS 3.480) must meet. These immersion suits must be combined with a JTSO lifejacket.

The Working Group for the Civil Aviation Authorities are also preparing a separate standard for an "Integrated Immersion Suit for Helicopter Crew and Passengers". In this suit the lifejacket functions are integrated as a permanent part of the immersion suit.

Much of the standardisation work for immersion suits/survival suits have taken place during the last 10-20 years. It can therefor be foreseen that these standards will be adjusted and modified with regards to requirements and test methods as experience are being gained for the standards in their present form.

One area has been of particular concern, the evaluation of the thermal properties of the suit. The majority of such evaluation are presently being performed as manned tests using human subjects. To reveal any problems with the thermal properties of the suits the tests have to include exposures which could be considered extreme. Several countries have expressed concern and reluctance for performing such tests on ethical grounds. Proposed changes to the suit standards have been prepared, recommending such evaluation being performed using thermal manikins. Unfortunately a convincing relation between the results obtained on manikins and human subjects for the same suits has not been established. Thermal manikins for wet environments are presently available only in a very low number.

The replacement of human thermal testing with manikin testing has consequently been delayed.

Even though the testing performed as defined in the standards may be considered extreme, experience from real accidents at sea indicate that these test conditions are far from being as demanding as the conditions in many real accidents.

The thermal evaluation is a good example on this, as sea accidents in cold environments have demonstrated that the cooling of the victims' bodies have been three times as fast as measured in the approval tests. The main reason for this difference is due to the fact that the approval test does not ask for low air temperatures, high wind speeds, waves and water spray, which are normally occurring in rough water, and which are affecting the body cooling of the victims. It is therefor strongly warned against trying to extrapolate the laboratory test results to predict survival times in real sea accidents.

Considering the extreme conditions against which the diving suits shall protect the wearer. Such protective suits have received surprisingly little attention. Notified bodies have, however, been faced with the problem of lacking common standards for the

evaluation and certification of the diving suits. Comparing the tests performed and evaluation criteria used for certifying the suits by different notified bodies reveal significant differences.

Finnish Institute of Occupational Health (FIOH) took the initiative to propose a working group for developing a common European standard for diving suits.

This group was established as WG12 in TC162, and started its work 2 years ago.

The working group is preparing 4 standards for 4 different groups of diving suits:

I	Wet suits
II	Dry suits
III	Actively heated or cooled suits
IV	One atmosphere suits

The working group has recently presented the first working documents for these diving suits standards. The final standards is expected to be presented for formal voting within a two year period.

Heat preservation behavior of diving suit

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Introduction

Heat preservation is one of the important functional attributes to design diving suit for the survival of divers. Many researchers investigated the mechanism of heat and moisture transfer in porous media such as textiles (Ogniewicz & Tien, 1981; Motakef & El-Masri, 1986; Henry, 1939; Luo et al., in press). The aim of this paper is to simulate the dynamic distribution of heat and water condensate in a diving suit consisting of two layers of fabrics with different porosity in diving environment. In simulating the dynamic heat and moisture transfer in a diving suit, we focus on comparing numerical results computed by using fabrics with different porosity due to the time limit for completing the paper for this conference.

Model and methods

Governing Equations

The mechanism and mathematical model to heat and moisture transfer in a porous fabric can be described by the following equations (Luo et al., in press):

$$\begin{cases} C_v(x,t)\dfrac{\partial T}{\partial t} = \dfrac{\partial}{\partial x}(k(x,t)\dfrac{\partial T}{\partial x}) + \dfrac{\partial F_R}{\partial x} - \dfrac{\partial F_L}{\partial x} + (1-\varepsilon(x))\lambda(x,t)\Gamma(x,t) \\[2mm] \dfrac{\partial F_R}{\partial x} = -\beta F_R + \beta\sigma T^4(x,t) \\[2mm] \dfrac{\partial F_L}{\partial x} = \beta F_L - \beta\sigma T^4(x,t) \\[2mm] \varepsilon(x)\dfrac{\partial C_a}{\partial t} + (1-\varepsilon(x))\Gamma(x,t) = \dfrac{D_a\varepsilon(x)}{\tau}\dfrac{\partial^2 C_a}{\partial x^2} \end{cases}$$

where β is the absorption constant, σ is the Stefen Boltzmann constant, and $\Gamma(x,t)$ is the (de)sorption rate, condensation rate or freezing rate by fibers in the case of gas, liquid or solid, respectively. Details of all nomenclatures are given in (Luo et al., in press).

When there is no condensation on the surface of a fiber in a fabric, $\Gamma(x,t)$ is in the form of $\Gamma(x,t) = \dfrac{\partial C_f(x,t)}{\partial t}$ to describe the sorption/desorption of moisture by the fibers, which obeys Fick's law of diffusion. The water content of the fiber is determined by $W_c(x,t) = C_f(x,t)/\rho$. When the relative humidity exceeds 100 % at a position and/or water content in a fiber reaches the saturation, condensation occurs. In the condensation region, the liquid water and water vapor reach thermodynamic equilibrium. The vapor

concentration is saturated and solely determined by temperature, i.e., $C_a^* = C_a^*(T(x,t))$. Under such circumstances, the water condensation rate $\Gamma(x,t)$ can be determined by the mass balance equation, i.e.

$$\Gamma(x,t) = \frac{\partial C_f(x,t)}{\partial x} = \frac{\varepsilon(x)}{1-\varepsilon(x)}\left(\frac{D_a}{\tau}\frac{\partial^2 C_a^*(x,t)}{\partial x^2} - \frac{\partial C_a^*(x,t)}{\partial t}\right),$$

where

$$C_a^*(x,t) = 216.5 \times Vap(T(x,t)) \times 10^{-6}/T(x,t).$$

With $\Gamma(x,t)$, the water content can be calculated by $W_c(x,t) = \frac{1}{\rho}\int_0^t \Gamma(x,t)dt$. When

$W_c(x,t) = \frac{\varepsilon(x)\cdot\rho_{water}}{\rho_{fiber}} + (1-\varepsilon(x))\cdot regain$, water sorption reaches its maximum at the

point x under the assumption of that water is immobile in the fabric.

Boundary conditions

To simulate heat transfer and water distribution in the diving suit in dividing environment, we assume that heat flux between diver's skin and the suit decrease exponentially with time, i.e.,

$$\begin{cases} k(x,t)\dfrac{dT(x)}{dx}\Big|_{x=0} = ce^{-pt} \\ k(x,t)\dfrac{dT(x)}{dx}\Big|_{x=L} = \dfrac{T_{b1}-T_b}{R_1} \end{cases} \text{ and } \begin{cases} D_a\varepsilon\dfrac{\partial C_a}{\partial x}\Big|_{x=0} = \dfrac{C_a|_{x=0}-C_{ab0}}{w_0} \\ D_a\varepsilon\dfrac{\partial C_a}{\partial x}\Big|_{x=L} = \dfrac{C_{ab1}-C_a|_{x=L}}{w_1} \end{cases},$$

where C and p are an initial heat flow and attenuation coefficient of the heat flow respectively.

Results and conclusion

We assume that a diving suit consist of two layers - cotton and wool fabrics, which is coated at the inner and outer surfaces. The dynamic heat and moisture transfer processes in the diving suit is simulated for the situation when a diver wears a diving suit and moves suddenly from an initial warm condition to a cold environment of deep sea. The initial external condition is assumed to be 20 °C and 80 % RH, and the cold condition is assumed to be 0 °C and -20 °C, 100 % RH, respectively. The inner surface of the diving suit is assumed to be close to the human skin and the microclimate next to skin is assumed to be initially at 33 °C and 96 % RH. In our numerical experiments, we will take large parameter w_1 (resistance to water vapor transfer) for the outer surface of the diving suit according to the design of the suit.

In computation, the values of the material parameters are listed as follows:

$\rho = 1310 Kg/m^3$ (density of wool), $1550 Kg/m^3$ (density of cotton);

$R_f = 1.03e^{-5}m$ (mean radius of wool), $0.66e^{-5}m$ (mean radius of cotton);

$$\lambda_w = \begin{cases} 16025e^{-11.72W_c} + 25220 KJ/Kg & in\,dry\,region \\ 2260 KJ/KG & in\,wet\,region \\ (2260+333)KJ/kg & in\,freezing\,region \end{cases} \quad \lambda_c = \begin{cases} 10309e^{-2239W_c} + 25220 KJ/Kg & in\,dry\,region \\ 2260 KJ/KG & in\,wet\,region \\ (2260+333)KJ/kg & in\,freezing\,region \end{cases}$$

$C_v = 373.3 + 4661.W_c + 4.221T \ KJ/m^3 K$ (Volumetric heat capacity of wool fabric);

$C_v = (1663 + 4184W_c)/(1+W_c) \ KJ/m^3 K$ (Volumetric heat capacity of cotton fabric).

The following parameters are also used in the computations:

$\tau = 1.2$ (Effective tortuosity of the wool and cotton fabric)

$K_a = 0.025 w / mk$ (Thermal conductivity of still air)

$D_a = 2.5e^{-5} m^2 / s$ (Diffusion coefficient of water vapor in the air)

$L = 0.04m$, $e_1 = e_2 = 0.9$, $\beta = 400 s / m$.

The thermal conductivity in our computation is calculated as the same as in (Luo et al., in press). The resistance to heat transfer of the inner (R_0) and outer (R_1) fabric was taken to be $0.003 m^2 K / W$ and $0.00001 m^2 K / W$, and the water vapor resistance of the inner (w_0) outer (w_1) fabric was taken to be $10^{-4} s / m$ and $10^4 s / m$. The attenuation coefficient p and constant c are taken the values of 0.5 and 0.05 in our computation, respectively.
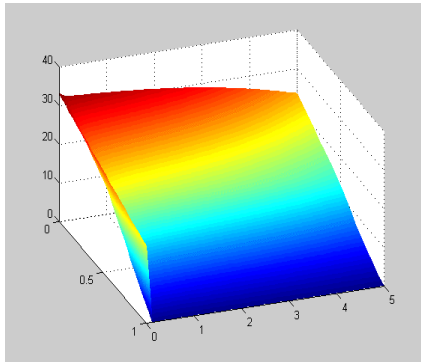
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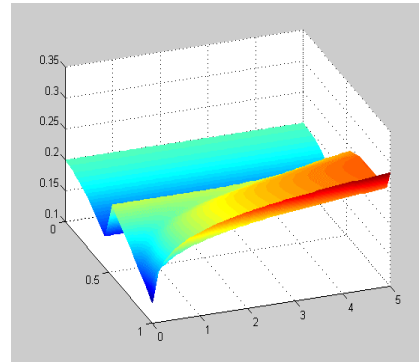
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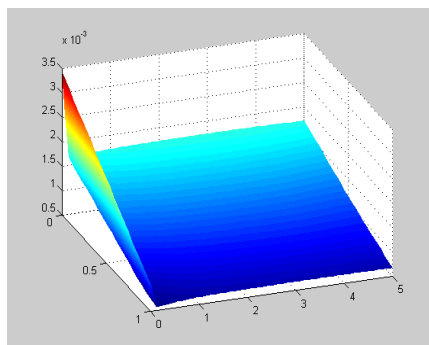
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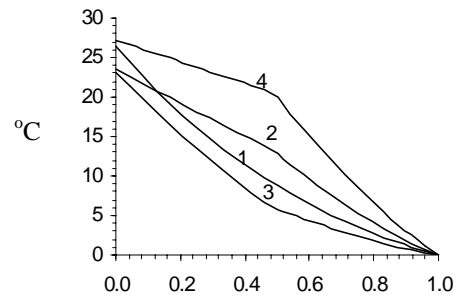
Figure 4.

Figure 1 and Figure 2 show that the distributions of temperature and water condensate accumulation with time in the diving suit with cotton fabric of 60 % porosity and wool fabric of 80 % porosity. The numerical results imply that the temperature in the suit decrease rapidly at the outer surface to 0 °C, followed gradually by the inner layers of the suit. Different levels of moisture condensations are predicted in the two layers of fabrics of the suit during the first 5 hours of simulation. The distribution of water vapor concentration in the suit, however, shows a pattern of rapid decrease across the thickness of the suit (Figure 3). Figure 4 compares temperature distributions after 5 hour in the sea among four different combinations of porosity in the cotton and wool fabrics: 1. $\varepsilon_c = 91.9\%$, $\varepsilon_w = 92.5\%$; 2. $\varepsilon_c = 60\%$, $\varepsilon_w = 80\%$; 3. $\varepsilon_c = 80\%$, $\varepsilon_w = 60\%$; 4. $\varepsilon_c = 60\%$, $\varepsilon_w = 90\%$. It can be seen from Figure 4 that the suits consisting of higher density in the inner cotton fabric and lower density in the outer wool fabric has better heat preservation behavior than those with lower density in the inner cotton fabric and higher density in the outer wool.
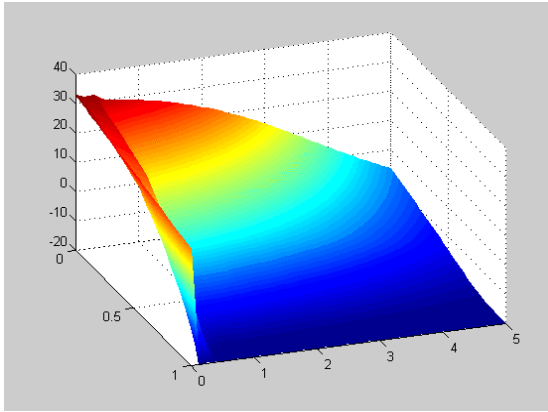
Figure 5.

To investigate and simulate the heat and moisture transfer in a diving suit under a very cold deep-sea environment, the outer boundary condition is assumed as -20 °C and the attenuation coefficient $p = \dfrac{5}{6}$. Rapid temperature drop is predicted across the thickness of the suit as shown in Figure 5, indicating that the survival time of the diver is much shorter in such an environment than in a warmer environment.

Acknowledgement

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The effect of the distribution of insulation in immersion suits on thermal responses

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Introduction

The IMO's thermal requirements for survival suits are linked to core temperature changes in test subjects. However, although the core temperature is relatively protected, cooling the peripheral regions of the body may cause discomfort and pain. Furthermore, severe cooling of the hands and feet affects physical performance and impairs the ability to move (Enander, 1987). In an emergency situation this may be lethal.

When a subject is protected with an insulated survival suit, only some parts of the body are immersed. The anterior part of the body with most of the head, hands and toe area is exposed to air, while the posterior part is exposed to water. Heat is lost to the environment mainly by conduction and convection. The rate of heat loss depends on the heat conducting properties of air and water together with the temperature gradient between the body in its survival suit and the surrounding air or water. Because heat conduction in water is about 25 times as great as in air, the potential for heat loss is greatest for the regions of the body exposed to water, i.e. the posterior part (Smith & Hames, 1962). Furthermore, water pressure compresses the air between clothing layers inside the suit, resulting in poorer clothing insulation. Heat loss also depends on the surface to volume ratio, which means that the feet, hands and legs will cool faster than the torso. In conjunction with a developing negative body-heat balance this produces vasoconstriction and decreased blood flow to the hands, legs and feet.

The thermoregulatory responses to temperature changes differ between different body regions. This presentation summarises some of our results that demonstrates the effects of increased regional insulation during cold immersion on the following parameters: local skin temperature, mean body temperature, core temperature, metabolic response to heat loss and subjective evaluation of thermal sensation and thermal comfort.

Results and discussion

Insulation of the hands

Six subjects dressed in neoprene survival suits underwent two hours of immersion in cold water (water temperature slightly above 0 °C, air temperature -5 °C and wind speed 5 m·s[1]). The core temperature fell by approximately 0.3 °C per hour, while the skin temperatures of the neck, abdomen and lower back also decreased slowly from between 32 and 36 °C to between 28 and 34 °C. All these temperatures were sensed as thermally comfortable. Skin temperatures of the posterior thigh and leg, hand, heel and toe fell much more rapidly, reaching temperatures between 10 and 20 °C.

The thermoregulatory responses we can deduce through these changes in body temperature involve vasoconstriction that reduces the temperature gradient between the body and its surroundings. The blood flow to muscles and subcutaneous fat is also reduced and this contributes to the protection of the body core temperature. Metabolic heat production increased three times the resting metabolic rate.

At the end of such a two-hour immersion period, the body core shrinks in terms of the proportion of tissue which is able to maintain a 37 °C blood supply. The requirements of the IMO regulations regarding core temperature are still met, but the thermal status of the body is not satisfactory. Leg and toe temperatures below 10°C are painful. Hand and heel temperatures are falling rapidly towards the same low values. In order to delay the cooling of the hands, the insulation of this body region was improved by a knitted woollen glove. At the end of the two-hour immersion the hand skin temperature had stabilised at 18 °C, resulting in a significant positive effect on local thermal sensation in the hand region. Furthermore, the ability to perform manual tasks was maintained.

Insulation of the posterior region of the body

In a further attempt to avoid rapid cooling of the peripheral body regions, an extra layer of neoprene was applied to the posterior of the suit, covering the area between the lower scapula and the knees. Figure 1 shows the development of posterior thigh temperatures in nine test subjects during six-hour of immersion in 2 °C water. Air temperature was 10 °C. Thigh skin temperature of subjects wearing the standard suit decreased 12 °C during the six-hour immersion period. The extra layer of insulation produced a 6.5 °C reduction in the drop in temperature during the same immersion period (Table 1). There were no significant differences in development of rectal temperatures between the two conditions.
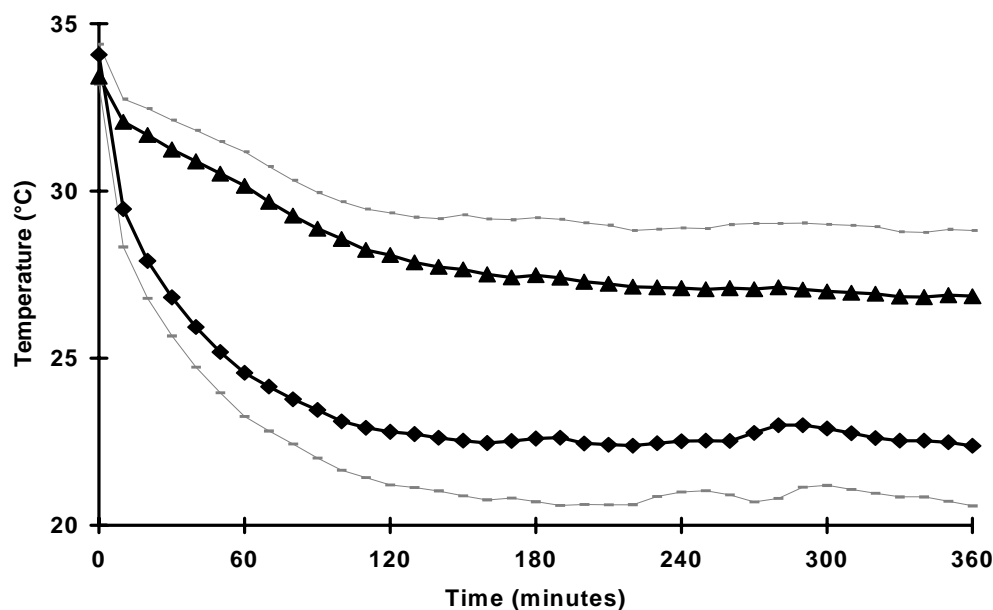

Figure 1. Time course of thigh temperature during six-hour immersion for the two conditions, standard suit (lower) and suit with extra insulation (upper). Values are means of nine subjects with standard deviation indicated.

Table 1. Body temperatures at the start and end of six-hour immersion. Thigh = posterior thigh. Values are means ± SD of nine subjects.

Condition	Measuring site	Temperature (°C) start	Temperature (°C) end
Standard suit	Thigh	34.1±0.4	22.3±0.7
	Mean skin	32.8±0.6	27.0±0.9
	Rectal	36.8±0.1	36.2±0.4
Extra insulation	Thigh	33.4±0.5	26.9±0.8
	Mean skin	33.2±0.3	28.2±0.7
	Rectal	36.7±0.2	36.2±0.1

Thirteen skin temperatures were measured with thermistors positioned at the forehead, chest, abdomen, upper arm, forearm, dorsal hand, anterior and posterior thigh, shin, big toe, heel, upper back and neck. Mean skin temperature was calculated from the un-weighted average of these sites. There was a significant difference between the drop in mean skin temperature for the standard suit and the suit with the extra insulation.

The improveded insulation also reduced total heat loss and thus the need to increase metabolic heat production during the immersion (Table 2) (Kuhnen & Jessen, 1988). Similar rectal temperatures and higher skin temperatures in the suit with extra insulation, would produce more afferent input from the thermosensitive reseptors in the standard suit condition (Jessen, 1990; Mittelmann & Mekjavic, 1991). Total, peak and increased heat production from resting value to peak value were all significantly different between the two conditions. This effect of the extra layer of insulation on metabolic heat production may enhance the potential of sustained heat production, and thus increase chances of survival in an emergency situation (Hesselberg et al., 1995).

The condition with the extra layer of insulation also resulted in significant differences between subjective ratings of thermal sensation and thermal comfort. All nine subjects wearing extra insulation reported a thermal state closer to "neutral" and "comfortable" than under the standard suit condition (Gagge et al., 1967).

Table 2 Heat production (HP) during a resting period before immersion, peak heat production, maximum increase of heat production and total heat production during the six-hour immersion period. Values are means ± SD for nine test subjects.

Condition	Start HP ($W \cdot m^{-2}$)	Peak HP ($W \cdot m^{-2}$)	Increased HP ($W \cdot m^{-2}$)	Total HP ($W \cdot m^{-2}$)
Standard suit	46.0±3.7	81.4±12.5	35.33±13.7	23.781±2.101
Extra insulation	49.3±4.5	69.4±10.1	20.2±9.9	20.930±1.954

Conclusions

The effects of improving insulation in selected regions of the body, may well include increased chances of survival and an improved ability to perform essential manual tasks. If the requirements of international standards focused on the total thermal condition of subjects, including comfort, and the skin temperatures of hands and feet as well as metabolic thermal responses, manufacturers could easily produce survival equipment that could satisfy such requirements and thus provide better protection in emergency situations.

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Lifevests - what is the value of the certification?

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Abstract

An accident on the coast of Norway last November, with the fast speed ferry SLEIPNER, in which 16 people died has resulted in a number of questions regarding the certification of life jackets.

The life jackets onboard this ferry was manufactured only a year prior to the accident and were marked to be approved according to SOLAS 74/83 Res. IMO A689(17). However, several of the survivors from the SLEIPNER reported problems with the life jackets. When retested on the request of the Norwegian Maritime Directorate it was found that the life jackets did not fulfil the IMO requirements for strength, for donning and for the water performance.

Investigation connected to life jackets, and particular the life jackets onboard SLEINER, has revealed differences between Notified bodies with regards to performing, witnessing or accepting tests performed by other institutions as a basis for issuing certificates for such survival equipment.

The discussion around the certification of life jackets has also resulted in intensified discussions about some of the acceptance tests in the IMO Regulations. In particular the tests for righting properties and free board have been focused upon. The tests are performed using human test results and with considerable differences in test results from one test subject to another for the same life jacket. A test less dependent of the test person and with more reproducible results is clearly preferable.

Improvements both with regards to test methods and practice for certification are needed.

Pass/fail criteria to evaluate the strength of buoyancy aids (50 N) and lifejackets (100 N) in accordance to EN 393:1993, EN 395:1993 and the A1:1998

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Introduction

Personal flotation devices (PFD) – lifejackets and buoyancy aids – must be sufficiently comfortable to wear and attractive to use, to ensure that they are not just purchased but also actually used. However, in accidental immersions, and especially during rescue operations in rough waters, not only good in-water performance but also sufficient strength of PFD is a vital requirement for survival.

The European standards EN 395:1993 for Lifejackets 100 N (for use in relatively sheltered waters) and EN 393:1993 for Buoyancy Aids 50 N (for use in sheltered waters when help is at hand and the user is a swimmer) require a horizontal load test to measure the strength of an assembly. This test is mainly for the body strength of PFD. The amendments EN 393/A1:1998 and EN 395/A1:1998 introduced also a vertical load test as a normative test. This is used mainly for testing the strength of the shoulder seams. However, the requirements are written in very general terms and thus clear pass/fail criteria are not available to a technical appraiser of notified bodies to assess the conformity of the tested products. In EN 393 and EN 395, clause 4.16.6 only states *"Strength of assembly shall be tested according to Annex A for (5.0 ±0.1) min in both wet and dry conditions. **No damage shall result which would result in the device failing to function in accordance with this standard**."* Annex A in standards EN 393 and EN 395 instruct the appraiser to *"examine the buoyancy aid or lifejacket for any resultant defects"* and to *"measure any adjustment device slippage".*

Pass/fail criteria have also been discussed at the test house experience exchange meeting (Vertical Group 8, Lifejackets, personal buoyancy aids, immersion suits) held in Cologne in April 1999. The meeting came to the conclusion that some damage could be accepted, and that if the jacket functioned after the test, then it would pass. This could be verified by additional subject tests. **What does this mean?** Should in-water performance tests be carried out on all test items that have been torn in the load tests? This would bring extra expenses for the manufacturers. The meeting also concluded that the damage was impossible to define in terms of length of the torn seam, and the decision was left up to the test houses. However, the vague pass/fail criteria have caused difficulties because the notified bodies in different countries have interpreted the given test results differently. This handicap has become apparent when the marketing controls on PFDs have been carried out. Many CE-marked PFDs have failed in the inspection tests.

This study summarizes the results of strength tests for buoyancy aids 50 N and lifejackets 100 N carried out during EC type-examinations conducted by notified body 0403, and during marketing control projects in Finland. The results are meant as a basis for further discussion in the EN/ISO standardization group for revision of the PFD standards (prEN ISO 12402 - Part 1-9, requirements and test methods) and in the test house meetings to exchange experiences.

Material and methods

The data have been collected from the PFD mechanical approval test reports of the accredited Finnish test house T013. The samples have been tested in 1998-2000, according to EN 393/A1:1998 and EN 395/A1:1998. A vertical load test is always performed after a horizontal test, and correspondingly, a wet test after a dry test on the same PFD sample.

This study includes 31 buoyancy aids and 33 lifejackets of 23 different designs and in several sizes from numerous manufacturers. The numbers of tested PFDs types (overall, jacket, and vest) are given in Table 1.

Table 1. Types of tested PFDs

Sample type	Overall	Jacket	Vest	Total
Buoyancy aid	6	9	16	31
Lifejacket	-	-	33	33
Total	**6**	**9**	**49**	**64**

All tested PFDs contained inherently buoyant material, but they were of very different designs, materials and seam types: i.e. from very crude and simple vests to very bizarre and purpose-built overalls. The most used fabrics were 100% Nylon and 100% Polyester. A zipper with /without a placket was the primary closure system in 59 samples, and an adjustable belt with a quick-release buckle of the waist in five (all buoyancy aids) samples. The most common secondary closure systems were fastening cords at the neck and hem.

Join stitching without a topstitch was the most commonly used seam type. In some of the samples the shoulder or side seams were sewed with a single or double topstitch. In a few samples there was also an overlock stitch. Some samples were constructed with side-pieces instead of a side seam.

Results

33 samples (52 %) of the tested PFDs were damaged in some way in the load tests, most often during vertical loading (Figure 1). Vest type PFDs were the worst in the load test.
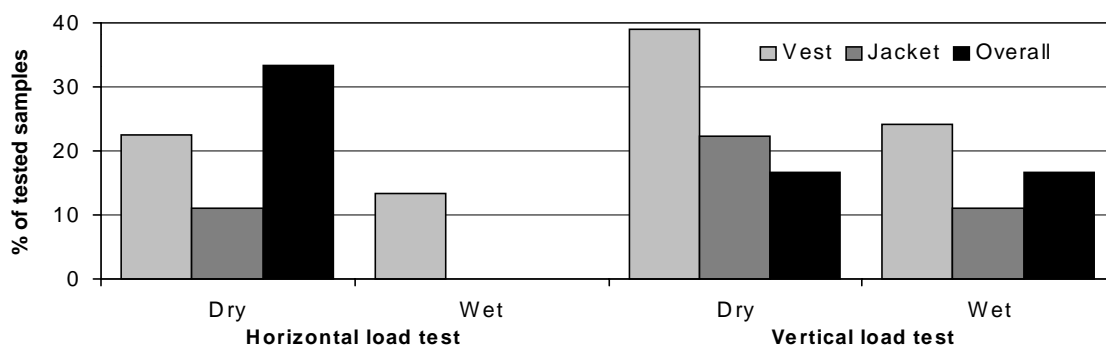

Figure 1. The number of damaged samples (%) in the load tests.

In the horizontal load test only zippers or belt buckles broke, the fabric and seams remained intact. In vertical load test, on the contrary, also the fabric tore in five samples, in three of which (2 / dry and 1 / wet) the side ripped open to the tightening cord (Figure 2a).

The fabric tore also down from the neck opening (Figure 2b, shown with ➜). The vertical load test were carried out for 51 samples, which passed the horizontal load test.

The side or armhole seams tore in eight PFDs during the vertical dry load tests. Three of the tears were so severe that the samples were not tested in wet conditions. The shoulder seam torn completely in one vest type buoyancy aid (Figure 2b). The tears in the side seams between the side and back or side and front ranged from 5 to 12 cm, and correspondingly, in the armhole seams from 1.5 to 12 cm (Figure 2c). In some cases the side (seam or fabric) was damaged so badly that only the belt kept the sample from falling off the test cylinder.
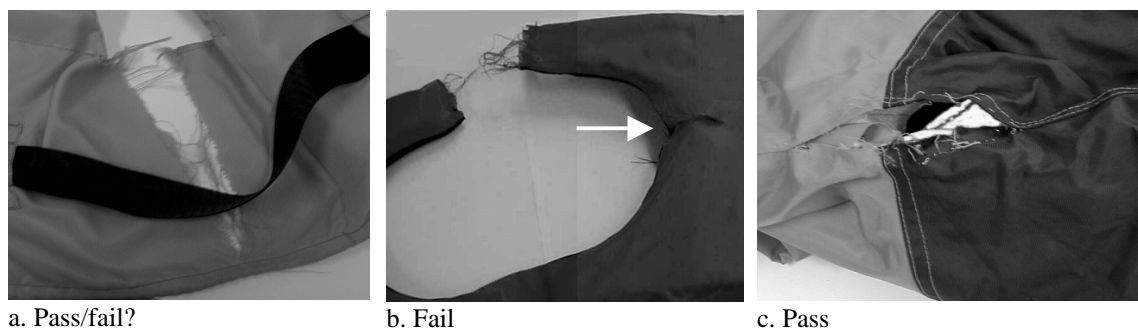

a. Pass/fail?   b. Fail   c. Pass

Figure 2a, b and c. Some examples of damaged PFDs after the vertical load test.

Also the components turned out to be fairly weak. Some belts slid through the buckles as much as 19 cm in the horizontal load test, and 8 cm in the vertical load test. Also a few belt buckles broke totally, and some belt loops were torn off. The slide fastener opened or broke down totally in both the horizontal and vertical load tests even in some vest type PFDs in which the zipper was the primary closure. The final condition of the tested PFDs after the load tests is given in Table 2.

Table 2. The number of the tested PFDs classified according to thin final condition after the load tests.

Sample type	No damage	Material, shoulder or side seam tore 1-5 cm	Material, shoulder or side seam tore completely or > 5.1 cm	Other type of damage occurred
Overall	4	-	1	1
Jacket	7	1	1	-
Vest	20	-	12	4
Total	**31**	**1**	**14**	**5**

Discussion

The results of the load tests carried out during type-testing clearly demonstrated that the strength of the fairly cheap and simple design Lifejackets 100 N and Buoyancy aids 50 N, which are very popular in Scandinavian wear conditions in lake areas, is poor. These PFDs do not guarantee survival. Their construction is not strong enough to allow the use of the PFD for lifting a victim out of water during a rescue operations.

Surprisingly, also many CE-marked products that have been tested and approved by different test houses and notified bodies failed in the marketing control inspections. This means that despite the efforts of notified bodies to pursue identical interpretation of the requirements given in the standards, the technical appraisers come to different decisions on passing or failing. It is understandable that the diversity of the damages makes the de-

cisions difficult when unique criteria are lacking. This allows poorly constructed products to be put on the market.

We recommend, on the basis of our results, that, as long as there are no harmonized pass/fail criteria, at least a small-scale (with a limited number of test subjects) in-water performance test must be conducted on the PFDs damaged in the strength tests. If the device passes this test, it functions and conforms with the standard.

All the conducted tests also demonstrated the need to improve the test apparatus for the load tests, so as to be more realistic: i.e. the test cylinder defined in the EN standards for PFD ought to be replaced by a standardized human-like torso.

Conclusion

The pass/fail criteria of the PFD standards should be revised so that ambiguities are removed from the text. Meanwhile, active discussion is encouraged between the test houses and notified bodies in comparing the test results and their interpretations. They should be encouraged to give a statement if application of the standard in its present form leads to confusion at a homogenous performance level.

Furthermore, we recommend strict market control of PFDs to ensure the safety of the end users.

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The effect of protective clothing on thermoneutral zone (TNZ) in man

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Abstract

Personnel operating the Sea king helicopters are required to wear survival suits (clo-value = 2.20 °C m^2/W) during flights. This may lead to pilots and crew suffering from heat stress during flight and cold stress when immersed in cold water in case of an accident. Gradual accumulation of heat in the body caused by personal protective equipment (PPE) during long exposure, gradually decreases cognitive performance (Enander, 1989). TNZ is a range of T_a at which metabolic rate is minimal and constant (Withers, 1992). The aim of this study was to define TNZ in the cockpit for these pilots. We hypothesised that the ambient temperature in the cockpit today is above the TNZ for pilots wearing a survival suit and they may easily be exposed to heat stress.

   Eight volunteer subjects participated in the study; their heart rate, rectal (T_{re}) and 13 skin temperatures (T_{sk}), metabolic heat production (VO_2), humidity and subjective evaluation of thermal sensation and thermal comfort were measured during one hour for five different ambient temperatures, 0, 10, 14, 18 and 25 °C respectively. The results show that 10 and 14 °C (T_a) fulfil the criteria of thermal neutrality, where mean skin temperature (MST) is 33,6-34,1 °C, VO_2 at its lowest (0,331 ± 0,05 sV`O$_2$ (l/min)) and the subjects were comfortable. The conclusion of the study is that the ambient temperature in the cockpit is above the TNZ for pilots wearing the survival suit.

Passenger survival suits - a new emergency equipment

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Abstract

Considerable effort has been put into the work of improving the safety for people engaged in activities at sea. For passenger transporting ships the recent strategy has been that dry evacuation should be possible. However, several accidents, also recent accidents have demonstrated, that people evacuating such ships very often are immersed in water before being rescued. Immersed in cold water protected only by personal clothing and a life jacket, people would by at a high risk for experiencing cold shock and hypothermia with fatal consequences.

The Norwegian Maritime Directorate has taken the initiative to look into the possibility of developing a simple passenger survival suit with low production cost, shall packing volume, easy donning, preventing unacceptable water ingress, and providing thermal protection against the cold water.

The manufacturer Helly Hansen Spesialprodukter has responded to this invitation, and has manufactured a passenger survival suit. This suit has a packing volume less than 2.0 dm^3, and was able to meet the recommended acceptance levels for water ingress. When tested by six test subjects in water temperature below 5 °C for two hours, none of the six test subjects had rectal temperatures exceeding 2 °C.

When dressed by test subjects with no earlier knowledge about the suit it was demonstrated that the donning time was less than 2 minutes, including the time to put on and secure the life jacket.

Aspects of firefighter protective clothing selection

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Introduction

This paper discusses aspects for consideration by fire brigades when selecting new protective clothing (specifically tunic and trousers) for firefighters. The major difficulty is the range of situations and environments in which firefighters are expected to perform in one set of protective garments. These include: sub-zero conditions at night-time; high levels of humidity, ambient air and radiant temperatures during operational and training heat exposures; confined space work at road traffic accidents (RTA's) and in collapsed structures; heath and scrub fires; and flooding and rescue. Due to cost implications, stowage on fire appliances, and time limits within which a fire appliance must attend an incident, one set of firekit must be suitable for use in all these scenarios. The procurement procedure within most fire brigades in the UK at present involves purchasing 'off-the-peg' fire-kit, the choice of which is usually based upon subjective views of past performance, or perhaps the advice of another brigade. However, since the costs involved in procurement are so high, both in terms of PPE (personal protective equipment) expense and the preservation of firefighters' lives, this approach is no longer acceptable.

   Therefore, this paper attempts to bring together a number of the many issues faced by fire brigades during the PPE procurement process: garment design; garment testing; the procurement process; compatibility; garment care; and finally, litigation issues.

Garment design

Material combination

Firefighting tunics and trousers are constructed around a layered approach: the outer material layer, a vapour permeable membrane, a thermal barrier and a liner. There are many available combinations of these layers, each of which can be provided in various weights and weaves. Typical ambient temperatures during firefighting range from 38°C to 66°C according to Abeles (1973), but other studies report far more extreme temperatures (Foster & Roberts, 1994; Stirling & Parsons, 1999). Therefore, high insulative properties are traditionally provided in firekit. However, maximal physical work performance has been reported to be impaired during long-term heat exposure by thick and heavy clothing materials with high insulating properties that have a vapour barrier, which limits body cooling through evaporation (Ilmarinen *et al*, 1994; Mäkinen *et al*, 1995; White & Hodus, 1987). Therefore, although such garments are designed by manufacturers to provide effective insulation from the external environment, no consideration is given to the dissipation of heat from the body. One study (Louhevaara *et al*, 1995) investigated the effects of a multi-layer firefighting turnout suit designed to fulfil European standard EN 469 (1994). When it was used over standardised clothing with SCBA, the study found an average decrease in the maximal power output, in terms of maximal working time and walking speed, of 25% compared to the control of standardised clothing only. The authors concluded that all possible means to decrease the mass of both the fire-protective

clothing system and the SCBA for maintaining sufficient power output in physically demanding firefighting and rescue tasks need to be considered. This emphasises the importance of the balance between the provision high levels of thermal insulation and the degree of disability afforded by this. Essentially, if a wearer considers the consequences of wearing the PPE to be worse than the likely consequences of not doing so, then the PPE will not be worn (Graveling, 1999).

Garment cut

Traditional 'bunker' style tunics are becoming a thing of the past and many brigades now wear shorter, more tailored tunics, both for ease of movement and aesthetics. EN 469 states that an overlap of 30 cm must be present between the tunic and trousers (to prevent exposure). Therefore, if the bottom of the tunic is higher, the top of the trousers must be as well. The result is a 30 cm high double layer of protection further up the body, covering a high proportion of the torso. Some of the less controversial advances in firekit design include action-back slits and under-arm gussets, which increase the range of movement without compromising protection, as the tunic is less likely to rise up.

Removable liners

There are two reasons for considering the incorporation of removable liners in firefighting kit. Firstly, a laundering and replacement issue: for example, if the outer layer becomes soiled and requires either cleaning or disposal, yet the layers beneath are still fit for purpose, only the outer layer need be dealt with. Secondly, firefighters can experience hot ambient conditions in summertime but with no immediate risk of fire, for example, attending an RTA. Such a garment construction would allow the thermal barrier to be removed, reducing the likelihood of thermal discomfort. This, however, is also a management and risk assessment issue.

Sizing

It may well be that in anthropometric terms, a population of firefighters differs significantly from the general population, and the author is unaware of any such work documenting this or otherwise. However, it has been shown that a poor design and fit of fire-protective clothing or the shoulder harness of SCBA may decrease the mechanical efficiency of moving and breathing, as well as cause discomfort during both submaximal and maximal work (Louhevaara et al, 1984). Therefore, correct sizing of firekit is vital in order to provide the thermal protection it was designed for. There is an increasing proportion of female firefighters in UK fire brigades who also need to be catered for. If firekit fits tightly around certain areas of the body, thermal protection will be compromised. This will be the case if female firefighters do not have specifically designed firekit.

Garment testing

In order for garments to be manufactured and sold as firekit, they must pass EN 469. However, none of the tests in EN 469 incorporate the garments being worn by humans carrying out firefighting activities. Heus and colleagues (Heus et al, 1992) developed a method which allows firekit to be evaluated in this way. Leicestershire Fire & Rescue

Service (UK) have further developed this method and recently carried out extensive tests on firekit, incorporating many aspects of the job of a firefighter.

The methodology includes tests of radiant heat protection and simulated structural fire-fighting work in hot ambient conditions. A battery of ergonomics tests considers garment cut, fit, comfort, fastenings, pocket placement, interfacing with other items of PPE, and how well the wearer can reach, jump, run and bend in the garment. There is a confined space test which identifies issues such as elbow and knee pad placement, and items attached to the outside of the firekit, such as torches and personal lines, getting caught. The method allows for the conspicuity of the firekit with regard to reflective tape type and configuration to be assessed. In addition, a water protection test evaluates the effectiveness of the firekit at preventing water absorption and leakage. This is not only necessary for comfort, but in the prevention of steam burns.

Procurement

Once a brigade has made a decision as to the material combination and garment cut of the firekit they wish to purchase, they then enter the procurement process. This entails providing the exact specifications of the garment, right down to the type of stitching used. Unless fire brigades are to become experts in the manufacturing industry, they require some guidance in the specification and procurement procedure if they are to make a sound purchase.

Compatibility

Since the financial consideration of procuring new fire-kit is often the priority for most brigades, it is common practise to purchase fire tunics and over-trousers first, followed by other items of PPE as and when the budget allows. A vital consideration here is that all the components of the firekit interface correctly; and this is unlikely if they are produced by various manufacturers who do not communicate. Mutual compatibility is a requirement under Regulation 5 of the PPE Regulations, yet the end result of problematic PPE in this respect may be that one or other item is not worn correctly, reducing the effective level of protection from that intended (Graveling, 1999).

Garment care

It has now been recognised that home cleaning of firekit is not acceptable. Instead, special care and expert cleaning is required, for example, to reactivate and reapply fluorocarbons on the outer material layer, to prevent shrinkage, and to deal with substances such as oil and body fluids effectively and safely. EN 469 states that garments must pass the standard after they have been cleaned five times. However, this does not include any wearing in the meantime, and there is no information available on the performance of firekit after a controlled number of wears and cleans. Therefore, apart from subjective opinion, brigades do not know after how many wears a garment should be cleaned, and after how many cleans a garment should be replaced. Time is not a useful indicator, due to the variation in the number and type of calls on different fire stations. Bar coding and batch testing may provide an answer to this problem over time, although such a system would require close control and would be an extensive project.

Litigation

Although finance is always a major issue for fire brigades, due to justification to local authorities, it is very difficult to exonerate a decision to buy cheaper firekit that does not protect or perform as well when a fatality occurs. Also, in less serious but significant incidents, a brigade should be able to categorically state the number of times a garment had been worn and cleaned when the incident occurred, and was it 'fit for purpose'?

Conclusions

Manufacturers and cleaners of firekit need to work more closely with fire brigades to determine the needs of a firefighter at work. An evaluation procedure such as that developed by either TNO or Leicestershire F&RS would contribute to this process, and also would be a valuable addition to current firefighting clothing standards.

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Investigating new developments in materials and design via statistically designed experiments

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Introduction

This paper discusses the improvement of a major product line at Draeger Ltd. Draeger is a German owned producer of high quality, high tech breathing equipment with a large market share in carbon composite, fully wrapped compressed air cylinders. The characteristics of the carbon fibre / resin matrix used to wrap the seamless aluminium liner and the conditions of the wrapping process, are known to be important factors in obtaining a consistently strong cylinder. A systematic experiment was designed to examine their combined effects in detail. The main features of this experiment are presented here. The usual way of assessing the strength of a cylinder is via a destructive test, however, an additional non-destructive method was also investigated. The relationship between the two tests was examined. Both sets of results are presented and the conclusions discussed. The potential of statistically designed experiments for understanding processes and making more robust, higher quality products is enormous and a number of other applications are discussed.

'Design of Experiments' Methodology

When investigating processes, in order to gather information quickly and effectively it is possible to experiment over a small balanced sub-set of the total number of possible combinations of factors without a serious loss of information. The sub-sets of possible combinations are often referred to as 'orthogonal' designs. These methods (DoE) have been known for some time, were first described by (Fisher 1960), and have been made popular amongst engineers recently following work by the engineer (Genichi Taguchi 1986). A number of books and papers describe the basic theory behind these methods, for example (Montgomery 1991), and (Cochran & Cox 1992). In the context of product performance optimisation, as in this work, the idea is often to minimise the number of experiments required to establish which parameters are important and why.
   There are number of advantages to using DoE.

- The number of experiments can be minimised, giving speedier and cheaper results.
- The results can be used to predict outcomes within the entire experimental range.
- We can identify the most important factors over a range of conditions.
- The effect of changing several factors settings at the same time can be estimated.
- The effect of changing one factor setting in relation to the others can be estimated.
- We can estimate levels of background uncertainty (experimental error).
- We can accurately estimate the cost of the experimental programme in advance.
- We can often estimate the effects of factors not actually included in the design, provided that these are also monitored and measured.

- When there are many responses, we don't need to know which is critical at the outset.
- We can overcome human errors such as the incorrect setting of factors.
- The method is 'robust' in the sense that lack of control over the factors is not fatal.
- We can investigate the effect of new factors if we want at a later date.

The Problem and the design

The investigation is of the cycle life of the pressure cylinder. The standard prEN 12245, requires that one cylinder per batch of 200, should be tested over a pressure cycle ranging from 0-450 bar at a maximum frequency of 15 cycles per minute for up to 7500 cycles. The pass point is 3750 minimum cycles without leakage. The second test is for permanent expansion of a cylinder after Auto-frettage. This is tested by weighing the water displaced by the cylinder, using an electronic scale. If there is significant correlation between the results the second test may be used to predict the first. The factors thought to influence results are given in Table 1 and show the ranges tested over. Table 1 also designates the factor settings -1 or +1 as explained below. Resin tack level is an estimate of the degree to which the epoxy resin contained within the pre-impregnated fibre is "advanced". Greater advancement can result in varying resin flow during the cure process.

Table 1. Experimental factors.

Factor	Label	Low (-1)	High (+1)
Carbon Fibre UTS	UTS	5.4 Gpa	5.85 Gpa
Resin Tack Level	RT	Low	High
Winding Tension	WT	3.6 kg	4.5 kg
Auto-Frettage pressure	AF	580 bar	600 bar

With four factors tested at two levels the total number of possible combinations is (2^4) = 16. The design used was a 'Half fraction' of 8 runs as shown in Table 2. This sub-set, of the 16 runs, is balanced in that every combination of settings is represented equally. The 'interactions' are used to estimate the effect of changing combinations of factor settings together. In this design each interaction column is the sum of two potential effects 'confounded' together. If such a sum is seen to be significant, we may have to run further tests to untangle the confounding. The results of the tests are also shown.

Table 2. Orthogonal array with results.

	Factor settings				Interactions			Results	
Run	UTS	RT	WT	AF	UTSxRT WTxAF	UTSxWT RTxAF	RTxWT UTSxAF	Cycle Life	Exp'n
1	-1	-1	-1	-1	1	1	1	5595	54.7
2	1	-1	-1	1	-1	-1	1	6200	55.3
3	-1	1	-1	1	-1	1	-1	6517	64.3
4	1	1	-1	-1	1	-1	-1	6210	54.9
5	-1	-1	1	1	1	-1	-1	6334	51.5
6	1	-1	1	-1	-1	1	-1	4935	41.5
7	-1	1	1	-1	-1	-1	1	8004	50.7
8	1	1	1	1	1	1	1	5528	54.7

Results and discussion

The effects of factors and interactions are determined by comparing the difference between the average of the results of all the +1 and -1 settings in each column. The resultant values show the average effect of changing from the high to the low setting of a factor (main effect), or of an interaction effect. The effects from both tests are given in Table 3. We can compare these effects with the background or experimental uncertainty using a Half-Normal plot (Grove & Davis 1992). Those effects that fall away from a straight line passing through the origin are seen to be significant ones.

Table 3. Factor effects.

	Factor	UTS	RT	WT	AF	UTSxRT WTxAF	UTSxWT RTxAF	RTxWT UTSxAF
Effect	Exp'n	-3.7	5.4	-7.7	6	1	0.7	0.8
Effect	Cycle Life	-894	799	70	-41	-497	-1043	333

It can be see from Table 3 and Figure 1 that all the Main Effects have a significant effect on permanent expansion. An increase in permanent expansion may follow a reduction in WT or use of carbon fibre with lower UTS. Higher AF or high RT will also cause an increase in Permanent Expansion. The situation with Cycle life is not so simple.
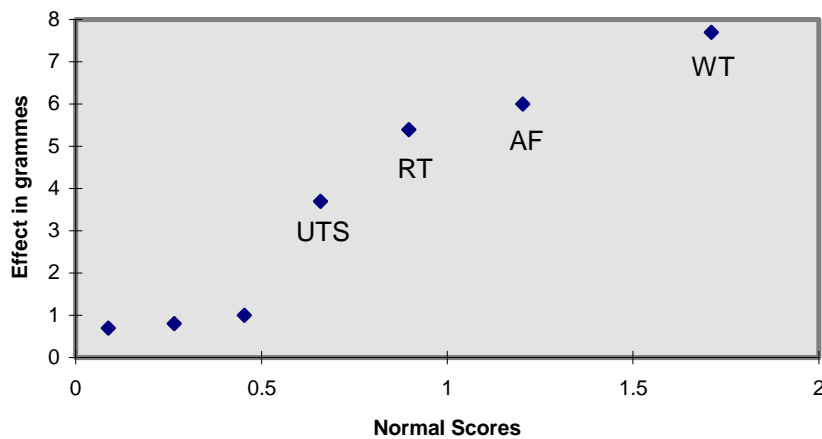
Figure 1. Half-normal plot of permanent expansion effects.
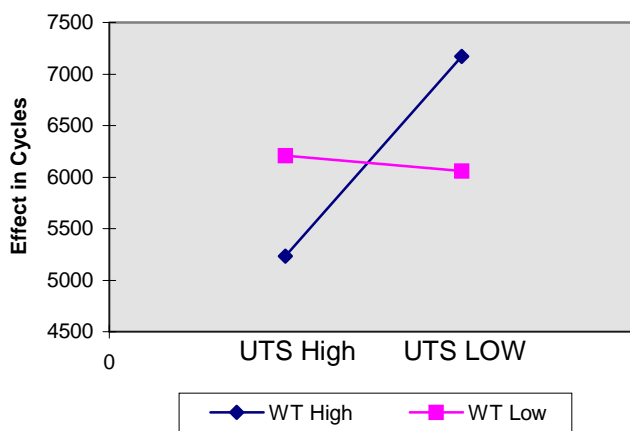
Figure 2. Interaction diagram of UTS and WT for cycle life.

It is clear from Table 3 that we need to do further test of cycle life to establish which of the confounded interactions are the significant ones. What this means is that although

both the carbon fibre and Resin tack levels are important we need to take into account the way settings of one or more factors are effected by the settings of others. For example Figure 2 shows the interaction plot for cycle life assuming that the UTSxWT interaction is the important one. In that case then winding tension does have an effect on cycle life if it is set high. The higher the Winding tension (WT) the longer the cycle life provided that carbon fibre (UTS) is low. If WT is set low then UTS has little effect. It is also clear, from Table 3, that changes in UTS and WT settings effect the cycle life and permanent expansion similarly. Once we know the effect of all interactions on cycle life we should be able to predict this via the expansion test by choosing optimum factor settings.

Untangling the interactions can be achieved by either completing the other half of the Full factorial, or by running just a few of them. In fact by running four more trials, as a balanced sub-set of the remaining eight, we can untangle the three confoundings.

Conclusions

By testing only 8 cylinders we have established the effect of changing the settings of any of four factors on Permanent expansion, and found much of the same information about cycle life. We will soon be able to optimise the four factor settings to maximise cycle life and get a good match between the two tests. Thus we will not have to rely on a single test when assessing the general fatigue capability of an entire batch of cylinders. An improved understanding of the factors that are critical to cycle life and permanent expansion after auto-frettage presents an opportunity for quality improvement. We may introduce Statistical Process Control to help minimise variation in these important factors. By doing this, a more consistent and reliable product may be produced.

These same DoE methods can be used in any situation, dynamic or otherwise. Material strength, fireproofing, impact resistance and the like can all be maximised using simple systematic experimentation in this way. More complicated factors with more than two levels can also be accommodated in other types of orthogonal array and these are discussed in several of the references quoted below.

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Design of UK firefighter clothing

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Introduction

The design of protective clothing for firefighters presents a challenging quandary. A high level of thermal protection is required against the extremely adverse environments to which the wearer might be exposed. However, this protection also severely disrupts the avenues for heat loss from the body, causing potential for considerable heat retention, particularly where the firefighter is engaged in heavy physical activities.

   This paper outlines the findings of a major study of UK firefighter clothing. The main purpose of the study was to determine the physiological and subjective responses to wearing various forms of protective clothing that met industry specifications. Based on both laboratory and simulated firefighting activities, it compares different types of, and approaches to, clothing design (one-piece; two-piece bunker coat etc.), and makes recommendations for the design of these garments.

Methods

The study collected data on the use and acceptability of different forms of firefighter garment through three questionnaires, and a series of laboratory tests and simulated and live fire exercises to determine subjective and physiological responses.

   Firstly, all UK Fire Brigades completed a questionnaire concerning the garments they currently used. Information was collected on the types of garments used as well as the policies and procedures in relation to inspection garments for damage, laundering and other administrative issues. A second questionnaire was developed and sent to individual firefighters to obtain their views on the garments that they wore, covering issues such as comfort, effective protection and interaction with other PPE. A third questionnaire was developed to collect information on accidents (including burn injuries) that occurred during operational duty.

   In order to examine differences between garments in more detail, subjective and physiological wearer trials were conducted on thirteen different firefighter's clothing ensembles grouped into five clusters based on the nature of the ensemble (including differences in clothing worn underneath). A total of 96 subjects took part in these trials, drawn from 18 UK based Fire Brigades. A standardised set of activities (e.g. dressing in a tender, climbing ladders, crawling and shovelling) were undertaken to examine the wearability of the clothing. Subjects completed a questionnaire following these activities to report on any discomfort, restriction of movement or other problems they had experienced with the garment. Physiological trials were also conducted to estimate the energy cost associated with the different garments; subjects walked on a treadmill in ambient conditions in control clothing (shorts and T shirt) and in the firefighter's clothing ensemble.

   Two simulated fire exercises were also undertaken and the physiological impact of the environment and the garments estimated based on core temperature and heart rate re-

cordings. The first exercise involved moderate physical work in a warm-humid environment (typically 34 °C WBGT); the second, light physical work while exposure to radiant heat (10 KWm^{-2} source, typically 79 °C globe temperature). They performed each test twice, once wearing self contained breathing apparatus (SCBA) and once without, as it was thought that wearing SCBA could interact with the effect of the clothing. Finally, a live fire exercise was undertaken in which subjects entered a burning building and extinguished the fire, again wearing SCBA. As earlier work by the IOM (Love *et al*, 1996) had demonstrated significant differences in physiological impact between different forms of SCBA, it was decided to standardise on a single, widely-used make of SCBA, and to select Brigades which used that make.

Results

At the time of the survey, UK Brigades used tunics provided by seven different manufacturers. However, the postal questionnaire showed that the vast majority of UK Fire Brigades (82 %) were using the same form of tunic (from the same supplier), so few comparisons could be made between them.

Altogether, 746 firefighters completed the postal questionnaire concerning the usability of the garments; over 80 % reported that they were comfortable to wear, although significant minorities (typically just under 20 %) reported that they caused some restriction of movement and most (80 %) stated that they became very sweaty when working in the garments. One third of respondents reported that a gap formed at the wrist when reaching up, although nearly 90% regarded cuff protection as adequate. Only 11 (1 %) of the firefighters reported ever having to withdraw from an incident early as a result of wearing a damp tunic. A question on this issue was included as it was seen to be a particular concern by some Brigades.

Over 700 completed questionnaires were received concerning accidents during operational duty. Nearly a quarter of these accidents related to burns injuries; the majority of these occurred at the head / neck and hands / wrists, areas that are not usually covered by PPE. Burns to head and neck were taken into account in subsequent research, investigating the value of firehoods (Johnstone *et al* 1996). Although some anecdotal reports had previously been received, there were few burns through or underneath the clothing; where these did occur, it was usually due to prolonged contact with hot material.

Further to this, wearability and fit were examined systematically for each ensemble during the wearer trials where subjects commented on these issues. The majority of adverse comments were minor, mainly relating to fit, although some design issues were also identified. Fit was particularly an issue with the one-piece garment which, by its nature, was closer fitting. The two-piece ensemble with short jacket and dungaree style leggings was generally preferred to the conventional two-piece with a 'bunker' coat. Whatever style was used, it was clear that good sizing was important.

The results of the physiological trials showed that, on average, the clothing imposed a 15 % increase in physiological cost over the control conditions. One ensemble showed a significantly lower physiological cost than others, although this finding was not repeated when the same tunic was worn with other leggings. No other consistent differences in physiological response were found between garments.

During the two simulated fire exercises and the live fire exercise, many of the participants experienced near-maximal heart rates and, in many cases, considerable increases in aural temperature, mirroring findings from earlier studies (Love *et al*, 1996). Few systematic differences between clothing ensembles emerged, although there were some indi-

cations that there could be advantages in utilising a cotton coverall instead of the standard uniform trousers and T-shirt under the firekit. Also, in some situations there may be a slight advantage in using a one-piece style overgarment, although this was not a strong effect and was not apparent in all test conditions.

When wearing SCBA the work rate in the hot and humid conditions was reduced to account of the increased metabolic load due to SCBA; no significant physiological difference was therefore found when wearing SCBA. However there was a statistically significant clothing x SCBA interaction.

Discussion

Modern firefighters' clothing appears to be very effective in fulfilling its primary purpose, that of protecting the firefighter against the direct effects of the severe environments in which he or she may have to work. Few instances were reported of burn injuries to firefighters where the clothing protection appeared to be inadequate, most reported burn injuries incurred on the skin areas not covered by the clothing.

The research has, however, demonstrated and quantified the negative aspect of this protection: that the clothing itself increases the physiological cost of working whilst wearing it; and the clothing can create a risk of heat stress through its considerable disruption of the thermoregulatory pathways.

At the onset of the research, firefighter's clothing in the UK was regulated by a UK Home Office standard (A26), superseded during the study by a European Standard (BSEN 469). All garments used in these trials conformed to the UK Standard, and therefore incorporated a vapour-permeable fabric layer as required. There has been some debate in the scientific literature regarding the value of such layers, in particular in relation to their efficacy at facilitating heat loss through the evaporation of sweat.

Despite the presence of this vapour-permeable layer, the questionnaire responses from serving firefighters indicated that becoming 'very sweaty' whilst wearing their standard issue garments was a very common problem, clearly suggesting some disruption of the evaporative heat loss pathway.

There is evidence that, although all garments tested during the study complied with the requirement for vapour permeability, the extent of that permeability varied considerably between the fabric layers used in the different makes of garments tested. Despite this, no clear advantage between similarly styled garments could be shown for one fabric combination over another. There must therefore be some question as to the value of such fabrics, endorsing the views expressed by others (e.g. White and Hodous, 1988; Goldman, 1990).

The study showed that there was some scope for improvement in wearability/fit of firefighters' clothing. For example, garment sleeves could tend to ride up with reaching or stretching movements, potentially creating an unprotected gap at the wrists. This problem had been recognised by a number of manufacturers who had incorporated thumb loops into the knitted wrist cuffs of their garments to aid retention. Unfortunately, inadequate allowance had sometimes been made for arm extension and, as a result, some firefighter's found their arm movements to be restricted if they used the thumb loop. This occurred in activities such as lifting ladders from tenders; climbing ladders; or other activities where arm extension was required. Other problems encountered included leggings with insufficient provision for the expansion in thigh diameter in squatting or kneeling; insufficient leg length; knee padding incorrectly located in leggings; and insufficient or excessive body length in one-piece garments. Whilst many of these problems are not

unique to firefighters' clothing, the extreme environments in which they are to be worn throws any deficiencies into stark relief.

Finally, given the level of protection required of such garments, a degree of heat retention and potential heat stress seems unavoidable. Therefore, recommendations were also made regarding the development and introduction of other risk control measures, including administrative measures such as steps to enhance heat tolerance as well as technical solutions possibly including pre-cooling of fighters.

Conclusions

The main conclusion was that no garment style and no fabric combination in the same basic style offered any meaningful advantage over any other in terms of physiological load. All created significant accumulation of body heat, even in the warm-humid environment where conditions were by no means extreme.

In summary, during the laboratory trials, standard firefighter clothing typically increased physiological cost (oxygen consumption) by 15 % over control sessions. In simulated firefighting exercises and other trials at elevated temperatures, no consistent differences were identified between different styles or fabrics. The study supported earlier US studies in concluding that there appeared to be little scope for reduction in the risk of heat stress through garment/fabric design (e.g. vapour-permeable fabrics) in these conditions, although attention to other ergonomic aspects of clothing design could be beneficial.

Based on the study, recommendations were made concerning firefighter's clothing. While there is little significant physiological difference between clothing and fabrics, it is thought that there is scope for improvements in wearability. In particular, more appropriate sizing would be advantageous, particularly where garments are bulky. The provision of styling details such as loops over the thumb may also help protect the wrists, although these can cause discomfort; sleeve length must also be appropriate if they are to be used. Other means of managing and controlling heat stress should also be considered.

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Effects of clothing design on ventilation and evaporation of sweat

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Introduction

An important aspect of thermal comfort in protective clothing is the possibility to dissipate heat by evaporating sweat. If the produced sweat is not transported away from the body, it just drips off and is inefficient in cooling the body. To have optimal cooling, the evaporated sweat should encounter no impediments in flowing away from the skin. However, while wearing protective clothing, the flow of sweat is impeded by the clothing. Analogous to the heat resistance, or insulation, the vapour resistance denotes the resistance to evaporated sweat due to clothing. The resistance to heat and water vapour decreases due to wind and body movements. Wind and body movements move the enclosed air beneath the clothing, thus reducing its insulation, called the pumping effect. The amount of vapour that is transported away depends on: air-permeability of the fabric, the presence of openings, the amount and location of enclosed air and maybe other factors. Considering these factors it can be assumed that the design and fit of clothing will also influence the transportation of sweat from the body.

In a number of previous studies, the effects of air permeability of (protective) clothing materials on vapour transfer trough clothing and on heat stress has been shown (Havenith et al., 1997, Den Hartog et al., 1998). In this paper, the results of pilot experiments on the effects of clothing fit and design on vapour transfer through clothing are reported.

Methods

Ventilation measurements

The vapour resistance was determined in a series of experiments on three subjects by determination of the ventilation of a tracer gas (Argon) at room temperature. The method has been described extensively by Lotens and Havenith (1988, 1990). The subjects wore a harness of polyethylene tubes which blew air, enriched with 10 % Argon under the garments. A similar harness was used to suck out air at the same rate. Both harnesses were connected to a pump which provided the constant air flow. The concentrations of Argon in the air flow to the suit (C_{in}), coming out of the suit (C_{out}) and in the surrounding air (C_{air}) were measured with a mass spectrometer. From these concentrations the ventilation under the suit was calculated by:

$$(1) \qquad Vent \quad = \quad V'_{pump} \cdot \frac{(C_{in} - C_{out})}{(C_{out} - C_{air})} \qquad \left[l \cdot \min^{-1} \right]$$

In which V'_{pump} is air flow generated by the pump. To calculate the ventilation only the relative differences of the concentrations are used. Therefore, it was not necessary to

calibrate the output signal of the mass spectrometer. Via the ventilation (*Vent*) the vapour resistance (d, in mm air equivalent) can be calculated by:

$$(2) \qquad d \quad = \quad \frac{D_{Ar} \cdot A_D \cdot 60 \cdot 10^6}{Vent} \qquad \left[mm \right]$$

In which D_{Ar} is the diffusion constant of Argon, A_D is the body surface area and $60 \cdot 10^6$ is a constant to transform the vapour resistance to mm air equivalent. From equation (2) it becomes clear that the vapour resistance of the garment is dependent on the ventilation of the garment.

Experiments

Two pilot experiments were performed with different aims. In both experiments one subject participated, wearing the harness mentioned above.

In the first experiment the subject wore three cotton coveralls over the ventilation harness, all made from the same highly air permeable cotton fabric. The first coverall was a commercial "off the shelf" product (CO, size 40). The second coverall was adapted to the body length and waist circumference of the subject (MC), in fact the waist and hip widths were enlarged for this subject. The third coverall was tailor made to the subjects body dimensions (MM). The ventilation in all three coveralls was determined: 1) while standing still, 2) walking on a treadmill and 3) standing still and waving his arms. The coverall were measured in the order MM - CO - MC - MM. In each condition the ventilation was determined four times.

In the second experiment two protective clothing garments were used (A and B) which were equal in insulation and vapour resistance, as measured on a thermal manikin, but different in design, especially in the length of the coat and the trousers. The garments were comparable to fire fighters' garments in terms of thickness and insulation. Both garments were tested in one subject while doing various movements of arms and legs. In each condition the ventilation was determined three times.

In both experiments the statistical analysis was performed by a repeated measures ANOVA, with $p < 0.05$ as a significant difference.

Results

In figure 1 the results of the ventilation measurements on the three coveralls are presented. The statistical analysis showed that the ventilation in the MC coverall was significantly larger than in the MM coverall ($p = 0.002$) and the CO coverall ($p = 0.02$) in all conditions. The difference between the CO coverall and the MM coverall was not significant over all conditions ($p = 0.08$). The effect of body movement on ventilation is clearly demonstrated, as it increases from about 170 l/min standing still, to about 300 l/min during movements of arms and legs.

In figure 2 the results of the experiments on the protective clothing garments are presented. The tests showed that while standing still the ventilation of garment A was 17 l/min whereas, the ventilation in garment B was 12 l/min (71 %), leading to values for the vapour resistance (d) of 102 mm and 144 mm (garments A and B respectively). Thereafter, measurements were performed during various movements, such as walking, running, waving arms and kneeling/standing up (figure 2). The ventilation of garment A during movements was on average about 100 l/min (d = 17 mm), whereas the ventilation of garment B was about 50 l/min (d = 34 mm), a decrease of 50 %. Furthermore, for both

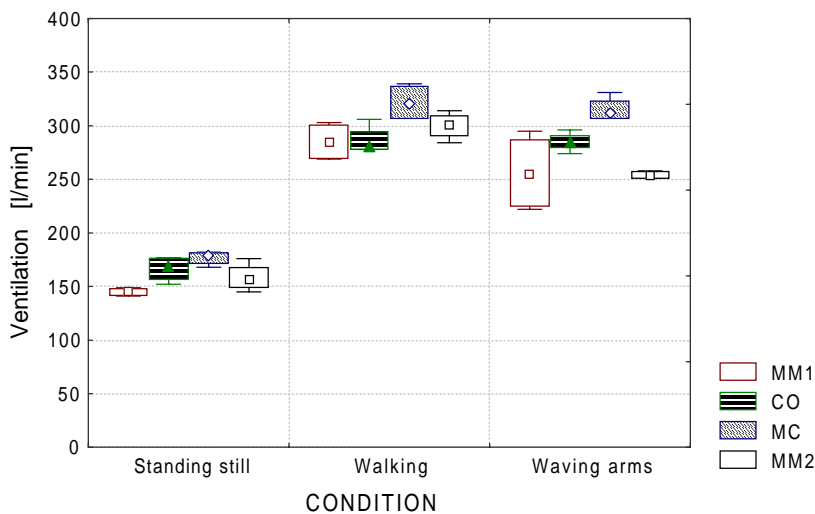garments the increase in ventilation due to arm movements was larger than due to leg movements.

Figure 1. Results of the ventilation measurements in the three different coveralls. The results are shown in order of measurement, MM1 is the 'made-to-measure' coverall measured for the first time. CO is the confection coverall. MC is the confection coverall adapted for body length and waist circumference. MM2 is the made to measure coverall measured for the second time. The symbolsdenote the median values, the bars denote the 25th percentiles and the whiskers denote the ranges.
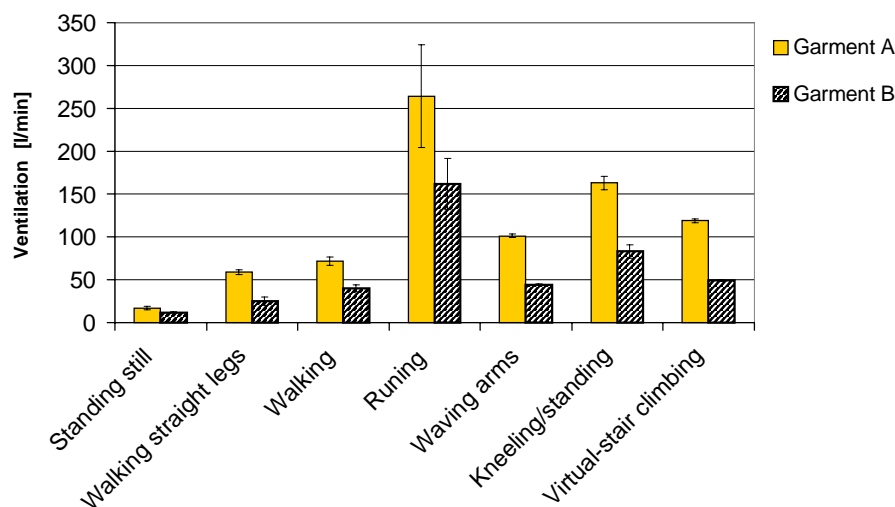
Figure 2. Results of the ventilation measurements in to protective clothing. On the x-axis the various movements are indicated, during which the ventilation has been measured. In all conditions the ventilation in garment A was higher. The bars indicate the errors from the repeated measures.

Discussion

Analogous to previous studies, the first result of all ventilation measurements is that the ventilation and, therefore, the vapour resistance, is strongly decreased by any movement of the subject. The overall ventilation, as obtained from the measurements, is a summation of the ventilation through the fabric and the ventilation through the openings of the

garment (sleeves, collar, etc.). In both experiments performed in this study the materials were the same between garments, but the design of the garments differed. Thus, we obtained information about the effects of clothing design and fit on the ventilation, and thus, on the vapour resistance to evaporated sweat.

The coveralls of the first experiment were made of normal cotton, and had normal sleeves and collars. The overall ventilation levels were high in all conditions, but the ventilation in the MC coverall was significantly larger than in the other coveralls. On average the lowest ventilation, corresponding to the highest vapour resistance, was found in the MM coverall. The explanation can be found from the design and the sizing of the coveralls. The hip and waist widths of the MC coverall were largest (990 and 923 mm). The CO coverall had widths of 973 mm and 915 mm, and the MM coverall was smallest (855 and 910 mm). As the front of the coveralls consisted of a closure with buttons, the arm and leg movement caused most ventilation to occur in the waist area. The MC coverall enclosed the largest air layer at the waist, this probably led to the largest ventilation values during movements.

However, one should realize that the measurements were performed at only one subject, which limits the statistical power. Moreover, the differences in ventilation will be too small to cause differences in thermal comfort and physiological parameters as heart rate, sweat rate or skin temperature (Havenith et al., 1998). On the other hand, it is surprising that any differences in ventilation are found in these highly air permeable coveralls. It leads to the idea that physiologically significant may be found in thicker or less air permeable (protective) clothing.

In the second experiment two protective clothing garments, similar to fire fighters' garments, were tested. In these garments, the absolute ventilation levels were much lower than in the coveralls. Both garments had similar characteristics as measured on a thermal manikin. Due to design differences the ventilation in suit B was 40 % to 50 % lower during body movements. The vapour resistance during movements was computed as 12 mm for garment A and 23 mm for garment B. This difference may very well lead to physiological differences in heat strain, especially during moderate work under normal environmental conditions.

In conclusion, the design of protective clothing may have a significant influence on the ventilation through the clothing. Differences in ventilation as large as found in this study may lead to differences in thermal comfort while wearing the garments.

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Physiological load during tunnel rescue

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Introduction

Accidents in tunnels may cause dangerous and time-consuming work situations for the rescue personnel. Yet, the number of tunnels and underground constructions are steadily increasing and so is the number of people working or being transported in such installations. The rescue problems are associated with long distances where the work often must be manual because of debris and other obstacles. Such rescue conditions may imply a substantial physical load to the people involved. Trials have revealed low endurance at self-paced rescue work. Two groups of six, all well-trained firemen, had to stop after less than one hour because of exhaustion despite of favourable environmental conditions. Smoke and high temperatures make the work much more dangerous and stressful. To reduce the risk of injury, individual protection must be used most of the time. If self-contained breathing apparatus is needed longer than 20 minutes, compressed air can not be used because of its limited capacity. For longer periods extra air bottles must be brought, a situation that may increase the physical load further. An alternative solution is to use a re-breathing device using oxygen as respiration gas.

The purpose of this investigation was to study the physical load of protective ensembles and respiration devices used, on firemen performing a simulation rescue work in a rock tunnel. The aim of the study was also to predict what length of work period can be endured during various climatic conditions and work loads.

Methodology

The investigation was performed in a rock tunnel, being one part of an underground naval dockyard. The mission was to rescue victims from the scene of an accident to the tunnel mouth, a distance of 540 m. Six full-time employed firemen, five men and one woman, participated. Their average age, mass and height were 33 years, 77 kg and 181 cm, respectively. They wore protective turnouts and used breathing apparatus. Each fireman participated four times wearing either a thick fire-protective turnout (RB90) or a navy combat uniform (SSD93) and breathed compressed air (Interspiro) or oxygen (Dräger BG4). The total mass of ensemble and breathing apparatus was roughly 25 kg. The firemen pulled a rescue cart loaded with compressed air bottles at the speed of 1.0 m/s. The cart was designed also for transportation of victims lying on stretchers. The weight of the cart, without victim, was about 250 kg. The climate along the rescue path was recorded by data loggers attached to the cart. During almost two hours four missions were completed with one victim (mass approx. 90 kg) rescued each time. Hence, the total distance covered was 4.3 km. The order of used ensemble and breathing apparatus was different for each participant. During each mission the two firemen pushed and pulled the cart in turns. The power demand was measured and calculated from four methods; by measuring lung ventilation rate and oxygen fraction in expired air minute by minute (separate test),

by recording the pressure in the oxygen bottle at every start and stop of activity and by weighing the oxygen bottle before and after each mission (main study) and finally by a continuos measurement of the force needed to pull the cart along the rescue route and then add the measured power demand when walking without pulling the cart (separate test). Furthermore, rectal temperature, nude and clothed body mass were recorded before and after completed mission whereas heart rate was collected continuously. Perceived exertion and temperature were rated at each stop. The RB90 ensemble was composed of a jacket with hood and trousers, briefs, stockings, long underwear, helmet, boots and gloves. The SSD93 ensemble was composed of field jacket (without hood) and trousers, briefs, stockings, long vest, sweater, helmet, boots and gloves. The main difference between the two ensembles in respect of thermal properties was that RB90 is considerably thicker and has a hood.

Results

The climate in the rock tunnel is very stable during the year and with only minor variations along the rescue route. The average temperature was 12 °C and the relative humidity was 45 %. The radiation temperature from the rock walls and the paved road was similar to the air temperature. There was no external wind. The mean metabolic power was 462 W and there were only small differences (about 20 W) between the techniques used. The most strenuous part of the rescue work was to reach the victim, lying on a staircase, place him on the stretcher and then carry him to the cart, a total distance of 50 m. The power demand of this procedure was roughly 700 W. Highest average heart rate for the whole mission was obtained for RB90+air (130 beats/min) while the lowest was for SSD93+oxygen (117 beats/min). Breathing oxygen seems to reduce heart rate with at least 5 beats/min compared with compressed air irrespective of ensemble worn. The average heart rate increased slowly throughout the trial. The individual values did not vary much along the route with one exception, the transportation of the victim to the cart. Then heart rate reached 160-180 beats/min. RB90+air produced greatest body mass loss (1.9 kg) while SSD93+air caused a loss of 1 kg. Both the ensemble and respiration gas contributed significantly to the mass loss. The difference between the various combinations in respect of water evaporation was minor but for a given ensemble breathing oxygen resulted in significantly greater evaporation than using compressed air. About 20 % of the evaporation were lost from the lungs. Including this part about 50 % of the body mass loss evaporated when SSD93 was worn whereas 35-40 % was evaporated from RB90. The differences between ensembles as well as respiration devices were significant. Rise in rectal temperature was significantly higher for RB90 than for SSD93. For a given ensemble the oxygen device produced greater rise in rectal temperature but this difference was not significant. However, oxygen apparatus produced about 4 °C higher face temperature than compressed air did. Breathing temperature was also rated significantly warmer with the oxygen device. RB90 was considered significantly warmer than SSD93 in respect of body temperature. For a given ensemble oxygen breathing tended to give higher perceived (body) temperature but this difference was not significant. Rated perceived exertion did not display any significant differences between the various combinations.

Discussion

The metabolic rate measurements showed that the load was shared approximately equal between the subject pulling the cart and the one pushing it. The power demand on each fireman was about 460 W of which roughly 40 % referred to walking, carrying clothing and breathing apparatus while 40 % referred to pulling/pushing the cart. The remaining 20 % refer to the basic metabolic rate. The power demanded can be estimated to about 650 W if only one person pulls the cart at 1m/s. The grade of the rescue route was ± 1° so with steeper slopes the load can rapidly become exhaustive. The estimated demand on two people sharing the job is 600 W per person if the speed is 1.35 m/s. This was the average speed chosen by the two groups failing during the initial test. A power demand of about 500 W during eight hours should be endured as the participating firemen has a maximum work capacity exceeding 1050 W, assuming favourable heat dissipation conditions. This was not the case as the work was performed in protective garments. To reduce the risk of heat exhaustion the speed was strictly kept at 1.0 m/s. Yet, heart rate continued to rise during the whole mission. The dehydration rate was not alarming, less than 2.5 % on average, but yet one individual exceeded 4 %. The RB90 ensemble caused the greatest heat load, an expected result, as this ensemble is considerably thicker than SSD93. The hood certainly added to this difference. The oxygen breathing apparatus also contributed more than the compressed-air device to the heat load, an effect of warmer respiration gas giving a warmer face. This effect was however smaller than the effect of ensemble. In spite of favourable tunnel climate and a relatively low work rate, a steadily increasing heat storage followed. The almost two-hour mission could be sustained but the 4-hours capacity of the oxygen-breathing device could probably not have been utilised. The firemen estimated that another hour could have been endured in the RB90 ensemble and about 1.5 hours wearing SSD93. This illustrates two problems arising in long rescue work, the intensity of activity and the level of protection chosen. Even though most of the participating subjects were experienced firemen two groups from the initial test did not realise that they worked too hard and consequently became exhausted. The two groups who could accomplish the mission chose a lower speed, about 1.1 m/s. Obviously, during long rescue activities the work rate must be guided. This should also concern the protection level chosen. In case of high temperatures or open fire a thick whole-body-covering turnout must be used to prevent from burn injury and "external" heat exhaustion. But, there is a number of situations where these conditions are not expected to occur. Still, firemen are most often wearing their thick turnouts with very little ambition to adjust their protection level. Rescue work in tunnels is associated with great physical and mental load on the personnel. The environmental conditions are not always that favourable as in this study. A fire in a tunnel causing a temperature of 500 °C at the scene of accident may cause a temperature of 80 °C, 500 m from the seat of fire if the tunnel is dry or 35 °C and 100 % rh if wet (Wolki, 1991).

A simulation program, INSULA, was used to estimate the physiological load based on the work conditions prevalent during the tests. Calculations showed e.g. that the rise in core temperature and heart rate were very close to those measured for the various combinations of ensemble and breathing apparatus. Calculations also predicted well the heart rates reached during the initial test. These agreements gave support to predictions of the effects of various work rates and environmental conditions on the thermal load. Figure 1, left panel, shows the accumulated body heat (kJ/kg) after 1.5 hours of rescue work in a climate similar to that during the initial test. The figure shows that 600 W, corresponding to a walking speed of 1.35 m/s, would give a heat storage exceeding 10 kJ/kg, a level that is associated with heat exhaustion. This explains why the two failing groups only

managed to work about one hour. The two successful groups had a speed of about 1.1 m/s giving a metabolic rate of about 500 W. Estimated heat build is around 7 kJ/kg, a level that well-trained firemen are expected to manage. Another calculation was done, assuming that a vehicle was used for the transportation, reducing the metabolic rate to 175 W during this phase (Figure 1, right panel). The other activities and the personal equipment were unchanged but the air temperature could adopt different values. Figure 1, right panel, shows that the exhaustive level of 8 kJ/kg is reached after 1.5 hours when the air temperature is about 36 °C, a situation that hardly can be considered as extreme, especially if there is a fire in the tunnel. These two simulations indicate that long rescue efforts are associated with a significant heat load if protective ensemble is worn. The situation is improved if heat production is kept as low as possible, but this will be insufficient at elevated ambient temperature and humidity unless the rescue people has access to external cooling. If the fireman can be connected to a cooling system during the vehicle transport, the accumulated body heat reaches only 1.2 kJ/kg after 1.5 hours of rescue work if 5 litres of dry cool air (+20 °C) is allowed to ventilate the turnout every second. These simulations indicate that the rescue capacity could increase considerably if a motor vehicle is used to reduce physical load. Such vehicle should also deliver cool air for ensemble ventilation to reduce the risk of heat exhaustion.
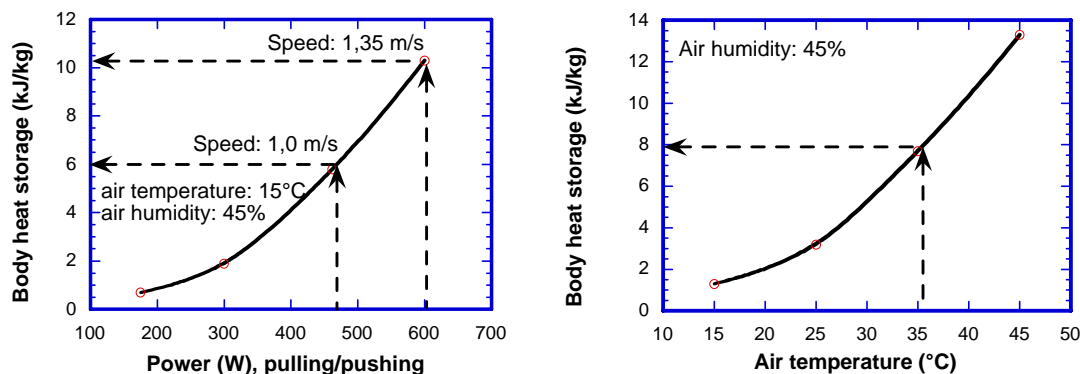
Figure 1. Calculated body heat storage reached after 1.5 hours of rescue work including movements of the victim (metabolic rate, MR=700 W) and short rests (MR=150 W). Fire protective turnout and oxygen apparatus are used. **Left panel** shows the effect of metabolic rate (speed) when the cart is pulled/pushed. External wind is the same as that of the walking speed (≈1 m/s) **Right panel** shows the effect of air temperature assuming that a motor vehicle, MR=175 W, is used for the transportation. Air speed inside the vehicle is 0 m/s.

Conclusions

Rescue in tunnels may cause heat exhaustion, also in cool climates, if the work period is sufficiently long. The protective clothing is the main cause of the elevated risk although the work intensity is of importance too. Because of that, the advantages of the oxygen rebreathing system cannot be utilised unless work rate is low and/or personal cooling equipment can be used. A motorised vehicle can provide these demands and this would improve the rescue capacity substantially.

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Effectiveness of a light-weight ice-vest for body cooling in fire fighter's work

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Introduction

Fire-fighter's work, especially smoke-diving, often involves exposure to heavy physical work and heat stress. This combination of stress factors reduces efficient work time and productivity and may increase the risk of heat-related illnesses.

Several different auxiliary personal body cooling devices have been developed for the industry (Kamon et al., 1986; Muir et al., 1999). They are, however, often of limited value for fire fighters because of their weight. An ideal body cooling device for fire fighters should be rather light-weight, should not interfere with the job performance, and it should be feasible and easy to use during the fire alarms.

The aim of the present study was to examine, in a systematic way, the effects of wearing the ice-vest on physiological and subjective responses in fire fighter's work. The experiments were carried out in a climatic chamber, in a container under extreme radiant heat, and during simulated smoke diving. In addition, the physical cooling effect of the ice-vest was measured with a thermal manikin.

Subjects and methods

Subjects: Four experienced fire fighters participated in the experiments. They were healthy, moderately physically active, and all had a normal blood pressure. Their physical characteristics were; mean age 36 years (range 32-39), height 1.86 m (1.85-1.88) and weight 87 kg (78-98).

Clothing and icevest: In all tests, the subjects wore the standard clothing for Swedish fire fighters (RB90) with self-contained breathing apparatus (AGA Divator). During the laboratory tests, the face mask was not used because this would interfere with the measurement of oxygen consumption. The total weight carried was 21-23 kg.

The ice-vest was developed in co-operation between the Swedish Rescue Board and Flexy-Ice AB. The material is cotton. The inside consists of two removable flat plastic containers, which have several small pockets for water/ice. Five different vests were used in the tests. Their weight varied slightly (1.0-1.1 kg). The ice-vest covered most of the trunk area and it was worn over the underwear. The vests were kept in a freezer at -20 °C over night before the experiments.

Laboratory experiments: Laboratory experiments were carried out in a climatic chamber, where the air temperature was 45 °C, and relative humidity 30 %. In the tests, the subjects walked on a treadmill for 30 minutes twice at a moderate exercise intensity (4 km/h, 0 degrees), and twice at heavy exercise intensity (4 km/h, with an inclination of 4 de-

grees). At each work intensity, one test was done without and one with the ice-vest. A 5 minute rest period preceded each test. For each subject, only one test was done in one day.

Measurements: Rectal temperature was measured with a thermistor probe (YSI401, USA) inserted 10 cm beyond the anal sphincter. Skin temperatures were measured with thermistors (StowAway) taped to the skin. The sites for skin temperature measurements were forearm, upper arm, chest, back, thigh, and calf.

In all tests, heart rate was measured once a minute with the telemetric SportTester system (PolarElectro, Kempele, Finland). Oxygen consumption was measured with a portable gas analysing system (Metamax, Cortex, Germany) twice during each test (10-15 min and 25-30 min). For that purpose the subjects wore a half-face mask during the tests instead of the full-face mask of AGA Divator.

The amount of evaporated sweat and the amount of sweat in the clothing items were estimated by weighing (Mettler-Toledo, KC 240, ±2 g).

During the tests, the subjects rated their perceived exertion (RPE), thermal sensations, and comfort with standard scales.

Results and discussion

Oxygen consumption was, on average, very similar between the tests with and without the ice-vest; 1.17 and 1.18 l/min at moderate work and 2.23 and 2.25 at heavy work. The variability in metabolic rate was due to differences in body weight between the subjects.

During the first 15 minutes of walking at the moderate work level the average heart rate was similar between the tests with and without the ice-vest. However, during the last 15 minutes of walking the heart rate was lower with the ice-vest. At the end of walking the heart rate was ca. 10 beats/min lower with the ice-vest compared to walking without it.

At the heavy work level the heart rate increased continuously during all tests. As shown in Figure 1, throughout the walking the average heart rate remained about 10 beats/min lower when the ice-vest was worn compared to walking without the vest.
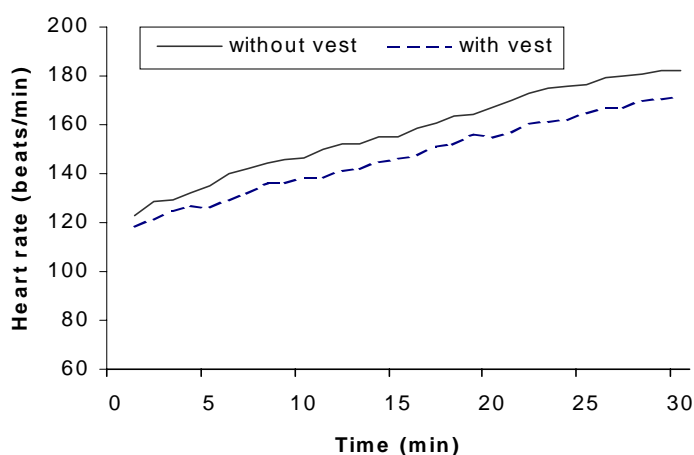

Figure 1. The average heart at the heavy work load with and without the ice-vest.

At both work levels, rectal temperature increased continuously during the tests, reaching higher values at the heavy work level (Figure 2). During both tests, the resting level of average rectal temperature was slightly lower with the ice-vest. Therefore, the increase in rectal temperature was rather similar between tests with and without the ice-vest.
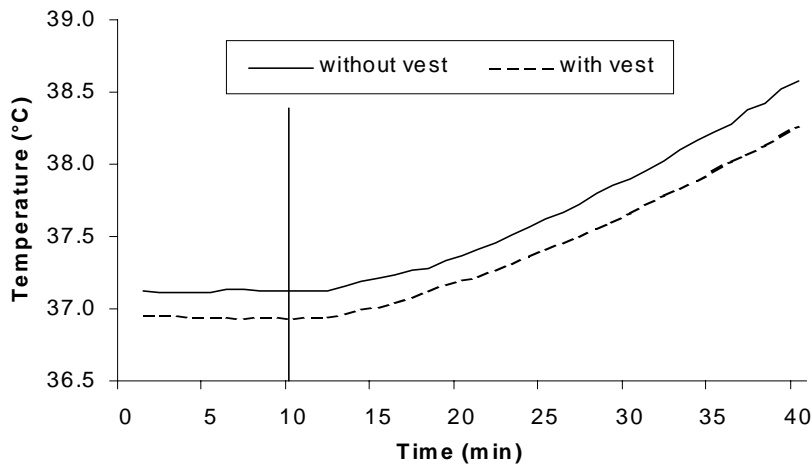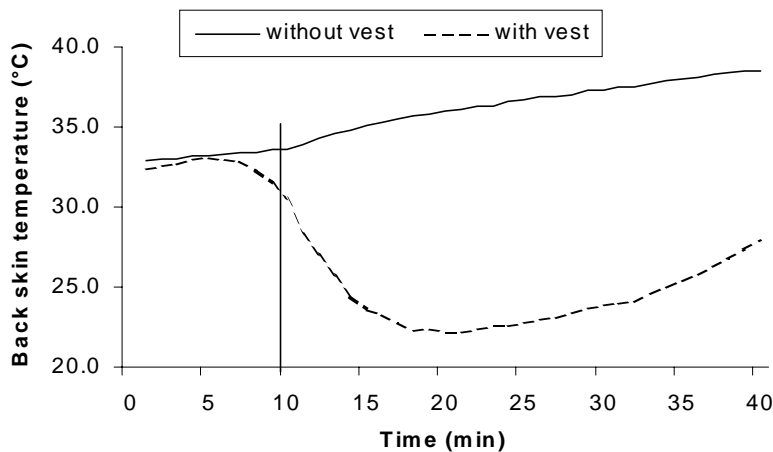
Figure 2. The average rectal temperature during walking in the heat at the heavy work load with and without the ice-vest. The walking started at minute 10.

During tests with ice-vest the back skin temperature decreased during the first 10-15 minutes over 10 °C compared to tests without the vest (Figure 3). Then it gradually started to increase due to warming up of the melted water. The decrease in chest skin temperature with the ice-vest was much less than in the back. This difference was very likely caused by the pressure of the gas cylinders on the back causing reduced insulation between vest and skin. In other skin areas the temperature differences were rather small.

Figure 3. The average back skin temperature during walking in the heat at the heavy work load with and without the ice-vest. The walking started at minute 10.

At both work levels the amount of sweat was less with the ice-vest compared to tests without the ice-vest (Table1). At the moderate work level the reduction in sweat production was 17 %, and at the heavy work level 9 %.

Table 1. Amount of sweat produced and evaporated sweat during the tests with and without ice-vest at the moderate and heavy work level. The values are the means (range) for 4 subjects.

Work level	Total sweat (g)		Evaporated sweat (g)	
	Without ice-vest	With ice-vest	Without ice-vest	With ice-vest
Moderate	443 (385-485)	369 (250-447)	183 (146-206)	135 (99-187)
Heavy	608 (497-693)	555 (505-598)	210 (175-250)	195 (183-217)

The amount of sweat in clothing was slightly less when the ice-vest was used (Table 1). Also, the absolute amount of evaporated sweat was slightly less. But expressed in per-

centage of sweating, the amount of evaporation did not differ between tests with and without the ice-vest.

At the moderate work level the rating of perceived exertion (RPE) was similar between tests with and without the ice-vest. At the heavy work level, RPE was during the first 10 minutes very similar between the two test conditions, but at 20 and 30 minutes of walking the RPE was about 1 unit lower with the ice-vest.

At both work levels, the subjects felt cooler in the whole body when wearing the ice-vest. Naturally, the cooler sensations were felt under the ice-vest on chest and back. Also, thermal sensations were slightly lower in other areas with the ice-vest (Table 2), especially at the heavy work level. In addition, the subjects felt more comfortable at the heavy work level when the ice-vest was used compared to walking without the vest.

Table 2. Thermal sensation of the whole body during tests with and without the ice-vest at the moderate and heavy work level at minutes 10, 20, and 30. The values are the means (standard deviations) for 4 subjects. See table 1.

Work level	Time	Without ice-vest	With ice-vest
Moderate	10	1.2 (0.5)	0.0 (2.2)
	20	1.8 (0.5)	0.3 (1.7)
	30	2.0 (0.0)	1.3 (0.5)
Heavy	10	1.5 (0.6)	0.3 (1.7)
	20	2.0 (0.0)	1.0 (0.8)
	30	3.0 (0.0)	1.5 (1.0)

Conclusions

It can be concluded that the light-weight ice vest reduces circulatory, thermal, and subjective strain during moderate to heavy work in a hot environment.

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Fire fighter garment with non textile insulation

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Introduction

Fibres and yarns are not the real thermal insulators of a garment. It is the locked still standing air. Fibres conduct the heat 10 to 20 times better than still standing air. This was the idea to substitute the traditional textile insulation by an air cushion. GORE-TEX® Airlock® is a combination of moisture barrier and thermal protection: Heat stable „spacers" of foamed silicone on the GORE-TEX® moisture barrier create the insulating air buffer.

Hot plate measurements showed that at similar heat resistance we gained a 40 % lower water vapour resistance with the new system whereas the water vapour absorption was reduced by 60 %. Transient measurements showed that the Airlock® system features a higher transportation rate but lower absorption rate for liquid water. Consequently a combination with Airlock® causes a significantly shorter drying time.

Conclusion out of this physical data: For wear situations with strong sweating, as experienced by fire fighters, a material combination with an Airlock® liner can be expected to show a better physiological performance than a material combination with a conventional textile insulation. In a controlled wear test on a treadmill in the climatic chamber we tried to proof this.

Methods

Five professional fire fighters wore the following ensembles at 30°C / 50 % RH for 95 min:

- Leather jacket with lining but without moisture barrier, Paris style, GORE-TEX® fire fighting trousers
- Textile jacket (Nomex, Aramid lining, GORE-TEX® barrier), Berlin style, GORE-TEX® fire fighting trousers
- Textile jacket (Nomex, Airlock®, lining), Paris style, modified Airlock® fire fighting trousers

Long-legged underpants and long-sleeved undershirt of a functional material (Ullfrotté: 60 % wool; 25 % PES; 15 % PA) have been worn underneath. To be close to practice each test subject wore its boots, gloves, helmet, belt and breathing apparatus (without respirator mask).

The load regimen was based on former studies and consisted of work and rest cycles:

10 min	4 km/h	0 %
10 min	rest	
5 min	5 km/h	5 %
10 min	rest	

5 min	5 km/h	10 %
10 min	rest	
5 min	5 km/h	8 %
40 min	rest	

Parameters measured: Core temperature (rectal), heart rate, skin temperatures, relative humidity between underwear and suit, weight loss of subject, weight gain of clothing. At the end of each cycle, the test subjects rated their heat and moisture perception as well as the wear comfort.

Results and discussion

Core temperature: Up to the 25th test minute, the temperature increases of the body core lay within a relatively narrow temperature band and on a comparatively low level. From that time on, however, distinct increases were observed. In the Leather fire fighting jacket, the body core temperature rose by 0.9 K, in the Berlin GORE-TEX® jacket by 0.65 K, whereas an increase of only 0.45 K was measured in the jacket Airlock®-Paris. In the Leather jacket the body core temperature was continuously rising, even after the load phase had ended (55th test minute), and kept on rising until the end of the test in the 95th test minute. In the two other jackets, the body core temperature kept gradually falling from the 75th test minute on.

Mean skin temperature: The temperature curves lie within a band of approximately 2 to 1.3 Kelvin; Leather on the top (more than 37 °C) and Airlock®-Paris the lowest skin temperature (nearly 36°C). Berlin GORE-TEX® was in the middle.

Heart rates: They rose in a way, which was typical for the load regimen of the test and lay within a physiologically plausible bandwidth. The small differences between the mean value curves reveal that the individual jacket types have less influence on the heart rates. It was only in the fire fighting jacket Airlock®-Paris that the heart rates returned nearly to the starting levels from the 65th test minute on.

Weight change: The weight losses of the test persons were, on an average, approximately 1 kg in the Airlock®-Paris jacket, 1.3 kg in the Berlin GORE-TEX® jacket and 1.7 kg in the Leather jacket. The water uptake of the garment ensembles coincided with the weight losses: 0.5 kg in the Airlock®-Paris jacket; 0.7 kg in the Berlin-GORE-TEX® jacket and 1 kg in the Leather jacket.

Relative humidity: The humidity measured in the Leather jacket ranged about 5 to 10 % above the levels measured in the two other jackets, throughout the test. It was especially in the Airlock®-Paris jacket that the humidity reached a steady state slightly above 80 % RH.

Heat perception: It was ranked on a scale from 0 to 7 (0=comfortable; 1=slightly warm; 2=warm; 3=very warm; 4=hot; 5=very hot; 6=uncomfortable; 7=intolerable). Up to the end of the last walking period (55th min) the Airlock®-Paris jacket was perceived as warm to very warm; Berlin GORE-TEX® as hot and Leather as very hot. This perception continued till the end of the test, whereas the two other jackets showed an improvement.

Moisture perception: It was ranked on a scale from 0 to 7 (0=dry; 1=chest or back slightly moist; 2=chest or back moist; 3=body moist; 4=body moist with clothing partly sticking to the body; 5=perspiration is running down at some spots; 6=perspiration is pouring down the body in many areas; 7=intolerable). Up to the end of the last walking period (55th min) Airlock®-Paris ranked 3rd and Berlin-GORE-TEX® and Leather 5th.

Wear comfort: It was ranked on a scale from 1 to 6 (1 = excellent; 2 = good; 3 = satisfactory; 4 = uncomfortable; 5 =very uncomfortable; 6 = extremely uncomfortable). Throughout the test period, Airlock®-Paris was perceived as excellent; Berlin GORE-TEX® as good and Leather as very uncomfortable.

The outcome of the study was that for all parameters, except for the heart rate, a clear rank can be assigned to each jacket type tested (rank 1 = best, rank 3 = worst performance):

1. Airlock®-Paris
2. Berlin GORE-TEX®
3. Leather

Conclusions

In the fire fighting suits with the new combination of thermal protection and liquid barrier very favourable thermophysiological conditions prevailed. Such suits can be expected to produce less heat stress at the wearer. Fire fighting suits with Airlock® fulfil EN 469 and had been successful in thermo-man-tests. With the new concept the bulkiness of insulation could be reduced while maintaining the same level of heat protection. Due to minimal moisture absorption and high moisture vapour transfer the risk of injuries by scalding should be reduced. High flexibility and reduced weight of such suits increases the wear comfort.

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Assessing fire protection afforded by a variety of fire-fighters hoods

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Introduction

Fire fighting crews on Royal Navy (RN) warships wear multi-layered Proban® treated Flame-Retardant (FR) clothing, breathing apparatus (BA), a helmet, gloves and boots. They also wear a single-layered FR treated cotton `anti-flash' hood to protect the areas of the head not covered by the BA mask or helmet. Previous work has demonstrated that this hood provides insufficient protection and serious head burns are probable if the fire fighter was accidentally engulfed in flame for more than four seconds (House, 1998). This study was undertaken to assess how better to protect the head from flame to explore the effect of using up to four material layers in a prototype hood. The study was designed to test the hypotheses that:

a. protection will increase with the number of layers added;
b. the greatest improvement will occur when doubling layers from 1-ply to 2-ply;
c. using three or more layers affords little extra protection.

Methods

Four prototype hoods of similar design (1, 2, 3 and 4-ply) were constructed and these were tested in comparison to the current hood, a RN aircraft-crash fire-fighting hood and a US Navy hood. The level of protection against fire provided by the hoods was assessed using a flame manikin head form as described earlier in these proceedings (Squire *et al.*, 2000). The head incorporates 30 thermocouples distributed over it's surface and is engulfed in flame using 30 propane cup burners that produce a mean incident heat flux on the head of 53 kW·m^{-2}, peaking at 85 kW·m^{-2} (Squire *et al.*, 2000). During the tests, head "skin" temperatures were recorded every second for sixty seconds from the time of the initial flame exposure. Heat flux incident upon the head was calculated from these data. Predictions of pain and tissue damage could be made from heat flux data using a model developed from human experiments (Stoll & Greene, 1959; Stoll & Chianta, 1971). Further details about the development of the manikin testing method, the method of use and the prediction of burn injury are published earlier in these proceedings (Squire *et al.*, 2000). Predicted burn injuries were described as first (1°), second (2°), and third (3°) degree burns. This classification describes the depth of damage to the skin. In simple terms:

1° degree burn is superficial reddening of the skin, which is painful but does not cause blistering;
2° degree burn damages some of the skin layers with resultant blistering but does not cause scarring;
3° is a full thickness burn, through the skin to the tissues below and results in scarring.

The fire-fighting hoods tested are shown in Table 1.

Table 1. Description of the hoods tested.

Hood Type	Identifier	No. of layers	Hood fabric
RN anti-flash	RNAF	1	Proban® cotton
RN prototype	RNP-1	1	50 %/50 % Kermel / FR Viscose
RN prototype	RNP-2	2	50 %/50 % Kermel / FR Viscose
RN prototype	RNP-3	3	50 %/50 % Kermel / FR Viscose
RN prototype	RNP-4	4	50 %/50 % Kermel / FR Viscose
RN aircraft-crash	RNAC	1	Proban® cotton
US Navy	USN	1	80 % Rayon / 20 % PBI

In each test, the hood was placed on the manikin head and engulfed in flame for specified periods of between one to ten seconds. 2 to 5 seconds being the most likely duration of fuel explosion events and ten seconds being considered the maximum likely possible survival time in full flame exposure (House, 1998). The hoods were normally challenged initially for four seconds so that the duration of subsequent challenges could be determined. If no burns were predicted after a four-second challenge then there was no need to conduct shorter duration tests and likewise if severe burns were predicted there was no requirement to conduct longer duration challenges. At least two examples of the hoods were tested at each flame challenge to ensure reproducibility of the results.

Whilst the `proper' RN fire fighting teams, like almost all civilian fire-fighters, wear a helmet and BA mask on the head, those providing the initial response to the fire on a ship may be wearing only the hood, or the hood and BA mask on their head. Therefore, the protection afforded by the hood should be tested both with and without a BA mask, and a BA mask & helmet. During a pilot study it was shown that in all cases none of the "skin" directly under the helmet or the BA mask recorded a burn injury even after ten seconds of flame challenge. Therefore, it was possible to test the hoods alone and to predict the extra protection afforded if a BA mask or BA mask & helmet had been worn thereby reducing the number of destructive tests required.

Results

Although 1° burn injuries were predicted they are not reported here. These type of injuries, although painful are not serious and heal quickly without permanent injury. All results quoted refer to the total predicted 2° and 3° injuries, which are more serious, rapidly debilitating, often cause permanent injury and are potentially fatal. Figure 1 shows the burn injury when the prototype hoods were challenged with flame for up to 10 seconds. It can be seen that the level of injury was reduced as the number of hood layers increased. It is also apparent that the greatest improvement in protection occurred when increasing the hood layers from 1 to 2, with diminishing improvements in protection as subsequent layers were added. *E.g.* after 4 seconds of flame engulfment the predicted burn injuries were 78 %, 24 %, 11 % and 8 % with 1-ply, 2-ply, 3-ply and 4-ply hoods respectively. Similar results were seen when the effects of adding the BA mask and the helmet were added to the predictions, although the difference between the hoods was reduced as a smaller surface area of the head was exposed to flame.

Figure 2 shows the burn injuries for the current hood (RNAF) in comparison with the RNAC, USN and RNP-2 hoods.

It is clear that the RNP-2 hood provided more protection than the current RN AF hood whilst the USN hood provided the best protection. Of interest was the finding that the

RNAC hood provided much less protection than the RN AF hood despite being made from exactly the same weight of Proban® treated FR cotton.
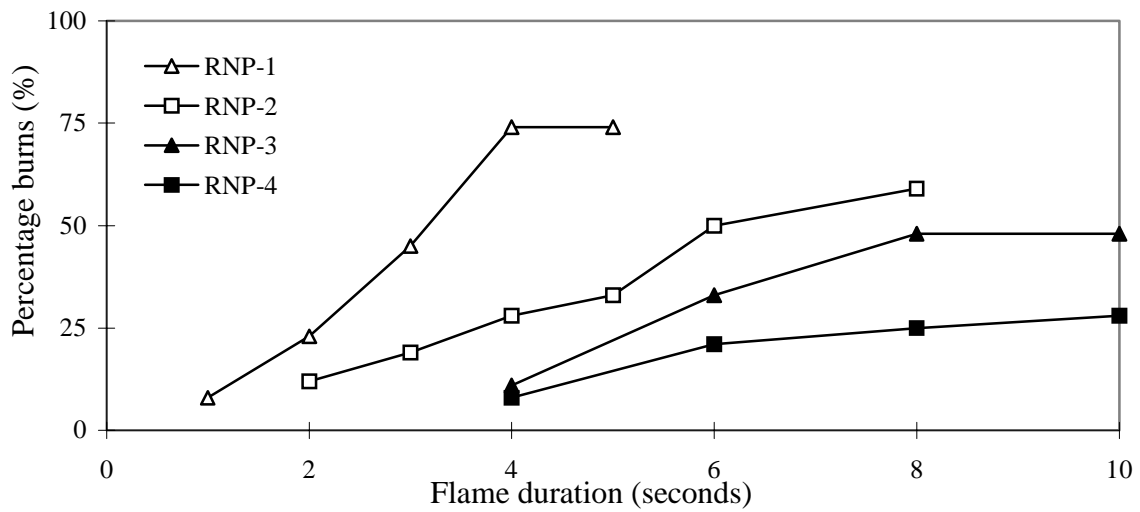

Figure 1. Percentage of head with a 2° or 3° burn injuries when the prototype 1 to 4-ply hoods were engulfed in flame.
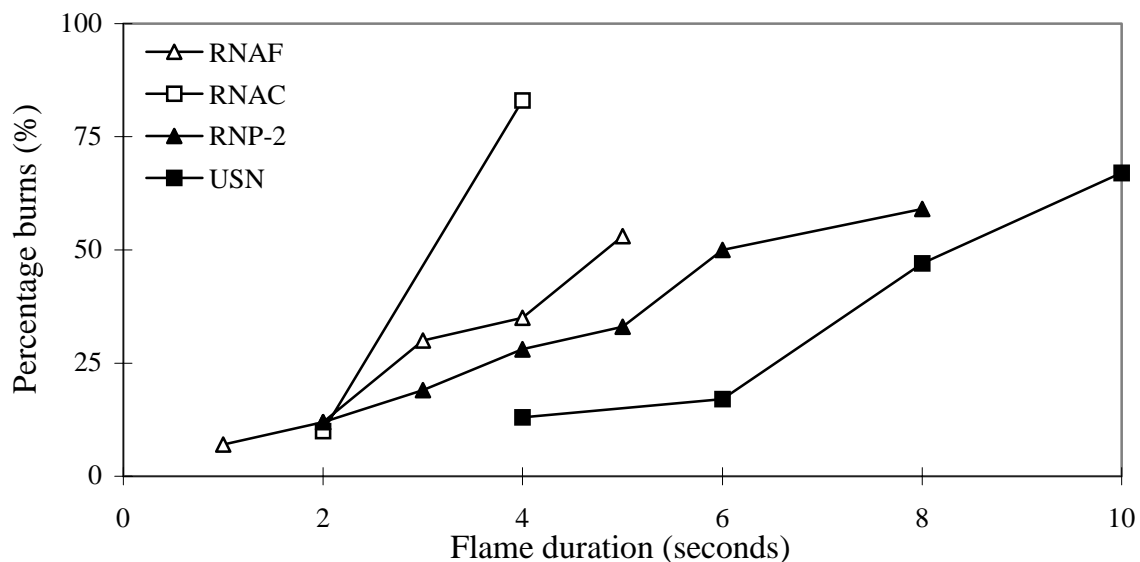

Figure 2. Percentage of head with a 2° or 3° burn injuries when the fire hoods were engulfed in flame.

Conclusions

As expected, the level of protection from fire afforded to the head increases as the number of layers of FR material in a hood is increased. As hypothesised, the majority of the improvements in protection occur when a single layer is increased to a double layer with subsequent improvements being less significant. For the RN, the introduction of a new fire fighting helmet and communications system which included a skull conduction microphone required that the number of layers in the hood be restricted to two. Whilst the RNP-2 hood offered increased protection compared to the current RNAF hood, the USN (2-ply) hood provided the best level of protection; the increased protection is assumed to be due mostly to the material differences between the RNP-2 and the USN navy hoods, as their designs were essentially similar. Consequently the RN is introducing the USN

hood to fire fighters as an interim measure whilst the RNP-2 (which fits more easily around the BA mask) is manufactured in the same materials as the USN hood.

An interesting finding was that the RNAC hood provided much less protection compared to the RNAF hood as both of these were constructed from the same weight of Proban® treated cotton. The difference was due to the RNAC hood having perforations at the ears on each side of the hood, to avoid interfering with hearing and supposedly to allow fire fighters to `detect the heat of a fire'. No evidence has been found to show that fire hoods interfere with hearing to an extent significant enough to reduce safety. It is further suggested that allowing fire fighters to `detect the heat' by leaving small areas of the head unprotected (usually the ears) when the rest of the body is enclosed in multi-layer FR materials is inappropriate. If fire fighters have to detect dangerous levels of heat, it is suggested that this could be achieved easily, and more safely, by using cheap temperature sensitive indicating strips that are readily available.

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Fire fighters' views on ergonomic properties of their footwear

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Introduction

The foot is a complex support structure formed by 26 bones and has the highest concentration of bone structure in the human body. The bones of foot have to admit continuous variations in the load. Ideally all shoes should meet the following ergonomic requirements; fit properly both in length and width, grip the heel firmly, there should be a straight line from the heel to the end of the big toe to prevent turning of the big toe, and there should be enough room for the toes. There should also be some way of fastening across the top of the foot to prevent the shoe slipping on and off while walking (Steemson 1988). Clumsiness, heaviness and poor contact sensitivity were the most frequent complaints about safety boots among firefighters (Louhevaara, 1995; Mäkinen, 1991; Marr, 1990). Biomechanical aspects of footwear have been studied, a.o., from the point of view of poor fitting (Audemars, 1978; Oakley, 1984; De Moya, 1982), needs for shock absorbency (Audemars, 1978) and unhindered mobility and ease of movement (Oakley, 1984). In laboratory experiments leather boots were found to have advantages with regard to biomechanical aspects (Neevees et al., 1989). Hawes et al. compared differences in forefoot shape and dimensions between North American and Japanese or Korean males, and concluded that the shape of these two groups differ. Thus different shoe lasts for each population are required for optimal shoe comfort (Hawes et al., 1994).

   Ergonomics of PPE is one essential requirement of PPE directive 89/686/EEC. So far some ergonomic requirement only exists in a few harmonised EN standards. A research project on fire fighters' protective footwear supported by The EU Commission started last year. Part of this project aims to clarify fire fighters' perceptions of needs in their footwear. The aim of this paper is to identify fire fighters' perceptions of the ergonomic and biomechanical properties of their footwear when engaged in different tasks.

Methods

An inquiry was made with selected fire brigades in six European countries, Austria, Britain, Finland, France, Spain and Sweden. Fire fighters opinions on the ergonomic and biomechanical properties of their footwear, in use, were asked. The questions concerned the following general properties: restrictions caused by the footwear during various activities, discomfort caused by the footwear. Biomechanical properties investigated were: sizing and fitting problems, weight, flexibility and stability, and the thermal comfort of footwear. Some of the questions allowed yes/no answers, while others required a degree of agreement to various statements using the following scale: strongly disagree, disagree, not sure, agree, strongly agree. The questionnaire also had two open questions where the

fire fighters were asked to specify what boot properties have been sensitive to wear and ageing effects, and what are thought to be the causes if the fit was not good.

Analysis of variance (ANOVA) was used to analyse the data. Some data manipulations were necessary to make different responses comparable and to give them similar structure. Means comparisons and General Linear Models were used for testing differences.

Results and discussion

Answers from 754 fire fighters were received. More leather boots and shoes than rubber boots were in use in Finland (61 %), Sweden (55 %), in Spain (86 %), and in France (100 %). It might have been useful if the answers had been classified according to leather or rubber material. This was not done because many fire fighters have both types in use simultaneously.

Safety footwear has caused some restrictions in fire fighters work e.g. 58 % of Finnish fire fighters, 52 % of Swedish, 32 % of French, 31 % of English and 27 % of Spanish fire fighters. There were differences between countries in activities where footwear caused restrictions (Figure 1).
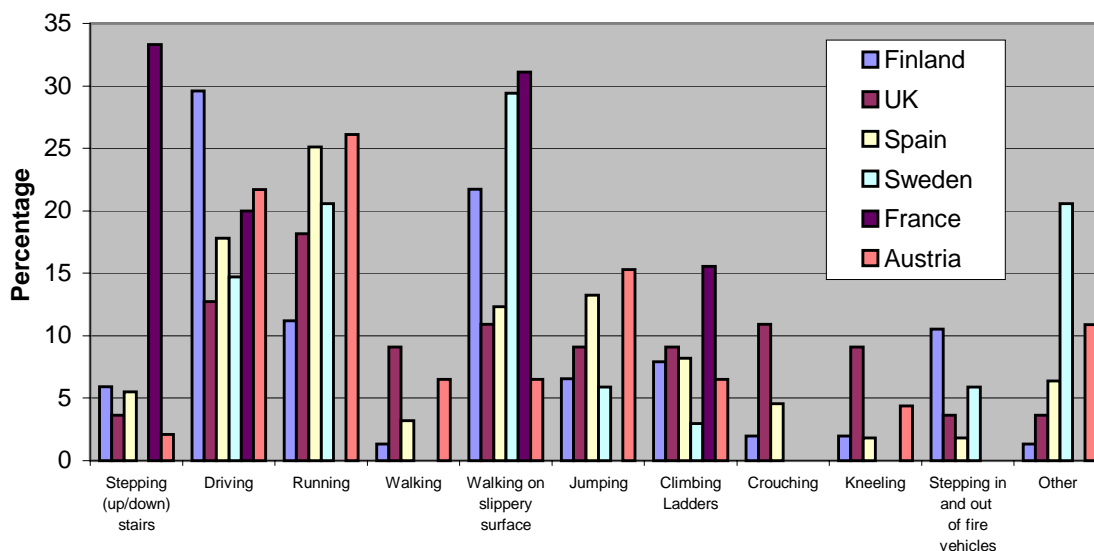
Figure 1. The comparison between countries of the restrictions caused by the footwear.

36 % of Finnish fire fighters, 11 % of Swedish, 33 % of English, 34 % of Spanish, 14 % French, and 24 % of Austrian fire fighters reported some discomfort caused by footwear. The cause was reported as the material in 32-50 % of answers, and wrong size or design in 34-67 % of answers.

57 % (N=80) of Finnish firemen, 12 % (N=41) of English, 33 % (N=80) of Spanish, 23 % (N=35) of Swedish, 80 % of French (N=21), and 39 % of Austrian firemen had observed some loss of protection due to wear and ageing of your footwear. The reported causes were due to upper or lining material, outsoles, seams, toe cap, inserts, water proofing and heat.

15-29 % of fire fighters in different countries reported about some problems obtaining correct footwear sizes. There were differences between countries in obtaining the correct sizes. In Finland and Sweden the main reason was the height of the metatarsal area, in Britain the width and in France and Spain the length of the footwear.
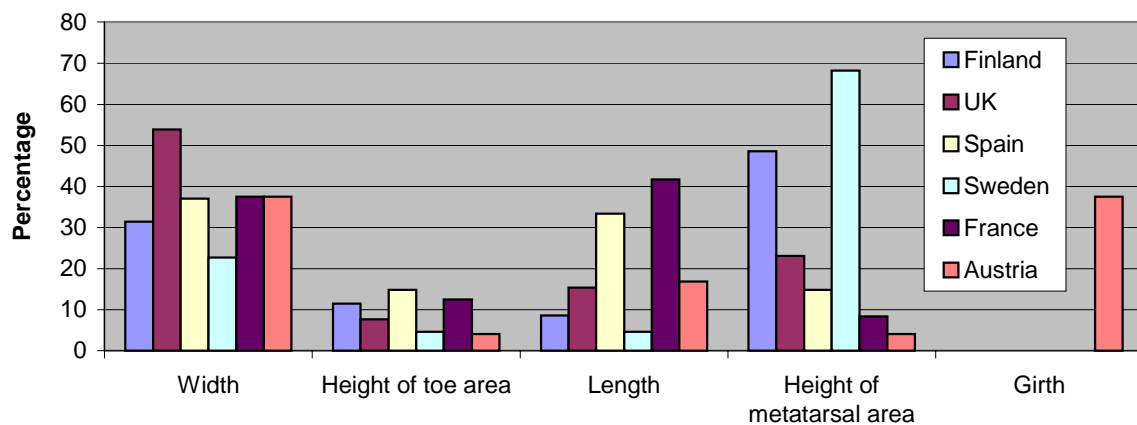
Figure 2. The problems with sizing of the footwear by answered fire fighters in different countries.

The areas, where the fire fighters had problems obtaining the correct size of boots, are shown in Figure 2. These results indicate that there are differences in different areas of Europe; north or south.

17 % of the Finnish fire fighters, 28 % of English, 27 % of Spanish, 21 % of Swedish, 46 % of French, and 14 % of Austrian fire fighters disagreed that their footwear has good fitting properties. Swedish and Finnish fire fighters in particular reported that. The main causes were due to material, size, width, instep, general fitting, loose fitting, fastenings etc.

The answers concerning biomechanical properties are summarized in Table 1. More Spanish fire fighters complained than others, Austrian fire fighters complained less than fire fighters in other countries. Feet sweating and weight and flexibility of footwear were the most important biomechanical properties in Spain. The flexibility of footwear was more important in Finland than in other countries. For French fire fighters foot stability was more important than in other countries, but feet sweating and flexibility of footwear were not as important for them.

Sweating was the biggest concern in all countries except France. Ankle flexion was of little importance in most countries, being more clearly of lower importance in Spain and Austria than in the other countries.

Table 1. Fire fighters' opinions about the problems in biomechanical properties of their foot-wear, significance was determined, in relation to sample size, by country or property.

Country	Weight %	Flexibility %	Ankle flexion %	Foot stability %	Sweating %
Finland (N=102)	35	37*	27	20=	62"
Britain(N=47)	21	34*	23	25	57"
Spain (N=132)	61*"	36*	27"	23"	79*"
Sweden (N=69)	25	12	10	23	49"
Austria (N=180)	22	10⁻	8⁻	18⁻	38⁻"
France (N=150)	28	7⁻	19	60*	15⁻

* This biomechanical property is significantly more important in this country than in other countries
⁻ This biomechanical property is significantly less important in this country than in other countries
" This biomechanical property is significantly more important, than other properties, in this country
= This biomechanical property is significantly less important, than other properties, in this country
There is less than a 5% chance that any of the significant differences indicated are not true.

Conclusions

In general there were differences between general and biomechanical properties with bio-mechanical being the most important. 27-58 % of fire fighters though that their footwear had caused some restrictions in their work specially when driving, running, walking on slippery surfaces and jumping. 11-36 % of fire fighters think that footwear causes some discomfort in their work. Only about 27 % of fire fighters reported that they had ever had problems with boot size. There were differences between the countries with regard to footwear measurements, the width and girth of the footwear being the most important. Further research is needed to explain the reasons why fire fighters in different countries have different types of sizing problems; is the reason different foot anatomy, or the use of different footwear design methods in different countries?

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