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The European Conference on Protective Clothing (ECPC) is organized every 3 years by the European Society of Protective Clothing (ESPC) which was founded in 2000 in Stockholm. The purpose of ESPC is to act as a forum for experts cooperation in the field of protective clothing (including gloves and shoes) all over the Europe, but the experts from all over the world are also welcome. The forum was created in 1984 in Scandinavia where NOKOBETEF (Nordic Coordination Group on Protective Clothing as a Technical Preventive Measure) was founded. ESPC and Nokobetef are independent organizations.

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Despite the latest achievements in technology aimed at new solutions in safety at the work place, there are still traditional and new hazards and risks against which application of personal protective equipment and protective clothing is necessary. Risk compounded by simultaneous exposure to several harmful or dangerous factors must not be overlooked, either. At the same time it is crucial to take into account workers’ growing expectations of comfort while using personal protective equipment. Thus high-performance protective clothing continues to be an important tool for creating safe working conditions and therefore research in this field is indispensable.

Application of new solutions, such as high-tech materials and microelectronics, in designing products can help achieve equilibrium between protection, comfort and durability of protective clothing. In accordance with the principle of balanced protection, both scientific and applied research aimed at the development of innovative materials and clothing is necessary. Smart protective clothing is a good example of successful research; it, for example, enables self-adjustment of the microclimate under a protective barrier and indication of safe wearing time of clothing. Improvement of testing and measurement technology, which should map real-use conditions of protective clothing and make objective assessment of new products possible, also constitutes an important area in research.

Intensive exchange of knowledge and experience among experts is needed for successful development of optimal products.

That is why representatives from various institutions, organizations and enterprises involved in protective clothing, including gloves and footwear are meeting in Gdynia, Poland. The 3rd European Conference on Protective Clothing is an excellent opportunity for scientific discussions, an exchange of information and co-operation among experts.

In these conference proceedings you will find abstracts of all oral presentations and posters presented in Gdynia. The complete papers are available on a CD.
To better comprehend the present state and future projections of protective clothing, it is beneficial to review the developments in protective clothing over the past few decades. In the past, the so-called blue overall was typical work wear regardless of the type of work performed. Only certain occupations, such as fire fighters, were covered by national regulations for protective clothing. In 1984, the topics covered in the first NOKOBETEF 1984 conference and the first ASTM symposium "Performance of protective clothing" provide an idea as to what type of protective clothing research was being conducted at that time. The papers presented at the 1984 NOKOBETEF conference entailed chemical protective gloves and clothing. Chemical protection was also the main theme at the ASTM-symposium in addition to sessions on thermal protection, fire fighters' protective clothing and ergonomics. The emergence of these specialised symposia illustrate the growing interest on the subject matter, as well as the importance of protective clothing for the protection and well-being of workers.

During the early 1990s, there was a surge of new developments in protective clothing. At this time, the European Directive on personal protective equipment (PPE) came into effect, and subsequently protective clothing was regarded as true personal protective equipment. Nine CEN Technical Committee (TC) 162 working groups prepared European standards for protective clothing. There are currently twelve TC 162 working groups and they have prepared over 100 clothing and glove standards concerning requirements and/or test methods for protection against a variety of hazards. Similarly, the CEN TC 161 has prepared dozens of footwear standards. Now at the beginning of the millennia, revisions of many standards have already been published.

What is the current state of protective clothing?

The basis of the following market review, is an article published in Technical Textiles 3/2005: In Western Europe, protective clothing and gloves account for an estimated 60% of the total PPE market, out of which protective clothing comprises the largest sector. Protective clothing sales are expected to increase at a rate of 5.5% a year. The type of PPE used varies based on the work demands of the particular industry under consideration. Petrochemical companies and emergency services have the largest number of employers using PPE. The most common hazards, against which protection is needed, are mechanical in nature. The next common hazards are ones involving heat, flame, chemicals, and flying particles. Out of the 227 sampled West European companies, a typical customer’s total PPE expenditure comprised of 50% protective clothing, 20% headwear, 20%
footwear, and 10 % safety gloves. A significant driving force for the PPE market growth has been the EU-regulations and standards.

The trend seems to be the development of products, which offer multilevel protection, which in turn need to meet the ever-growing list of EN-norms. Fabrics for multilevel protection must exceed the protection requirements for hazards identified in the risk assessments. Furthermore, the technology levels and product functionality are increasing. Work wear is becoming more and more trendy and the development is customer oriented. The workers are more fashion conscious and the work wear has become a part of the company’s image. The materials are more advanced and the designs are mowing towards leisurewear and sportswear fashions. The first generation of high performance products, such as membranes and breathable coatings, are practically everyday components in protective clothing, as well. For greater details on the contemporary situations and future directions of protective clothing, please refer to a 2005 published book "Textiles for Protection" from Woodhead Publishing Limited and edited by Richard A. Scott.

Future Directions?

According to the presentation given by Dr D. Couvret from of Institut Francais Textile - Habillement at the Techtextil Symposium 2005 in Frankfurt, the present protective clothing market trends include protective clothing for medical use, thermal protection, eletric and magnetic protection, alert systems using specialty products, flexible high technology, knowledge-based processes, intelligent production, and high added value products for high added value markets.

Nanoscience and nanotechnology are the buzzwords for the future development in all areas, including protective clothing offering enormous potential for wide range of end uses. The ability to manipulate atoms in desired ways increases production precision. It is anticipated that in 15 to 20 years, presently inconceivable nanotechnology based solutions will become a reality in protective clothing area too. Nanostructured fibres are divided into three main groups: nanofibres, nanocomposite fibres, and nanocoated fibres. They offer new solutions to improve the properties and performance of existing materials, e.g. for more hygroscopic properties of man-made fibres, protection against chemicals and biological hazards (e.g.viruses), UV shielding, photo-oxidising capacity, fire protection, mechanical protection, mechanical strength, antistatic properties, insect-repellent, care free wrinkle resistant fabrics, stain and water repellent finishing, and controlling odour and having self-sterilising functions. Nanotechnolgies can be applied to develop intelligent personal protective equipment with novel functions. They open up new opportunities for fibres as sensors to develop smart garments, which sense and react to environmental conditions and stimuli. There are already existing prototypes of smart clothes using wearable technologies, although commercial versions are still to come.

The future holds significant challenges in protecting people in work and leisure activities. Success in these areas requires effective research, education, and training. It also necessitates greater collaboration outside of the traditional textile and clothing industries, as well as novel processes, new manufacturing technologies, industrial strategic partnerships, new logistics solutions, technological structures, and new business networks. All parties involved need increasingly dynamic work and fast responding to new questions. The Seventh Framework Programme of the EC will soon be open and will subsequently provide new funding opportunities to further facilitate the development of protective clothing. Parallel to the development work, the scope, requirements and test methods of the PPE standards should be reviewed. For example, the applicability of these standards to new products should be investigated. Nanoscience is a new area and may therefore have disadvantages yet to be
discovered. Consequently, the possible health and safety aspects of handling nanoparticles, nanofibres, and nanocoatings must be kept in mind and research is needed in this area, too. As is true for the entire textile field, the eco-efficiency, as well as waste and energy balance has to be included into the protective clothing development and design process.
DEVELOPMENT OF A TEST METHOD AGAINST HOT ALKALINE CHEMICAL SPLASHES

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ABSTRACT

Hot alkaline chemical liquids have been related to injuries and hazardous situations during normal work and maintenance tasks in pulp manufacturing mills. There are no requirements and/or testing method standards concerning protection against hot alkaline chemical splashes. In many work places, the protective clothing meeting the EN 531 specifications have proven to provide insufficient protection. For the purposes of a study on protective clothing of recovery boiler workers, we have developed a testing method able to test and find materials appropriate for hot liquid chemical hazard protection. During the development process we used elements of the EN 373 method, a method that assesses a material’s resistance when used as protective clothing against molten metal splashes. Two main problems had to be solved: 1) How to keep the liquid chemical from spilling, and 2) how to measure the protection level of these materials. In the first phase, the liquid was spilled through a stainless steel funnel and the protection performance was evaluated using PVC-skin under the test material as specified in the EN 373. Warming elements were added to the sides of the funnel, but with this addition the hot chemical ignited the stainless steel funnel. As a result, a graphite crucible was used for warming and spilling the chemical and a copper calorimeter with four independent measuring areas was designed to measure the temperature under the material samples. The calorimeter was designed to respond quickly so that peak temperatures could be measured. Despite successful resolution of the main problems, we were unable to keep the spilled amount of chemical constant, with the unfortunate results of significant variability in data. Nonetheless, the test results for over 40 different types of materials and material combinations indicate the difficulty in finding material with sufficient protective properties.

1. INTRODUCTION

The primary cooking chemicals for pulp manufacturing are sodium hydroxide and sodium sulphide. In the recovery boiler, black liquor is burned at high temperatures, which results in a very aggressive chemical liquid consisting of sodium carbonate (70%) and sodium sulphide (30%) with a rapid phase shift from liquid to solid. This hot alkaline solution (800 - 900°C) is conveyed through open channels out of the boiler. The hot liquid frequently produces precipitation in the channels, which culminates in
process malfunctions. While opening channels, workers are exposed to droplets of the hot liquid. Therefore, body and face protection is essential (1).

A pulp mill contacted the Finnish Institute of Occupational Health (FIOH) in 2003 subsequent to some serious accidents that had occurred in the mill, despite the mill’s adherence to utilising standard type heat protective clothing as per the EN 531 (2). The available protective clothing standards proved insufficient. The general type of heat protective clothing was used in the mill because special requirements and/or test method standards related to hot chemical liquid hazard are currently unavailable.

This paper describes different steps of the test method development. The aim was to develop test methods to reliably identify materials and material combinations for protective clothing and other necessary personal protective equipment (PPE) for recovery boiler workers. The development process is described in another paper, also being presented at this conference (3).

2. METHODOLOGY

The starting point for this method development was the EN 373 method (4). This method specifies a process for assessing the resistance of protective clothing materials to molten metal splash. Materials are tested by pouring quantities of molten metal onto the test specimen supported at an angle to the horizontal on a pin frame. Damage is assessed by placing an embossed thermoplastic PVC sensor film directly behind, and in contact with, the test specimen, and thereby noting changes to the film after pouring. Any adherence of the metal to the test specimen surface is also noted. Depending on the result, the test is repeated using a greater or a smaller mass of metal, until the minimum quantity to cause damage to the film is identified. The testing apparatus consists of a furnace, a motorised crucible holder, a specimen holder, and a sand tray. Instead of pouring, a predetermined amount of heated liquid chemical was spilled onto the sample utilising a funnel with holes.

The pulp manufacturing mill provided the chemical to be tested in solid form. For measurement purposes in the laboratory, the solid chemical was heated in an oven up to 800-900 °C at which temperature this chemical becomes liquid. The liquid was then spilled through a funnel with holes onto the material sample. The ignition melting and hole formations of the material were evaluated and the effects on the skin were assessed. During the first steps, the protection performance was evaluated using PVC-skin under the test material; for the latter steps, a copper calorimeter-system was developed for assessment purposes.

2.1. STEPS 1A AND B

a) Measurements at a recovery boiler mill. Specimen holder and the size of the specimen followed the specifications indicated by the EN 373. About 1 dl of hot liquid was taken from the channel and spilled onto to the samples through a stainless steel funnel furnished with 2 mm holes. PVC sensor film was used for assessment of a burn injury. Figures 1 and 2 illustrate the field measurement.

b) Measurements in the laboratory: The measurement procedure was similar to step-a as described above with the exception that 50 g of chemical was heated within the furnace in a crucible and the spilled liquid was then weighed. A hot air fan was used to prevent rapid cooling of the funnel.
2.2. STEPS 2A AND B

Step 2a. Identical to step-1b, except that a copper calorimeter with four separate thermometers was used for assessment (Figure 3 and 4). The copper thickness was 0.5 mm.

Step 2. Identical to step-2a, except that three heating patrols around the funnel with distance of 120° were used to prevent the cooling of the funnel.

2.3. STEP 3

Step 3. Similar to step-2b, except the liquid was spilled through a graphite funnel with 4 mm holes. An induction oven was used to prevent the cooling of the funnel. The measurement system and the funnel were insulated using Mica electrical insulation plates to prevent radiation heat from escaping into the environment. The developed laboratory measurement system is shown in Figures 5 and 6.

The materials were conditioned at (20 ± 2) °C and (65 ± 5)% before testing. In various phases, traditional flame retardant (FR) fabrics, as well as coated materials and material combinations from the market, were measured. The materials were tested without pre-washing. For the most promising materials and combinations three parallel measurements were performed.

3. RESULTS

Step 1
During the field measurements, there were difficulties with obtaining comparable amounts of liquid from the recovery boiler funnel for spilling purposes. The liquid began to cool and rapidly solidify, and subsequently stuck to the funnel walls. Through the measurements of these 22 fabrics and fabric combinations, initial impressions of the aggressiveness of this chemical were formulated. Typical flame retardant (FR) fabrics provided insufficient protection. Some fabrics ignited and continued to burn despite meeting the EN 531 requirement for limited flame spread. In most of these cases, the PVC-skin melted through. Similarly, layered fabrics with moisture barriers and surface fabrics, also of aramid fibres, appeared unsuitable given that chemical drops tended to stick to the fabric’s surface. The PVC-skin surface patterns melted in several of these cases. Aluminium coated fabrics burned through and the PVC-skin under the fabric melted through, as well.

In the laboratory measurements, the temperature of the spilled liquid was 800 -830 °C, and the mass of the spilled liquid varied between 14.4 and 48.8 g. It was difficult to keep the funnel holes clear. Moreover, because a fan was used to prevent the funnel from cooling, the hot liquid tended to drip onto the backside of the sample. Silicon coated fabrics and leather provided the best protection. For these fabrics there where only a few melted spots on the PVC-skin.

Step 2
The new warming-system that includes heating patrols, kept the chemical in liquid form, but the steel funnel was unable to withstand the increased temperature and aggressive alkaline chemical, and subsequently began to burn.

Step 3
The ceramic crucibles functioned well for several consecutive spills, although the holes for spilling tended to increase in diameter with use, so any given funnel could only be used for 8 spills.
During steps 2 and 3, 26 different materials and material combinations from the market were tested. The temperature of the spilled chemical was 824 - 933 °C. Between 41 and 66 grams of chemical was spilled at a time. The lowest maximum temperature increase (40-53 °C) was measured for Teflon-finished 50/30/17/3% FR CV/WO/PES/R-stat fabric with 55/45% MAC/CO knitted fabric (Figure 7). The time for 12 and 24 °C temperature increases was very brief for most of the measured fabrics. The chemical did not run off but penetrated most materials causing a rapid and high temperature increase (Figure 8).

4. DISCUSSION AND CONCLUSION

The development process began with bringing the test device to the work place, and positioning it near the recovery boiler. The test results provided protective level estimates for some typical FR fabrics used in paper mills. The tests were continued in a laboratory environment. Despite modifications during the development process, the quantity of the spilled chemical and the temperatures measured by the calorimeter remained variable. This may have been due to a possible change in the chemical formula [composition], such as one occurring through the solid chemical received from the pulp mill being exposed to air. During the field tests, the chemical was obtained directly from the recovery boiler process. Other possible explanations for the temperature variations include the chemical sticking to the outer surfaces of the material, differences in spilling procedure, and the rapid phase change of the chemical (i.e. from liquid to solid) despite the additional warming system.

5. REFERENCES

2. EN 531:1995 Protective clothing for industrial workers exposed to heat. European Committee for Standardization, Rue de Stassart 36, B-1050 Bruxelles
3. Mäki S, Koskinen H, Mäkinnen H, Protective clothing and other personal protective equipment against high temperature liquid splashes for recovery boiler workers. 3rd European Conference on Protective Clothing (ECPC) and Nokobetef 8 10-12.05.2006, Poland, Gdynia.
4. EN 373:1993 Protective clothing. Assessment of resistance of materials to molten metal splash. European Committee for Standardization, Rue de Stassart 36, B-1050 Bruxelles

Fibre abbreviations:
FR CV, flame retardant viscose
WO, wool
PES, polyester
MAC, modacrylic
CO, cotton
Figure 1. Drawing chemical from channel

Figure 2. Testing device in the field

Figure 3. Testing in laboratory

Figure 3. Copper calorimeter for temperature measurement

Figure 4. The furnace for heating the chemical

Figure 5. The modified testing arrangement

Figure 7. Example of low temperature increase

Figure 8. Example of fast and high temperature increase
PROTECTION FROM STEAM AT HIGH PRESSURES: DEVELOPMENT OF A TEST DEVICE AND PROTOCOL

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ABSTRACT

Increased use of steam in the oil and gas sectors has led to incidents where workers were seriously injured by exposure to steam or condensate. Steam pressures are as high as 4300 kPa, with temperatures up to 150°C. Objectives for this research were to: (a) analyze conditions at work-sites, develop an understanding of the physics involved and establish threshold criteria, (b) establish appropriate parameters and test conditions, (c) develop and construct test equipment and (c) evaluate some existing FR materials to refine the test protocol and establish material specifications. Theoretical considerations included heat and mass transfer, yarn and fabric structure, relationship to properties such as air and vapour permeability, and clothing design parameters.

Several iterations of a test device were developed. The current version will be described. It comprises a torso-like cylinder with several skin-simulant sensors connected to a temperature data-logger, an optional spacer, and a high-pressure steam source with pressure regulator and gauge. Fabric specimens are mounted on the cylinder before steam exposure.

FR materials with different water vapour permeabilities were tested. Experimental variables also included steam pressure and distance between steam nozzle and fabric specimen. Four dependent variables were calculated from temperature/time curves for each sensor: peak temperature, peak heat flux, time to reach peak heat flux, and total transferred energy. Results demonstrate that the test protocol can differentiate among fabrics at various steam pressures and distances. Recommendations for further development of the test protocol and for development of steam protective clothing will be discussed.

1. INTRODUCTION

The purpose of this research was to develop a test device and procedure to measure heat transfer through fabric systems exposed to steam under high pressure. Potential for exposure to such hazards is high in the oil and gas sector in Alberta, Canada. Although workers in these industries wear flame resistant (FR) protective clothing to prevent skin burn injuries from flash fires, steam is another substantial hazard for which little protection is provided. Incidents have been documented by the
Canadian Petroleum Safety Council where workers have been injured due to steam exposure, including one fatality (1).

No performance standard for evaluating steam protective properties of clothing exists currently. By examining the rate of heat and moisture transfer through fabrics during steam exposure, and through understanding the mechanisms of such, differences among FR clothing materials can be evaluated and improved clothing systems can be developed. Although extensive research has been conducted to understand mechanisms of heat and vapour transfer through different clothing systems, most has focused on heat and vapour transfer from human skin towards the environment. Analyzing the transfer of steam through different textile layers to a sweating body, Rossi, Indelicato and Bolli (2) reported that energy transfer was dependent on the water vapour permeability, thickness and thermal insulation of the specimens. They concluded that materials which are impermeable to vapour provide better protection to hot steam than semi-permeable ones. Le and Ly (3) studied heat and mass transfer through an absorbing fibrous medium consisting of layers of textile fabric in a condensing flow of steam at relatively high temperature and pressure as found in pressure-decatizing of wool fabric. Under such conditions they considered convection to be the primary mechanism of heat and mass transfer. Li (4) concluded that the transfer of heat in mostly porous textile assemblies is governed by conduction by both air and fibres, convection and radiation, while moisture transfer mechanisms include vapour diffusion in void space, moisture absorption by fibers, evaporation, and capillary effects. Schnieder, Hoschke & Goldsmid (5) reported that heat transfer generally increases with increasing fiber regain. As the fabric is saturated thermal conductivity of water influences heat transfer more than thermal conductivity of the material. No study reviewed dealt with heat transfer through fabrics exposed to steam under the high pressure conditions experienced in the oil and gas sector.

2. DEVELOPMENT OF TEST DEVICE

This paper reports the design and development of a laboratory test device to measure such a hazard. A cylinder of 230 mm diameter and 460 mm height was built with fiberglass and polyester resin, and was fixed onto a steel frame. Skin stimulant sensors were mounted on the surface of the cylinder to measure energy transfer. These sensors are connected to a data-acquisition device that records the temperature as a function of time. Sensors are evenly distributed over the front face of the cylinder. Figure 1 shows elements of the test device. Several factors were taken into consideration in the design of the test device, including:

- The shape of fabric mounting surface: a cylindrical shape was selected to simulate a human torso. The energy distribution for a flat surface differs from that for a curved one when exposed to forced convection, such as occurs during steam exposure. For a flat surface the steam concentrates on a localized area rather than surrounding the surface as may be observed for curved surfaces. Thus, larger surface areas are likely to be exposed for curved surfaces than for flat ones.
Nozzle Thermocouple to measure steam temperature at nozzle outlet
Central Sensor
Pressure Gauge Stand (Base)

Figure 1. (a) Cylinder with sensors on the test device; (b) Test device in operation

- Type of temperature sensor: nine skin simulant sensors based on that developed by Dale et al. (6) were placed on the front surface of the cylinder to measure the heat transfer through fabrics.
- High pressure steam source and regulator: the highest pressure available in the main line in a laboratory setting was 345 kPa. A pressure regulator was installed to achieve uniform steam flow during the tests, further reducing the maximum pressure available for testing. Two pressures were selected for testing: 69 kPa and 207 kPa.
- Exposure time: the exposure time was determined based on a probable worst case scenario. Although a person coming in direct contact with steam may try to escape almost instantly, in some situations this may not be possible. The exposure time was set at 10 sec during all experiments.
- Proximity between the hazard and subject: after preliminary experiments, two distances (50 mm and 100 mm) between cylinder and steam nozzle were selected for the experiments to simulate worse case scenarios.
- Nozzle design: three nozzle geometries giving different patterns of steam distribution on the fabric surface were considered. A vertical slit design was selected because it most closely resembled a major industrial hazard, namely a piece of gasket blown off between two flanges.

3. METHODS

A laboratory experiment with three independent variables (fabric, steam pressure, and the distance between nozzle and cylinder surface) and four dependent variables (peak temperature, peak heat flux, time to reach peak heat flux and total energy) was conducted to determine heat transfer through different FR fabrics exposed to steam. Two replications of the experiment were conducted with good consistency between replications.

3.1. MATERIALS

Three fabrics were chosen based on their differences in water vapour diffusion resistance (Dm). Fabric A had relatively low resistance to water vapour diffusion (Dm=1.05 mm still air) and was also permeable to liquid water. Fabric B (Dm=19 mm) was impermeable to liquid water but permeable to vapour, and Fabric C (Dm>150 mm) was impermeable to both liquid and vapour. Fabric thickness for Fabric A (0.56 mm) and Fabric B (0.64 mm) were relatively close compared to Fabric C which was
thinner (0.34 mm). Total heat loss was highest for Fabric A (692 W/m²) followed by Fabric B (363 W/m²) and Fabric C (227 W/m²).

3.2. PROCEDURE

Fabric specimens (45cm x 45cm) were conditioned in a standard atmosphere of 20°C and 65 % R.H. and were taken in a sealed poly bag from conditioning room to the lab where the tests were performed. Each specimen was clamped onto the cylinder within 60 seconds of its removal from the sealed bag. Steam was discharged on the test specimen for 10 seconds. Sensors connected to data loggers measured temperature as a function of time for 90 seconds, including the exposure time. The relative humidity of the environment during the test was recorded, as was the steam temperature at the nozzle outlet. Air was applied to cool the sensors after every test. Figure 1 (b) shows the test device in operation.

3.3. CALCULATION OF DEPENDENT VARIABLES

The highest temperature (peak) reached was obtained from each temperature/time plot. The temperature data obtained from skin simulant sensors were inversely transformed to obtain the heat flux. Heat flux was calculated over 90 seconds, and the highest value was obtained from each curve. Time to reach peak heat flux was obtained from each heat flux versus time curve. Total energy is the integrated value of the area under the heat flux/time curve over 90 seconds.

3.4. STATISTICAL ANALYSES

Descriptive statistics (means and standard deviations) were calculated for all four dependent variables (peak temperature, peak heat flux, time to reach peak heat flux and total energy) for each fabric at two distances and two pressures. Three way analyses of variance (ANOVA) were conducted to determine significant differences in each dependent variable for each of the independent variables as well as their interaction effects. Each replication was analysed separately and aggregate data from the two replications was also analysed. Main effects for each independent variable and two-way and three-way interaction effects were determined. To identify differences among fabrics, Duncan’s post hoc test was conducted.

4. RESULTS AND DISCUSSION

4.1. TEMPERATURE VS. TIME PLOTS

For the severest condition at 207 kPa and 50mm between nozzle and fabric surface (Figure 2), temperature rise is very sharp in Fabric A. Several other sensors close to the main sensor are also affected for Fabric A but much less so for Fabrics B and C. For Fabric B, the peak temperature reaches almost 75°C by 10 seconds but falls sharply when the heat source is removed at 10 seconds. For Fabric C, the temperature rises very rapidly and reaches a peak above 80°C after the heat source is removed.
4.2. ANALYSES OF VARIANCE: EFFECTS OF FABRIC, PRESSURE AND DISTANCE

Because the results for the two replications were similar, only the aggregated data will be discussed. Most three-way interaction effects (fabric x distance x pressure) were not significant. On the other hand, many two way interaction effects for fabric-by-distance were significant ($p<.001$), suggesting that the differences in heat transfer among fabrics depended on the conditions of the test. However, most of the fabric-by-pressure interactions were not significant, suggesting that pressure has less influence on differences among fabrics. Significant distance-by-pressure interaction effects for peak temperature and total energy suggest that, for these dependent variables, the effect of one parameter may be dependent on the other.

The main effects for both pressure and distance were significant for all dependent variables except for time to reach peak heat flux. The main effect for fabric was highly significant ($p < 0.001$) for all four dependent variables suggesting that the test device was able to differentiate well among the three fabrics. Higher values were reported at 50mm than at 100mm for peak temperature, peak heat flux and total energy, with no significant difference for time to reach peak heat flux. Similarly, higher values for peak temperature, peak heat flux, and total energy were observed at high pressure than at a low pressure.

Results of Duncan’s post-hoc tests of differences among fabrics (Table 1) confirm significant differences for all four dependent variables. These analyses are based on data for both replications. All three fabrics differ significantly from each other for peak temperature, peak heat flux and total energy, but there is no significant difference between Fabrics B and C for time to reach peak heat flux. The differentiation among different test conditions referred to earlier can also be seen in Table 1.
Fabric | Peak Temperature (in °C) | Peak Heat Flux (in kW/m²) | Total Energy Transferred (in Joules) |
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A, B, C For each condition (column), fabric means with different superscripts differ significantly from each other.

Table 1. Heat Transfer through fabrics

4.3. EFFECT OF FABRIC PERFORMANCE PROPERTIES ON STEAM RELATED HEAT TRANSFER

Of the three fabrics tested, fabric A has the highest air permeability and very low resistance to water vapour diffusion, making it vulnerable to permeation of steam at high temperature and pressure. Steam easily penetrated through the fabric and instantaneously increased the temperature of the fabric and of the skin simulant sensors behind the fabric. This phenomenon was observed on the surface of the cylinder which was completely wetted during steam exposure and could be examined when the specimen was removed from the cylinder surface. Fabric B with very low air permeability and moderate Dm offered better resistance to heat transfer than Fabric A. Although the water vapour resistance for Fabric C is highest (Dm = >150), it is thinner and more dense than Fabric B, likely contributing to a higher rate of heat transfer, mainly by conduction.

5. CONCLUSION, IMPLICATIONS AND RECOMMENDATION

The test device was able to differentiate among fabrics in terms of heat transfer when exposed to steam pressures up to 207 kPa. Under all four conditions fabrics differed significantly for peak temperature, peak heat flux and total energy. For each fabric, both distance and pressure had significant effects on peak temperature, peak heat flux and total energy, with the greatest heat transfer being at 50 mm and 207 kPa. Although no concrete conclusion could be made about the relationships between fabric parameters and heat transfer, we understand from previous research that factors such as thickness, fabric structure, finish, water vapour permeability, air permeability, thermal insulation and
total heat loss definitely influence the heat and vapour transmission. In this research fabric properties such as resistance to water vapour diffusion (Dm), air permeability, thermal insulation (Rct) and total heat loss seemed to interact with fabric characteristics such as thickness and presence of a coating/laminate in determining steam penetration and heat transfer.

The results presented here are significant for the industries where steam is utilized in several different applications and where steam pressures in the pipelines are high. It is evident that both distance and pressure influence heat transfer. The experiments were conducted at much lower pressures compared to industrial settings where the typical steam pressure existing in lines for the day to day operations can be up to 620 kPa. In the current research it was observed that the temperature in all three fabrics rose above 50°C under most conditions, implying second degree burn to the skin tissue (7), and could be much worse if the exposure time is higher.

This research has stimulated a need to develop specifications for clothing systems to prevent partial or full-thickness burns from heat transfer onto the skin during or after steam exposure. One limitation of this research was that achieving reliable steam pressures above 207 kPa during the tests was not possible. Therefore, further work at higher pressure is needed to assess the hazard in more detail and to verify the validity of testing at somewhat lower pressures.

Generally in textile testing or other material testing facilities it is rare to find steam pressures as high as 620 kPa as found in industry. It is therefore recommended that theoretical models that could predict heat transfer through different fabrics in the event of steam exposure be developed. This research has outlined three important variables (fabric, pressure and distance) that significantly influence the heat transfer. Besides pressure and distance, we know that fabric characteristics and performance properties should influence heat transfer. Hence more work is needed to develop a numerical model incorporating the testing parameters (pressure, distance and temperature of steam) and fabric characteristics and performance properties. Several different types of fabrics should be tested on the test device developed in this study to more accurately determine the combined influence of such fabric parameters on steam related heat transfer before such a model can be developed.

6. REFERENCES

ALTERNATIVE METHODS OF DETERMINATION OF WATER VAPOUR RESISTANCE OF FABRICS BY MEANS OF A SKIN MODEL

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ABSTRACT

In the paper the widely used method of testing of thermophysiological comfort of textile fabrics according to the ISO 11092 is briefly described and some theoretical reasons of reduced measurement precision of this method are discussed. One of the possible sources of the lower measurement precision is the difference in the character of boundary layer of free instrument surface and the surface of tested fabrics, as water vapor and thermal resistance values of these boundary layers are considered equal in calculation of water vapor and thermal resistance of the tested fabric.

In the second part of paper, first alternative method of determination of thermophysiological comfort of textile fabrics is presented. This method is based on measurement of resistance values for one and two layers of fabrics. The difference between these values then should correspond to the resistance value of single layer.

Preliminary experiments revealed, that for fabrics with smooth surfaces the water vapor resistance levels determined by the classical and the first alternative methods are practically identical.

In the final part of the paper, the principle of evaluation of water vapor permeability of fabrics by means of the so called relative water vapor permeability is briefly described.

Key words: physiological comfort, textile fabrics, water vapor permeability, ISO 11092, measurement precision, alternative measurement method

1. INTRODUCTION

The most important standard for testing of thermo-physiological comfort of fabrics presents the ISO 11092. This very complex standard became the basic one for the manufacturers of special performance fabrics or garments with high added value. That is why increased attention is paid to the application of this standard in recent decades, especially when quality of generally expensive protective clothing is evaluated.

As this standard is available to anybody, just brief description of the method and related measuring instrument will be mentioned.
The instrument called “Skin Model” consists of heated metallic plate surrounded on most of its surface by a thermal insulation layer adhering to metallic heated ring (envelope) kept at the same temperature by means of the temperature controlling system. Due to this isothermal arrangement, no heat is transferred out of this plate, except the heat passing through the only free surface. Free surface of this measuring plate covered by the porous layer is exposed to parallel air flow of 1 m/s velocity moving in the special wind channel.

When measuring the fabric thermal resistance \( R_{ct} \), the air temperature in the channel is kept at 20 °C, and the measuring plate is dry. First, the power \( H \) supplied to the hotplate in order to heat the measuring system to temperature 35 °C is measured. Then, the tested fabric (specimen) is placed on the porous layer of the measuring plate and the electric power representing the heat passing through the system to the outer air is measured again.

When evaluating the water vapour resistance \( R_{et} \), both the measuring plate and the air temperature are kept at 35°C (to achieve the isothermal conditions) and the porous layer is continuously filled with water. Then, again the heating power \( H \) without a specimen is first measured and saved. In the second step, the specimen is inserted between the measuring plate and the wind channel and the steady-state and the heating power \( H \) is recorded again. All the power values then serve for the calculation of thermal resistance and water vapour resistance values according to the simple formulas presented in the ISO 11092.

2. SIMPLIFIED ANALYSIS OF PRECISION OF THE FABRIC RESISTANCE MEASUREMENT BY MEANS OF A SKIN MODEL

During the measurement of thermal resistance, the heat is transferred from the hotplate and fabric surface into the environment by convection and radiation, as this way of measurement requires to apply certain temperature gradient. The portion of heat transferred by radiation depends on surface emission coefficients of the tested fabric, surface emission coefficient of the porous surface of the hotplate and surface emission coefficients of the surrounding walls. Nevertheless, the ISO 11092 Standard does not contain any indication about the required surface emission coefficient of the surrounding walls. Thus, the amount of heat transferred by radiation in two Skin Model instruments with different surface emissivity levels of the interior walls can differ.

Transfer of moisture from the wet porous plate through the dry tested fabric to the parallel air flow in the instrument air channel is executed by convection. From the declared isothermal conditions at the water vapour resistance measurement should follow, that no heat is simultaneously transferred. However, in the praxis, the hotplate surface cooling may cause some negative temperature gradient \( \Delta t \) against the hotplate bottom temperature which even the very precise temperature controlling system cannot compensate, unless some special temperature sensors inside the hotplate in very special positions are used. This fact is due to certain level of the hotplate thermal resistance \( R \). Let us suppose that the bottom surface of the hotplate is kept at the same temperature \( t_b \) as the surrounding air \( t_a \). The effective heat flow \( q_{\text{evap}\,(\text{eff})} \) passing through the porous plate generates the mentioned negative temperature gradient \( \Delta t \) as follows:

\[
\Delta t = q_{\text{evap}\,(\text{eff})} R
\]  

When measuring thin fabrics, this temperature gradient should appear at the fabrics outer surface, thus
causing the fabric heating by convection, characterized by the heat transfer coefficient \( \alpha \). Heat flow by convection

\[
q_{\text{conv}} = \alpha \Delta t
\]  

then heats the tested fabric, and in this way reduces the measurement precision:

\[
q_{\text{evap (eff)}} = q_{\text{evap (theor)}} - q_{\text{conv}} = q_{\text{evap (theor)}} - \alpha R q_{\text{evap (eff)}}
\]  

After algebraic treatment of the Eqs.1-3 we have

\[
q_{\text{evap (eff)}} / q_{\text{evap (theor)}} = 1 - [\alpha R / (1 - \alpha R)]
\]  

In order to get the first left term close to 1, the measuring system thermal resistance must be as low as possible.

3. ADVANTAGES OF THE SKIN MODEL MEASUREMENT ACCORDING TO THE ISO 11092

The same measuring instrument is used for the determination of both thermal and water vapour resistance of thin and relatively thick textile specimens as well.

Parameters characterising the outdoor conditions (air temperature, velocity and humidity) can be controlled with high precision.

The large system enables assembling of additional measuring devices (to simulate rain, ventilation effects etc).

The method is largely used in Europe and becomes used in the rest of world as well, because it reflects the needs of industry and market.

4. PRINCIPAL DISADVANTAGE OF THE ISO 11092 TESTING METHOD

The proper principle of this method for determination of both thermal and water vapour resistance levels is based on subtracting the boundary layer resistance (corresponding to smooth free measuring plate) from the total resistance consisting of fabric resistance and fabric boundary layer resistance, where the fabric boundary layer resistance can differ from the boundary layer resistance of the instrument measuring plate. This difference can result from different air friction against the fabric surfaces with different surface profiles (sweaters, blankets), which affects the degree of turbulence and hence the thickness of the boundary layer. As the boundary layer thickness divided by diffusion coefficient (or by air thermal conductivity) presents approximately its water vapour resistance (or thermal resistance), the calculated levels values of both these principal comfort parameters can differ from the real ones.

Thus, these uncertainties in the determination of water vapour resistance and thermal resistance of boundary layers adhered to the free measuring surface and to surface of the tested fabrics may theoretically cause certain measurement imperfection. In next research we have investigated, whether
these imperfections are substantial or not. From the large practical use of the ISO 11092 follows, that in most cases the possible reduction of the measurement precision does not prevent the successful application of the ISO 11092 in many textile areas.

5. PROPOSAL OF ALTERNATIVE METHOD OF EVALUATION OF THE WATER VAPOUR PERMEABILITY OF FABRICS

In the first step of application of this method, total water vapour resistance and total thermal resistance values, simply indicated as the $R_{tot}(1)$ corresponding to the sum of fabric $R_f$ and boundary layer resistances $R_{bl}$ are determined according to the ISO 11092 procedure. In the second step, the procedure is repeated, but this time 2 fabric layers are attached on the Skin Model measuring porous surface. This time, the measured total resistance values $R_{tot}(2)$ include double values of fabric resistance $R_f$ and single value of boundary value resistance $R_{bl}$. Then the following difference between results of both measurements

$$(2R_f + R_{bl}) - (R_f + R_{bl}) = R_f, \quad (5)$$

should present the fabric resistance values (both evaporative and thermal ones). This time, the boundary layer resistance $R_{bl}$ in Eq. 5 presents the real surface resistance of the tested fabric.

The proposed method was tested in our laboratory by means of the modernized PERMETEST instrument – see in [1]. This small Skin Model employs the air in the climatised laboratory with the temperature slowly varying in the range 21-23°C. In case of the water vapour resistance measurement, the measuring head temperature is kept at the mentioned air temperature with the precision 0,05°C, thus maintaining the isothermal conditions of measurement. Due to the slightly curved contact porous plate, it is possible to cover this measuring plate by several textile layers and achieve a good thermal contact between the layers. The instrument was calibrated by means a special 100% POP woven fabrics with $R_{et}$ value determined in the original Skin Model according to the ISO 11092.

This hydrophobic POP plain weave of square mass 220 g/m² and thickness 0,6 mm was also used in the next experiment. The air temperature was 22,5°C, air relative humidity 36% and the air velocity in the measuring channel 1, 5 m/s. The hydrophobic POP fabric was used here in order to avoid the effect of varying air relative humidity of the fabric swelling, which might influence the fabric porosity. During the experiment, the $R_{et}$ (or $R_f$) values of single and multiple layers of these fabrics were determined, first according to the ISO 11092, then by means of the alternative principle with the help of Eq. 5.
The results shown on the Fig. 1 indicate first, that the contact resistances between the fabric layers do not reduce the measurement precision substantially – if the resistance values are linked with the line, in both cases the lines pass through the initial point \( x = 0, y = 0 \). More important result is, that for smooth fabrics, the differences between the classical and new method are almost negligible[2].

6. PROPOSAL OF AN ALTERNATIVE METHOD OF EVALUATION OF THE WATER VAPOUR PERMEABILITY OF FABRICS

For practical purposes, the determination of the so called relative water vapour permeability \( p_{rv} \) has been proposed. Any skin model can be used for this purpose [1],[3]. The measurement is carried out under the isothermal conditions and the proper procedure also starts with the measurement of the heat flow level or heating power \( H_{rv0} \) without the sample. In the next step the level of heat flow or heating power \( H_{rv} \) is determined, but contrary to the ISO 11092 (requiring the deduction of both values), the ratio of both parameters is calculated, as follows from the next relationship

\[
p_{rv} \% = 100 \left( \frac{H_{rv}}{H_{rv0}} \right)
\] (6)

The advantage of this method is its easy applicability in textile praxis. Thus, 100% here represents the free surface, and 0% means the full non-permeability for water vapour. Moreover, this method
enables to compare the measurements on fabrics carried out in non – climatised testing rooms, as the ratio of driving forces (difference of partial water vapour pressure) keeps the same.

6.1. SOME PRACTICAL LEVELS OF THE RELATIVE WATER VAPOUR PERMEABILITY

Winter jackets 5-20%, Denim fabrics 15-25%, Goretext laminates 25-40%, Man’s shirts 45-55%. Unfortunately, when determining the water vapour permeability of multilayer textile systems, the individual values of the relative water vapour permeability cannot be summarized.

7. CONCLUSIONS

In the paper the principle of testing of thermophysiological comfort of textile fabrics according to the ISO 11092 was briefly described and some theoretical reasons of reduced measurement precision of this method were discussed. Besides that, an alternative method of determination of thermophysiological comfort of textile fabrics was presented, based on measurement of resistance values for one and two layers of fabrics. The difference between these values then should correspond to the resistance value of single fabric layer.

First experiments revealed, that for fabrics with smooth surfaces the water vapor resistance levels determined by the classical and the alternative methods are practically identical. It can be concluded, that the measurement precision in this particular case was high. Experiments involving the fabrics with rough surface or surface texture will follow.

In the last paragraph, the principle of evaluation of water vapor permeability of fabrics by means of the so called relative water vapor permeability was briefly described.

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NIGHTTIME VISIBILITY ASSESSMENT OF GARMENT DESIGNS

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ABSTRACT

More and more companies, not obliged to follow the EN 471 see the need of high visibility protection for their employees, especially at nighttime. Depending on the outcome of the risk assessment high visibility features are integrated into the corporate garment design in a fashionable way to still keep the corporate identity. To allow improved conspicuity of the wearer in all work situations the equal distribution of the visibility features is of major importance. This paper is about a method to reliably evaluate the visibility of garment designs. The method has been developed to assess the luminance distribution and, accordingly draw conclusions regarding the visibility.
THE EFFECT OF THE GLOVE MATERIAL STRETCH DEFORMATION ON CUT RESISTANCE

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ABSTRACT

More than 25% of the workplace accidents are hand injuries and an important part of them are cuts caused by metal pieces and tools. To characterize the glove resistance to cuts, standard test methods ISO 13997 or ASTM F1790-05 are used. In previous studies a complete analysis of the cutting phenomenon in protective material based on standard cut test methods was performed. It was established that cutting of rubber glove materials is strongly controlled by the friction distribution. The total energy required to cut through a rubber material is the result of the contribution of two components; a lost energy dissipated by the lateral force exerted by the sample material on the blade sides and a cutting energy at the tip edge of the blade. These energies have opposite effects on the measured cut resistance; the lateral force contributes to increase the material cut resistance while the one at the tip of the blade correspond to the necessary energy to cut through the material. When wearing protective gloves, the rubber materials can be stretched at various levels. The immediate retraction of a stretched rubber material when the material cutting is initiated reduces the lateral friction and consequently affects the measured value of cut resistance. The objective of this work was to investigate the effect the stretch deformation on the cut resistance of rubber gloves materials.

The results in this study demonstrated that the cut resistance of a stretched rubber glove material, as determined by the standard tests methods, is reduced as much as five to ten times of the value measured in an un-stretched material. When the stretched samples deformation is enough to eliminate the lateral friction during cutting, the cutting horizontal force and the energy in these tests are both related to the cutting process at the blade tip. The cutting energy measured under this condition does not depend on the nature and the geometry of the blade. The cutting energy determined in stretched rubber samples is in agreement with the cutting energy measured in the absence of friction, under a pure Mode I cutting experiment. This study demonstrated that the stretch deformation of rubber glove materials decrease its cut resistance and should be considered in the standards intended to characterize the performance of glove materials to mechanical risks.
EVALUATION OF THE FLEXIBILITY OF PROTECTIVE GLOVES

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ABSTRACT

Two methods are under development for the characterization of the flexibility of protective gloves, a key factor affecting their degree of usefulness for workers. The first method is directly adapted from the ASTM D 4032 standard relative to fabric stiffness and simulates the deformations encountered for gloves that are not tight fitted to the hand. The second method characterizes the flexibility of gloves that are worn tight fitted. Its validity was theoretically verified for elastomer materials. Both methods should prove themselves as valuable tools for protective glove manufacturers, allowing for the characterization of their existing products in terms of flexibility and the development of new ones better fitting workers’ needs.

1. INTRODUCTION

Hand injuries represent a major source of accidents, in particular at the workplace. In Québec, they account for 17% of all occupational lesions compensated for by the provincial occupational health and safety organization (Commission de la Santé et de la Sécurité du Travail du Québec) between 2001 and 2004¹. Wearing protective gloves can reduce the occurrence of such injuries, but with a price in terms of loss of dexterity and sensitivity, and additional muscular constraints among others². This can lead to either the worker not being able to perform adequately his tasks, or deciding not to wear protective gloves. In both cases, the risk of injury is increased.

Flexibility is one of the major properties that define how a glove interferes with the worker ability to perform his tasks. Several methods³, ⁴, ⁵ have been developed for characterizing film and fabric stiffness or flexibility (its inverse). Most of them are based on uniaxial bending, which may not be representative of the type of solicitations subjected to gloves in usage. On the other side, the ASTM D 4032 standard⁴ makes use of a circular bend procedure for measuring the stiffness of a fabric, thus measuring multi-directional deformations. A flat-headed cylindrical probe forces a folded piece of fabric through a circular orifice in a platform. The maximum force required to push the fabric through the orifice is measured and used as an indication of the fabric stiffness.
In order to characterize the flexibility of gloves, this method has been adapted, in particular by enlarging the gap between the probe head and the orifice edge, and by using a more relevant shape for the probe. This free-deforming method measures mostly out-of-plane material deformations and can be seen as describing the behavior of gloves that are not tight fitted to the hand.

For simulating the behavior of gloves that are worn tightly fitted, a fixed technique is proposed, which uses the same type of probe geometry as for the free-deforming method, but with securing the glove material along the circumference of the orifice. In that case, deformations are mostly in the plane of the tested material. The measurements performed on elastomer gloves were compared to a theoretical description based on the Mooney formalism\(^6\) using uniaxial tensile tests.

2. EXPERIMENTAL

2.1. THE FREE-DEFORMING TECHNIQUE

As for the ASTM D 4032 standard, this technique is based on the use of a probe to push a film sample through an orifice drilled in a platform. However, in order to measure protective gloves, a few modifications had to be brought. First, to account for glove larger thickness compared to fabrics, the value of the gap between the probe head and the orifice edge was almost doubled. Second, in order to limit the stress concentration at the probe head and to better simulate the type of solicitations applied to gloves while in use, a cylindrical probe with a spherical-conical shaped head was selected, producing double curvature deformations\(^7\). Third, to account for the influence of glove fingers, the diameter of the probe was maintained at a constant value up to the top, as illustrated in Fig. 1, which displays the experimental set-up inserted into an 1137 Instron tensile testing frame with a glove positioned palm up above the orifice.

![Figure 1: Experimental set-up of the free-deforming technique.](image)

An example of the force displacement curve recorded by the testing frame as a glove is pushed by the probe through the orifice is shown in Fig. 2. Principal and secondary maxima correspond to the passage of glove fingers through the orifice. In terms of data analysis, the value of the maximum force was determined, in accordance to the ASTM D 4032 standard. In addition, following some authors studying fabric comfort\(^8\), the total work of the force necessary to push the entire glove through the orifice was calculated, this work being proportional to the deformation energy, itself inversely proportional to flexibility.

![Figure 2: Example of force displacement curve measured as a glove is pushed through the orifice.](image)
2.2. THE FIXED TECHNIQUE

In order to obtain a realistic determination of the flexibility of tight fitting gloves, the above set-up was modified so that a layer of the glove material was secured along the circumference of the orifice as illustrated in Fig. 3. The same geometry of the probe was used and the deformation of the membrane was recorded as a function of the force applied by the probe.

Figure 3: Set-up of the fixed technique.

Figure 4: Example of a force deformation curve measured with the fixed technique.

Figure 4 displays an example of a force displacement curve measured for a natural rubber glove. In that configuration, the material stiffness can be characterized as the slope of the force displacement curve, the flexibility being its inverse.

2.3. MATERIALS AND METHODOLOGY

Ten models of protective gloves from two manufacturers (Best and Ansell) were measured using the free-deforming technique. Some are made of pure elastomer, one of a knit fabric, and some feature a knit liner dipped in a polymer. For each model, five measurements were performed on different gloves to ensure that the measurement uncertainty includes property variability between gloves of the same model.

Five models of gloves were characterized with the fixed technique, three of them elastomers, along with two thicknesses of a neoprene membrane. As for the free-deforming test, each result is the average of five measurements.

3. THEORETICAL DESCRIPTION OF THE FIXED TECHNIQUE

In order to validate the developed fixed technique, a theoretical description is presented below corresponding to the deformation of elastomer materials.
As shown in Fig.5, the surface of the deformed membrane can be divided into three zones: a lower one (zone A) in contact with the spherical part of the probe head, a middle one (zone B) in contact with the conical part of the probe head and a top one (zone C) not in contact with the probe. The force applied by the probe is the sum of two contributions: $F_A$ relative to zone A and $F_B$ relative to zone B.

For the description of the elastomer mechanical properties, the Mooney formalism, valid for elastic, isotropic and incompressible materials, has been used in its two-constant version by the way of the Mooney strain energy function $W$:

$$W(\lambda_1, \lambda_2) = C_1 (\lambda_1^2 + \lambda_2^2 + \lambda_1^{-2} \lambda_2^{-2} - 3) + C_2 (\lambda_1^{-2} + \lambda_2^{-2} + \lambda_1^2 \lambda_2^2 - 3)$$

(Eq. 1)

Where $\lambda_1$ and $\lambda_2$ are respectively the radial and circumferential extension ratios in the $(\rho, \xi)$ cylindrical coordinate system (see Fig. 5). The Mooney-Rivlin constants, $C_1$ and $C_2$, can be obtained by uniaxial tensile tests performed according to the ASTM D 412 standard. The resulting stresses $T_1$ and $T_2$ per unit edge length respectively along the radial and the circumferential directions become:

$$T_1 = 2h\left(\frac{\lambda_1}{\lambda_2} - \lambda_1^{-3} \lambda_2^{-3}\right)\left(C_1 + \lambda_2^2 C_2\right)$$

$$T_2 = 2h\left(\frac{\lambda_2}{\lambda_1} - \lambda_1^{-3} \lambda_2^{-3}\right)\left(C_1 + \lambda_1^2 C_2\right)$$

(Eq. 2)

With $h$ the thickness of the membrane.

In zone A, at the tip of the probe, the membrane is in an equibiaxial stress state, leading to $\lambda_1=\lambda_2=\lambda_0$. The force applied by the probe on the membrane inside zone A can be expressed as:

$$F_A = 6RC_1 h \left(1 - \lambda_0^{-2}\right)\left(1 + \alpha \lambda_0^2\right)$$

(Eq. 3)

With $R$ the radius of curvature of the spherical part of the probe head and $\alpha = C_2 / C_1$.

In zone B corresponding to the conical part of the probe head, the force can be expressed as:

$$F_B = 2\pi(R_2 - R_1) \cos \theta \ C_1 h \left(\frac{\lambda_1}{\lambda_2} + \frac{\lambda_2}{\lambda_1} - \frac{2}{\lambda_1^3 \lambda_2^3}\right) + \alpha \left(2\lambda_1 \lambda_2 - \frac{1}{\lambda_1^3} - \frac{1}{\lambda_2^3}\right)$$

(Eq. 4)

Where $\theta$, $R_1$ and $R_2$ are respectively the angle and the two radii of the conical part of the probe head and $\bar{\lambda}_1$ and $\bar{\lambda}_2$ are the average values of $\lambda_1$ and $\lambda_2$ over the zone B section of the membrane.

4. RESULTS AND DISCUSSION

Table 1 displays the results of the maximum force and total work values measured with the free-deforming method for ten models of protective gloves. Both parameters lead to the same ranking of
the gloves on a decreasing flexibility scale (rank 1 corresponds to the most flexible glove). Also provided in Table 1 is each glove composition and total thickness measured at the palm.

The low variability of the results as well as the fact that both the maximum force and the total work lead to the same ranking of the glove flexibility show this free-deforming technique as a valuable tool for the determination of the flexibility of loosely fitting protective gloves. However, these flexibility measurements may include a slight parasitic contribution of the glove surface properties due to friction developing between the glove and the orifice edge surface.

The theoretical validation of the fixed technique for the determination of tight fitting glove flexibility was performed by comparing the measured and calculated values of the force corresponding to the position where the contact zone between the membrane and the probe head reaches the top of the probe head conical part (corresponding to the schematic in Fig. 5). Table 2 provides the results for a nitrile rubber and two natural rubber gloves as well as for a neoprene membrane, the thickness value corresponding to the measured layer of material.

<table>
<thead>
<tr>
<th>Model</th>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Maximum force (N)</th>
<th>Total work (N.cm)</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ansell Canners &amp; Handlers # 392</td>
<td>Natural rubber (NR)</td>
<td>1.1</td>
<td>3.8 ± 0.3</td>
<td>0.51 ± 0.04</td>
<td>1</td>
</tr>
<tr>
<td>Ansell Goldknit Kevlar 70-225</td>
<td>Kevlar knit</td>
<td>4.5</td>
<td>22.5 ± 2.6</td>
<td>7.2 ± 0.7</td>
<td>2</td>
</tr>
<tr>
<td>Ansell Hyflex 11-900</td>
<td>Nitrile rubber on cotton knit</td>
<td>2.0</td>
<td>22.6 ± 0.9</td>
<td>7.7 ± 1.0</td>
<td>3</td>
</tr>
<tr>
<td>Best Nitri-Solve® 747</td>
<td>Nitrile rubber</td>
<td>1.2</td>
<td>51.6 ± 2.0</td>
<td>22.0 ± 1.8</td>
<td>4</td>
</tr>
<tr>
<td>Best Latex HD® 55</td>
<td>Natural rubber</td>
<td>2.1</td>
<td>130 ± 17</td>
<td>51 ± 11</td>
<td>5</td>
</tr>
<tr>
<td>Best KPG® 960</td>
<td>PVC on cotton knit</td>
<td>3.7</td>
<td>222 ± 18</td>
<td>93 ± 3</td>
<td>6</td>
</tr>
<tr>
<td>Best Skinny Dip Aramid® 4811</td>
<td>NR on Kevlar aramid knit</td>
<td>4.3</td>
<td>235 ± 32</td>
<td>98 ± 19</td>
<td>7</td>
</tr>
<tr>
<td>Best The Original Nitri-Flex® 4000P</td>
<td>Nitrile rubber on cotton knit</td>
<td>1.7</td>
<td>250 ± 22</td>
<td>99 ± 12</td>
<td>8</td>
</tr>
<tr>
<td>Ansell PowerFlex 80-100</td>
<td>NR on poly/cotton knit</td>
<td>3.6</td>
<td>267 ± 21</td>
<td>110 ± 7</td>
<td>9</td>
</tr>
<tr>
<td>Best Nitri-Pro® 7000P</td>
<td>Nitrile rubber on cotton knit</td>
<td>1.7</td>
<td>433 ± 65</td>
<td>138 ± 52</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1. Results of the free-deforming technique measurement for ten models of protective gloves.

<table>
<thead>
<tr>
<th>Material / Model</th>
<th>Thickness (mm)</th>
<th>Measured force (N)</th>
<th>Calculated force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural rubber (Ansell Canners &amp; Handlers 392)</td>
<td>0.5</td>
<td>162 ± 19</td>
<td>153</td>
</tr>
<tr>
<td>Neoprene membrane</td>
<td>0.4</td>
<td>239 ± 33</td>
<td>218</td>
</tr>
<tr>
<td>Natural rubber (Best Latex HD® 55)</td>
<td>1.0</td>
<td>324 ± 49</td>
<td>299</td>
</tr>
<tr>
<td>Nitrile rubber (Best Nitri-Solve® 747)</td>
<td>0.8</td>
<td>495 ± 60</td>
<td>449</td>
</tr>
</tbody>
</table>

Table 2. Comparison of the measured and calculated force for the validation of the fixed technique.

The force values correspond within the error bars. Indeed, for elastomers, and by extension, isotropic materials, material flexibility is independent of the type of deformation. For such materials, flexibility can be characterized by a simple uniaxial tensile test. However, for gloves made of anisotropic materials, a multi-directional deformation measurement such as the fixed technique is required.

The results in terms of the calculated flexibility coefficient (the inverse of the slope of the force displacement curve) are displayed in Table 3 for five models of gloves as well as for two thicknesses
of a neoprene membrane. Due to limitations in the load cell capacity of the testing frame used for these measurements, the total extent of the linear part of the force displacement curve was not obtained for the composite gloves, leading to a slightly higher measurement uncertainty.

<table>
<thead>
<tr>
<th>Model</th>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Flexibility coefficient (mm/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ansell Canners &amp; Handlers 392</td>
<td>Natural rubber</td>
<td>0.5</td>
<td>0.118 ± 0.010</td>
</tr>
<tr>
<td>Membrane</td>
<td>Neoprene</td>
<td>0.4</td>
<td>0.080 ± 0.009</td>
</tr>
<tr>
<td>Best Latex HD® 55</td>
<td>Natural rubber</td>
<td>1.0</td>
<td>0.062 ± 0.007</td>
</tr>
<tr>
<td>Best Nitri-Solve® 747</td>
<td>Nitrile rubber</td>
<td>0.8</td>
<td>0.036 ± 0.003</td>
</tr>
<tr>
<td>Membrane</td>
<td>Neoprene</td>
<td>1.57</td>
<td>0.023 ± 0.002</td>
</tr>
<tr>
<td>Ansell Goldknit Kevlar 70-225</td>
<td>Kevlar knit</td>
<td>2.13</td>
<td>0.014 ± 0.002</td>
</tr>
<tr>
<td>Ansell Hyflex 11-900</td>
<td>Nitrile rubber on cotton knit</td>
<td>1.1</td>
<td>0.0043 ± 0.0006</td>
</tr>
</tbody>
</table>

Table 3. Values of the flexibility coefficient measured with the fixed technique.

For natural rubber and neoprene, for which two thicknesses are available, the flexibility coefficient is inversely proportional to the material thickness, which is consistent with equations 3 and 4. With this fixed method, non-elastomer based gloves do show a much smaller flexibility compared to elastomer ones, producing a different glove ranking than that obtained with the free-deforming technique. To circumvent the reduced flexibility of composite materials while taking advantage of their increased protective properties, composite gloves are either worn oversized compared to hand dimensions or are uncoated on the back to allow more movement freedom for the user.

5. CONCLUSIONS

Two methods adapted from the ASTM D 4032 standard have been developed for the characterization of the flexibility of protective gloves. The free-deforming technique simulates the behavior of gloves that are worn loosely fitted while the fixed technique characterizes the flexibility of tight fitting gloves. The validity of the fixed method was theoretically validated for elastomer materials. Both techniques produced rankings for the tested gloves in terms of their flexibility, either in the loose fitting configuration or mimicking the tight fitting behavior. These rankings will be compared with a perception test currently underway.

Acknowledgements

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NEW DEVELOPMENTS IN CUT RESISTANCE – AN UPDATE ON STANDARDS AND PRODUCTS

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Teijin Twaron GmbH
GERMANY

ABSTRACT

Today different standards for the determination of the cut resistance of protective gloves are in use: ASTM F 1790-04, ISO 13997 and DIN EN 388. These standards are continuously further developed to reduce test variability and to harmonize international standardization. In the scope of this presentation an update on the latest developments in standardization will be given.

Comparative evaluations on these standards were done on basis of the Twaron PREMIUM LINE. The recently launched Twaron PREMIUM LINE is designed to meet highest demands on performance and wearing comfort.

In the first part this presentation we will give an update on the current standards for the determination of the cut protective performance. The different methods will be demonstrated by comparing a standard Twaron glove to a glove made of Twaron Premium Line. The second part will introduce the latest developments of the Twaron Premium Line.

<table>
<thead>
<tr>
<th></th>
<th>Standard Twaron</th>
<th>Premium Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Yarn</td>
<td>4 x Nm 28/2</td>
<td>2 x Nm 5,7</td>
</tr>
<tr>
<td>Glove weight (g)</td>
<td>34</td>
<td>43</td>
</tr>
<tr>
<td>g/m²</td>
<td>545</td>
<td>651</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>2,10</td>
<td>1,93</td>
</tr>
</tbody>
</table>

Tab. 1. Description of test samples

1. UPDATE ON STANDARDS ON CUT RESISTANCE TESTING

Currently three different test methods are used for the determination of the cut resistance of a glove which are DIN EN 388, ISO 13997 and ASTM F 1790-04. In the following a short description of the test methods will be included as an update.
1.1. DIN EN 388

The cut tester described in the standard is the so-called Coupe Tester. The Coupe tester is using a round blade having a diameter of 45 mm. The blade is loaded with a constant force of 5 N and moved back and forth with a constant speed in one slot of the sample holder. Upon cutting through of the specimen an electric contact occurs and the blade stops. Based on the cycles needed to cut the material and the calibration cut on cotton, a cut index is obtained. Based on the lowest obtained cut index for a test series, the cut resistance is classified:

<table>
<thead>
<tr>
<th>Level</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut index</td>
<td>≤ 1,2</td>
<td>1,2 - 2,5</td>
<td>2,5 - 5</td>
<td>5 – 10</td>
<td>10 – 20</td>
<td>≥ 20</td>
</tr>
</tbody>
</table>

Tab 2. Classification according to DIN EN 388

In the 2003 version of the DIN EN 388, for cut levels 4 and 5 the ISO 13997 is recommended.

A comparative evaluation was done on a glove based on a standard Twaron glove and Twaron Premium Line Cut glove (Fig. 2). Twaron Premium Line Cut is a hybrid yarn containing metallic filament.

Fig. 2: Cut resistance of Twaron Premium line and a standard Twaron glove according to EN 388

While the standard Twaron glove is in line with protection level three, the glove made of Premium Line Cut is meeting the requirements of protection level five. What will be the result when testing according to a different test method?

In contrast to the Coupe test method the load versus distance concept was developed. This concept relates the applied force to the cutting through distance. Two test methods have been developed to using the concept. One method is described in ISO 13997 using the TDM tester and one method is described in ASTM F1790 using the CPP tester.
1.2. ISO 13997

This standard describes the test method using the TDM (Tomo Dynamo Meter) tester. The standard defines three classes of cut length. For each class cuts have to be done using a chosen weight. Based on the results the force is obtained needed to cut 20 mm.

In case the ISO test is done as part of the EN 388 the results are classified as follows:

- $\geq 13 \text{ N}$: cut protective level 4
- $\geq 23 \text{ N}$: cut protective level 5

![Cut resistance of Twaron Premium line and a standard Twaron glove according to DIN EN ISO 13997](image)

**Fig. 4:** Cut resistance of Twaron Premium line and a standard Twaron glove according to DIN EN ISO 13997

For the standard Twaron a force of 9.4 N is found. For the glove made of Twaron Premium Line a cut resistance of 67.7 N is found which is again a very good level five.

1.3. ASTM F1790-04

In the following the method using the CPP (Cut Protection Performance) tester is described. The standard defines three classes of cut length. For each class five cuts have to be done using a chosen weight. Based on the results the force is calculated needed to cut a specified distance (20 mm).

The American National Standard for Hand Protection Selection Criteria ANSI/ISEA 105-2000 is providing information on the selection and classification of hand protection. This standard classifies the results of testing according F1790-97 as follows:

<table>
<thead>
<tr>
<th>Level</th>
<th>Weight needed to cut through the material with 25 mm of blade travel (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$&lt; 200$</td>
</tr>
<tr>
<td>1</td>
<td>$\geq 200$</td>
</tr>
<tr>
<td>2</td>
<td>$\geq 500$</td>
</tr>
<tr>
<td>3</td>
<td>$\geq 1000$</td>
</tr>
<tr>
<td>4</td>
<td>$\geq 1500$</td>
</tr>
<tr>
<td>5</td>
<td>$\geq 3500$</td>
</tr>
</tbody>
</table>

**Tab. 5.** Classification of cut resistance according to ANSI/ISEA 105-2000
Currently the ANSI/ISEA standard is under revision to adjust it to the ASTM F 1790-04.

According to the ANSI/ISEA 105-2000 the standard Twaron glove is in line with protection level three and the Premium Line Cut glove is fulfilling the requirements of protection level 5.

2. TWARON PREMIUM LINE

Under the brand name “Premium Line” Twaron is launching different product addressing special requirements of the users:

2.2. PREMIUM LINE CUT

The Premium Line Cut has been developed to offer highest cut resistance in combination with wearing comfort. The Premium Line Cut was introduced to the market place on the Techtextil 2005 in Frankfurt.

2.3. PREMIUM LINE COMFORT

The Premium Line Comfort will be launched shortly. The Premium Line Comfort is designed to offer improved wearing comfort and higher dexterity compared to a standard 13 gg Twaron glove without significant losses in cut protection. The Premium Line Comfort is based on the Twaron Microfiber and an elastic yarn. Products based on Microfibers are known for their high wearing comfort.

2.4. PREMIUM LINE CUT COMFORT

The Premium Line Cut Comfort is combining the excellent cut protective performance of the Premium Line Cut (Fig. 8) and the high wearing comfort and dexterity of the Premium Line Comfort. This product will officially be launched on the Expoprotection in November this year.
The cut resistance of the Premium Line Cut Comfort is in line with protection level 5. Though its cut protective performance is lower compared to the Premium Line Cut, the cut protection of the Premium Line Cut Comfort is excellent.

3. CONCLUSIONS

In the last years a lot of work was done to develop the existing cut resistance standards. Due to the high complexity of the topic, still lot of work needs to be done to investigate the mechanism of cut resistance in more detail and to overcome the drawbacks of the current standards. When evaluating results generated according to one of these standards, it should be considered that they only provide comparative data on the performance.

The comparative ASTM study on different materials used in protective gloves showed that para-Aramid is offering the highest cut protective performance. To address needs for even higher protection, the Twaron Premium Line was developed.

The demonstrated results show a cut level 5 for both, Twaron Premium Line Cut and Twaron Premium Line Cut Comfort. This high cut protection is found in combination with high wearing comfort.

The Twaron Premium Line Comfort is designed to achieve a “gloveless” feeling. This glove offers high wearing comfort in association with high dexterity.

Premium Line Cut was already successfully introduced to the market place in 2005, Premium Line Comfort and Premium Line Cut Comfort will follow this year.

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SEAM CHARACTERISATION IN ANTISTATIC PROTECTION GARMENTS

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ABSTRACT

Prevention of electrical discharges occurring from garments are of concern for the risk of explosion in potentially explosive atmospheres. In applications where the garments shall be grounded, it is important to be able to characterise the conductivity of the seams. This shall be done when garments are developed, after manufacturing and at some time during their lives. When garments don’t need to be grounded (for they use core conducting conductive threads), it is also important to check that “contacts” at seams are of the same quality as those at grid crossings.

Our method uses two 2.5 kg electrodes with 60 mm (⌀) carbon conducting pads, placed diagonally across an A4-size sample put in a strictly controlled atmosphere. The sample includes a seam parallel to its small edge, combining together two A5 size fabric pieces. If necessary, the measurement can be done on a whole garment taking into account that more than one seam can be present along the conduction path.

In the measuring technique developed by Centexbel, increasing potential differences are applied across the sample to stress the material globally and locally under higher and higher electric fields. The results are presented as the “Resistive Signature” of the material. This signature is a coloured plot of the sample resistance in function of the applied voltage where the colouring scheme discloses the chronological progress of the measurement.

This “Resistive Signature” is useful for characterising seams, at least, for detecting how far from conductive they are. In case of less than perfect seams, the resistive signature starts at high resistance values for suddenly dropping to lower values at some threshold voltage. The voltage at which this phenomenon occurs is a good indication to the confectioner of how far from adequate the seam is.
1. INTRODUCTION

Prevention of electrical discharges occurring from garments are of concern both for the risk of explosion in potentially explosive atmospheres and for the risk of damaging electronic components during handling and mounting. In the former case, the project group 2 of CEN TC162 WG1 “Antistatic properties of protective clothing”, which emanates from CEN TC 162 “Protective clothing including hand and arm protection and life jackets”, is in charge of revising EN 1149 “Protective clothing - Electrostatic properties”. In the latter case, the project team 2 of IEC TC101 WG5 “Tests methods for garments” deals with the revision of standard IEC 61340-5-1 “Protection of electronic devices from electrostatic phenomena – general requirements”.

Both types of garments have seams that shall be evaluated during garment conception, after garment production as well as during the whole garment utilisation. Our method can be used for all these assessments.

2. METHOD DESCRIPTION

The basic idea of our method is to apply increasing potential differences to the sample to stress the material globally and locally under higher and higher electric fields. Electrodes are used at two extremities of the sample to impose a high voltage difference between two fabric regions, for example across the diagonal of a A4-size sample. This method gives a global characterisation of a piece of material; in this special case, a seam is purposely placed between the electrodes but the principle of the measurement is independent of the presence of a seam.

In our method, the potential difference is increased stepwise under control of a PC driven software that allows for choosing the voltage steps and their timing; moreover, the program records the resulting current through the sample. The software also monitors the climate inside the room (Relative Humidity and Temperature). The climatic conditions as well as the maximum voltage, the number of steps, the delay between steps and the maximum allowed current can be chosen in function of the nature of the material. During the whole measurement, the instantaneous values of all the parameters can be displayed as well as graphical representation of either \( V \) (voltage) and \( I \) (current) in function of time (see Figure 1), \( R \) (i.e. \( V/I \)) in function of time (see Figure 2) or \( R \) in function of \( V \).
The measurement can proceed with the potential difference reverting to zero or not. Processing back to 0V can emphasise any modification in the seam characteristic that has appeared due to the flowing current. It also indicates whether these modifications are permanent or only temporary.

Moreover, the software stops of increasing the voltage as soon as a maximum current is reached, in a tentative way not to modify the material under test; unfortunately, in some cases, the change in resistivity is so sudden that the damage is already done when the detection happens. However this problem can be solved by exercising the sample first with some low potential difference, then, in a second step, to a higher difference, then, finally, if still no hint of conduction has shown, to the maximum voltage allowed.

The results most interesting presentation is the “Resistive Signature” of the sample. This is a coloured plot of $R$ in function of $V$ where the colouring scheme allows to recover the chronological aspect of the measurement: a $R$ value recorded at time 0 will get a green colour and a value recorded at the end time (normally back to a 0 potential difference) will get a yellow colour; $R$ values in between go through a cyan, blue, magenta, red and orange gamut. For example, when a measure takes a total time of 1200s, the resistance value for the voltage at time 0s is displayed in light green, 200s in green, 400s in cyan, 600s in blue, 800s in magenta, 1000s in red and 1200s in yellow (see Figure 3).
For fabric samples, the measurement uses two 5 lbs. electrodes with 2.5 in. ($\varnothing$) carbon conducting pads, placed diagonally across A4-size rectangles. In this way, we prevent direct conduction between electrodes due to lone conductive fibres, a phenomenon that is not representative of the global behaviour of the material, and that excludes the use of classical concentric electrodes for resistivity measurement of this type of material. When the method is used for seams conductivity evaluation, the sample includes a seam parallel to the small edge of the A4-size sample, roughly dividing it into two A5-size fabric pieces (see Figure 4). If necessary, the measurement can be done on a whole garment taking into account that more than one seam can be present along the conduction path between the electrodes.

**Figure 3: Resistive Signature**
The measurements are done in a climatic room where temperature is maintained at 23°C and whose relative humidity can vary from 10% to 50%. Furthermore, the room is shielded against electromagnetic perturbations (see Figure 5).

3. RESULTS

All the measurements of the “Resistive Signature” hereafter were made at a temperature of 23°C and a relative humidity of 25% RH.

In Figure 6, where there is no seam between the electrodes, one can see that the Resistance doesn’t depend on voltage and stays around 1 MΩ. In Figure 7, we can see the effect of a bad seam on garment conductivity; only very high potential differences were able to produce conduction between
the two sewn fabrics. Two conduction paths were consecutively built one at 4 kV and the other at about 7 kV; at 13 kV, a very high conduction arose damaging the sample.

Figure 8 and Figure 9 show the conduction of core conducting fabrics sewed together. In both case, the resistance is very high until the voltage reaches 4 kV where some conduction path is built. However, when the voltage is brought back to 0 V, the resistance goes high very soon showing that the fabric has been altered during the process. Figure 8 and Figure 9 correspond to two different orientations of the grid at the seam level. The “Resistive Signature” shows clearly the effect of this orientation on the electrical properties of the seam.

4. CONCLUSIONS

Centexbel has developed the “Resistive Signature” method that allow for the global electrical characterisation of fabrics. This test method is also useful for characterising seams. A global seam resistance is computed although, for bad seams, the evolution of the resistance in function of voltage contains further information: in case of less than perfect seams, the resistance stays high before suddenly dropping to lower values for some applied potential difference. The voltage at which this phenomenon occurs is a good indication to the confectioner (laundry, end user, …) of how far from adequate the seam is.
THE NEED OF CONTINUOUS IMPROVEMENT OF THE 
EN STANDARDS ON PPE AND OF THE INFORMATION 
gIVEN TO CONSUMERS

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Rapporteur to CEN/BT for the PPE sector

ABSTRACT

The quality of the PPE put on the EU market is now globally satisfactory. Thereby margins of progress still exist to improve the representativity, reproducibility and repeatability of the test methods by means of inter-comparison tests, uncertainty of measurement evaluation, assessment of the PPE efficacy and comfort in real conditions of use... If having safe, reliable and comfortable PPE is of very high importance, we should not forget that the sensitizing and information of purchasers, end-users and consumers on products especially on their correct use, maintenance is one other essential route for the prevention of accidents. As a matter of fact, purchasers and consumers are not generally aware about the limited level of protection of many PPE. Thereby, information of the consumers trough e.g. appropriate instructions for use, guides of selection, information at sale point, is a vital part of any product and of the health and safety management.

1. INTRODUCTION

The European standards developed in support to the PPE directive 89/686/EEC aim at removing barriers to the free movement of PPE within the EU market. According the Art 95 of the EU treaty the new approach is based on a high level of health and safety protection, taking account in particular of any new development based on scientific facts. This general provision means that EN standards shall not only be developed to facilitate the free marketing of the products but also to ensure the high level of protection that society can expect for the protection of the health and safety of the European citizen in his private and professional capacity.

This means that the technical specifications laid down in the standards must:

- Reflect current state of the art, in other words correspond to the highest level of safety and ergonomics that can be reasonably expected of PPE
- Be updated to take into account of the evolution of the state of the art.

To meet these fundamental objectives, all stakeholders have made in the ten past years a lot efforts to improve the completeness and consistency of the existing PPE standards. The quality of the PPE put
on the EU market is now globally good. Thereby important margins of progress still exist to improve
the existing situation for the benefit of the manufacturers and of the consumers.

Many deficiencies and imperfections identified by the users of PPE standards have to be considered to
make up the existing standards. One can quote for example: *the lack of validation of the
reproducibility and repeatability of test methods, the not enough consistent organisation of the set of
standards, the too high number of level of performances which do not facilitate the user’s choice, the
lack of harmonisation of the markings and pictograms, the lack of consideration for ergonomics
aspects, lack of tools to evaluate the real service life of the PPE*...

But today, I would like to insist particularly on two other important aspects, the representativity of the
test methods and the need to get reliable test results.

2. THE IMPORTANCE OF THE REPRESENTATIVITY OF THE TEST
METHODS

The test methods and the specifications developed to assess the performances of the PPE shall be
representative of:

- The risks that the PPE is intended to protect the user against,
- All foreseeable conditions of use, which can affect the efficiency and comfort of the PPE.

In practice the assessment in laboratory of the efficiency and comfort of PPE remains, in many cases,
rather theoretical. As a matter of fact, the standardised tests methods adopted and used as basis for this
assessment are very often empirical and simplistic. But, this was often the only way for standardizers
to get repeatable, reproducible and unnecessary expensive tests.

Consequently, PPE having satisfied all the tests in laboratory can sometimes appear in real conditions
of use, less efficient and comfortable than expected. These differences in appreciation can come to
light when the real qualities of the PPE are difficult to assess objectively in the laboratory. This
applies to all PPE, when their performances are closely linked to the morphological characteristics of
the end-users and to the difficulty to identify the constrains related to all foreseeable conditions of use.
This is the case for efficiency aspects, such as the air tightness of respiratory protective devices and
the noise attenuation of hearing protectors. This is also the case for the assessment of characteristics
like practicability, thermal comfort, impairment of sensory perception.

To reduce as much as possible these discrepancies, it is always advisable to try to correlate the results
obtain in laboratory with the reality of the work places. This could be done by conducting assessments
in real situation of use of PPE being worn by the operators while carrying out their normal tasks.
Many studies have been carried out in particular by Health and Safety Institutes (BGIA, FIOH, INRS,
INSHT, CIOP, NIOSH…) in particular on respiratory protective devices, hearing protectors, safety
footwear, gloves, protective clothing, kneepads, eye protectors [1]. They sometimes have shown very
big differences between the theoretical performances evaluated in laboratories and in real condition of
use.

One very recent example is related to hearing protectors. Their noise attenuation is measured
according to the standard EN 24869-1 on the basis of measurement conducted with 16 test subjects
trained in the wearing of the hearing protective device and its adjustment. The attenuation values
found at work places and with untrained subjects, reported in various reports are appreciably lower
than those measured in laboratories. These studies result in recommending significant corrections to
the performances claimed by the manufacturers in order to make sure that the users of these equipments are effectively correctly protected. NIOSH recommends that the noise attenuation obtained by using trained subject should be derated: 25% for earmuffs, 50% for formable earplugs and 75 % for all other earplugs In France corrections are also proposed: – 5 decibels for ear mufffs and individually moulded ear plugs, -10 decibels for formable ear plugs and – 7 decibels for ear mufffs mounted on safety helmets! This is of particular importance, on account of the entry in force in February 2006 of the directive (2003/10/EC) layiing down a new obligation which request that the noise exposure (hearing protectors included) of workers must not exceed 87 dB [3].

This example among others, demonstrate how beneficial it could be for end users and the effective prevention of occupational accidents and diseases to consider carefully the need to carry out such “post-normative” studies in sensitive field, in particular for PPE against chemicals, heat or cold protective such as protective clothing and gloves. No test methods related to key health and safety characteristics should be accepted in EN standards without preliminary representativity validation.

3. ANOTHER IMPORTANT ASPECT: THE RELIABILITY OF THE TEST RESULTS

Tests, measurements and analyses are made to assure that the prescribed limit values of the standards are met and thus to judge acceptability or conformity of the products.

Every body knows that test results are never perfectly precise and that in practice there are numerous sources of systematic and random errors - even for the most careful - which can affect the result. This margin of doubt shall be quantified to be able to make a consistent decision and estimate the degree of risk associated with this decision. Measurement and test results represent the basic information for the conformity statement of many products or activities. Without knowledge of the precision of test methods and of uncertainty of results, decisions may be incorrect and sometimes may lead to serious adverse consequences.

For example, on the economical field when rejecting instead of accepting a product during a certification process…on the judicial field when returning a verdict of guilty instead of not guilty in case of market surveillance or of accident… on human field when falsely classifying dangerous products as safe… on ethical field when having overly optimistically or unduly pessimistically interpretation of results leading to a non - fair competition between manufacturers and between testing laboratories…

So, it is really vital to quantify the reliability of the test results to effectively offer a high level of confidence in the conformity statement and to minimize considerably matters of disputes and negative consequences of proceedings at law. [4]

There also several other advantages linked with the evaluation of the uncertainty of measurement: It assists in the credibility of the test results, it can represent a competitive advantage by adding value and meaning to the result, it provides objective elements for improving the reliability and optimising the test procedures, the calibration costs can be minimized by identifying quantities which do not substantially contribute to uncertainty.

A big majority of test laboratories are accredited according the worldwide reference standard EN ISO 17025:1999 [6]. This standards specifies, in particular that testing laboratories shall have and shall apply procedures for estimating the uncertainty of measurement and that test report, when the
uncertainty affects compliance to a specification limit, shall include a statement on the estimated uncertainty. In practice for complex tests, forming equation - according to the recommendations of the international guide to expression of uncertainty in measurement (GUM) [5]- with all the components of the uncertainty becomes very difficult.

Several organizations, have investigated intra and inter-approaches to deal with this problem: **modelling approach, single laboratory validation approach, interlaboratory validation approach and proficiency testing approach** [7].

![Diagram of uncertainty evaluation methods](image)

**Figure 1**: Typology of uncertainty evaluation methods [8].

The more simple approaches to uncertainty analysis are based on results of inter-laboratory tests. The first method called “Test methods performance Approach” founded on ISO 5725:1994 [9] is described in ISO TS 21748:2004. [10]. It consists in using the estimated reproducibility, repeatability and trueness to evaluate the uncertainty of measurement.

The second one, called “ Proficiency testing Approach” based on the ISO guide 43/1:1997 [11] and the ISO/FDIS 13528:2005 [12] consists "simply» in carrying out inter-comparison tests with one reference sample. This approach which could reduce the work of the laboratories, who have neither time, neither competence, nor taste of uncertainties… is not yet the object of an international document.
In the past 10 years tenths of round robin tests were performed at the initiative of the CEN/TC’s themselves or of the vertical groups of the European coordination of Notified Bodies “PPE”. They were based on a similar approach using the same sample of PPE circulating in all participating laboratories. Only a very low percentage of them have shown a very good consistency of the test results. In some cases a factor of several hundreds even more were sometimes observed in the tests results. This demonstrates how important inter-comparison tests are in order to ensure the credibility and reliability of the test results. No test methods related to key health and safety characteristics should be accepted in EN standards without preliminary inter-laboratory validation tests.

4. THE IMPORTANCE OF THE PROPER INFORMATION TO USERS

If having safe, reliable and comfortable PPE is of very high importance, we should not also forget the need to properly inform end-users. As a matter of fact, there is not ideal PPE which allows to protect against all industrial risks in terms of nature and levels and which does not cause any discomfort or constraint to work. PPE can sometimes only offer a limited level of protection to the user and have sometimes a limited lifetime depending on the product characteristics themselves and also the effective conditions of storage, use, cleaning, servicing and maintenance. Purchasers and consumers are not generally aware about these limitations. Thereby, information of the consumers is a vital part of any product and of the health and safety management [13].

Improving the quality of information increases consumer’s ability to make correct choice and satisfaction. Those who supply a high standard of consumer information enhance their commercial reputation, and save time and money by reducing enquiries and complaints. Appropriate consumer information is also one mean to give appropriate knowledge on health and safety prevention concepts to the consumers and to promote the appropriate use of the PPE.

This is of particular importance in sports, leisure, DIY activities where the PPE users, believing being protected against any risk, are often taken higher risks than usual. This shows that the users are not always aware about the limited protection capacity given by the PPE.

Among all the actions already taken in the past years at European level to improve the situation, one can quote:

- The organisation of information and training courses intended for the manufacturers, distributors and retailers of PPE in various European EFTA and EU countries. They aim not only to better knowledge of the European regulation but also at a better appropriation of the prevention of the accidents of work and occupational diseases concepts. Certificate or diplomas are generally awarded to trainees who pass successfully the evaluation tests [14].

- The development of 40 guides or informative annexes to existing EN standards on PPE. They are related to respiratory protective devices, eye and face protectors, safety footwear, hearing protectors, PPE against falls and protective clothing. They aim at clarifying in particular the link between the risks to be covered or the activity to be carried out and the performance levels defined in the EN standards [15]

- More recently, the finalisation of a CEN guidance document on the drafting of the instructions for use supplied by the PPE manufacturers to the users according to the requirement of the PPE directive. This document will be available on the CEN PPE Sector web pages [16].
Other complementary actions should also be considered:

- The improvement of the availability and accessibility of the instruction for use at the sale point,
- The development of selection software in particular to facilitate, in cases where a rather high level of competence is needed, the proper choice of PPE by the purchasers, OHS officers…,
- The clear identification of the manufacturers on the PPE or in the instructions for use in order to allow consumers to address complaints, transfer feedback or raise specific technical questions on the use/maintenance of the products.

5. CONCLUSIONS

The success obtained over the last 15 years in the standardization of PPE, must not hide the necessity of going further, to reach the common objective which is not only to provide good standards for manufacturers and notified bodies, but also and above all to provide safe and healthy life conditions to PPE users.

The efforts to increase the robustness and the reliability of the test and measurement methods must continue; many progress being desirable and possible in this field.

But, we should not forget that the proper sensitizing and information of purchasers, end-users and consumers on products especially on their correct use, maintenance is one other essential route for the prevention of injuries and accidents. To achieve this difficult goal, none of the possible ways of action of whatever legal, normative, educative or informative character, must be neglected. All interested parties at European and National levels should consider more carefully the social and economical benefits of good information of end-users and purchasers of PPE.

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PPE PROGRAMME AS A PART OF SAFETY MANAGEMENT

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ABSTRACT

In order to have the planned protection from the use of Personal Protective Equipment (PPE), it shall be selected, used and maintained correctly. The selection shall be based on proper risk assessment and evaluation on the possibilities to eliminate or reduce the level of hazards. The characteristics of the users and working environment shall be considered. The efficient and proper training and information of the users are prerequisite for the correct use of PPE. The maintenance and the competence of those making it will ensure the protection level and usability of PPE during its entire service time.

Normally work places have specified procedures and work instructions for risk assessment, purchasing, training and control activities. Some services or equipment are subcontracted and there are certain procedures for the subcontracting contract. These procedures may be parts of some management systems like ISO 9001, ISO 14001 or OHSAS 18001.

The matters dealing with PPE shall be integrated into the existing management system to ensure that the requirements on the selection, use and maintenance of PPE are really taken into account in the daily management. This paper describes some essential elements of the management systems which should also contain all aspects dealing with PPE.
PROTECTIVE CLOTHING AGAINST RAIN OR LOW TEMPERATURES – OVERVIEW OF EUROPEAN STANDARDS

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ABSTRACT

At millions of workplaces within the European Economic Community (EEC), protective clothing for protection against rain or low temperatures is used occasionally, frequently or even constantly. At workplaces outside buildings, persons concerned include e.g. workers and supervisors in the building, forest and fishing industry as well as in agriculture, in stationary industries, in transportation industries (railway, airport, shipping traffic) etc. Inside buildings, workplaces with low or very low temperatures can be found, for instance, in the food-processing industry, e.g. during the processing, packaging and storage of meat, fish, fruit, vegetables and milk. Protective clothing used in the industry falls under the PPE Directive 89/686/EEC and therefore has to be CE-marked. The relevant European standards support the relevant basic requirements relating to occupational health and safety of the PPE Directive, and are important for the production, testing and specification of protective clothing. This paper will therefore provide an overview of the current European standardisation work within the standardisation committee CEN/TC 162/WG 4 and some important requirements in European standards for protective clothing against rain and low temperatures. It will also address some significant changes regarding European pre-standards and new test standards.

1. INTRODUCTION

Protective clothing against rain or low temperatures is occasionally, frequently or constantly used at millions of workplaces across the European Economic Area (EEA). Outdoor users include workers and supervisors in the construction industry, forestry, agriculture, fishery, stationary applications, and the transport sector (railway, airports, shipping). Cool to cold indoor workplaces can be found in particular in the food industry, e.g., with respect to the processing, packaging and storing of meat, fish, fruit, vegetables, and dairy products. According to estimates, approx. 30% of the more than one million cold workplaces in Germany are situated in refrigerated rooms. Because of higher demands in terms of quantity and quality of refrigerated food products the number of cold workplaces in this sector is likely to rise [1].

Inappropriate or no protective clothing for the above applications constitutes a health hazard for workers. Potential consequences include colds, rheumatic diseases, circulatory disorders, reduced
immune status, reduced powers of observation and slower reactions, and, as a result of this, compromised occupational health and safety. Procuring appropriate protective clothing will help reduce sick days and must therefore be demanded for health and economic reasons alike.

Since protective clothing against rain and cold for occupational use is governed by the PPE Manufacturing Directive 89/686/EEC it must be CE marked which is the pre-requisite for its being placed on the market in all 28 member states of the European Economic Area. The relevant European standards are of great importance to make some applicable basic health and safety requirements of the PPE Manufacturing Directive more specific and also for the manufacturing, testing and invitations to tender for these types of protective clothing. For this reason, an overview of the current progress of European Standardisation in the standardisation group CEN/TC162/ WG 4 and some important requirements of the European standards for protective clothing against rain and low temperatures will be provided. Furthermore, a report on some significant changes with respect to European pre-standards and new test standards will be presented.

2. STANDARDISATION OF PROTECTIVE CLOTHING AGAINST RAIN

At the end of 2003, the European Standard EN 343 was published which contains minimum requirements placed on materials and seams, as well as on marking and the manufacturer’s information with respect to protective clothing against rain [2]. The water penetration resistance and water vapour resistance are especially important characteristics of protective clothing against rain. The most important product property is the water penetration resistance (WP [Pa]) which is measured at the outer material layer together with a water-proof layer (e.g., liner), if any. The test is carried out with new and conditioned (e.g., friction, abrasion, fuel, oil) samples and samples of the garment’s seams. The water penetration resistance must be at least 8000 Pa (80 cm water column) to meet the requirement of the standard.

Another important characteristic which must be determined is the water vapour resistance $R_{et}$ [m²Pa/W] of all material layers. A low water vapour resistance promotes the evaporation of perspiration and, thereby, the cooling of the body. This improves the wearing comfort and reduces physiological stress. In the highest performance class 3, for instance, the water vapour resistance $R_{et}$ of all layers of clothing material may not exceed 20 m² Pa/W (approx. 0.2 lm²/h).

Further material requirements concern, inter alia, tensile, tear and seam strength of the outer material layer, as well as dimensional changes (shrinkage) of all clothing material layers. The marking must comprise a pictogram (ISO 7000-2413) and the WP and $R_{et}$ classes identified (Table 1). The annex to the standard contains information on the recommended period of use of the protective clothing against rain as a function of the ambient temperature and the $R_{et}$ class.
Table 1: European product standards for protective clothing against rain or low temperatures

In EN 343, the requirements relating to protection against rain were taken over from the prestandard ENV 343:1998 (Protective clothing against foul weather), but the limit value for the water vapour resistance class $R_{et}$ was changed from 150 to 40 $m^2 Pa/W$ to extend the period of use and improve the wearing comfort of this type of protective clothing. Product requirements placed on a (separable) thermal lining which used to be part of ENV 343 have now been included in the new standard EN 14058.

A specific test method was defined in EN 14360 to test the rain tightness of ready-made protective garments. The protective clothing being tested is put on an upright dummy wearing detector underwear and the rain tightness of the protective clothing is tested in artificial rain of 450 $l/m^2 h$ for 60 minutes. This test method is already being applied by some European test houses [3,4,5].

3. STANDARDISATION OF PROTECTIVE CLOTHING AGAINST LOW TEMPERATURES

3.1. GARMENTS FOR PROTECTION AGAINST COOL ENVIRONMENTS

Requirements placed on material characteristics, test methods, marking, and the manufacturer’s information for garments protecting the body against cool environments have first been compiled in EN 14058:2004 [6]. This standard defines a cool environment as a possible combination of air humidity and wind at temperatures of $-5 \degree C$ and above. In particular as far as the temperature range of $-5 \degree C$ up to approx. $+15 \degree C$ is concerned, there are numerous applications for protective garments such as jackets, coats, overalls, trousers, and vests with thermal insulation for indoor and outdoor workplaces.

The most important material property is the thermal resistance $R_{ct}$ [$m^2 K/W$] which is categorised in three classes from 0.06 to a maximum value of 0.25 $m^2 K/W$. Garments consisting of material layers with a higher value are usually not covered by the scope of this standard. In addition, the following

<table>
<thead>
<tr>
<th>No.</th>
<th>EN : year</th>
<th>Protective clothing against</th>
<th>Pictogram ( ISO 7000 no.)</th>
<th>Mandatory information next to the pictogram on</th>
</tr>
</thead>
</table>
| 1.  | 343: 2003| Rain                         | ![Rain Pictogram](ISO 7000 – 2413) | - Water penetration resistance class  
- Water vapour resistance class |
| 2.  | 14058: 2004| Cool environments (≥ - 5 °C) | ![Cool Environments Pictogram](ISO 7000 – 2412) | - Thermal resistance class |
| 3.  | 342: 2004| Cold (≤ - 5 °C) | ![Cold Pictogram](ISO 7000 – 2412) | - Thermal insulation  
- Air permeability class |
characteristics may be of relevance to marking in individual cases: air permeability, water penetration resistance and water vapour resistance of all material layers, as well as the thermal insulation value of the garment, measured on a thermal manikin. Depending on the thermal insulation value and the type and duration of work the minimum ambient temperature for using the protective clothing may be estimated in Annex A for a number of practical cases. The marking of the garment must include a pictogram (Table 1) and the designation of the standard, i.e., EN 14058, must be shown to prevent confusion with protective clothing against cold.

3.2. CLOTHING ENSEMBLES AND GARMENTS FOR PROTECTION AGAINST COLD

Requirements and test methods for clothing ensembles (e.g., one and two-piece suits) and for individual garments (e.g., coat or bib-and-brace trousers protecting against cold) are specified in EN 342:2004 [7]. Taking the definition of “cool environment” into account (see EN 14058), cold is, in accordance with this standard, a combination of humidity and wind at an air temperature of less than –5 °C. The most important obligatory information in the marking includes the thermal insulation and air permeability of the clothing ensemble or garment.

The thermal insulation is measured with a thermal manikin in accordance with EN ISO 15831 at the clothing ensemble or test garment which has been supplemented with reference garments (A) to form an ensemble in order to determine the insulating effect both of all material layers and the cut of the clothing [8]. This principle of testing the entire clothing ensemble differs from many other protective clothing standards which only stipulate that material characteristics be measured. The resultant basic thermal insulation \( I_{cler} \) \([\text{m}^2\text{K/W}]\) from the skin to the outer clothing surface is determined by means of a moving manikin and, in the case of protective clothing against cold, must be at least 0.31 \( \text{m}^2\text{K/W} \) in accordance with EN 342.

The value \( I_{cler} \) of clothing ensembles is determined with underwear (B) defined according to Annex A of EN 342 or with underwear (C) specified by the manufacturer. Two reference clothing ensembles for calibrating the \( I_{cler} \) measurement with respect to the test and evaluation method (e.g., parallel or serial model) are included in Annex C and were used in a European research project (SUBZERO [9]) in comparative trials. Information on the use and selection of protective clothing against cold is provided in Annex B where the necessary \( I_{cler} \) values are compiled for light to medium activities for different periods of use and temperatures.

Since wind may significantly change the convection heat losses of protective clothing, the air permeability of all material layers of clothing must be determined. Three performance classes (low, medium, high) were defined for air permeability \( \text{AP} \) \([\text{mm}/\text{WS}]\). Additional requirements were defined with respect to the tear strength of the outer material layer, water penetration resistance and water vapour resistance. Accumulation of moisture in protective clothing against cold, e.g., as a result of perspiration, should be avoided because moisture may significantly reduce the insulating capacity of protective clothing. It was demonstrated with test persons that, even at –20 °C, low water vapour resistance reduces the accumulation of moisture in clothing and allows clothing to dry more quickly [10].

In comparison with pre-standard ENV 342:1998, the scope, inter alia, was extended to include single garments, requirements placed on the water penetration resistance were supplemented with 2 performance classes, and limit values of the air permeability performance class were modified. Furthermore, the standard underwear A was replaced with the new underwear C and the Annex with
respect to the thermal manikin measurement was removed because the special standard EN ISO 15831 has been completed in the meantime.

EN ISO 15831 specifies the test method for the thermal insulation and the requirements placed on the thermal manikin which must consist of a minimum of 14 body segments and for which segment-wise control of the surface temperature and measurement of the heat flux are required. The two measurements are carried out at least twice with an upright or moving manikin (arm and leg movements specified, walking speed approx. 3.5 km/h) in a climate chamber with a wind velocity of approx. 0.4 m/s. The thermal insulation of the clothing ensemble can be calculated either by adding up the surface-related thermal insulation values at the different body segments (serial model) or by using the total heat flux from the manikin’s body (parallel model).

4. OUTLOOK

After many years’ work in CEN/TC 162/WG 4, European test and product standards are now available for most protective clothing products against rain or low temperatures to manufacturers, certifying bodies and users. These standards are also of great importance for combinations of protective functions, e.g., high-visibility clothing with protection against rain and low temperatures. When such standards are used shortcomings and potential improvements are usually noticed. Due to information provided by material manufacturers, for example, a change in the required abrasion characteristics of externally coated materials has already been planned in the draft amendment to EN 343. Useful suggestions can also be expected from the European exchange of experience of the notified bodies for protective clothing. Such proposed improvements must be considered in the following revision of the test and product requirements in the relevant standards.

5. REFERENCES

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PROTECTIVE CLOTHING AGAINST THE THERMAL RISKS OF AN ELECTRICAL ARC – REQUIREMENTS FOR DEVELOPMENT, TESTING AND EVALUATION

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ABSTRACT

Electrical arc accidents during maintenance activities under live working conditions happen rarely. But statistics demonstrate that the risk is permanently existing and the occurring injuries are very harmful and sometimes mortal. Therefore the use of a suitable protective clothing tested under considerably real-life conditions is very important.

Following the key aspect of the Directive 89/686/EEC to protect the wearer with the PPE, an evaluation only based on simplified parameters seems to be not sufficient. Therefore the presentation will inform about the testing and evaluation phases of a protective clothing against the thermal risk of an electrical arc based on a practice-oriented test standard.

Although there are different possibilities to expose textile fabrics and garments to an electrical arc, the lecture will demonstrate the imperative to define objective test parameters for a reproducible testing and an appropriate evaluation of the protection effect. Safety relevant parameters for the fabric and design requirements for the whole garment are given.

A practice-oriented method for testing of textile material as well as garments will be presented by introducing the test set-up and procedure development of the European Box-Test-Standard TS 50354. In testing according to this standard the radiant and convective heat effects of electric arcs are considered as well as the consequences of metal splash and vapour.

1. INTRODUCTION

Electric arcs are a potential risk for people and plant although accidents during maintenance activities under live working conditions happen rarely. But statistics demonstrate that the risk is permanently existing and the occurring injuries are very harmful and sometimes mortal. Particularly the protection against the thermal effect of an electrical arc is of largest importance for human injury while working in, at or near to electric power installations. Essential contributions to this protection can be offered by appropriate protective clothing tested under considerably real-life conditions. Following the key aspect of the Directive 89/686/EEC to protect the wearer with the PPE, an evaluation only based on simplified parameters seems to be not sufficient.
2. METHODS FOR ARC TESTING

During the years different methods to expose textiles to an electrical arc have appeared. Many of them were created from power supply companies or accompanying institutions. The foremost aim was to find an internal testing possibility of the company-own clothing. Therefore the possibility to shoot an arc on a textile and assess the garments feedback visual was quite often the major interest. Related questions i.e. additional required parameters for protection effect assessment, necessary variables to control the reproducibility or the possible influence of the set-up and/or the environment were mostly not considered.

But these things are very important for a test standard which can be harmonised. Hence from the international point of view only two different testing and evaluation standards for the protection effect of arc protective textiles are used commonly.

2.1. DETERMINATION OF ATPV

The IEC 61482-1 specifies a method to determine the arc thermal performance value (ATPV). The ATPV represents a material property parameter which is used to assess fabrics or garments with respect to their protection effects against thermal arc consequences. In arc testing the ATPV is the incident energy on a material or a multilayer system of materials that results in a 50% probability that sufficient heat transfer through the tested specimen is predicted to cause the onset of a second degree skin burn injury based on the Stoll curve, without Breakopen. Especially in US and Canada working activities have been classified by means of ATPV levels and there are different guidelines and recommendations for categorisation. The IEC 61482-1 test procedure is based on an open arc fired in a 6 or 10 kV test circuit (MV conditions) between electrodes with a 300 mm gap. Each of the three panels used contains 2 calorimetrical sensors to measure the pass through energy which is compared with the Stoll burn criteria predicting second degree burn from the standard.

2.2. BOX-TEST STANDARD

But in Europe there are only few experiences regarding this ATPV classification and application. Therefore another test method, tailored to the special European needs, has been established. Test setup and conditions of the so-called Box-Test are based on the specifications of CLC/TS 50354 (former ENV 50354). The test conditions represent the typical low voltage environmental ones during service. As shown by statistics, serious electrical accident with fault arcs occur in LV power installations mainly. In difference to the ATPV method a directed and constrained electric arc in a low voltage circuit will be used. Conditions simulated by the Box-Test are worst case ones for switchgear assemblies and installations in LV power systems in the according short-circuit current range. Besides the impact of radiation, convection as well as these of molten metal splashes the special box design allow to take into account thermal arc consequences which may result from the amplifying effect of installation back and side walls.

An electric arc is fired in a 400 V AC test circuit, burning between two vertically arranged electrodes which are surrounded by a special test box. Test circuit parameters and set-up ones (current, duration, distances,...) remain unchanged within a test series which is necessary for statistical reasons.

Limits for practical use of tested materials are given with these test conditions. Extending the test procedure of CLC/TS 50354, a measurement and evaluation of the incident energy transmitting the
sample is made in addition to the visual assessment of the material or garment heat response (after flame, hole formation, melting-through, dripping, etc). The heat flux measurement by calorimeters simulating the human skin behaviour allows the objective assessment of the protection level by comparing the measured incident energy with the Stoll criterion describing the onset of second degree skin burns.

Two protection classes can be tested. Protection class 1 (4kA prospective current) and 2 (7kA prospective current) are safety requirements covering actual risk potentials due to electric fault arcs to a very large extent. Difference is made with respect to the test current level, being also criterion for the practical use in reference to the short-circuit currents in the electric system.

In this so-called Box-Test materials, material-assemblies and protective clothing are evaluated using a directed and constrained electric arc under defined laboratory conditions. A practical scenario concerning test set-up and test conditions, electrical and constructional parameters is selected.

The following Figure 1 shows details of the test device for fabrics (method 1). The backside of the test plate shows the two calorimeters according to EN 367 with thermocouples type T. This allows the measurement of the heat flux through the material and an assessment of the burning risks (comparison to STOLL curve for second degree skin burns). The Figure 2 shows the instrumented mannequin for the test of ready-made garments (method 2).

![Figure 1: Set of the electrodes with test plate, Calorimeters (Method 1)](image1)

![Figure 2: Test mannequin with calorimeters in the chest area (Method 2)](image2)

Although the mannequin is equipped with calorimeters of the same type too, the results of the measurement shall not be used as an alternative to the test and evaluation of the fabric. It have to be considered that the heat flux measured at garments will be influenced by outer and/or inner pockets covering the calorimeters. Therefore the heat flux through the plain fabric can be higher then measured on the garment.

The test standard was developed in co-operation of the Saxon Textile Research Institute Chemnitz (STFI) and the Technische Universität Ilmenau. In the near future the international standard IEC 61482-1 will be divided in the two mentioned test principles. The IEC 61482-1-1 will be contain the test method for the determination of the ATPV. The IEC 61482-1-2 will be cover the Box-Test method with the 2 protection classes. Both methods have already being used in practice for several years.
3. PRINCIPLES OF THE BOX-TEST

The following Figure 3 shows test principle of the Box-Test. A free-burning high-current arc of defined input power $P_{LB}$ and duration $t_p$ is reproducibly fired in an electric test circuit (test voltage $U_p$, test current $I_p$). The arc is ignited by means of a fuse wire by switching-on the voltage and, after the burning interval $t_p$ of 500 ms, switched-off by circuit breaker. The arc energy $W_{el}$ is converted during the arc duration.

![Figure 3: Principle of testing](image)

Due to the box is open to only one side, a directing effect of arc heat radiation and flux can be realized (without box a diffuse spread to all direction would appear). The test plate (method 1) or mannequin (method 2), containing the calorimeters, is placed 300 mm in front of the open box side. The sensors measure the temperature rise $d_T$ or incident energy $E_i$ and heat flux $Q$. The maximum heat load $E_{io}$ is measured by a test without a sample whereas the calorimeters indicate the transmitted incident energy $E_{it}$ during a test with the sample. The characterizing electrical and calorimetric parameters are recorded for each test. An example of the protocol is shown in Figure 4.

![Figure 4: Example of the protocol for electric (right) and calorimetric (left) parameters](image)

The calorimetric parameters primarily analyzed are the time curves of calorimeters temperature rises $dT(t)$ as well as the maximum values $dT_{max}$ (delta peak temperatures) and the related time points $t_{max}$ (time to delta peak temperature). The incident energy $E_i$ transmitting the sample is proportional to the maximum temperature rise $dT_{max}$. These reference values allowing to assess the textile effects by comparing, are also important for the quality management of the tests since a test may be checked referring to the deviations of actual exposure conditions to the standard ones.
For an evaluation of a fabric four specimens shall be exposed to the arc under unchanged conditions. A fabric can be considered as arc resistant if all of the four specimens show no ignition/burning or afterflame (> 5 s), no dripping or melting-through the inside and no hole formation or break-open (> 5 mm). In addition to these basic criteria none of the 8 calorimetric values shall exceed the so-called Stoll criterion which represents the onset of second degree burning of human skin.

4. REQUIREMENTS FOR TESTING AND CERTIFICATION

With respect to an EC type examination the arc protection garment must satisfy basic safety requirements of the Directive 89/686/EEC in order to ensure the health protection and safety of users. Therefore it is necessary to have an objective test procedure which combines a best-possible reproducibility and practice-oriented test conditions for arc protection textiles.

4.1. FABRIC REQUIREMENTS

For an evaluation of the arc protection effect of the garment the assessment of the fabric according to Method 1 of CLC/TS 50354 extended with additional calorimetric heat flux measurement shall be the first step. Protective clothing against the thermal risk of an electrical arc have to be seen as special kind of heat and flame protective garments. Therefore the general fabric requirements during the exposure of an electrical arc are quite similar:

- afterflame time < 5 s
- no melting through to the inside
- no flaming debris
- no hole formation > 5 mm in any direction
- maximum temperature rise at the backside of the specimen below the STOLL-curve

4.2. GARMENT REQUIREMENTS

Beside these fabric requirements, for the certification of the ready-made-product additional factors have to be considered. With respect to the general requirements mentioned in EN 340 the garment shall be designed in a way, that it does not influence or hinder the wearer. Due to the special kind of use there are “arc-related” requirements which are relevant for the garment including all accessories, i.e. reflective stripes, embroideries, badges or logos. Furthermore no exposed external metal parts are permitted and all pockets must be covered by a flap.

For the arc resistance test of the garment the Method 2 of CLC/TS 50354 with a mannequin is used. This gives the opportunity to test the function of the protective clothing after an arc exposure including all the garment findings, sewing tread, fastenings and accessories. After the garment was exposed to the arc the following requirements have to be fulfilled:

- no break-open through all layers
- the opening function of fasteners is still present

In the near future the new IEC 61482-2 which is presently under consideration will specify all relevant requirements within one standard.
5. SUMMARY

The extreme thermal risks of an electrical arc require an appropriate test procedure for fabrics as well as for garments. The actual used CLC/TS 50354 represents such a test method for analyzing the arc resistance and the protecting effect. In testing according to this standard the radiant and convective heat effects of electric arcs are considered as well as the consequences of metal splash and vapour always accompanying real arcing faults. Extended with the calorimetical measuring of the heat flux this method is well reproducible and near to the practice. Besides the basic requirements, similar to each other heat and flame protective clothing standard, for an EC type examination the other safety relevant aspects of an arc protection garments shall be considered. In any cases for the certification procedure the testing of fabrics (method 1) and garments (method 2) should be demanded.
approaches for incorporating cbRN requirements as part of protective ensemble standards for emergency responders

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Abstract

The growing concern for terrorism threats involving the weapons of mass destruction across the world has prompted new approaches to protect the first responders that are most likely to confront these hazards. While the majority of protective clothing approaches have focused on the qualification of hazardous materials protective clothing, there has been industry recognition that existing first responder ensembles can also be modified to deal with chemical, biological, radiological, and nuclear (CBRN) terrorism agents. This direction is needed because many first responders may find themselves involved in an incident without any anticipation of severe hazards. These first responders may also lack the needed personal protective equipment that is afforded to specialized teams. It is possible to adapt clothing and equipment used by firefighters, police, rescue workers, and emergency medical technicians to provide the needed material barrier and clothing integrity performance against CBRN terrorism agents. To aid in defining necessary performance levels, criteria have been established to account for appropriate levels of permeation resistance of materials against chemical warfare agents, toxic industrial chemicals, biological pathogens, and radiological particles using modified, current test methods. The further use of a man-in-simulant test and an overall particulate penetration test enable the complete evaluation of full clothing ensembles against a range of CBRN threats. This paper will provide a detailed description of the testing methods and the application of newly implemented test criteria for different levels of first responder protective ensembles in a number of applications. Examples of the ensembles meeting these criteria will also be described.

Introduction

One lesson of 9/11 was clear, the world has changed and firefighters along with other police, emergency medical technicians and other first responders will be among the most impacted. Today, there is now an understanding that a fire may be caused by improvised explosive devices designed to distribute chemical/biological weapons of mass destruction. Firefighters responding on a “fire call” may now find that they are also exposed to chemical and biological toxins. Protective clothing for structural firefighting has been designed to provide protection from fire and heat, but not these new
challenges. HazMat suits exist but are not acceptable for normal firefighting calls, since they are typically one time use, very bulky, very hot, very uncomfortable and often highly flammable. Other first responder organizations face similar challenges.

**BACKGROUND: CBRN THREATS AND APPROACH**

First responders must be ready to face exposure to a variety of specific agents that now can become part of emergency activities. These threats commonly called CBRN for chemical, biological, radiological, and nuclear exposures involve chemical warfare agents, toxic industrial chemicals, biological agents, that may be liquid or airborne pathogens, and particulates from radiological materials that have been dispersed as the result of a “dirty” bomb or nuclear release. Following 9/11, there has been a significant study of the potential exposure levels for first responders. There is also the realization that many first responders may not be aware of the full range of exposure hazards during a large disaster, which unknowingly involve CBRN agents. Further, there is an expectation that first responders will be the principal personnel involved in any such disaster for immediate rescue and site control as more specialized, better equipped teams will not be available for hours following any event.

Work in the United States is currently underway for the development of a new generation of structural fire fighting personal protective equipment (PPE) offering CBRN protection. These development programs combine efforts for identifying and evaluating candidate materials, creating designs that addresses interfaces between ensemble elements, and pursuing standards that rigorously define needed levels of protection. The specific programs in place currently focus on the needs of structural firefighters to provide CBRN protection, which is integrated into the garments, hood, gloves, and footwear of a fire fighter protective ensemble in a manner that limits the effects of the additional protection on the wearer. Each of the critical interface ensemble element interface areas has been addressed by applying innovative designs that prevent inward leakage and also increase the overall ensemble’s performance in the primary mission of structural fire fighting. Work with the National Fire Protection Association (NFPA) has been necessary to establish suitable requirements for CBRN protection in ongoing revisions of NFPA 1971 (structural fire fighting protection) and NFPA 1994 (CBRN protection). These efforts are further supported by extensive evaluations at the materials, ensemble, and field test levels. As the result of these efforts, it is expected that new ensembles will become available that permit normal work but also offer CBRN protection in a fashion that allow protection under extraordinary circumstances. This approach is becoming a model for designing similar ensembles for law enforcement, rescue workers, and emergency medical workers.

**DEVELOPMENT OF STANDARDS AND CRITERIA**

A key to developing new technology has been the parallel development of new standards and criteria. This development has involved the following approach:

- NFPA 1971 was modified to include an option for CBRN protection. The option addressed the establishment of criteria for each elements as well as the complete ensemble of clothing and equipment, including the respirator. Tests were added for determining the permeation resistance of barrier materials to chemical warfare agents and toxic industrial chemicals as well as overall ensemble tests for integrity. Performance of barrier materials were set to be consistent with the material requirements currently specified in NFPA 1994 for Class 2 (see
In addition, special provisions were added to address flexibility of design criteria to accommodate new interface designs, appropriate ensemble labeling, changes to product certification practices, and the provision of user information.

- NFPA 1994 sets criteria for first responders engaged in incidents involving CBRN hazards. The standard is premised on disposable, one-time used clothing with a hierarchy of performance levels depending on the types of threats present. The standard is being revised with three classes – Class 2, 3, and 4 with the former Class 1 moved to a different standard as a specialized high-end protective ensemble. Class 2 performance was aligned with self-contained breathing apparatus use and situations considered immediately dangerous to life and health while Class 3 was made consistent with the conditions that permit the use of air-purifying respirators. Class 4 was added to address biological and radiological particulates in the absence of chemical vapor hazards.

The two principal applied tests are permeation resistance and man-in-simulant testing. Permeation testing is performed on both chemical warfare agents (soman and distilled mustard) along with toxic industrial chemicals that may be involved in a terrorism event (acrylonitrile, acrolen, ammonia, chlorine, and dimethyl sulfide). The concentration for chemicals exposed to the material during testing is varied according to the class of performance with more rigorous challenges applied for the higher classes of performance. These criteria can be applied to any type of ensemble but are modified to account for the expected service life. For example, where the clothing is specifically used for CBRN incidents and considered for a single use, material are preconditioned prior to permeation testing by an appropriate number of flexing and abrasion cycles. In contrast, materials that are used in structural fire fighting clothing that are subject to ordinary use over several years prior to their possible use in an CBRN incident, a much more severe preconditioning regimen is used to simulate repeated washing, wear, and exposure to temperature extremes.

The second critical test was the assessment for overall ensemble integrity. An evaluation of the ensemble for showing its protection against chemical and biological agents is conducted using the Man-In-Simulant-Test (MIST). This technique, used by the military for years for testing battlefield chemical warfare agent protective clothing, has been proposed for testing first responder ensembles in both NFPA 1994 and for the CBRN option of NFPA 1971. MIST involves the placement of special adsorbent pads on test subjects at several different locations. The test subjects then wear the ensemble and perform a series of exercises replicating response activity inside a closed chamber where they are exposed to a surrogate chemical agent (methyl salicylate). After the 30 minute exposure, the adsorbent pads are removed from the test subjects and then analyzed to determine how much surrogate chemical penetrated the ensemble. The results are provided by individual body location based on the position of the adsorbent pad, providing information for where the leakage occurs. The information from all of the pads is also used to provide an overall protection factor for the ensemble. The protection factor is the ratio of the outside agent concentration to the inside concentration of surrogate agent collected on the pads. For Class 2 and the CBRN option in NFPA 1971, a minimum overall protection factor of 360 has been proposed while a requirement of an overall protection factor of 120 has been recommended for Class 3 ensembles.
TECHNOLOGY DESCRIPTION

In one development program for structural fire fighting ensembles with optional CBRN protection, a multiphase approach has been used encompassing:

- Moisture barrier material identification, testing and selection
- Composite materials identification, testing, optimization, and selection
- Ensemble interface design, testing, and selection
- Laboratory testing of ensembles
- Field testing of prototype garments at selected fire departments
- Specific service life considerations that address ensemble durability, care, and maintenance

In the identification, testing, and selection of materials, existing and emerging material technologies were solicited that met target criteria that accounted for required NFPA 1971 and NFPA 1994 performance properties. Additional criteria were added to cover performance areas not covered or anticipated in the standards, such as liquid chemical retention resistance. The materials industry responded with candidate materials for each of the ensemble elements. The critical area of material selection in garments is a replacement material for the conventional moisture barrier, which is the middle layer of a composite that includes both an outer shell and innermost thermal barrier. For this purpose, a CBRN barrier layer has been substituted for the moisture barrier thereby retaining the normal 3-layer constructions found in fire fighter protective clothing. However, the CBRN layer must demonstrate acceptable levels of permeation resistance to chemical warfare agents and selected toxic industrial chemicals while still meeting the normal requirements for flame and heat resistance in addition to providing breathable performance to lessen the stress of wearing. Similar CBRN barrier layers are required in the hood, gloves, and footwear, though the specific requirements for these layers change with the respective testing and criteria applied to the different ensemble items.

The proposed ensemble configuration has been based on the traditional structural fire fighting protective ensemble. The ensemble garment, hood, gloves, and footwear have been modified in a manner to retain an overall structural fire fighting protective ensemble appearance. Specific attention has been paid to the interface areas. The specific approaches used in design of ensemble interfaces involve the following features:

- A special vapor penetration-resistant zipper is used in combination with a material baffle to minimize inward leakage through the front closure.
- A zipper-less gusset is used in the front pant closure.
- The hood is directly integrated with the coat and provides a full composite with CBRN layer rather than the normal knit hood used for structural fire fighting protection.
- A gasket built into the hood opening seals around the body of the self-contained breathing apparatus (SCBA) facepiece.
- The liner of the pants have extended boot-like socks that extend into footwear that has been modified by the removal of the normal liner and that includes hook/loop closures to secure the bootie into place.
- Hard rings containing high-temperature-resistant magnets are used in the coat sleeves and glove gauntlets to align and hold the gloves in place.
- Suspender studs are replaced by flat loops to minimize gaps between the coat liner and the pants outer shell; take-up straps on the sides of the coat help secure the coat against the pants of the wearer.
A collector cap on the exhalation port of the SCBA facepiece channels exhaust air from the wearer into the coat torso through a hose and bulkhead connector on the upper right front chest area of the coat. Spacers on the lining side of the hose penetration direct air through the coat providing upper torso positive pressure.

The ensemble is being designed to function routinely for structural fire fighting activity with passive protection to the end user for CBRN protection, i.e., the wearer will not have to deploy special features for enhanced protection against CBRN terrorism agents. In addition, many of the material and design features will provide enhanced protection from structural fire fighting hazards.

DEVELOPMENT STATUS

The selected materials and design have undergone preliminary testing against the proposed requirements for CBRN protection included as part of the 2006 edition of NFPA 1971. CBRN protection is specified as an option in the NFPA 1971 standard and includes rigorous requirements for barrier material performance as well as demanding requirements for overall integrity of the ensemble. Ensemble elements must also meet all of the base requirements that apply to ordinary structural fire fighting, including criteria addressing heat/flame protection, physical protection, and breathability.

The following evaluations have proven the workability of the new technology:

1. At least one CBRN barrier layer has been identified that show permeation resistance to both chemical warfare agents and toxic industrial chemicals after multiple material pretreatments that simulate wear and use of the ensemble.

2. The selected barrier materials in combination with qualified shell and lining materials demonstrate heat insulation levels and breathability values that are comparable to existing industry composites and compliant with the NFPA 1971 base requirements. These include heat insulation values established by thermal protective performance (TPP) testing and thermal stress reduction values shown in total heat loss (THL) measurements. For selected composites, a range of 38 to 42 cal/cm$^2$ has been achieved in TPP testing, while the corresponding THL values span 215 to 240 W/m$^2$. The respective minimum requirements in proposed 2006 edition of NFPA 1971 are 35 cal/cm$^2$ and 205 W/m$^2$.

3. Overall integrity testing of prototype ensembles using Man-in-Simulant Test procedures has recently shown overall protection factors between 450 and 540 (the proposed revision in NFPA 1971 specifies a minimum protection factor of 360). In comparison, a properly fitted standard ensemble provided protection factors of 13 and 14, when tested in the same fashion. Analysis of individual body regions according to the proposed NFPA criteria also shows each area to meet the local area protection factor requirements (shown in Figure 1 below).
4. In practical performance testing of prototype ensembles to evaluate fit and function, end users that had never seen or used the ensemble before unanimously preferred the new ensembles over their current gear. Comments from the end users indicated that the new ensembles were lighter and more comfortable and kept them drier than their current standard structural fire fighting protective clothing.

SUMMARY

This paper has shown how criteria can be created and technology developed to meet the new protection needs for first responders. This same approach is also being applied to other types of first responder ensembles.
A REVIEW OF EUROPEAN METHODS OF ESTIMATING THE COVERS PROTECTING AGAINST THE BLUNT INJURY


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ABSTRACT

In the paper a review of the standards in force within the European countries has been given, concerning the covers to protect the wearer against the injury caused by hit of the blunt objects. The kinds of the covers recommended for various sports competitors are discussed (including the martial arts), as well as for the policemen, prison guards, for the employees of safeguard agencies, etc.

Described in the collected normative documents the research and test methods suitable for estimation of diverse blunt shocks cushioning performance are presented. There is specified and analyzed the parameter of resistance to knocking the selected covers, i.e. vests and limb protectors, regarding different kinds of threats capable to cause blunt injuries potentially.

Resistance to hitting is one of the most important parameters considered for estimation of usage properties of the goods designed for protection against various types of mechanical impact. Such a threat is common. You can observe them at most of the sports as well, as in everyday life. On a basis of rating the potential hazard occurring in a given situation, the selection of suitable protection has to be made. It's job is best possible protection of the user against the potential injuries resulted from blunt strikes, while ensuring the comfort when in use.

Within the scope of the scientific work “Research for capability of energy attenuation by multi-layer compositions and optimizing them for applying into impact-resistant goods” funded by state science budget for 2005-2007 as the research project, the analysis of guidelines regarding the requirements and rating methods of various impact-resistant products is done. The normative regulations of European countries were its basis.

The review of European standards allowed for selection of the following documents to specify the objective matters regarding the selected kinds of protections, at various applications aspects. It goes:
In the mentioned Standard (1), the requirements and test methods of testing the impact-resistant protections applied into the motorcyclist clothing. They are to prevent the wearer’s injuries possible while hitting the road surface in case of accident. They also can partially reduce the injuries resulted from the collision with other objects i.e. vehicles.

Part 1 concerns the protections for such the human organs as: shoulder, arm, forearm, hip, knee and shin. According to the PN-EN 1621-1 the impact-resistance testing of protections are to be conducted at the workplace providing the vertical descent of the 5000±10g impactor onto the sample placed on the anvil. The kinetic energy of the falling impactor should be 50J. The standard specifies the sizes of both impactor and anvil, as well, as determines usage of the appropriate measure apparatus able to register the force transferred beneath the sample. According to the standard’s requirements, the mean value of the force shouldn’t exceed 35kN, in the testing course on each of the protections mentioned above, and no particular value should exceed 50kN.

About 13% of motorcyclists’ injuries resulting from the traffic accidents are the injuries towards their back. That’s why part 2 of the document discussed is dedicated to protection of this part of body. The back protectors for motorcyclists are for wearing under, or over other protective clothing. They cover the central part from the waist to neck.

Sometimes the back protectors are joint with the belts lapping the body, with loins reinforcement, called loins protectors. Concerning back and loin protectors, there are two levels of impact-resistance”

- **level 1** – if the mean peak force registered beneath the anvil would be less than 18kN and none of the particular test results exceeds 24kN,
- **level 2** – if the mean peak force registered beneath the anvil would be less than 9kN and none of the particular test results exceeds 12kN.

The objective Standard (3) includes the requirements and testing methods concerning instep, shin, forearm and trunk protectors in use among martial arts, like: taekwondo, karate, kick-boxing and sports alike.

The Table 1 includes the requirements regarding the energy attenuation by the protectors mentioned.
Table 1

<table>
<thead>
<tr>
<th>Kind of Protector</th>
<th>Minimum number of the areas tested</th>
<th>Impactor’s hitting energy [J]</th>
<th>Maximum value of Force transferred beneath the sample, [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>instep</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>shin</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>forearm</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>torso</td>
<td>3</td>
<td>12</td>
<td>3</td>
</tr>
</tbody>
</table>

According to the PN-EN 132777, the measure of impact-resistance of all the protective elements included to the Table 1 should be executed at the workplace equipped with:
– an anvil of the size and shape selected properly for the sample to be tested,
– an impactor falling freely,
– a sample supporting element (half-cylinder or metal plate),
– a force converter.

Regarding their ability of energy attenuation, the protectors for martial arts adepts are conforming to the discussed Standard, provided the maximum value of the force transferred beneath the sample shall not exceed the values shown in Table 1.

**PN-EN 13158:2002 Protective clothing. Protective jackets, body and shoulder protectors for horse riders. The requirements and test methods.**

The Standard mentioned (4) covers the requirements and methods of testing the protective jackets, body and shoulder protectors for horseback riders and for horse care personnel to minimize the injuries resulting from blunt impact, a fall or from being kicked.

**Protective jacket** is a sort of garment with short or long sleeves, made of materials conforming to the requirements specified for body and shoulder protectors, covering certain areas of trunk, lower back and shoulders.

**Body protector** is the part of garment without sleeves, covering certain areas of trunk and lower back, consisting of one or more layers of material.

**Shoulder protector** is a product considered the part of garment for covering the side part of shoulder and for certain areas of front, back and top parts of shoulder. The shoulder protectors may be integrated into the protective jackets, fasten to the body protectors or may be a separate piece of garment, ie. shirt or pullover.

In order to carry the test properly, conforming to the standard, the workplace for testing the impact-resistance of riders’ protective garment should be equipped with the set of impactors shaped to simulate the threat of falling, kicking by the horse or hitting with a narrow bar. The altitude of the impactor to fall onto the tested samples of garment should provide the impact energy suitable for a given level of protection (Table 2). The anvils and secure rings set should simulate the shapes of relevant body parts. The standard recommends to mount a force sensor directly under each of the anvils or the converter to register the dynamics of the force value in time, or the peak value of the force transferred beneath the tested sample.
Table 2

<table>
<thead>
<tr>
<th>Testing conditions</th>
<th>The impact energy for the protection level [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level 1</td>
</tr>
<tr>
<td>Flat impactor for testing body protectors and trunk area of protective jackets. Secure ring – 0mm</td>
<td>25</td>
</tr>
<tr>
<td>Narrow impactor – the bar for testing body protectors and trunk area of protective jackets. Secure ring – 10mm</td>
<td>20</td>
</tr>
<tr>
<td>Wide impactor – the bar for testing shoulder protectors and shoulder area of protective jackets</td>
<td>60</td>
</tr>
</tbody>
</table>

As the Table 2 shows, the standard considers three protection levels for protective jackets and body protectors, and one protection level for should protectors.

The protective garment elements for horseback riders conform to the PN-EN 13158:2002 if:
– mean value of the maximum forces transferred beneath the sample for the body protectors and relevant area of protective jackets is lower, than 4kN and no particular value exceeds 6kN,
– mean value of the forces registered beneath the anvil for shoulder protectors and relevant area of protective jacket is lower, than 25kN, and no particular value exceeds 30kN.

BS 7971 Protective clothing and equipment for use in violent situations and in training
Part 1:2002 General requirements
Part 4:2002 Limb protectors – Requirements and test methods
Part 8:2003 Blunt trauma body, shoulder, abdomen and genital protectors. Requirements and test methods

The clothing and equipment for use in violent situations and related training activities is widely useful among the officers, who meet violence and threat on duty. The users are policemen, penitentiary officers, security agencies staff, escort etc.

It is intended for reducing the ailment or preventing the injuries of soft tissues of the covered surfaces, resulted from the blunt trauma. The trauma may arise from the hit of a projectile from the air (bricks, bottles, metal rods, pieces of wood, etc.) or from the direct attack with baseball bats, bricks etc. The part 4 of the Standard (5) determines the requirements, rules and ways of proceeding when rating the parameter of impact-resistance of the limb protectors named in the Table 3.
Table 3

<table>
<thead>
<tr>
<th>Protected area of the body</th>
<th>Mean peak value of the force transferred (maximum single value) [kN]</th>
<th>Anvil type</th>
<th>The impact energy [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Level 1</td>
</tr>
<tr>
<td>Arm, forearm, shin</td>
<td>≤ 8 (12)</td>
<td>Vertical plate</td>
<td>5</td>
</tr>
<tr>
<td>Shoulder Knee</td>
<td>≤ 10 (15)</td>
<td>Spherical work-surface cylinder radius 50mm</td>
<td>5</td>
</tr>
<tr>
<td>Elbow</td>
<td>≤ 5 (7,5)</td>
<td>Spherical work-surface cylinder radius 35mm</td>
<td>2,5</td>
</tr>
<tr>
<td>Tigh</td>
<td>≤ 5 (7,5)</td>
<td>Spherical work-surface cylinder radius 100mm</td>
<td>5</td>
</tr>
</tbody>
</table>

Part 8 of the standard specifies the requirements and test methods suitable for determining impact-resistance of the protectors for pedestrians’ and horse-riders’ trunk, shoulders, abdomen and groin (Table 4).

Table 4

<table>
<thead>
<tr>
<th>Kind of protector</th>
<th>Mean peak value of the force transferred (maximum single value) [kN]</th>
<th>Anvil type</th>
<th>The impact energy [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestrians’ trunk protectors</td>
<td>≤ 4 (6)</td>
<td>Cylindrical anvil, radius 100mm with protective ring</td>
<td>20</td>
</tr>
<tr>
<td>Horse-riders’ trunk protectors</td>
<td>≤ 4 (6)</td>
<td>Cylindrical anvil radius 100mm with protective ring</td>
<td>20</td>
</tr>
<tr>
<td>Arm protectors</td>
<td>≤ 8 (12)</td>
<td>Cylindrical anvil, radius 50mm</td>
<td>30</td>
</tr>
<tr>
<td>Abdomen protectors</td>
<td>≤ 3 (4,5)</td>
<td>Cylindrical anvil, radius 100mm with protective ring</td>
<td>10</td>
</tr>
<tr>
<td>Soft groin protectors</td>
<td>≤ 3 (4,5)</td>
<td>Cylindrical anvil, radius 100mm with protective ring</td>
<td>10</td>
</tr>
</tbody>
</table>

The BS 7971 standard includes precise description of the workplace for testing the impact-resistance of all of the protectors mentioned in the tables 3 and 4. It is equipped with a set of anvils of various shape and sizes adopted for the tested protective elements adequately. It also includes a set of impactors to allow for complex tests accordingly. Last, but not least the workplace is also equipped with the apparatus for recording the impact energy and the value of force transferred below the surface tested.
**PN-EN 13546:2005** Protective clothing. Hand, arm, chest, abdomen, leg, foot and genital protectors for field hockey goalkeepers, and shin protectors for field players. Requirements and test methods

The presented standard (6) includes the requirements and test methods for the protectors in use of field goalkeepers to provide protection for arms, chest, abdomen, legs, feet and groin, as well, as for protection of field players’ shins.

The impact-resistance of the covers mentioned above is tested with the usage of impactor falling freely onto the test-sample placed on the anvil. Various anvils and the protective ring system simulate the shapes of individual body parts. Yet, the impactors: hemispherical and flat-front reflect the shapes of the objects possibly causing the injuries typical to this sport: by the ball and by the hockey stick.

The standard distinguishes 5 levels of protection regarding most of the protectors, the field hockey players are equipped with, depending on the hit energy. The energy depends on given level and area of the protected body part. The document also specifies the accepted maximum values of force transferred under the test sample, to guarantee minimized injuries possible.

**PN-EN 13061:2004** Protective clothing. Shin guards for association football players. Requirements and test methods

The presented standard (7) includes the requirements and test methods for the footballers’ shin protectors. The football is a contact kind of sport and the threat of injuries is common. The protectors meeting the requirements of the document are designed for remarkable reducing the heavy attrition, contusions and wounds caused by the impacts.

Testing the resistance of the shin protectors to the blunt impact should be executed at the workplace equipped with:

- 15mm diameter anvil with the cylindrical top surface mounted on a fixed force sensor,
- a conical shaped piece simulating a leg, put onto the anvil,
- an impactor of a rectangle transverse cross-section,
- a system recording the dynamics of force or its peak value.

Each of the samples is to be hit at three different points, both central, and side of the protector, at the proper velocity. 3 different, random samples of product are subject to the same procedure. The test is passed if the mean value of peak force transferred at 3 single impacts at the same point of the protector does not exceed 2kN for each tested surface.

Shin protectors for footballers should be also subject to estimation of their resistance to the hit with metal bolt falling freely at the appropriate velocity onto the sample put on the horizontal, cone-shaped piece. During this kind of test the internal surface of the protector may not be pierced or torn and none of the hard elements should break.
SUMMARY

The analysis of the gathered European standards and other document covering the requirements and methods of estimating various impact-resistant protectors (for: footballers, motorcyclists, hockey players, horse riders, martial arts adepts, policemen, security staff, escorts etc.) allows for the statement:

- the way of determining resistance to impact at various protectors is based on the same rules. The falling freely impactor with a conformable energy hits tested sample located on an anvil.
- there is a sensor under the anvil to register the peak or the dynamics of force transferred beneath the tested object,
- weight and shape of the impactor imitate the objects which cause potential injuries,
- shape of the anvils simulate relevant areas of body to protect
- the standard-permissible values of both hit energy and force transferred beneath the protector take into account:
  - estimation of occurrent threat risk in specific situation,
  - kind of the body area exposed to an injury possible.

The precision of requirements appearing in each of the documents analyzed focuses on providing the guarantee of maximum safety in certain situations. The European standards published regard protectors for various sports adepts. Only the BS 7971 includes the guidelines concerning the protective garments and equipment for policemen, prison guards, security agency staff, escorts and couriers.

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   Part 8:2003 Blunt trauma body, shoulder, abdomen and genital protectors. Requirements and test methods.
FLAME RESISTANT MULTIFUNCTIONAL FABRICS AGAINST ELECTRIC ARCS

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ABSTRACTS

1. Fabric for protective suits have to perform to various requirements due to different usages. This depends on the source and potential of the danger. (requirements)

2. Protection against electric arcs is nowadays possible on a far higher level than the low one required by the current European and American standards (standards).

3. Protective suits against electric arcs can also include antistatic properties for electrostatic protection without any problem. This is important when working in so called ex-atmospheres, e.g. at gas-pipes or petrol stations. (additional properties)

4. Even the high visibility requirements of the EN 471 be fulfilled in yellow (RAL 1026) for protective suits against electric arcs. High visibility orange and red is possible too, but only on the lowest level of flame retardancy of the weak European and American standards. (current possibilities)

5. Further functional properties, such as chemical resistance, EN 13034 Type 6, or water-, oil- and stain repellency can be applied nowadays on a very high and long lasting level. (additional finishes / Nano technology)

6. Wear properties of the various blends. (comparison)

7. New fabrics with better prevention of heat transfer better are under development. Maybe that this as well as high visibility red or orange can already be reported at the ECPC.

Schümer is an old established textile company, founded more than 200 years ago in Germany, producing primarily 100% Cotton as well as various blends of Wool, Viscose, Polyester and Aramid in its younger history.
Nowadays, our strength is the production of flame-resistant “High-Tech-Cotton”, known as Schümer SECAN®, a registered trade mark since 1982.
Different fabrics made of different blends feature different benefits – in terms of safety and wear properties, as well as in terms of additional functional properties. Schümer’s “High-Tech-Cotton” SECAN® offers the best possible solution and combination for all aspects, which is essential, as only protective clothing which is well liked and therefore actually worn, can protect the worker.

100% Cotton can absorb moisture up to 20% of its own weight and still feels dry, whereas synthetic fabrics can store – if at all – only up to 4%, and the moisture moves along the fibre and the wearer feels wet or even cold due to heat lost by evaporation.

Beside of these pleasant wear properties of 100% High-Tech-Cotton, Schümer SECAN® offers the best possible flame-resistant properties for fire fighters (EN 469), welders (EN 470) and heat exposed workers (EN 531) as well as workers, exposed to the risk of electric arcs (ENV 50354).

Many other producers of flame resistant fabrics will say this about their fabrics.

With regard to the fulfilment of the existing relevant European Norms based on the EN 15025 (test method for limited flame spread) or ENV 50354 (electric arc test method), everyone is right.

But these Norms are not only very low, they are actually not sufficient enough to protect workers in the case of really serious accidents, which the norm does not cover.

Fabric that fulfils the EN 15025 does not necessarily need a long-lasting and good flame resistant finish. It just needs to withstand a little 4cm flame, held against the surface of the fabric in an angle of 90° (or edge – version B) for 10 sec. after 5 simple household washes at 60°C.

Schümer does use a 10cm flame, held against the edge of the fabric, as long as it needs to start a flame – we do this after 40 to 60 industrial washes at 93°C and we do this special test with every production roll of approx. 120 m!
DEVELOPMENT OF A VERSATILE INSULATING JACKET USING NiTi ALLOY TWO-WAY SMA CONICAL SPRING

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ABSTRACT

In order to develop a temperature-adaptable insulating garment, we applied NiTi alloy two-way shape memory springs to a windproof jacket. Insulation and buffering properties were evaluated under the transient temperatures (30°C, 55% RH to 0°C and -5°C) using the HCE (Human-Clothing-Environment) simulator. A significantly high microclimate temperature inside the clothing system was observed at the two-way SMA spring attached jacket from subjective wear trials and buffering property was perceived by wearers at the transition moment from warm to cold. The results proposed a possibility of an intelligent garment for cold weather using two-way shape memory materials.

1. INTRODUCTION

Integrating intelligent materials into a clothing system is becoming a hot field, which opens up huge applications. Intelligent and dynamic garment can be defined as the garment can sense and react to the wearer’s and/or the environmental conditions. New types of 'smart' clothing which adapt to changing temperatures to keep the wearer comfortable have been being developed. For the insulation purpose, air has been known as the best material in terms of the efficiency. Furthermore, its versatility and environmental friendliness are ideal for the next generation insulating material for an intelligent garment.

The shape memory alloys have two different sets of properties above and below a certain actuation temperature. Below this temperature the alloy has a martensite structure and easily deformable, and above the temperature, the alloy tends to return to a previously set shape. The actuation temperature can be set by altering the ratio of alloys. If the actuation temperature is reached, the alloy returns to the originally memorized shape. When activated in garments, one-way shape memory alloys provide increased insulation according as the air gaps between adjacent layers of clothing are increased. Upto now, therefore, one way SMAs have been generally utilized to protect against extreme heat sources [1]. In this study, we applied the two-way shape memory alloy (TWSMA) for the temperature adaptable cold weather
protection. Two-way shape memory effects of the SMA were investigated under transient warm to cold conditions with fabric level tests and garment wear trials.

2. METHODOLOGY

2.1. NiTi ALLOY TWO-WAY SHAPE MEMORY SPRING

A 1mm diameter NiTi wire was used to form a flat conical spring with an actuation temperature of 5 °C. The springs were trained by thermo-mechanical treatment to have two-way shape memory effect. The final parameters of the springs were: the mean diameter of the spring 35 mm and the pitch of the spring 10 or 15 mm. The springs were designed to be flat at room temperature and to be extended below the actuation temperature. The austenite phase SMA was set to be as flat as possible to ensure minimum thermo-physiological effect when insulation is not required between the fabric layers.

2.2. APPARATUS

For the test under transient conditions, HCE (human-clothing-environment) simulator was used [2, 3]. The system consists of a power supply with a temperature control unit, a sweating hot plate, two environmental chambers, and a data-logging system. Two detachable environmental chambers are separately controlled. Specimens are set in a sample holder and placed over the plate with appropriate air space to simulate clothing layers. For the test of a layered system, layers can be added to the system in the same manner. Temperature sensors are located in each layer to measure the microclimate. The plate unit can be rotated easily and is suspended from a metal rod that connects the two chambers. Thus transient conditions can be achieved in a very short time by quickly moving the plate from one chamber to another. For the dry test, the plate temperature is maintained at 33°C to simulate the skin temperature of the human body at comfortable conditions. The temperature in each garment layer is continuously measured during the test period. The data are collected and recorded through a computer connected to a data-logger.

2.3. TEST PROCEDURE

TWSMA conical springs were applied to a three-layer clothing system; a PET blended undershirt, a PET shirt, and a water proof breathable jacket (PET lining + 2-layer ePTFE film laminated fabric). The TWSMA springs were attached between the PET lining and the waterproof breathable fabric at even distances. Next to the skin simulating hot plate, the PET blended undershirt, PET shirt fabric, TWSMA spring attached PET liner, and the ePTFE laminated fabric were mounted in order. The test unit was stabilized in a warm environment (30°C, 55% RH) for 20 minutes, and then quickly moved to the cold environment (0°C or -5°C) for 40 minutes. The temperature profiles within each layer and on the fabric surfaces were collected and recorded every 30 seconds. The insulation efficiency and buffering properties against temperature changes were calculated based on the temperature profiles [4].

For the subjective wear trials, six healthy, non-smoking males were selected. Their average age, weight, and height were 25.2±2.5 years, 175.3±5.3cm, and 69.0±4.5kg, respectively. They wore the garments
made of identical fabrics that we used in fabric tests except an extra fleece jacket for the insulation of subjects. Skin temperature and microclimate temperatures within each layer were measured every 10 second. Test protocol is in Fig.1. The subjective thermal sensations were rated using 7 point scales at every 10 minute.

<table>
<thead>
<tr>
<th>Time</th>
<th>30min</th>
<th>60min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Environmental Temp</td>
<td>25°C</td>
<td>0°C</td>
</tr>
<tr>
<td>Activity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Test protocol for subjective wear trials of TWSMA incorporated jacket and control

2.4. STATISTICAL ANALYSIS

T-test and a nonparametric Wilcoxon sign-rank test were used to compare the microclimate temperatures and subjective ratings between the test garment and control.

3. RESULTS

3.1. TRANSIENT INSULATION USING HCE

At 0°C of environmental temperature, 1.9 and 2.7°C increases of microclimate temperatures were observed for the 10mm and 15mm of TWSMA attached clothing systems, respectively. At -5°C, 1.4 and 2.2°C increased for 10mm and 15mm, respectively, in comparison with a control (Fig. 2). The increased insulation in comparison with a control were 11~16% at 0°C and 7~11% at -5°C, depending on the pitch of the spring. The temperature buffering properties were improved by 26~38% at 0°C and 13~22% at -5°C depending on the pitch of the spring.

3.2. MICROCLIMATE TEMPERATURES OF GARMENT TEST

As shown in Fig. 3, average microclimate temperature, measured on the outer surface of the TWSMA attached layer was significantly higher than a control at cold condition. The mean skin temperature of the TWSMA jacket, however, showed significantly higher than control only at the initial transition for short period (32~35min).
Figure 2. Temperature changes on the outer surface of liner fabric of TWSMA attached clothing system with two different TWSMA heights and control at 0°C and -5°C.

Figure 3. Microclimate temperatures below the outmost layer (left) and mean skin temperatures (right) of TWSMA attached jacket and control (n=6).

3.3. SUBJECTIVE THERMAL SENSATIONS

Even though the subjects reported that they feel warmer in the TWSMA attached jacket throughout the all periods of cold conditions, it was period 5 that thermal sensation was rated significantly better for the TWSMA applied jacket as shown in Fig. 4. This result verified the buffering property of the TWSMA applied jacket.

4. DISCUSSION AND CONCLUSIONS

In this study, we attempted to develop an intelligent thermal insulation clothing using NiTi alloy two-way shape memory conical springs. Using the Human-Clothing-Environment simulator, we investigated the transient thermal insulation and buffering property of the inflated air formed by the TWSMA springs. It was found that at the transient condition of warm to cold, the inflated air by the TWSMA increased the temperature and kept the temperature constantly. The temperature buffering property was obtained from self-operating inflation by TWSMA springs at cold exposure. Results of wear trials with full size garments
verified the insulation and buffering capacities of the TWSMA applied jacket at transient conditions. Incorporating two-way shape memory alloy into a garment might provide a possibility of a new versatile and environmental friendly insulating system combining temperature adaptability of PCM and insulation consistency of still air. For more effective application, composition and design of shape memory materials have to be studied further.

Figure 4. Subjective thermal sensation ratings according to the period (n=6).

REFERENCES

COMFORTABLE PROTECTION AGAINST MOLTEN IRON SPARKS AND SPLASHES

Y. BADER, H. EICHINGER

DuPont Personal Protection, SWITZERLAND
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For more than 25 years, DuPont Personal Protection (DPP) is active in heat and flame protective market with NOMEX® and KEVLAR® fibres. So, DPP is in direct contact with many industries in most European countries and has gained many years of field experience.
Over the years, the need for a comfortable protection against molten iron splashes in Europe has increased steadily.
Although there are important differences in the behaviour of the various metals and alloys when hitting a fabric surface, the fundamental mechanisms can be described as follows:
Molten metal splashes are a heat source of 700°C to 1500°C.
This heat source can ignite the garment and/or burn through the garment causing personal body burn injuries.
To protect the worker, his/her PPE should evacuate this heat source immediately and totally. This effect is called “shedding”.
Crucial indicators for a suitable material for PPE (personal protective equipment) against molten metal are:
– it should not ignite when in contact with a heat source,
– the hot fluid should not stick to it (shedding capability),
– capability to block heat transfer through the garment.
For all these technical requirements, norms and standards have been created and adequate testing infrastructure developed. However, there are only very few testing facilities that allow assessing PPE in fabric and garment form meeting the whole spectrum of requirements. Therefore, the presentation will deal with testing equipments like DuPont Molten Metal-Man® and DuPont Thermo-Man®.
DuPont has developed a new product NOMEX® METALPRO protecting against iron splashes. Based on test results and wear trials, this new development shows excellent protection performance considering its very low weight. In addition, the comfort aspects are outstanding.
The examples discussed will show how solutions can be a balance between heat protection, comfort/ergonomics and value-in-use. Other novelties regarding coated fabrics will be presented.
KNITTED TEXTILE MATERIALS PROTECTING AGAINST STATIC ELECTRICITY

dr inż. Anna PINAR, dr inż. Edyta MATYJAS-ZGONDEK
TRICOTEXTIL Institute of Knitting Techniques and Technologies
Łódź, POLAND

ABSTRACT

In the paper the research results of application of the knitting techniques in technology of materials with protective properties against static electricity are presented. The assumption of designing and researching work was the development of technology of materials with durable anti-electrostatic properties designed for protective clothing and fancy materials. These materials have the anti-electrostatic properties resulted from the insertion of the electro-conductive yarns into their structure. The designing of the knitted wear structures was intended to elaboration of the knitwear fulfilling requirements of the standards for homogeneous and heterogeneous anti-electrostatic textiles. The subject of the research was the knitwear made with use of weft and warp knitting techniques. The finishing process of knitting fabric was realized on the base of traditional procedures adequate for used raw material. Also the evaluation of the anti-electrostatic and usable properties was made in dependence on structural solution. The results of the investigation showed the rightness of the established technological assumptions and possibility of optimization of anti-electrostatic properties for these materials.

1. INTRODUCTION

The electrostatic properties of textile materials which contain the conductive fibres depend on the type of used raw materials and technological solutions. To the most important factors that hale an influence on electrostatic properties of materials from this group is involved conductivity of electro-conductive fibres, the amount and way of their replacement and type of a companying raw material. These factors have also direct impact on intensity of disappearing electric charges gathered on material fibres surface [1 – 4].

The presented in the article anti-electrostatic materials was made by knitting techniques. There were used two basic constructive solutions of knitted fabrics in a dependence on their usage which are upholstery and clothing materials. The electrostatic properties were given to materials by introducing of yarns which contain electro-conductive components into their structure. The yarns were introduced into knitted fabrics’ structure in two systems, where as a result that is knitted fabrics present the
properties of anti-electrostatic homogeneous materials (upholstery materials) and non-homogenous (clothing) [2, 3, 5].

The special advantage of using electro-conductive fibres in electrostatic materials technology is high durability of given electrostatic properties and a possibility of their optimising in a dependence on material structural properties and finishing methods [2].

2. TESTING MATERIAL

The testing material contained two groups of materials made by knitting techniques. The first one contains knitted fabrics for upholstery materials which have anti-electrostatic and anti-flammable properties [2, 4]. The second one includes the knitted fabric for clothing which has protective properties against static electricity [1, 4].

2.1. TESTING MATERIAL – UPHOLSTERY MATERIALS

The testing material contained four variants of anti-electrostatic and anti-flammable knitted fabrics. The basic criterions of designed knitted fabrics structures includes the way of electro-conductive yarn introduction, the type of basic raw material and pattern values. The stitch solutions of knitted fabrics were developer for weft-knitting by suggested properties of electrostatic homogenous material. There was used the not full two threads jacquard, where definite by the repeat of pattern stitches are differential by the type of used yarn towards themselves. The material background was made of texture polyester yarn with linear mass of 167 dtex and filaments numbers of 32. The knitted fabrics were made in two variants which were differentiated by type of electro-conductive yarn (table 2.1.1) [2].

Table 2.1.1 The variants of anti-electrostatic knitted fabrics.

<table>
<thead>
<tr>
<th>Marking the variant of knitting fabric</th>
<th>Kind of electro-conductive yarn</th>
<th>Linear mass of electro-conductive yarn, tex</th>
<th>Share of electro-conductive yarn in knitting fabric, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Yarn made of segmental fibres VSs LENZING 1,3/38 in plaid of polyester monofilament, containing of carbons compound RESISTAT 100dtx F9606* Percentage participation of yarn components, appropriately: 75% and 25%.</td>
<td>40</td>
<td>40,3</td>
</tr>
<tr>
<td>E</td>
<td>Yarn of PES monofilament structure in plaid of segmental fibres, containing of polyacrylonitrile fibres with anti-static coat of copper sulphide PAC (Permanent Access Cable)** Percentage participation of yarn components, appropriately: 10% and 90%.</td>
<td>2 x 25</td>
<td>49</td>
</tr>
</tbody>
</table>

The anti-flammable properties were given to knitted fabrics during finishing process with usage of anti-flammable agents. The finishing of knitted fabrics was made in two variants which were differentiated by the type of applied anti-flammable agent. (table 2.1.2)
The knitted fabrics finishing process was realised in laboratory conditions [6] in a following way:

- finishing of material with using active water emulsion of synthetic polymer TEXAFLAM CM with the concentration 800 g/l in the form of foam and quantity ca. 170 g/m². Drying process was carried out in temperature 150°C in time of 3 min;
- material impregnation of the solution and with following contents:
  - 650 g/l TEXAFLAM BS;
  - 40 g/l TEXACRYL IS (acrylic polymer soluble in water).

The used film forming polymer causes surface junction between the non-flammable agent and fibre. Impregnated samples were drying in temperature of 120°C in time of 2 minutes and curing 2 minutes in temperature 170°C.

### 2.2. TESTING MATERIAL – CLOTHING MATERIALS

The testing material contained two groups of knitted fabrics differentiated by a way of electro-conductive yarn introduction. There were used structural solutions with supposed properties of electrostatic non-homogenous material. In the first group of knitted fabrics the electro-conductive yarn was introduced in vertical system in along wised direction of knitted fabric (knitted fabrics indication 1_p, 2_p, 3_p), and in the second group in net system (knitted fabrics variant indication (1_s, 2_s, 3_s)). The knitted fabrics were made by warp-knitting technique. Both groups of knitted fabrics were made in three variants which were differentiated by electro-conductive yarn share and the degree of knitted fabrics fulfilment by background yarn (table 2.2.1 and 2.1.2). There was used an electro-conductive double-component yarn of ordinal fibres VSs LENZING 1,3/38 (75%) in braid of polyester monofilament containing carbon compounds RESISTAT 100dtex F9605 (25%) with linear mass of 40tex. The knitted fabrics’ background was made of polyester yarn of filament fibres with linear mass of 110dtex f24.

### Table 2.1.2 The variants of anti-flammable finishing of anti-electrostatic knitted fabrics.

<table>
<thead>
<tr>
<th>Marking the variant of knitting fabric</th>
<th>S_1</th>
<th>S_2</th>
<th>E_1</th>
<th>E_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kind of slow-burning agent</td>
<td>TEXAFLAM CM</td>
<td>TEXAFLAM BS</td>
<td>TEXAFLAM CM</td>
<td>TEXAFLAM BS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Marking the variant of knitting fabric</th>
<th>1_s</th>
<th>2_s</th>
<th>3_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share of electro-conductive yarn in knitting fabric, %</td>
<td>4,0</td>
<td>6,1</td>
<td>4,6</td>
</tr>
<tr>
<td>The index of background surface fulfilment of knitted fabric, Z_p</td>
<td>2,8</td>
<td>1,6</td>
<td>2,3</td>
</tr>
<tr>
<td>The index of background volume fulfilment of knitted fabric, Z_o</td>
<td>0,78</td>
<td>0,54</td>
<td>0,68</td>
</tr>
</tbody>
</table>
Table 2.2.2 The variants of knitted fabrics with electro-conductive yarn introduced in net system.

<table>
<thead>
<tr>
<th>Marking the variant of knitting fabric</th>
<th>1S</th>
<th>2S</th>
<th>3S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share of electro-conductive yarn in knitting fabric, %</td>
<td>12,8</td>
<td>10,1</td>
<td>9,8</td>
</tr>
<tr>
<td>The index of background surface fulfilment of knitted fabric, Zp</td>
<td>2,85</td>
<td>3,38</td>
<td>2,74</td>
</tr>
<tr>
<td>The index of background volume fulfilment of knitted fabric, Zo</td>
<td>0,83</td>
<td>1,11</td>
<td>0,84</td>
</tr>
</tbody>
</table>

3. METHODOLOGY, SCOPE AND TEST RESULTS

3.1. UPHOLSTERY MATERIALS

For raw and finished knitted fabrics were established basic structural parameters [7] and surface mass [8] (table 3.1.2).

Flammable properties were described for finished knitted fabrics for two source of ignition which were the imitation of cigarette’s smouldering flame (ind. 0) and match’s flame (ind. 1). With flammable medium activity were treated the right usage sites of materials. The tests were realized in the temperature of 23°C, by relative air humidity of 37% [9]. The test results of combustibility indicators are shown in table 3.1.3.

The tests of electrostatic indicators of knitted fabrics were carried out for knitted fabrics after finishing and for comparison for raw knitted fabrics (indications S₀ and E₀) [10]. The test results of knitted fabrics electrostatic properties are show in a table 3.2.4. The right usage site of material was treated. Purposing the showing of electrostatic homogenous material properties were carried out additional tests of electrostatic indicators on the left site of knitted fabrics. The additional tests were carried out for raw knitted fabrics. The test of electrostatic properties were realised in dry climate conditions with relative air humidity of 25,5% and in temperature of 23,2°C.

The knitted fabrics after anti-flammable finishing were assessed under content of free and hydrolysed formaldehyde [11]. The results are shown in a table 3.1.1.

The knitted fabrics’ tests were realised in accredited laboratories of Science and Research Institutes according to standards requirements ***.

Table 3.1.1. The test results of content of formaldehyde in knitted fabrics after anti-flammable fishing

<table>
<thead>
<tr>
<th>Marking the variant of knitting fabric</th>
<th>S₁</th>
<th>E₁</th>
<th>S₂</th>
<th>E₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content of formaldehyde, mg/ kg</td>
<td>6,92</td>
<td>9,25</td>
<td>13,8</td>
<td>9,04</td>
</tr>
</tbody>
</table>
Table 3.1.2. The basic structural parameters and surface mass of raw and finished knitted fabrics

<table>
<thead>
<tr>
<th>Marking the variant of knitting fabric</th>
<th>( S_0 )</th>
<th>( S_1 )</th>
<th>( S_2 )</th>
<th>( E_0 )</th>
<th>( E_1 )</th>
<th>( E_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Course density, number of courses /dm</td>
<td>124</td>
<td>101</td>
<td>124</td>
<td>120</td>
<td>105</td>
<td>138</td>
</tr>
<tr>
<td>Wale density, number of wales /dm</td>
<td>102</td>
<td>128</td>
<td>110</td>
<td>97</td>
<td>120</td>
<td>88</td>
</tr>
<tr>
<td>Surface density, number of loops /dm²</td>
<td>12684</td>
<td>12928</td>
<td>13640</td>
<td>11640</td>
<td>12600</td>
<td>12144</td>
</tr>
<tr>
<td>Thickness, mm</td>
<td>1,18</td>
<td>1,10</td>
<td>0,99</td>
<td>1,42</td>
<td>1,32</td>
<td>1,14</td>
</tr>
<tr>
<td>Surface mass, g/m²</td>
<td>268</td>
<td>444</td>
<td>364</td>
<td>269</td>
<td>416</td>
<td>352</td>
</tr>
</tbody>
</table>

Table 3.2.3. Flammable properties of fished knitted fabrics

<table>
<thead>
<tr>
<th>Ignition source</th>
<th>Marking the variant of knitting fabric</th>
<th>Time, s</th>
<th>Damage, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Flame burning</td>
<td>Smouldering</td>
</tr>
<tr>
<td>0</td>
<td>( S_1 )</td>
<td>0 / 0</td>
<td>0 / 0</td>
</tr>
<tr>
<td></td>
<td>( S_2 )</td>
<td>0 / 0</td>
<td>0 / 0</td>
</tr>
<tr>
<td></td>
<td>( E_1 )</td>
<td>0 / 0</td>
<td>0 / 0</td>
</tr>
<tr>
<td></td>
<td>( E_2 )</td>
<td>0 / 0</td>
<td>0 / 0</td>
</tr>
<tr>
<td>1</td>
<td>( S_1 )</td>
<td>2 / 0</td>
<td>0 / 0</td>
</tr>
<tr>
<td></td>
<td>( S_2 )</td>
<td>0 / 0</td>
<td>0 / 0</td>
</tr>
<tr>
<td></td>
<td>( E_1 )</td>
<td>25 / 33</td>
<td>0 / 6</td>
</tr>
<tr>
<td></td>
<td>( E_2 )</td>
<td>0 / 0</td>
<td>0 / 0</td>
</tr>
</tbody>
</table>

Table 3.1.2. The electrostatic properties of raw and finished knitted fabrics

<table>
<thead>
<tr>
<th>Marking the variant of knitting fabric</th>
<th>( R_S, \Omega )</th>
<th>( \rho_S, s )</th>
<th>( R_V, \Omega )</th>
<th>( t_{50}, s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_0 )</td>
<td>4,93 x 10⁴</td>
<td>3,20 x 10⁴</td>
<td>9,76 x 10⁵</td>
<td>6,34 x 10⁵</td>
</tr>
<tr>
<td>( S_1 )</td>
<td>2,10 x 10⁵</td>
<td>—</td>
<td>4,16 x 10⁵</td>
<td>—</td>
</tr>
<tr>
<td>( S_2 )</td>
<td>2,07 x 10⁵</td>
<td>—</td>
<td>4,10 x 10⁶</td>
<td>—</td>
</tr>
<tr>
<td>( E_0 )</td>
<td>3,33 x 10⁵</td>
<td>3,89 x 10⁵</td>
<td>6,59 x 10⁶</td>
<td>7,70 x 10⁶</td>
</tr>
<tr>
<td>( E_1 )</td>
<td>2,70 x 10⁶</td>
<td>—</td>
<td>5,35 x 10⁶</td>
<td>—</td>
</tr>
<tr>
<td>( E_2 )</td>
<td>4,74 x 10⁶</td>
<td>—</td>
<td>9,37 x 10⁶</td>
<td>—</td>
</tr>
</tbody>
</table>
3.2. Clothing material

For finished knitted fabrics were described basic structural parameters [7], surface mass [8] and electrostatic properties [10]. The tests were realised in accredited laboratories of Science and research Institutes. The test results were presented in tables 3.2.1 and 3.2.2. The electrostatic properties of knitted fabrics were described in dry climate conditions with relative air humidity of 26% in temperature of 22,7°C. The left site of knitted fabrics which is the right site of usage material were treated.

Table 3.2.1. The basic structural parameters and surface mass of fished knitted fabrics

<table>
<thead>
<tr>
<th>Marking the variant of knitting fabric</th>
<th>1_p</th>
<th>2_p</th>
<th>3_p</th>
<th>1_s</th>
<th>2_s</th>
<th>3_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Course density, number of courses /dm</td>
<td>176</td>
<td>129</td>
<td>171</td>
<td>160</td>
<td>153</td>
<td>118</td>
</tr>
<tr>
<td>Wale density, number of wales /dm</td>
<td>69</td>
<td>70</td>
<td>69</td>
<td>72</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Surface density, number of loops /dm²</td>
<td>12144</td>
<td>9030</td>
<td>11799</td>
<td>11520</td>
<td>10710</td>
<td>8260</td>
</tr>
<tr>
<td>Thickness, mm</td>
<td>0.63</td>
<td>0.53</td>
<td>0.59</td>
<td>0.73</td>
<td>0.65</td>
<td>0.70</td>
</tr>
<tr>
<td>Surface mass, g/m²</td>
<td>145.0</td>
<td>86.0</td>
<td>119.0</td>
<td>132.0</td>
<td>152.0</td>
<td>122.7</td>
</tr>
</tbody>
</table>

Table 3.2.1. Electrostatic properties of knitted fabrics

<table>
<thead>
<tr>
<th>Marking the variant of knitting fabric</th>
<th>1_p</th>
<th>2_p</th>
<th>3_p</th>
<th>1_s</th>
<th>2_s</th>
<th>3_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface resistance, Ω</td>
<td>1.49 x 10⁵</td>
<td>2.57 x 10⁵</td>
<td>1.52 x 10⁵</td>
<td>2.05 x 10⁵</td>
<td>1.03 x 10⁵</td>
<td>7.09 x 10⁴</td>
</tr>
<tr>
<td>Surface resistivity, Ω</td>
<td>3.00 x 10⁶</td>
<td>5.14 x 10⁵</td>
<td>3.04 x 10⁶</td>
<td>4.10 x 10⁶</td>
<td>2.06 x 10⁵</td>
<td>1.42 x 10⁶</td>
</tr>
<tr>
<td>Cross resistance, Ω</td>
<td>1.3 x 10¹¹</td>
<td>1.3 x 10¹¹</td>
<td>1.2 x 10¹¹</td>
<td>8.53 x 10¹¹</td>
<td>1.52 x 10¹¹</td>
<td>1.34 x 10¹¹</td>
</tr>
<tr>
<td>Time of half-disappearing of electric charge, s</td>
<td>&lt; 0.01</td>
<td>0.070</td>
<td>0.022</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Index of monitoring, -</td>
<td>0.485</td>
<td>0.453</td>
<td>0.485</td>
<td>0.787</td>
<td>0.787</td>
<td>0.755</td>
</tr>
</tbody>
</table>

4. THE ANALYSIS OF TEST RESULTS

The analysis of test results for knitted fabrics for upholstery materials was carried out for the assessment of flammable properties and electrostatic properties in dependence on used types of electro-conductive yarns and anti-flammable finishing.

For knitted fabrics for clothing the analysis of test results contained the assessment of electrostatic properties in dependence on used structural solutions.
5. SUMMARY

The knitwear designed for upholstery materials meet the requirement in the scope of protection against static electricity for homogeneous materials but at the same time the lower resistance of carrying the electric charge is characterized for knitwear made of electro conductive yarn with the composition of VSs LENZING 1,3/38 75% and RESISTAT 25%. The important differences were not observed in the scope of electrostatic properties of materials in relation to kind of non-flammable agent applied to the fibers. In the applied stock solution, the knitwear finished using non-flammable agent TEXAFLAM BS do not burn and do not non-glow. These materials meet the requirement of the standards [12] for the acceptable content of formaldehyde (<300 mg/kg)

The knitwear designed for clothing materials meet the requirement of subject standard for anti-electrostatic protective clothing. The analysis of the test results show that the values of electrostatic indicators depend on the share of conductive yarns as well as the way of insertion them into the structure of materials and the properties of the material background.

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* Spolsin spol. sr. o. (CZ)
** Europa NTC Sp. z o. o.(PL)
*** INOTEX Ltd. Dvůr Králové ; Institute of Knitting Techniques and Technologies „Tricotextil” – Łódź; Textile Research Institute – Łódź; Textile Institute and Institute of Textile Materials Engineering – Łódź
NEW COOLING UNDERGARMENT FOR PROTECTIVE GARMENT SYSTEMS

dr. Barbara PAUSE
Textile Testing & Innovation, LLC

ABSTRACT

The newly-developed cooling undergarment is a suitable part of a protective garment system. The cooling undergarment is worn by fire fighters, steel mill workers and workers in nuclear and chemical facilities in order to avoid heat stress and related illnesses while performing their duties. The cooling effect is based on the latent heat absorption of phase change material (PCM), a highly-productive thermal storage mean. Due to the very high latent heat storage capacity of the selected PCM, a long-lasting cooling effect is already obtained with a relatively small amount of PCM which leads to a relatively low weight of the cooling undergarment. After taking off the cooling undergarment, the PCM is regenerated under room temperature and is available to cool again after a short period of time. The PCM is embedded in a polymer matrix from which a film-like structure is made. The polymer film with PCM is arranged between two fabrics. The application of the cooling undergarment leads to extended wearing times of the protective garment systems resulting in an enhanced productivity. The heat stress-related health risks the wearers of protective garments are exposed to have been minimized by the application of this new cooling undergarment.

1. INTRODUCTION

Most protective garment systems possess a poor thermo-physiological wearing comfort due to the insufficient transfer of heat and moisture through the layers the garment consists of. As a result, under strenuous activities and moderate to hot climatic conditions, the core temperature of the wearer’s body may rise above the comfort level into the heat stress zone. These heat stress conditions lead to discomfort and fatigue and, in severe cases, risk the health and safety of the garment’s wearer. The constant discomfort while wearing such protective garment systems can lead to a reduced productivity. A very expensive solution of the problem nowadays is the use of a bulky and heavy microclimate cooling system. However, a much cheaper and durable solution would be a light-weight and non-bulky cooling undergarment to which phase change material (PCM) – a highly productive thermal storage mean – is applied.
2. PHASE CHANGE MATERIAL (PCM)

Phase Change Material (PCM) possesses the ability to change its physical state within a certain temperature range. When the melting temperature is obtained in a heating process, the phase change from the solid to the liquid state occurs. During this melting process, the PCM absorbs and stores a large amount of latent heat. The temperature of the PCM and its surroundings remains nearly constant throughout the entire process. In the reverse cooling process, the latent heat stored in the PCM is released into the environment in a certain temperature range, and a reverse phase change from the liquid state to the solid state takes place. During this crystallization process, the temperature of the PCM and its surroundings remains also nearly constant. When the phase change is complete, a continued heating /cooling process leads to a further temperature increase / decrease. The absorption or release of high amounts of latent heat without a temperature change is responsible for the desire to use PCM as a heat storage mean.

In order to compare the amount of latent heat absorbed by a PCM during the actual phase change with the amount of sensible heat absorbed in an ordinary heating process, the ice-water phase change process will be used. When ice melts, it absorbs an amount of latent heat of about 335 J/g. When the water is further heated, it absorbs an amount of sensible heat of only 4 J/g while its temperature rises by one degree Celsius. Thus, water needs to be heated from about 1 °C up to about 84 °C in order to absorb the same amount of heat which is absorbed during the melting process of ice.

In addition to ice (water), more than 500 natural and synthetic PCMs, such as paraffins, or salt hydrates are known. These materials differ from one another in their phase change temperature ranges and their latent heat storage capacities.

3. DEVELOPMENT OF THE COOLING UNDERGARMENT

The development of the cooling undergarment was carried out by means of a computer simulation and calculation procedure. The development steps consisted of the following tasks:

- PCM selection,
- Determination of the necessary PCM-quantity,
- Selection of a suitable PCM-containment structure,
- End-use product design.

In the first step of the development process, temperature profiles were created for various protective garment systems. The temperature profiles are based on the heat transfer through the prevailing protective garment system under consideration of different application conditions. The temperature profiles are used to determine the temperature range in which the PCM is supposed to function. The PCM selection is carried out on the basis of this temperature range.

In the second step, heat balance calculations were used to determine the necessary PCM quantity. Knowing the heat generation by the human body under different activities is one requirement for that. Furthermore, the dry heat transfer and the wet heat transfer through the garment layers was calculated based on the components heat and moisture transfer characteristics. An activity simulation was then used to estimate the body’s heat generation, the percentage of heat which can be released through the garment layers and the amount of heat which should be absorbed or released by the PCM to keep the
heat balance equalized. Considering the pre-selected PCM’s latent heat storage capacity, the necessary
PCM quantity was determined.

In order to prevent dissolution while in its liquid the PCM needs to be durably-contained in a carrier
material which is then applied to the suit’s fabric structure. Therefore, a containment structure for the
PCM was selected. Support fabrics to hold the containment structure with the PCM were also
determined. In the cooling undergarment design, a construction was made which aims to maximise the
thermal benefit under the consideration that the suit should be as light-weight as possible.

4. COOLING UNDERGARMENT DESIGN

For the application in the cooling undergarment, a non-combustible salt-hydrate with a high latent heat
storage capacity of about 250 J/g has been selected. The selected PCM absorbs latent heat when its
temperature rises above the comfort range and releases latent heat under room temperature conditions.
The cooling undergarment possesses a very high latent heat storage capacity of more than 100 kJ
which leads to long lasting cooling effects. The release of the latent heat stored in the PCM during the
use of the cooling undergarment happens after the suit is taken off. The latent heat release lasts only a
few minutes under room temperature conditions.

The PCM has been contained durably in an about one millimeter thick polymeric film. Patches of the
polymeric film with incorporated PCM are quilted between two fabrics.

The cooling undergarment covers the body in the way long underwear does. The suit’s design makes it
comparatively light-weight and allows for a non-bulky construction. The cooling undergarment is
washable and is therefore designed for daily usage.

5. APPLICATIONS

The cooling undergarment is designed as a supplemental component for various protective garment
systems. The suit can be worn instead of underwear, for instance, by fire fighters, steel mill workers,
workers in petrochemical, nuclear and chemical facilities as well as military personnel in order to
avoid heat stress and related illnesses while performing their duties. Wearing the cooling
undergarment in conjunction with air-tight and moisture impermeable chemical protective garment
system is especially beneficiary and will enhance the wearers productivity substantially.

6. THERMAL EFFECTS

The cooling undergarment is worn close to the skin which leads to a direct thermal interaction with the
wearer’s body. In the cooling undergarment application, the PCM absorbs excessive heat generated by
the wearer’s body during strenuous activities. As a result, the temperature in the microclimate near the
skin remains in the comfort range over an extended period of time. Regulating the microclimate
temperature reduces the skin’s sweat production, which significantly enhances the overall thermo-
physiological wearing comfort of the protective garment system.
7. TEST RESULTS AND DISCUSSION

In order to determine the improvement in thermo-physiological wearing comfort of protective garment systems resulting from the phase change material application in the cooling undergarment, controlled wearing trials have been performed. These trials have been carried out in a climatic chamber under an ambient temperature of 21 °C and a relative humidity of 40 %. In the test, the test subjects were riding a bicycle-ergometer over a period of 60 minutes without interruption.

During the tests, each test subject wore a chemical protective suit in conjunction with either the cooling undergarment or regular underwear. While carrying out the described activity, a metabolic heat rate of about 18 kJ/min. is generated by the body. A dry heat transfer in the amount of 16 kJ/min. is released through the protective garment system.

During the test, locations skin temperature and moisture contents in the microclimate were recorded on several measuring points. The mean skin temperature and the average moisture content were calculated from these measurements. Figure 1 shows the development of the mean skin temperature during the test.

![Figure 1: Development of the mean skin temperature during the test](image)

The test results shown in Figure 1 indicate that there is a fast increase in the mean skin temperature when wearing the chemical protective suit with the regular underwear underneath it. After about 45 minutes, the mean skin temperature already exceeds 36 °C. At this point, a heat stress situation is likely. On the other side, the cooling effect by heat absorption of the phase change material leads to a substantial delay in the temperature increase while wearing the chemical protective garment with the cooling undergarment underneath it under the same conditions. At the end of the test, the difference in the mean skin temperature totals about 2 °C. The delay in the temperature increase results in a significantly smaller amount of moisture build up in the microclimate such as it is show in Figure 2.

While wearing an air-tight chemical protective overall, the moisture content in the microclimate underneath the suit rises substantially due to the lack in moisture transfer through the material the suit consists of. Already after about 5 to 10 minutes, the moisture content in the microclimate leads to a feeling of an uncomfortable dampness. In contrast, the delayed increase in the mean skin temperature by the heat absorption of the phase change material results in a substantially lower amount of moisture generated by the skin. Therefore, the moisture content of the microclimate is kept on a much lower level throughout the test. Thus, wearing the cooling undergarment with phase change material underneath the air-tight chemical protective garment leads to a significant increase in the thermo-physiological wearing comfort of the protective garment system.
8. CONCLUSIONS

The cooling undergarment with phase change material has proven to be a suitable tool to improve the thermo-physiological wearing comfort of protective garment systems. The test results indicate that the cooling effect of the phase change material can delay the temperature rise and, hence, the moisture increase in the microclimate substantially. As a result, the wearing time of the garments can be extended significantly without the appearance of heat stress as a serious health risk. The longer wearing times will further result in a significant higher productivity. The designed cooling suit is comparatively lightweight, non-bulky and easy to clean.
Protective clothing limits body heat dissipation and may lead to thermal strain and discomfort even at moderate exposure temperatures. Phase change materials (PCM) can be used to reduce thermal strain and provide improved thermal comfort for workers wearing protective clothing. The cooling effect of PCM depends on the cooling capacity of the material. PCM adds to the total weight of clothing and represents an extra barrier to evaporative heat loss and moisture transport. Therefore, the potential cooling contribution provided by PCM should be identified and evaluated as a part of the total heat loss mechanisms through the clothing system. The aim of this study was to investigate the effect of PCM in protective clothing used in simulated work situations characterized by moderate metabolic heat production and heat exposure. We hypothesized that it would be possible to optimize cooling performance by a design that focuses on careful positioning of PCM, minimizing total insulation and facilitating moisture transport.

Thermal strain and thermal comfort were estimated through the following measurements: Heart rate, body heat production, total sweat production, rectal and skin temperatures, temperatures and moisture between clothing layers, subjective ratings of thermal comfort, temperatures, and perception of skin and clothing wetness.

The results from 4 different field and laboratory experiments were conclusive in that reduced thermal strain and improved thermal comfort were related to amount and distribution of PCM, reduced sweat production and adequate transport of moisture to the outer clothing shell. The test subjects gave positive ratings to lowering of skin temperatures even though body core temperature did not decrease.
ABSTRACT

Five students of a rescue training school cycled at 50 W for 20 minutes at 20 °C before walking up to 30 minutes in a climatic chamber at 55 °C and 30 % relative humidity. Four different types of clothing ensembles were used differing in terms of thickness and thermal insulation value were tested on separate days. All subjects completed 28-30 minutes in light clothing, but quitted after 20-27 minutes in three firefighter ensembles due to a rectal temperature of 39.0 °C or subjective fatigue. No difference in the evolution of mean skin or rectal temperature was seen for the three turnout ensembles. Sweat production amounted to about 1000 g in the turnout gears of which less than 20 % evaporated. It was concluded that the small differences between the turnout gears in terms of design, thickness and insulation value had no effect on the resulting physiological strain for the given experimental conditions.

1. INTRODUCTION

Firefighter’s clothing is designed to protect against environmental hazards (1). It must resist heat, flames and hot substances and international standards are available for testing such properties (2). In burning buildings air may quickly become hot and humid, posing high levels of heat stress on the firemen. Their protective clothing, in addition, reduces or even completely prevents the body’s normal heat exchange with the environment. Above certain ambient temperatures and humidity levels there is no dissipation of heat by convection, radiation and evaporation from the body. The main effect of clothing is then to reduce environmental heat gain. Accordingly, heat stress develops quickly in live firefighting (3-8). The protective equipment worn by the firefighter can weigh more than 20 kg, imposing a considerable extra physical load (9-11).

The purpose of this study was to investigate the thermal stress of different turnout gears during moderate work in a hot, humid ambient condition. One hypothesis was that the thickness of clothing would affect heat exchange and the development of heat stress.
2. METHODS

The ethical committee at Lund University approved the study. A medical doctor and a study leader with first aid education were present at all tests.

Subjects

Five healthy male firefighting students volunteered to participate in the study. A written consent had been obtained before they participated in the experiments. Their ages were 20-39 years old (mean=25, SD=8), heights 1.78-1.84 m (mean=1.81, SD=0.03), weights 67.2-76.3 kg (mean=72.6, SD=4.2). Each subject came to the lab and performed each of four tests (4 clothing conditions) during the same period of the day with the intervals of at least one day in between the experiments. Prior to heat exposure the subjects passed a type of max-test in order to define exercise level for heat exposure. Their maximum heat rates were between 188-202 b/min (mean=195, SD=6) and oxygen consumption 3.97-4.63 l/min (mean=4.16, SD=0.29).

Clothing

Four types of clothing were used by the subjects in the tests and are shown in the following table. Table 1. Specification of garment components for the different ensembles.

<table>
<thead>
<tr>
<th>Code</th>
<th>Ensemble (weight, kg)</th>
<th>Garment components</th>
<th>Equipment</th>
<th>Insulation value clo, (m²°C/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UW</td>
<td>underwear (RB90) (2.76)</td>
<td>T-shirt, briefs, RB-90 underwear (long shirt and long trousers), socks, sports shoes</td>
<td>Full face mask, pulse belt and watch</td>
<td>1.43 (0.222)</td>
</tr>
<tr>
<td>RB90</td>
<td>RB90 system (20.7)</td>
<td>T-shirt, briefs, RB90 underwear (shirt and trousers), outer garment (RB90 jacket and trousers), balaclava, RB90 gloves, socks, firefighting boots</td>
<td>Helmet, full face mask, compressed air cylinder, pulse belt and watch</td>
<td>2.78 (0.431)</td>
</tr>
<tr>
<td>ARY</td>
<td>New firefighting clothes, Norway ARY (19.8)</td>
<td>T-shirt, briefs, new outer garment (jacket and trousers), balaclava, RB90 gloves, socks, firefighting boots</td>
<td>Helmet, full face mask, compressed air cylinder, pulse belt and watch</td>
<td>2.77 (0.430)</td>
</tr>
<tr>
<td>ARY+</td>
<td>ARY with added middle layer (21.2)</td>
<td>T-shirt, briefs, training overall (jacket and trousers), new outer garment (jacket and trousers), balaclava, RB90 gloves, socks, firefighting boots</td>
<td>Helmet, full face mask, compressed air cylinder, pulse belt and watch</td>
<td>3.03 (0.470)</td>
</tr>
</tbody>
</table>

Experimental procedure

During preparation, all clothing, equipment (i.e., compressed air supply container, mask, helmet, etc.), and subject (nude and with all clothing and equipment) were weighed. The rectal temperature and skin temperature (8 locations) were measured with a Labview program (National Instruments, USA) every 15 seconds.
After preparation, the subjects cycled on a bicycle ergometer at 50 W with all clothing except for compressed air container and gloves for 20 minutes in order to simulate preparation work before smoke diving. Oxygen uptake was measured by MetaMax for 6 minutes after 5 minutes of cycling. Heart rate was monitored by Polar heart rate monitor (Sport Tester, Polar Electro Oy, Finland).

The subjects were weighed again after 20 min of cycling, put on the air bottles, entered the climatic chamber on 23rd minute and started to walk on a treadmill at 5 km/h. The chamber temperature was controlled at 55 °C, relative humidity at 30%, wind speed at 0.4 m/s. Oxygen uptake was measured after 5 min of walking, heart rate, rectal and skin temperatures were recorded continuously. The termination of walking and exposure was based on one of the following three criteria: 1) subjects felt conditions intolerable and unable to continue, 2) rectal temperature reached 39.0 °C, 3) subjects walked 30 min on the treadmill.

After cessation of exposure subjects were weighed again immediately. Each piece of clothing was weighed separately immediately after the subjects removed it. Right after the subjects were undressed and the measuring equipment was removed, the subjects were weighed just wearing the briefs and the rectal sensor.

3. RESULTS

The individual values for certain parameters at the time of withdrawal were recorded and the average values are given in Tables 2 and 3.

Table 2. Working time at 55 °C, metabolism, heart rate and perceived exertion (RPE). Mean and 1 SD of 5 subjects. Values are taken at the time of cessation of exposure.

<table>
<thead>
<tr>
<th>Time, min,sec</th>
<th>Metabolism, W/m²</th>
<th>Metabolism, W/m²</th>
<th>Heart rate, bpm</th>
<th>RPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicycle</td>
<td>Walking</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UW</td>
<td>29.30</td>
<td>1.26</td>
<td>189</td>
<td>5</td>
</tr>
<tr>
<td>RB</td>
<td>22.15</td>
<td>2.52</td>
<td>204</td>
<td>12</td>
</tr>
<tr>
<td>N</td>
<td>24.12</td>
<td>2.02</td>
<td>201</td>
<td>15</td>
</tr>
<tr>
<td>NM</td>
<td>23.27</td>
<td>1.59</td>
<td>204</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 3. Thermal responses. Mean and 1 SD of 5 subjects. Values are taken at the time of cessation of exposure.

<table>
<thead>
<tr>
<th>Tsk, °C</th>
<th>Trec, °C</th>
<th>Total sweat prod, g</th>
<th>Evaporated sweat, g</th>
<th>Thermal sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>UW</td>
<td>39.5</td>
<td>38.9</td>
<td>38.9</td>
<td>3.1</td>
</tr>
<tr>
<td>RB</td>
<td>39.8</td>
<td>39.8</td>
<td>39.8</td>
<td>4.0</td>
</tr>
<tr>
<td>N</td>
<td>39.8</td>
<td>39.1</td>
<td>39.1</td>
<td>4.1</td>
</tr>
<tr>
<td>NM</td>
<td>39.9</td>
<td>39.1</td>
<td>39.1</td>
<td>3.9</td>
</tr>
</tbody>
</table>

The metabolic rate during bicycling was around 200 W/m² for all conditions. During walking and heat exposure it was 198 W/m² for UW and about 270 W/m² for the other ensembles (Table 2).

Heart rate increased only marginally during the bicycle exercise and measured between 100 and 120 beats per min. Under heat exposure heart rate increases sharply for all conditions and reaches values between 160 (UW) and 170-180 beats per min for the other conditions (Table 2 and Figure 1).

All subjects completed 28-30 minutes in UW, but quitted after 20-27 minutes in the other three ensembles (Table 2). The reason for quitting was that \( T_e \) reached the break criterion of 39.0 °C. In few cases only the subject voluntarily stopped the exposure before this criterion was reached. The exposure time is significantly longer only for UW versus the three suits, not between suits.
The evolution of rectal temperature responses are shown in Figures 2 as mean values of five subjects for the four ensembles. At the end of the 20 min bicycle exercise skin temperature levels off after a 1-2 °C initial increase. Rectal temperature increases only marginally.

Under heat exposure all temperatures increase and there is no levelling off in any conditions. The lines for the turnout gears stop at the time when the first subject drops out. The slope and shape of these three lines are almost identical. The evolution of skin and rectal temperature for the UW conditions are significantly different. The initial rise in $T_{sk}$ is somewhat quicker for UW due to lesser protection (insulation) against the environmental heat. This initial rise, however, slows down and the rate of increase becomes much slower already after 3-4 minutes. The main reason is that evaporative cooling is higher and the metabolic rate is lower with this two layer clothing compared with the turnout gears.

![Figure 1](image1.jpg)

**Figure 1.** Mean heart rates for five subjects during the exposure.

![Figure 2](image2.jpg)

**Figure 2.** Time course of rectal temperature during the exposure. Mean values for five subjects. Curves stop when the first of five subjects stops.
The final values of skin temperature at cessation of exposure are almost the same for all ensembles or close to 40 °C. Similarly the rectal temperature at cessation is around 39 °C (Table 3). The values in Figure 2 are slightly lower as they show the values at the time when the first subject drops out.

Total sweat amount was 869 g for UW and around 1000 g for the turnout gears. The individual variation was considerable. The evaporated amount of sweat was similar or around 170 g for all ensembles.

4. DISCUSSION

Thick, multi-layer clothing is required to protect firefighters against environmental hazards of thermal origin, such as hot air, radiant heat, flames, hot surfaces and splashes of burning or melting materials (1). However, thick clothing also prevents the escape of metabolic heat released with physical work. The final balance is determined by temperature and water vapour pressure gradients and thermal properties of the clothing.

The only means of heat dissipation to the environment under the experimental conditions is by evaporation. This, however, is severely hampered by the thick, multi-layer clothing. Nevertheless, approximately 70 g evaporated during the bicycle part and 105 g during the heat exposure.

The stored heat for the same period calculated from mean body temperature increase was about 150 Wh (5 °C in Tsk and 1.5 °C in Tre).

Two of the clothing ensembles had almost the same thermal insulation value; 0.43 m²°C/W. The insulation of the third ensemble was 10 % higher or 0.47 m²°C/W. This difference, however, had little or no effect on heat balance and physiological strain. In fact, with the above assumption regarding resultant insulation this would correspond to a difference in heat exchange by less than 5 W/m².

McLellan and Selkirk studied the effect of shorts or long pants under a firefighter ensemble on heat stress at various combinations of workrate and work time in 35 °C and 50 % relative humidity (12). They concluded that the reduction in clothing (and thermal insulation) did not influence heat stress during heavy or moderate exercise with exposure times less than 1 hour.

A 10 % reduction in metabolic rate (20-30 W/m²) can easily be achieved by the individual by adjusting his or her pace of work. Although not investigated in this study it can be speculated that such a reduction in metabolic rate would reduce total heat stress. From an operational point of view it seems that much is to be won by trying to establish an intelligent balance between physical loads and efforts and external stress factors. The results from the UW experiments show a significantly reduced thermal stress, resulting from the combined effect of lower metabolic heat production and better heat transfer to the environment, mainly by evaporative heat loss. The beneficial effect however is strongly dependent on environmental conditions.

In summary it can be concluded that light to moderate work at temperatures of 55 °C and higher implies extremely high levels of heat stress, in particular when exposure is combined with carrying protective clothing and compressed air respirators. Small variations in thermal properties of protective clothing have little or no effect on heat exchange and do not affect the resulting thermal strain.
5. REFERENCES

2. EN-469. Protective clothing for firefighters - Requirements and test methods. CEN.

This study was supported by funding from the Swedish Work Environment Authority.
Heat and mechanical protection properties of six fabric combinations commonly used in firefighter protective clothing were assessed before and after different heat treatments. It was shown that after heat exposure, the values obtained were generally lower than in the original state. The mechanical properties of the materials were more affected by the heat than the heat protective properties. In two cases, the degradation started before a visible change in the material could be observed, which might be potentially dangerous for the end user who will not realize the alteration of the material.

1. INTRODUCTION

The performance of a protective clothing system is usually assessed for each new fabric combination. However, the material changes over time are rarely considered, though these might reduce the level of protection and represent a potential hazard to the user. Vogelpohl and Easter [1] showed that used turnout coats showed reduced tensile strength, flame and water resistance. In another study [Rossi and Zimmerli, 1997], it was shown that the water vapour permeability of membranes may decrease after heat exposure. Slater [3, 4, 5] stated that molecular changes of fibres can occur during their lifetime and that the functionality of the materials may be impaired long before the user realizes it as these changes are often invisible to the naked eye. Efforts have been undertaken to trace the use of firefighter protective clothing by monitoring the number of washing cycles of each piece of clothing [6, 7], but it is nontrivial to assess a possible degradation of materials during use.

The aim of this study was to analyse the mechanical as well as the heat protection properties of fabric combinations used for firefighter protective clothing after exposure to heat and flames. The samples were exposed to either radiant (40 kW/m²) or convective heat (80 kW/m²) for defined periods. The tensile and tear strengths, as well as the heat transfer when exposed to radiant or convective heat, were then determined.
2. METHODS

We studied 6 different fabric assemblies typical for those used in firefighter protective clothing corresponding to EN 469 [8] (Table 1). First, after five washing cycles according to ISO 6330, Procedure 2A at 60°C [9], we determined the heat protection characteristics of the assemblies by measuring the times to reach a temperature increase of 12°C or 24°C in a calorimeter ($t_{12}$ resp. $t_{24}$) covered with the samples when exposed either to a radiant heat source of 40 kW/m² or a convective heat source of 80 kW/m² (Table 2). These tests corresponded to the requirements of EN 469 and the test methods applied are described in ISO 6942 [10] (protection against radiant heat) and EN 367 [11] (protection against convective heat). Furthermore, we determined the exposure time until a visible change occurred in the outer shell by an iterative process (exposure for a defined length of time (using Method A of ISO 6942 or EN 367).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Outer shell</th>
<th>Surface weight (g/m²)</th>
<th>Water barrier</th>
<th>Surface weight (g/m²)</th>
<th>Thermal barrier</th>
<th>Surface weight (g/m²)</th>
<th>Total weight (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PBI / Aramid</td>
<td>210</td>
<td>PTFE membrane</td>
<td>145</td>
<td>Aramid</td>
<td>110</td>
<td>465</td>
</tr>
<tr>
<td>2</td>
<td>Aramid</td>
<td>265</td>
<td>PTFE membrane</td>
<td>145</td>
<td>Aramid</td>
<td>130</td>
<td>540</td>
</tr>
<tr>
<td>3</td>
<td>Aramid</td>
<td>210</td>
<td>PES membrane</td>
<td>130</td>
<td>Aramid</td>
<td>290</td>
<td>630</td>
</tr>
<tr>
<td>4</td>
<td>Aramid / Basofil</td>
<td>245</td>
<td>PTFE membrane</td>
<td>135</td>
<td>Aramid</td>
<td>290</td>
<td>670</td>
</tr>
<tr>
<td>5</td>
<td>Aramid</td>
<td>190</td>
<td>PU membrane on aramid nonwoven</td>
<td>215</td>
<td>Aramid / FR viscose</td>
<td>170</td>
<td>575</td>
</tr>
<tr>
<td>6</td>
<td>Aramid</td>
<td>250</td>
<td>PTFE membrane</td>
<td>135</td>
<td>Aramid</td>
<td>345</td>
<td>730</td>
</tr>
</tbody>
</table>

Table 1: Description of the fabric combinations

In order to simulate thermal ageing of the materials, the combinations were then exposed to either the radiant or the convective heat source for a defined time. The time $t_{24}$ to reach a temperature increase of 24°C was the longest treating exposure time. After the heat exposure, the materials were conditioned again at 20°C and 65% rH for at least 24 h and different mechanical (tensile strength according to ISO 13934-1 [12] and tear resistance according to ISO 4674-1 [13]) or thermal properties of the combinations were then assessed.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$t_{24}$ (s)</th>
<th>$t_{24}$ - $t_{12}$ (s)</th>
<th>Colour change (s)</th>
<th>$T_{24}$ (s)</th>
<th>$t_{24}$ - $t_{12}$ (s)</th>
<th>Colour change (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.9</td>
<td>8.6</td>
<td>10</td>
<td>24.6</td>
<td>6.6</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>21.3</td>
<td>6.3</td>
<td>10</td>
<td>16.5</td>
<td>4.0</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>32.1</td>
<td>8.8</td>
<td>6</td>
<td>24.2</td>
<td>6.0</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>28.9</td>
<td>7.3</td>
<td>7</td>
<td>29.3</td>
<td>8.1</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>24.9</td>
<td>7.0</td>
<td>6</td>
<td>19.2</td>
<td>4.6</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>33.4</td>
<td>9.8</td>
<td>9</td>
<td>27.4</td>
<td>8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 2: Times in s to reach a temperature increase of 24°C or a colour change in the outer shell
3.  RESULTS

3.1.  HEAT PROTECTION

All the combinations used reached the limits of heat protection required by EN 469. Prior to the measurement of the heat protection, all the samples were exposed to the heat for a period corresponding to $t_{24}$. The determination of the heat protection times according to ISO 6942 and EN 367 after the initial heat treatment thus corresponded to a double heat exposure.

There was a reduction of heat protection level for all samples after the thermal treatment, except for sample 6. This reduction was generally larger for the convective heat exposure (Fig. 1) than for the radiant heat. This result can be explained by the fact that for a high heat flux exposure, the fabric combination acts as a heat sink before heat is transferred to the inner layers and to the calorimeter. Therefore, the temperature rise in the outer shell was probably much higher during the convective heat exposure at 80 kW/m² than during the radiant heat exposure at 40 kW/m². This fact probably also explains why sample 5 had the highest reduction of protection against convective heat (28.1%), as this sample had the smallest surface weight of all samples and was therefore probably damaged to a greater extent than the others during the heat treatment. As the samples all had quite high protection levels, the limits of protection as defined in EN 469 (performance level 2) were still reached ($t_{24} \geq 18.0$ and $t_{24} - t_{12} \geq 4.0$ for radiant heat; and $HTI_{24} \geq 13.0$ and $HTI_{24} - HTI_{12} \geq 4.0$ for convective heat) by all the samples except for sample 2, which apparently had too low a time difference $HTI_{24} - HTI_{12}$ after the treatment, although this sample showed the smallest reduction in heat protection of all samples. Sample 1 reached a slightly higher time difference $t_{24} - t_{12}$ after the radiant heat treatment than in original state, but this result lies within the uncertainty of measurement. Sample 6 reached better results for the convective heat protection after heat treatment. This sample was completely charred after the treatment, which can in general have a positive influence on heat protection. However, as the charred material becomes brittle, this material could no longer have been used in practice after such a heat exposure.

![Figure 1](image-url): Times to reach a temperature increase of 12°C and 24°C when exposed to a convective heat source (80 kW/m², EN 367) with and without thermal treatment (the times in brackets showing the length of the treatment)
3.2. MECHANICAL PROTECTION

The measurements of the tensile strength were made in the original state (after 5 washings), as well as after a heat treatment corresponding to the time to detect a colour change in the outer layer (Table 3). Samples 3, 5, and 6 reached about the same tensile strength after the heat treatment, which shows that the mechanical integrity of these outer shell materials was maintained until the change in the colour of this layer. The tensile strength of Sample 4 remained more or less constant after the radiant heat exposure but it was reduced by about 40% after the convective heat exposure. We repeated the measurement for this sample with a radiant heat exposure of one second longer (8 s) and obtained a tensile strength of 660 N, which corresponds to a reduction of nearly 50%. Sample 4 thus showed a large decrease of mechanical strength near the point of decolouration.

Sample 1 showed a reduction of tensile strength of about 40% after the radiant heat treatment and about 60% after the convective heat treatment. In this material, changes in the molecular structure due to the thermal load must occur before a change becomes visible to the naked eye. Some measurements were made with this material when treated to shorter heat exposures and confirmed that part of the reduction of tensile strength already took place before the limit of colour change was reached. Sample 2 also had a reduction of tensile strength, which was, however, much smaller (-19% after radiant, respectively -16% after convective heat treatment) than for sample 1. As the treatment times were different and as sample 1 and sample 2 were the ones with the longest treatment times, we assessed the tensile strength of all the samples after 7 s radiant heat exposure to analyse whether the reduction of strength occurred after a similar heat exposure for all samples. Samples 3, 4, 5 and 6 did not show any reduction in tensile strength after this heat exposure showing that the mechanical integrity of the bulk material seemed not to be affected by this heat load and that the decolouration of the samples was probably due to chemical changes in the dye only. In EN 469, the lower limit for tensile strength is set at 450 N, which was still easily reached by all samples even after the treatment.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Radiant heat treatment</th>
<th>Convective heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tensile strength (N)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>original</td>
<td>after</td>
</tr>
<tr>
<td></td>
<td>(s)</td>
<td>treatment</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>2090</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>2290</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>1180</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>1320</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>1160</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>1590</td>
</tr>
</tbody>
</table>

Table 3: Tensile strength before and after the heat treatment

The measurements of the tear resistance according to ISO 4674-1 showed results similar to the tensile strength: samples 3 and 5 with the shortest heat treatments reached the same values as the original fabrics. Sample 1 and sample 2 had the highest original values (123 N for sample 1 and 122 N for sample 2), but also the largest decrease after the thermal treatment: after 10 s exposure, sample 1 obtained 48 N and sample 2 65 N, which corresponds to a reduction of 61%, respectively 47%. After the convective heat treatment during 5 seconds, the drop was even greater for sample 1 (-79%) and the limit required by EN 469 (25 N) was almost reached. For sample 2, the reduction was much smaller...
(-14%), as the heat exposure only lasted for 2 s. The degradation of sample 4 started right at the point of decolouration: when we exposed this sample for 1 s less than the time for decolouration (i.e. 6 s radiant heat or 2 s convective heat), we obtained the same values as for the non-treated samples. However, if the exposure was longer, the tear resistance was strongly reduced (-24% after 7 s radiant heat exposure, respectively -33% after 3 s convective heat) and fell below the limit required by EN 469 when exposed 1 s longer than the time for colour change (i.e. 22 N after 8 s radiant heat treatment and 23 N after 4 s convective heat). Sample 6 also showed a decrease in tear resistance (-26% after 9 s radiant heat exposure and -13% after 2.5 s convective heat), but the values were still above the limit in EN 469, even if the exposure was 1 s longer than the time for colour change.

4. CONCLUSIONS

We assessed the heat and mechanical protection properties of 6 different fabric combinations used for firefighter protective clothing before and after thermal ageing. The performance of the samples was generally reduced after the heat exposure, but in most cases, the limits required in the standard for firefighter protective clothing EN 469 were still reached. Two of the six samples showed a reduction in mechanical strength before the time for a decolouration in the outer shell was reached. Therefore, the thermal degradation of the materials used in these samples seemed to start before a visible change in the material occurred.

REFERENCES

5. Slater, K., 1983, „Assessment of the protective ability of textile products“, Aspects médicaux et biophysiques des vêtements de protection (Conférence internationale, Lyon) 154-159.
8. EN 469, 2005, Protective clothing for firefighters – Performance requirements for protective clothing for Firefighting, European Committee for Standardization, Brussels


A NEW FACILITY FOR TESTING THE FIRE PROTECTIVE PERFORMANCE OF ENSEMBLES OF PPE

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WA14 5DW

ABSTRACT

There are several manikin based testing systems around the world that are used to assess the fire protective performance of clothing. Typically these systems consist of a male form manikin equipped with heat sensors on the torso, arms, legs and sometimes the head. BTTG’s long established RALPH manikin test system (Research Aim Longer Protection against Heat) is of this type and is therefore restricted to testing jackets/trousers or coveralls.

As a result of discussions between the UK Fire and Emergency Services and the PPE industry a need for a much more versatile fire test facility than currently provided by RALPH or other similar test systems was agreed. A project was therefore initiated by BTTG Fire Technology Services with the aim of creating a gender based integrated PPE assessment facility using flame engulfment manikins. The objectives were to construct male and female form manikins, both able to be dressed in a complete firefighter PPE ensemble (with the possible exception of footwear) with particular emphasis being given to assessing the protection provided at the PPE interfaces.

This paper explains more of the background to this project, details and discusses development decisions and concludes with some test results obtained during the final commissioning phase of this recently completed project.

INTRODUCTION

In recent years, due to the climate of equal opportunities in the workplace, women are increasingly being employed in roles which have been traditionally the preserve of men. When the roles require that the worker be protected from external hazards, for example those encountered during firefighting, personal protective equipment (PPE) must be provided if the risk of exposure to the hazards cannot be prevented by other means.

One of the tools available for assessing protection against intense heat and flame hazards is the heat sensing manikin, now the basis of an almost finalised test method that has been developed jointly by CEN and ISO, respectively the Committee for European Normalisation and the International Organisation for Standardisation. However, this test method and also all the leading test facilities that have developed facilities according to this test method or to variants of it only make use of an adult
sized “male” form manikin. It is therefore not possible to assess by manikin testing whether clothing currently worn by women gives adequate and/or comparable fire protection to that worn by men. Another limitation of leading test facilities is that the design of the manikins results in the wiring for the heat sensors being run out through the head/neck region meaning that it is not possible to dress this region of such manikins with PPE in a realistic way. The protection provided by a combination of PPE items such as helmets, fire hoods and breathing apparatus face masks cannot therefore be assessed.

A related issue of increasing importance to end users of combinations of PPE providing an ensemble to protect against intense heat and flame such as a “flashover” is the desirability of being able to test these ensembles in situ on a heat sensing manikin. Only by undertaking such testing can the necessary level of integration between items of PPE that have to be worn together be demonstrated, particularly the protection at PPE interface regions.

Since this project was commenced the incorporation of manikin based fire testing into EN and ISO specifications for fire protective clothing and related PPE has become more widespread. For example, the revised specification for clothing for firefighting (EN 469:2005) has an optional requirement for manikin testing to a prescribed level of challenge using the draft method of test, EN ISO 13506, the development of which is led by ISO but with CEN participation. More significant to the project described in this report is that an ISO committee set up in 2002 has now drafted two specifications for PPE ensembles for various firefighting tasks that include manikin testing of the ensemble and are planned to also set performance requirements that limit the predicted burn injury.

EN ISO 13506 will not include a “female” form manikin in its first edition but can be expected to do so as a first amendment – BTTG is directly represented on the UK delegations to the two ISO committees and one CEN committee working on the test method and on various performance specifications.

The project proposal prepared by BTTG in response to the issues set out above was accepted by various key UK government organisations, PPE end user safety bodies and companies in the PPE manufacturing sector to enable the project to commence in April 2003. BTTG wishes to thank formally all those whose sponsorship and technical contribution has enabled this project to be undertaken. In particular we wish to acknowledge the support provided by the Health & Safety Laboratory, UK and by EMPA Research Institute, Switzerland.

**DESIGN DECISIONS - DISCUSSION**

The first consideration was to decide how much of the content of the draft EN ISO method of test standard 13506 should be incorporated into the test facility. When BTTG commenced the development of RALPH (Research Aim Longer Protection against Heat), its first fire test manikin facility, in 1988, ISO and CEN work on this test method had not commenced and ASTM work was at an early stage. BTTG therefore took account of DuPont’s Thermo-Man and the University of Alberta’s “Harry” manikin test systems but decided with the agreement of its sponsoring group to undertake a simpler, cheaper ad hoc approach to heat sensor design, number, location; burner system and burn injury prediction calculation. By 2003 however, the EN ISO method of test existed as a draft which was based upon the published ASTM F 1930 standard. The decision was therefore taken to upgrade the entire RALPH facility so that when operating in one of its ‘male manikin modes’ it would be compliant with the EN ISO draft standard. In the interests of further harmonisation it was also decided to use the same specification of male manikin, heat sensor type, number and distribution as
the EN ISO draft standard compliant Thermo-Man and its equivalents. These decisions support the wish of end users of PPE for fire protection to see performance requirements written into specifications if reproducibility of key manikin fire test facilities can be demonstrated.

The more difficult decision was on what basis the shape and size of the female manikin would be decided! The specifications of the male manikin in the EN ISO draft standard and also in ASTM F-1930 were formulated more than 20 years ago and appear to have stood the test of time in not requiring re-consideration. The starting point for deciding the specification of SOPHIE (System Objective Protection against Heat In Emergencies) was the availability of 2 sets of UK anthropometric data in particular, one from a recent survey of several hundred female firefighters, the other from a continuously updated data base of the UK female population as a whole.

The female firefighter population will increase over time so the anthropometric data from this group will come to be even more representative of the UK female population as a whole than is the case now. This fact, coupled to the project objective of being able to use the female manikin test facility to assess PPE for fire protection in industrial situations, preferably worldwide, not just firefighting situations in the UK, led to the decision to specify the 50th%ile data from the UK female population data (age 18-39). Although 50th%ile values have been used to create the design for SOPHIE this does not mean that SOPHIE will represent the UK ‘average’ woman. This is because only a very few people (possibly only <1% of any country’s population) have 50th%ile measurements in all dimensions used. This decision means that there are appreciable and intended differences between new RALPH and SOPHIE, for example in terms of ratios of chest:waist and waist:hips.

The influence of cut and fit of garments is therefore likely to be more significant as a contribution to burn injury predictions than has been found to be the case with the more consistent circumference dimensions in current male manikins.

The other main design decision taken with respect to both manikins was to construct them so that the wiring for the heat sensors was routed via the feet rather than the head and/or neck region as in most current fire test manikins. This change of routing means that the head/neck region of both new BTTG manikins can be dressed realistically with helmet/fire hood/breathing apparatus/ face mask items, for example.

The other objective was to learn more about the protection provided at PPE interface regions. Each manikin therefore has the ability to be operated in a mode that initiates a greater density of heat sensors at interface regions such as the head/neck and wrists. As a start towards being able to assess hand protection, this first generation of SOPHIE and revised RALPH will be operable in a mode calling up sensors in each hand, a feature absent from the requirements of the EN ISO draft standard.

**THE TEST FACILITY**

The male manikin was supplied with 123 sensor sites (holes) which exceeds the minimum of 100 for EN ISO 13506 manikins and is the number used in Thermo-Man. BTTG Fire Technology Services chose to increase the sensor density at the head and interface areas at the wrists and neck by eight sensors. The detachable hands were also fitted with sensors sites; one on the palm and one on the back of each hand, to measure the performance of gloves. Therefore the total number of sensors on the male manikin RALPH is 135.
Table 1 Comparison of dimensions of the male and female manikins

<table>
<thead>
<tr>
<th>Measurement</th>
<th>RALPH (mm)</th>
<th>Draft EN ISO 13506 (mm)</th>
<th>SOPHIE (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total height</td>
<td>1800</td>
<td>1800 ± 20</td>
<td>1600</td>
</tr>
<tr>
<td>Chest/bust circumference</td>
<td>1040</td>
<td>1025 ± 20</td>
<td>950</td>
</tr>
<tr>
<td>Neck to wrist</td>
<td>780/770</td>
<td>755 ± 45</td>
<td>680/680</td>
</tr>
<tr>
<td>Shoulder to wrist</td>
<td>620/590</td>
<td>610 ± 30</td>
<td>580/580</td>
</tr>
<tr>
<td>Arm circumference</td>
<td>290/300</td>
<td>300 ± 10</td>
<td>240/240</td>
</tr>
<tr>
<td>Waist circumference (narrowest point)</td>
<td>840</td>
<td>845 ± 10</td>
<td>640</td>
</tr>
<tr>
<td>Waist circumference (12cm above hips)</td>
<td></td>
<td></td>
<td>780</td>
</tr>
<tr>
<td>Crotch to sole of foot</td>
<td>880</td>
<td>855 ± 25</td>
<td>750</td>
</tr>
<tr>
<td>Hips circumference</td>
<td>1020</td>
<td>1015 ± 20</td>
<td>970</td>
</tr>
<tr>
<td>Base of neck to waist</td>
<td>440</td>
<td>425 ± 20</td>
<td>360</td>
</tr>
<tr>
<td>Waist to base of heel</td>
<td>1150</td>
<td>1150 ± 50</td>
<td>1050</td>
</tr>
<tr>
<td>Thigh circumference</td>
<td>560/560</td>
<td>580 ± 20</td>
<td>540/540</td>
</tr>
</tbody>
</table>

The female manikin was supplied with 123 sensor sites (holes) in approximately the same positions as the sensor sites in the male manikin. As with the male manikin BTTG Fire Technology Services chose to increase the sensor density at the head and interface areas at the wrists and neck by in this case five sensors. The detachable hands were also fitted with sensors sites; one on the palm and one on the back of each hand, to measure the performance of gloves. Therefore the total number of sensors on the female manikin SOPHIE is 132.

Both manikins are held upright by foot supports through which sensor cables are routed. There are no cable routes or supports at the neck or head of the manikin thus allowing the correct dressing of headwear.
The resulting male and female manikins were sourced from one manufacturer (Composites USA who supply DuPont), made from the same material and have the same sensors. They differ essentially only in their shape and size so enabling one of the main project objectives, namely a direct comparison of the performance of heat and flame protective clothing and other items of PPE for men and women.

**TEST RESULTS**

**EN ISO 13506 interlaboratory trial**

The male manikin was dressed in a combination of 100% cotton knitted underwear and a Kevlar®/PBI® one-piece coverall (size 42) supplied as part of the interlaboratory trial for the draft EN ISO 13506 standard and subjected to a 4 second flame exposure using an average heat flux of $84\text{kW/m}^2 \pm 5\%$ and a standard deviation of $<20\text{kW/m}^2$ as specified in draft EN ISO 13506.

The results were compared with the interlaboratory trial results reported in the draft EN ISO 13506 standard.

The extra Fire Technology Services sensors were not included in the percentage burn damage calculation as there were no interfaces between garments and the sensors in the neck and head were assigned zero burn injury as they were not covered by garments. The burn injury was assessed using clause 9.4.2 of EN ISO 13506 “Predicted total area (%) of manikin based on the total area of the manikin containing heat flux sensors”. This test was repeated 3 times.

<table>
<thead>
<tr>
<th>Burn injury</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Average</th>
<th>Standard deviation</th>
<th>Standard deviation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>21.1</td>
<td>22.0</td>
<td>17.9</td>
<td>20.3</td>
<td>2.2</td>
<td>11</td>
</tr>
<tr>
<td>1\textsuperscript{st} ° Burn</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>2\textsuperscript{nd} ° Burn</td>
<td>19.5</td>
<td>17.0</td>
<td>22.0</td>
<td>19.5</td>
<td>2.5</td>
<td>13</td>
</tr>
<tr>
<td>3\textsuperscript{rd} ° Burn</td>
<td>31.7</td>
<td>35.0</td>
<td>30.1</td>
<td>32.2</td>
<td>2.5</td>
<td>8</td>
</tr>
</tbody>
</table>

*Table 2* Male manikin – EN ISO 13506 garment test

<table>
<thead>
<tr>
<th>Burn injury</th>
<th>Average</th>
<th>Standard deviation</th>
<th>Standard deviation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTTG result</td>
<td>51.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EN ISO 13506 trial (7 laboratories)</td>
<td>44.7</td>
<td>6.0</td>
<td>13.4</td>
</tr>
</tbody>
</table>

*Table 3* Comparison of the test results for 2\textsuperscript{nd} degree burn injury and above
REPEATABILITY TESTS – COVERALL: RALPH & SOPHIE

The manikins were dressed in appropriately sized FR treated 100% cotton one-piece coveralls, compliant with EN531 and subjected to a 3 second flame exposure. The test was repeated 3 times on each manikin.

<table>
<thead>
<tr>
<th>Burn injury</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Average</th>
<th>Standard deviation</th>
<th>Standard deviation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>41.5</td>
<td>35.0</td>
<td>40.6</td>
<td>39.0</td>
<td>3.5</td>
<td>9</td>
</tr>
<tr>
<td>1st ° Burn</td>
<td>3.2</td>
<td>4.9</td>
<td>0.9</td>
<td>3.0</td>
<td>2.0</td>
<td>67</td>
</tr>
<tr>
<td>2nd ° Burn</td>
<td>4.1</td>
<td>8.9</td>
<td>5.7</td>
<td>6.2</td>
<td>2.5</td>
<td>40</td>
</tr>
<tr>
<td>3rd ° Burn</td>
<td>1.6</td>
<td>0.9</td>
<td>1.6</td>
<td>1.4</td>
<td>0.4</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 4 RALPH: Coverall tests

<table>
<thead>
<tr>
<th>Burn injury</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Average</th>
<th>Standard deviation</th>
<th>Standard deviation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>33.4</td>
<td>33.4</td>
<td>35.8</td>
<td>34.2</td>
<td>1.4</td>
<td>4</td>
</tr>
<tr>
<td>1st ° Burn</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.5</td>
<td>173</td>
</tr>
<tr>
<td>2nd ° Burn</td>
<td>2.4</td>
<td>1.7</td>
<td>4.1</td>
<td>2.7</td>
<td>1.2</td>
<td>45</td>
</tr>
<tr>
<td>3rd ° Burn</td>
<td>0</td>
<td>0.8</td>
<td>0</td>
<td>0.3</td>
<td>0.5</td>
<td>173</td>
</tr>
</tbody>
</table>

Table 5 SOPHIE: Coverall tests

The burn injury results in these tests are consistently lower than with the same specification of garment when tested on the male manikin primarily as a result of less injury in the front abdomen area where the physique of the female manikin caused a significant air gap under the coverall.

REPEATABILITY TESTS – FIREFIGHTER'S GARMENTS: RALPH & SOPHIE

The manikins were dressed in appropriately sized jacket/trouser ensembles of typical composition complying with EN 469:1995 and subjected to an 8 second flame exposure. The test was repeated 3 times on each manikin.
<table>
<thead>
<tr>
<th>Burn injury</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Average</th>
<th>Standard deviation</th>
<th>Standard deviation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>19.5</td>
<td>22.7</td>
<td>24.4</td>
<td>22.2</td>
<td>2.5</td>
<td>11</td>
</tr>
<tr>
<td>1st ° Burn</td>
<td>2.5</td>
<td>1.6</td>
<td>3.2</td>
<td>2.4</td>
<td>0.8</td>
<td>33</td>
</tr>
<tr>
<td>2nd ° Burn</td>
<td>16.3</td>
<td>19.5</td>
<td>19.5</td>
<td>18.4</td>
<td>1.9</td>
<td>10</td>
</tr>
<tr>
<td>3rd ° Burn</td>
<td>16.3</td>
<td>9.8</td>
<td>13.8</td>
<td>13.3</td>
<td>3.3</td>
<td>25</td>
</tr>
</tbody>
</table>

**Table 6** RALPH: Firefighter’s garment tests

<table>
<thead>
<tr>
<th>Burn injury</th>
<th>Test 1*</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Average</th>
<th>Standard deviation</th>
<th>Standard deviation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>16.2</td>
<td>30.1</td>
<td>33.4</td>
<td>31.7</td>
<td>2.3</td>
<td>7</td>
</tr>
<tr>
<td>1st ° Burn</td>
<td>5.7</td>
<td>1.7</td>
<td>2.4</td>
<td>2.0</td>
<td>0.5</td>
<td>26</td>
</tr>
<tr>
<td>2nd ° Burn</td>
<td>18.7</td>
<td>16.2</td>
<td>19.6</td>
<td>17.9</td>
<td>2.4</td>
<td>13</td>
</tr>
<tr>
<td>3rd ° Burn</td>
<td>26.0</td>
<td>14.6</td>
<td>9.7</td>
<td>12.2</td>
<td>3.5</td>
<td>28</td>
</tr>
</tbody>
</table>

**Table 7** SOPHIE: Firefighter’s garment tests

* This test result was considered compromised by the ingress of the test flames between the jacket and trouser (clearly seen as damage to the internal lining) which resulted in increased burn injury to the abdomen area. The average results were based on Tests 2 and 3.

**CONCLUSIONS**

A heat sensing manikin test facility has been designed, built and commissioned which is able to operate comparably in ‘male’ and ‘female’ mode.

In ‘male’ mode the test facility complies with the draft standard EN ISO 13506 Protective clothing against heat and flame – Test method for complete garments – Prediction of burn injury using an instrumented manikin. A series of tests on garments provided to laboratories to enable them to compare their test results with those from other laboratories published in this draft standard has shown a good correlation. This proposed standard will not include a female form manikin in its first edition but can be expected to do so by future amendment.

An acceptable level of repeatability was achieved in trials undertaken with each manikin when dressed in a typical flame retardant coverall and when dressed in a typical structural firefighting suit.

Both manikins have been built with sensor data cables and supports at the feet so that they can be dressed with a complete ensemble, with the exception of footwear, designed for a particular task, for example firefighting. Tests involving PPE for head and hand protection are a next step.

An increased density of heat sensors at PPE interface regions of each manikin, compared to the requirements of the draft standard, will enable protection at these regions to be more thoroughly investigated.
The test facility achieves the primary aim of this project enabling a direct comparison of the performance of heat and flame protective clothing and other PPE items intended for male and female personnel. Future use will enable clients to predict if protection is comparable and adequate for men and women undertaking a common task.

The version of BTTG’s RALPH manikin that has been in use for clients since 1995 will now be replaced by this new and much more capable RALPH – SOPHIE facility.

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- W L Gore & Associates (UK) Limited
- HM Fire Service Inspectorate, England, Wales and Northern Ireland
- The Scottish Office Home Department

The input of Dr N Vaughan and colleagues at the Health & Safety Laboratory, Buxton, UK, is especially acknowledged.

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- Ms J Clay of Dickies (UK) Limited;
- Chief Fire Officer A Doig of Staffordshire Fire & Rescue Service, UK
- EnvironMech Design Limited, UK
- Composites USA Inc
REFERENCES

1 ISO/DIS 13506.3 (pren ISO 13506) was agreed to be developed into an FDIS in 2005. Title: Protective clothing against heat and flame – Test method for complete garments – Prediction of burn injury using an instrumented manikin.

2 ASTM F 1930: Standard test method for evaluation of flame retardant clothing for protection against flash fire simulations using an instrumented manikin.


4 PeopleSize database of British Females (aged 18-39). Available from Open Ergonomics Ltd www.openerg.com
ABSTRACT

Fire fighters are normally overprotected during the majority of their work hours because of the tendency to keep the personal protection level sufficient for the worst possible scenarios – flames and radiant heat. In most European countries fire fighter protective clothing, in accordance with the EN 469 standard is used as general workwear. This job-related experiment investigated thermal strain in subjects wearing two different personal protective clothing systems (PCS) during prolonged work simulation. The test drill was divided into two consecutive work sessions: 1) 95-min rescue simulation in neutral climate ($R_{\text{neutral}}$) and 2) 54-min rescue simulation with self-contained breathing apparatus (SCBA) performed in a climatic chamber at a $t_a$ of 45 °C combined with $rh$ of 35% ($R_{\text{hot}}$). The subjects were 23 healthy professional male fire fighters aged 26 to 44 years with maxOV2 ranging from 36 to 54 ml/kg-min$^{-1}$. The subjects were studied in random order, once in both of the test configurations i.e. 1) task fitted protective clothing system (PCS$_{\text{task}}$) during $R_{\text{neutral}}$ and in conjunction with EN 469 (1) protective clothing for fire fighters (FPE$_{\text{Stask}}$) during $R_{\text{hot}}$ and 2) EN 469 protective clothing system (PCS$_{\text{EN}}$) during $R_{\text{neutral}}$ and $R_{\text{hot}}$ (FPE$_{\text{SEN}}$). Continuous measurement included heart rate, heart rate variability, rectal and 7 skin temperatures. Sweat production was calculated from nude body weight changes. Subjective ratings of perceived exertion, thermal and wear comfort were also inquired. Wearing PCS$_{\text{task}}$ during $R_{\text{neutral}}$ considerably reduced total thermal and cardiovascular strain in prolonged rescue work. Sweat production was significantly higher and the subjects also perceived the physical work as significantly harder on average, and reported more intense subjective discomfort while wearing PCS$_{\text{EN}}$ and FPE$_{\text{SEN}}$ as compared to wearing PCS$_{\text{task}}$ and FPE$_{\text{task}}$.

1. INTRODUCTION AND STUDY AIMS

Fire fighters are multi-skilled rescuers. In Finland, as in many other countries, they are trained to carry out a wide range of tasks from fire-fighting to surface rescue and underwater rescue diving. Full-time professional fire fighters also work in fire prevention and other activities, and they are responsible for patient transportation and medical care in their area. As the level of protection for fire fighters must be sufficient for the worst possible scenarios, e.g. flames and radiant heat, this means that they are overprotected for most of their work hours. In Finland, protective clothing which meets the
requirements of the EN 469: 2005 European standard (1) is used in most fire brigades as multipurpose clothing and worn during most operations, except during water rescue and incidents with hazardous materials. However, a fire fighter in Finland only needs a multilayer turn out suit in structural and other fires about 10 times per year and the mean wearing time of the PCS in fire is only about 6 % of total working time (2). The rest of the time, fire-fighters are exposed to unnecessary thermal strain which also reduces work ability and efficiency (3).

The purpose of this study, which is part of a more comprehensive project, was to compare the degree of thermal strain in fire fighters wearing task-fitted protective clothing systems and protective clothing systems fulfilling EN 469 during a prolonged work simulation, consisting of different rescue tasks in a neutral and hot climate.

2. MATERIAL AND METHODS

2.1. SUBJECTS

The voluntary subjects were 23 healthy professional male fire fighters with an average age of 34 (26-44) years, height of 181 (172–196) cm, weight of 85 (69–102) kg, BMI of 26 (21–32), body fat of 16 (7–24)%., body area of 2.0 (1.8–2.3) m², 16 (7–24)%, and body area of 2.0 (1.8–2.3) m². Before the experiments, the subjects had a medical check-up including a clinical cardiopulmonary exercise test (CPET) measured under neutral conditions on a treadmill using modified Bruce protocol. The average VO₂max of the study group was 45.1 (35.6–54.0) ml/kg·min⁻¹.

2.2. EXPERIMENTAL DESIGN

2.2.1. Test protocol

The ethically approved test protocol provided a series of work tasks simulating typical rescue operations. The prolonged test drill conducted in the mornings was divided into two consecutive work sessions with a 10-minute rest between the sessions for body cooling (removing the jacket for ventilation of underwear), drinking ad libitum and putting on the required fire-protective clothing system (FPCS) including self-contained breathing apparatus (SCBA):

1) 1 h 35 min work in neutral (tₑ of 22–25 °C / rh of 45–50%) climate (Rₜₑₐₜₑₐₜₑₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐ¢

2) 54-min rescue work with FPES performed in a climatic chamber at a tₑ of 45 °C combined with 35% rh (Rₙₑₐₐₐₐₐₐₐₐₐₐₐ¢) and divided into two work bouts of 22 min with a 10-minute rest in a neutral climate between each work bout for changing the air container. The rescue simulation involved walking on a treadmill, transposing weights in hands, stepping, crawling under 70 cm high bars, and driving a bicycle ergometer.
2.2.1. Protective clothing systems (PCS)

Two types of PCSs were studied (Table 1). In random order, the subjects performed both of the test configurations once (4 weeks between the test days) i.e.

1) Task-fitted protective clothing system (PCS task) during \( R_{neutral} \) and PCS task in conjunction with turnout suit fulfilling EN 469:2005 (1) and SCBA during \( R_{hot} \) (FPE task), and

2) EN 469 protective clothing system PCS EN during \( R_{neutral} \) and PCS EN with SCBA during \( R_{hot} \) (FPE EN).

The total mass of the protective clothing systems averaged 4.0 kg for PCS task and 7.4 kg for PCS EN and, correspondingly, 13.8 kg for SCBA (Dräger PSS 100 ET, 6.8 L, 300 bar) and the helmet. The measured (4) thermal insulation \( I_r \) was 1.07 clo for PCS task, 1.90 clo for FPCS task, and 1.97 clo for PCS EN and FPCS EN.

Table 1. The items and the materials for task-fitted protective clothing system PCS task and for EN 496 protective clothing system PCS EN

<table>
<thead>
<tr>
<th>Protective Clothing System</th>
<th>Item</th>
<th>Material, PCS task</th>
<th>Material, PCS EN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underwear</td>
<td>66% PES /34 % CO, 210</td>
<td>100 % CO shirt with short sleeves,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>g/m², vest with long</td>
<td>trunk pants</td>
<td></td>
</tr>
<tr>
<td></td>
<td>sleeves, knee-length</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>underpants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermediate layer</td>
<td>Uniform trousers,</td>
<td>Three layer aramid with moisture</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50% CO/50%PES</td>
<td>barrier (EN 496)</td>
<td></td>
</tr>
<tr>
<td>Outer jacket and trousers</td>
<td>One layer, 75% CO /24%</td>
<td>Three layer aramid with moisture</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PE/1% antistatic thread, 250 g/m²</td>
<td>barrier (EN 496)</td>
<td></td>
</tr>
<tr>
<td>Safety boots and fire</td>
<td>Leather</td>
<td>Leather</td>
<td></td>
</tr>
<tr>
<td>gloves</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2.2. Physiological measurements

Heart rate (HR) and heart rate variability (HRV) was continuously recorded by a Suunto t6 wristop computer (Finland 2005) and analyzed using special software for ambulatory HRV analyses (Firstbeat Technologies Ltd., version 1.4.1, 2006, Finland). The RMSSD (the square root of the mean of sum of the squares of differences between adjacent RR intervals) was used as an index of HRV (5). Low values reflect the attenuation in parasympathetic drive, e.g. increased stress. The magnitude of the excess post-exercise oxygen consumption (EPOC) was also calculated. It reflects the disturbance of the body's homeostasis related to exercise. It takes into account the individual's cardiorespiratory fitness, the intensity and the duration of the work load and the duration and effectiveness of the recovery periods during intermittent work (6). It can be used as an index of cumulative metabolic load.

Rectal temperature (\( T_{re} \)) was continuously measured with a flexible thermistor probe (YSI 401) at a depth of 10 cm and, correspondingly, skin temperatures (\( T_{sk} \)) were measured at 7 sites (YSI 427) and registered once a minute (Veritec Instrument Type 1400, Canada). Mean skin temperature (\( \bar{T}_{sk} \)) was calculated as an arithmetic mean and mean body temperature (\( \bar{T}_{b} \)) was calculated using the weighting coefficients 0.65 for \( T_{re} \) and 0.35 for \( \bar{T}_{sk} \) under \( R_{neutral} \) and, respectively, 0.9 and 0.1 under \( R_{hot} \). The change in heat storage for certain exposure times was calculated from changes in \( \bar{T}_{b} \) using 0.97 Wh/kg·ºC for specific heat of the body. Sweat loss was determined with the change in nude weight measured before and after the exercise (Sauter EC 240, Type 1200 ± 5 g, Germany) and corrected with fluid intake.
2.2.3. Subjective evaluations

Ratings of perceived exertion (RPE) using the Borgs scale (6) from 6 (no exertion at all) to 20 (maximal exertion), thermal sensation and thermal comfort modified from ISO 10551(7) scale from -5 (bitterly cold) to +5 (exhaustive heat) for thermal sensation and correspondingly, from 1 (comfortable) to 5 (intolerable) for thermal comfort, as well as skin wettedness using the scale from 1 (dry) to 5 (watery wet) were requested at the start and at the end of each work tasks.

2.4. STATISTICS

Means ± SD, ranges were used for describing the data. The normality of the distributions was assessed with the Kolmogorov-Smirnov test. Before further statistical analyses logarithmic transformations were performed if the distribution was not normal. Paired t- tests were used in physiological strain differences between protective clothing systems, and Pearson's and Spearman's coefficients were used to test the correlations between different parameters. The <0.05 level of probability was considered statistically significant. Statistical analyses were performed using SAS-software (SAS Institute Inc., 1999).

3. RESULTS

3.1. CARDIOVASCULAR STRAIN

The HR was significantly higher for PCS\textsubscript{EN} during $R_{\text{neutral}}$ and for FPE\textsubscript{SEN} during $R_{\text{hot}}$ than for PCS\textsubscript{task} and for FPE\textsubscript{task} (Figure 1, Table 2). The mean EPOC increased to 125 ml/kg for FPE\textsubscript{EN} and to 91 ml/kg for FPE\textsubscript{task}, during $R_{\text{hot}}$. EPOC values increased significantly less during $R_{\text{neutral}}$ than during $R_{\text{hot}}$. However, the levels were higher while wearing PCS\textsubscript{EN} than while wearing PCS\textsubscript{task}. The RMSSD values were lower (higher stress) for PCS\textsubscript{EN} and FPE\textsubscript{EN} than for PCS\textsubscript{task} and FPE\textsubscript{task} (Table 2).

![Figure 1](image-url)
Table 2. The metabolic and circulatory strain in the fire fighters (N= 21) during intermittent rescue work simulations while wearing PCS_{task} and PCS_{EN} under R_{neutral} conditions and correspondingly, FPES_{task} and FPES_{EN} under R_{hot} conditions.

<table>
<thead>
<tr>
<th>Variable</th>
<th>PCS_{task} (R_{neutral})</th>
<th>FPES_{task} (R_{hot})</th>
<th>PCS_{EN} (R_{neutral})</th>
<th>FPES_{EN} (R_{hot})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean HR (min^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- R_{neutral}</td>
<td>105 (85 -120)</td>
<td>117 (91- 145)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- R_{hot}</td>
<td>127 (100 - 146)</td>
<td>137 (110 - 174)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean EPOC peak (ml/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- R_{neutral}</td>
<td>28 (10 - 48)</td>
<td>44 (3 - 70)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- R_{hot}</td>
<td>91 (16 -176)</td>
<td>125 (21 - 270)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean RMSSD (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- R_{neutral}</td>
<td>13 (10 - 48)</td>
<td>13 (5 - 27)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- R_{hot}</td>
<td>11 (4- 45)</td>
<td>6 (3- 24)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2. THERMAL STRAIN

3.2.1. Rectal temperature

The mean increase in T_{re} during R_{neutral} was 0.58 ± 0.21 °C for PCS_{task} and 0.69 ± 0.25 °C for PCS_{EN}, and further mean increase during R_{hot} was 0.79 ± 0.25 °C for FPES_{task} and 0.87 ± 0.25 °C for FPES_{EN} (Figure 2). The difference was nearly significant during R_{neutral} and significant during R_{hot}. The highest T_{re} values were registered at the start of the recovery period at 37.8–39.1 °C (≥39.1 °C; N=2) for FPES_{task} and correspondingly, 38.2–39.4 °C (≥39.1 °C; N=8) for FPES_{EN}.

3.2.2. Skin temperature

During R_{neutral} individual skin temperatures varied between 31.1 and 36.3°C for PCS_{task} and between 32.0 and 36.9 °C for PCS_{EN}. The difference in T_{sk} between PCSs was significant over time during R_{neutral} (Figure 2). At the end of R_{hot} the T_{sk} in both FPESs was at about the same level as T_{re}.

---

![Rectal Temperature](image1)

![Mean Skin Temperature](image2)

Figure 2. Time courses for rectal and mean skin temperature during a job-related rescue drill while wearing PCS_{task} (○) and PCS_{EN} (●) in R_{neutral} and FPES_{task} (○) and FPES_{EN} (●)in R_{hot}. 
3.2.3. Heat storage

Stair climbing at the beginning of $R_{\text{neutral}}$ resulted in very rapid heat accumulation in the body while wearing both PCSs, however, this was significantly greater for PCS$_{\text{EN}}$ ($148 \pm 29.4$ W/m$^2$) than for PCS$_{\text{task}}$ ($88.3 \pm 41.8$ W/m$^2$). At the end of $R_{\text{neutral}}$ the heat storage was still significantly greater in PCS$_{\text{EN}}$ than in PCS$_{\text{task}}$. During the first $R_{\text{hot}}$ work bout the increase in heat storage was $157 \pm 34.7$ W/m$^2$ for FPES$_{\text{EN}}$ and $171 \pm 26.0$ W/m$^2$ for FPES$_{\text{task}}$ and further increase during the second $R_{\text{hot}}$ was $64.4 \pm 13.7$ for FPES$_{\text{EN}}$ and $73.1 \pm 17.1$ for FPES$_{\text{task}}$. The difference in changes was not significant.

3.2.4. Body fluid balance

Sweat production for the whole test drill varied greatly between individuals, ranging from 1.2 to 3.7 L for PCS$_{\text{task}}$ + FPES$_{\text{task}}$ and from 1.5 to 4.3 L for PCS$_{\text{EN}}$ + FPES$_{\text{EN}}$. On average, sweat production was 2.4 ($\pm 0.6$) L for PCS$_{\text{task}}$ + FPES$_{\text{task}}$ and 2.8 ($\pm 0.7$) L for PCS$_{\text{EN}}$ + FPES$_{\text{EN}}$. The difference was significant. Water replacement was adequate in most cases and the average water deficit was only 0.8 ($\pm 0.8$)% for PCS$_{\text{task}}$ + FPES$_{\text{task}}$ and 1.0 ($\pm 1.1$)% for PCS$_{\text{EN}}$ + FPES$_{\text{EN}}$. However, in some subjects, a net deficiency in fluid intake of even 2 to 2.7 L was recorded, resulting in a 2.9 to 3.6% water deficit.

3.5 Subjective evaluations

Rescue work while wearing PCS$_{\text{EN}}$ and FPES$_{\text{EN}}$ was perceived on average as significantly harder as compared to that while wearing PCS$_{\text{task}}$ and FPES$_{\text{task}}$ (Table 2). Correspondingly, on average the subjects reported significantly more intense feelings of heat, skin wettedness and thermal discomfort.

Table 2: Ratings of RPE and subjective thermal evaluations at the start of the test drill and at the end of $R_{\text{neutral}}$ and $R_{\text{hot}}$. The values are means and ranges.

<table>
<thead>
<tr>
<th>Subjective evaluations</th>
<th>PCS$_{\text{task}}$</th>
<th>FPES$_{\text{task}}$</th>
<th>PCS$_{\text{EN}}$</th>
<th>FPES$_{\text{EN}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>7.5 (6–11)</td>
<td>12.7 (10–14)</td>
<td>16.1 (13–19)</td>
<td>14.0 (12–16)</td>
</tr>
<tr>
<td>End of $R_{\text{neutral}}$</td>
<td>16.1 (13–19)</td>
<td>9.0 (6–14)</td>
<td>14.0 (12–16)</td>
<td>17.2 (14–19)</td>
</tr>
<tr>
<td>End of $R_{\text{hot}}$</td>
<td>14.0 (12–16)</td>
<td>14.0 (12–16)</td>
<td>17.2 (14–19)</td>
<td></td>
</tr>
</tbody>
</table>

4. CONCLUSIONS AND RECOMMENDATIONS

The results show that circulatory and thermal strains were significantly greater, and correspondingly, there was more intense perceived exertion and subjective discomfort in fire fighters while wearing PCS$_{\text{EN}}$ and FPES$_{\text{EN}}$, compared with PCS$_{\text{task}}$ and FPES$_{\text{task}}$. The use of PCS$_{\text{EN}}$ increased the metabolic load by about 1 MET (metabolic equivalent) during typical rescue work tasks. The use of PCS$_{\text{task}}$ during the work under neutral conditions raises the fire fighters’ capacity to recover during physically demanding intermittent work bouts and maintains the body's capacity to adapt to other stressors, like mental and heavy heat load.

In order to prevent daily overprotection causing overstrain in fire fighters and to promote work ability it is highly recommended that fire fighters be issued a new layered PCS with a base layer onto which it
is possible to attach intermediate and external protection layers quickly and easily, also in moving vehicles, according to the required level of the hazards in question.

5. ACKNOWLEDGEMENTS

The authors appreciate the financial support of the Finnish Fire Protection Fund and the assistance of Espoo Firebrigade of Länsi-Uusimaa Depatment for Rescue Services.

6. REFERENCES

1. EN 469: 2005 Protective clothing for fire fighters – Performance requirements for protective clothing for fire-fighting.
ABSTRACT

Personal Protective Equipment (PPE) made of metallised materials are intended to protect industrial workers and firemen where other PPE does not more offer sufficient protection.

The protective properties of this type of clothing rely upon the ability of the outer material to reflect radiant heat, and therefore allow the workers and fire fighters to approach next to sources causing intense radiant heat.

Typical sceneries where aluminized PPE may be sensible used are e.g. bulk fires, aircraft fires, petrol tank fires, ship fires, steel mills, foundries, melting processes etc.

Caution! Metallisation has excellent reflective properties but may conduct contact or convective heat more than non-metallised materials. Therefore aluminized PPE may not be worn to enter fires except for a very short period only for rescue or to turn off a valve.

1. ABOUT THE AUTHOR

Since nearly 40 years in this business, at first as product manager, since 1980 as managing director and senior partner at ALWIT, a 50 years old German company specialised on protection against heat and flame.

Chairman of the National Standard Committee in Germany, head of German delegation in different European and International Standard Committees, and - of importance for this title - leader of CEN and ISO project group for reflective protective clothing for fire-fighters.

2. HISTORY

Since the early fifties of the last century aluminised textiles started to be developed. At first used for industrial applications (blankets, curtains, clothing) it was mainly made on the base of asbestos.

In Germany the army and civil defence defined the requirements for clothing intended to protect
against intense radiant heat of 40 kW/m² for at least 6 minutes when tested according to ISO 6942. But Round Robin tests have shown soon that all tested materials have been totally destroyed during such long exposition, and it has been realized that practise is quite different from laboratory test. Heat flux of 40 kW/m² has been confirmed as absolute necessary but exposition time has been reduced to 2 minutes maximum as we can find today in EN 1486 or ISO 15538.

3. EXISTING STANDARDS FOR ALUMINISED PPE

Table 1: Standards for aluminised PPE

<table>
<thead>
<tr>
<th>Title</th>
<th>ISO</th>
<th>EN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial workers exposed to heat</td>
<td>11612</td>
<td>531</td>
</tr>
<tr>
<td>Specialised fire fighting</td>
<td>15538</td>
<td>1486</td>
</tr>
</tbody>
</table>

4. SAMPLES FOR ALUMINISED PPE

5. SELECTION AND USE OF REFLECTIVE CLOTHING

5.1. BASIC MATERIALS

Generally all kind of fibres can be found worldwide as basic materials used for aluminized outer shell, but preferably aramide fibres, preox and fibreglass which are usually constructed as woven fabrics. Features of weight, strength and softness are here of importance for selection.

Table 3: Comparison of different types of basic materials

<table>
<thead>
<tr>
<th>Basic material fabrics</th>
<th>Flame retardant agent</th>
<th>Tensile strength*</th>
<th>Breaking strength*</th>
<th>Abrasion strength*</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR cotton</td>
<td>yes</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>FR wool</td>
<td>yes</td>
<td>fair</td>
<td>good</td>
<td>poor</td>
</tr>
<tr>
<td>Fibreglass</td>
<td>no</td>
<td>very good</td>
<td>poor</td>
<td>poor</td>
</tr>
<tr>
<td>Preox</td>
<td>no</td>
<td>very good</td>
<td>good</td>
<td>poor</td>
</tr>
<tr>
<td>Aramide</td>
<td>no</td>
<td>very good</td>
<td>very good</td>
<td>good</td>
</tr>
</tbody>
</table>

* Depending on construction and weight
Especially aramide fibres can also be found as knitted material. The advantage of knitwear as basic material for aluminized outer shell is the excellent insulation property against all kind of heat and its softness and comfort. However the mechanical strength is generally lower than with fabrics.

**Table 4: Comparison of woven fabric with knitwear**

<table>
<thead>
<tr>
<th>Basic material</th>
<th>Stiffness</th>
<th>Tensile strength</th>
<th>Abrasion strength</th>
<th>Breaking strength</th>
<th>Insulating properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woven fabrics</td>
<td>tough</td>
<td>very good</td>
<td></td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Knitted materials</td>
<td>very soft</td>
<td>good</td>
<td>very good</td>
<td>very good</td>
<td>very good</td>
</tr>
</tbody>
</table>

5.2. FINISHING

Basic material that do not show a smooth surface should be finished by pre-coating in order to receive better adhesion to glue and aluminization.

5.3. GLUE

Type of glue is very important for flame retardancy, ergonomic and environmental aspects.

**Table 5: Comparison of different types of glue**

<table>
<thead>
<tr>
<th>Type of glue</th>
<th>Heat resistance</th>
<th>Environment</th>
<th>Ergonomic</th>
<th>Molten metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyurethane (PUR)</td>
<td>180°C</td>
<td>Containing solvents</td>
<td>tough</td>
<td>poor</td>
</tr>
<tr>
<td>Polymer (NEOPRENE)</td>
<td>260°C</td>
<td>Containing halogen</td>
<td>soft</td>
<td>good</td>
</tr>
<tr>
<td>Polymer (SILICONE)</td>
<td>260°C</td>
<td>Few halogen</td>
<td>Very soft</td>
<td>Very good</td>
</tr>
</tbody>
</table>

5.4. ALUMINIZATION

**Figure 3:** Aluminization by metal sheet

**Figure 4:** Aluminization by transfer film

**Figure 5:** PET one-sided aluminized

**Figure 6:** PET both-sided aluminized “double mirror”
Table 6: Comparison of different types of aluminization

<table>
<thead>
<tr>
<th>Type of aluminization</th>
<th>Thickness of aluminization in µ</th>
<th>Stiffness</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR-radiation Metal splashes</td>
<td>&lt;1</td>
<td>soft</td>
<td>good</td>
</tr>
<tr>
<td>One-sided vaporized PET-film</td>
<td>6</td>
<td>tough</td>
<td>good</td>
</tr>
<tr>
<td>One-sided vaporized PET-film</td>
<td>12</td>
<td>Very tough</td>
<td>good</td>
</tr>
<tr>
<td>Both-sided vaporized PET-film</td>
<td>6</td>
<td>tough</td>
<td>very good</td>
</tr>
<tr>
<td>„Double mirror“</td>
<td></td>
<td></td>
<td>good</td>
</tr>
<tr>
<td>Both-sided vaporized PET-film</td>
<td>12</td>
<td>Very tough</td>
<td>very good</td>
</tr>
<tr>
<td>„Double mirror“</td>
<td></td>
<td></td>
<td>good</td>
</tr>
<tr>
<td>Aluminum metal sheet</td>
<td>12</td>
<td>Very tough</td>
<td>not suitable for PPE</td>
</tr>
</tbody>
</table>

Regarding the aspects shown in 5.1 – 5.4 it would be clear that aluminized materials are very sophisticated products. There is a big variation by combination of each layer of the laminate with different other layers not taken into consideration different constructions of weaving or knitting, different thickness of threads, number of threads, finishing etc.
That is the field where manufacturers can vary and develop materials different and not easy to compare with those from the competitor.

6. RISK ASSESSMENT

Following to risk assessment protective clothing that relies upon the ability of the outer material to reflect intense radiant heat shall be used for short periods only.
Because thermal requirements are most important for the selection of reflective clothing those should be considered following.

6.1. THERMAL REQUIREMENTS OF DIFFERENT STANDARDS

Table 7: Comparison of heat protection

<table>
<thead>
<tr>
<th>Requirement</th>
<th>EN 531</th>
<th>ISO 15538 Level 2*</th>
<th>EN 1486 Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convective heat ISO 9151 / EN 367 80 kW/m²</td>
<td>B1 ≥ 3 ≤ 6</td>
<td>HTI₂₄ ≥ 21</td>
<td>HTI₂₄ ≥ 21</td>
</tr>
<tr>
<td></td>
<td>B2 ≥ 7 ≤ 12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3 ≥ 13 ≤ 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B4 ≥ 21 ≤ 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B5 ≥ 31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiant heat ISO 6942</td>
<td>20 kW/m²</td>
<td>40 kW/m²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C1 t₂ ≥ 8 ≤ 30</td>
<td>RHTI₂₄ ≥ 120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C2 t₂ ≥ 31 ≤ 90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3 t₂ ≥ 91 ≤ 150</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C4 t₂ ≥ 151</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Requirement

<table>
<thead>
<tr>
<th>Requirement</th>
<th>EN 531</th>
<th>ISO 15538 Level 2*</th>
<th>EN 1486 Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact heat ISO 12127 / EN 702 300°C; threshold time</td>
<td>Not requested</td>
<td>≥15 s</td>
<td>≥15 s</td>
</tr>
<tr>
<td>Heat resistance ISO 17493 shrinkage</td>
<td>Not requested</td>
<td>260°C ≤5%</td>
<td>260°C ≤5%</td>
</tr>
<tr>
<td>Molten metal (AL) EN 373</td>
<td>g</td>
<td>Not requested</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>≥ 100</td>
<td>≤ 200</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>≥ 201</td>
<td>≤ 350</td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>≥ 351</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molten metal (FE) EN 373</td>
<td>g</td>
<td>Not requested</td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>≥ 60</td>
<td>≤ 120</td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>≥ 121</td>
<td>≤ 200</td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>≥ 201</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* There are only 2 levels in ISO 15538

### 6.2. PERFORMANCE LEVELS OF DIFFERENT ALUMINIZED TEXTILES

Comparison of performance levels of different aluminized textiles may facilitate the risk assessment.

**Table 8: Comparison of different aluminized textiles when tested according to EN 531**

<table>
<thead>
<tr>
<th>Material - Number</th>
<th>858.0</th>
<th>865.0</th>
<th>878.0</th>
<th>836.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade name</td>
<td>PREATEX</td>
<td>GLAWIT</td>
<td>ARATEX</td>
<td>BARATEX</td>
</tr>
<tr>
<td>Material description</td>
<td>70% carbon / 30% para-aramide</td>
<td>100% fibreglass backside coated</td>
<td>100% para-aramide</td>
<td>75% cotton / 25% para-aramide</td>
</tr>
<tr>
<td>aluminized by transfer film, PUR - glue</td>
<td></td>
<td></td>
<td></td>
<td>SILICONE - glue</td>
</tr>
<tr>
<td>Weight [g/m²]</td>
<td>720</td>
<td>545</td>
<td>420</td>
<td>385</td>
</tr>
<tr>
<td>Allergies</td>
<td>no skin irritation known</td>
<td>fibreglass may cause skin irritations</td>
<td>no skin irritation known</td>
<td></td>
</tr>
</tbody>
</table>

**Thermal Properties**

<table>
<thead>
<tr>
<th>Burning behavior EN 532</th>
<th>Level</th>
<th>Level</th>
<th>Level</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiant heat EN 366</td>
<td>C3</td>
<td>C2</td>
<td>C2</td>
<td>C4</td>
</tr>
<tr>
<td>Molten metal (Al) EN 373</td>
<td>D3</td>
<td>D1</td>
<td>D2</td>
<td>D3</td>
</tr>
<tr>
<td>Molten metal (Fe) EN 373</td>
<td>E3</td>
<td>E2</td>
<td>E3</td>
<td>E3</td>
</tr>
</tbody>
</table>
7. AGEING

Since aluminized materials may be easily affected by mechanical influence the question of ageing is very important. Therefore aluminized specimens have to be mechanical pre-treated before testing according to ISO 6942. Specimens have to be pressed and at the same time twisted 5000 times as shown below:

**Figure 7a:** Test apparatus without specimen

![Figure 7a: Test apparatus without specimen](image)

**Figure 7b:** Test apparatus with specimen (initial position)

![Figure 7b: Test apparatus with specimen (initial position)](image)

**Figure 7c:** Test apparatus with specimen (fully compressed and twisted)

![Figure 7c: Test apparatus with specimen (fully compressed and twisted)](image)

Aluminized PPE may not be washed or cleaned because at least moisture may intensify the oxidation process. Most types of aluminization will disappear after washing or cleaning procedures; some
“double mirror” films seem to withstand to dry cleaning procedures, but in fact just the aluminization on the inner side of PET film will remain. That seems the material still reflecting, however, the reflecting properties are reduced; the non-aluminized surface of PET-film will absorb the radiating heat.

8. ADVANTAGE / DISADVANTAGE OF REFLECTIVE CLOTHING

Advantage or disadvantage of suitable protective clothing is based on the compromise between protection and ergonomics. As seen before, material no. 836.0 seems to be the only real acceptable compromise. However there are remaining two points that should be considered:

8.1. DURABILITY OF ALUMINIZATION

Aluminium coatings either in form of transfer film or double mirror PET - film will peel off e.g. by oxidizing. Transfer films peel off in small aluminium particles while the PET – film will take off partly or completely. Since basic materials and glues own certain but low vapour permeability, sweat may penetrate the material and cause oxidation of the aluminium coat.

Samples with different types of glue or using additional primers to protect the aluminium coat or other metals than aluminium on the inside of double mirror film, e.g. chrome, have been tested in a lye simulating sweat for 7 days, in order to find the best solution.

Other samples have been tested according to ISO 6942 before and after 5 washings according to ISO 6330 with finally drying. The pictures show these samples new (right side) and washed (left side).

Table 9: Test results before and after washings
8.2. WATER VAPOUR RESISTANCE

High water vapour resistance is the second point of importance with aluminized PPE. A sample using a perforated PET – film (sample no. 836.D) has been tested according to ISO 6942 (see above), to EN 28011 and EN 31092.

Table 10: Test results of water resistance
Water resistance is needed in all fire fighting applications, because penetration of water or steam could cause steam burns. Therefore perforated materials cannot be used for PPE intended to fight fire.

**Table 11:** Test results of water vapour resistance

<table>
<thead>
<tr>
<th>Probenbezeichnung</th>
<th>Wasserdurchtritt bei [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>836.0</td>
<td>&gt; 13000</td>
</tr>
<tr>
<td>836.0</td>
<td>500</td>
</tr>
</tbody>
</table>

Even if water resistance would not be necessary, the water vapour resistance is so high, that we cannot speak about comfort.

### 9. LIMITATION

Generally use of aluminised PPE is limited by
- Air supply by SCBA
- Long term exposition to convective heat
- Long term exposition to contact heat
- Fitness of user
- Affect by chemicals
- Affect by electricity
- Oxidation of aluminization by humidity

### 10. TRAINING

Users should be trained in the use, care and maintenance of the protective clothing, especially of aluminized proximity suits, including an understanding of its limitations and of the necessity to remove PPE as soon as possible after an incident.
DETERMINATION OF THE PROTECTIVE PERFORMANCE OF THE WORN PC FOR THE FIRE FIGHTERS

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ABSTRACT

Protective clothing for fire fighters (PC) is one of the most important tools for their activities. Fire fighters need to recognize that PC do not have an indefinite span, that periodic inspection are necessary and that replacement criteria are based on number of factors.

The present work focuses on the brief description:
- of the worn “PC” used for the laboratory tests conforming to ČSN EN 532, ČSN EN 367, ČSN EN 366, ISO DIS 17493, ČSN EN 24920, ČSN EN 368, ČSN EN ISO 105-E01, ČSN EN 530, ČSN EN 13934-1, ISO 4674, ČSN EN 31092, ČSN EN 20811, ČSN EN 468 at the Fire Technical Institute (FTI) in Prague,
- of a discussion of these test results.
ABSTRACT

In this study we analysed the distribution of moisture in multilayered firefighter protective clothing on a sweating torso. Comparing cotton and aramid underwear, we found that generally more moisture was accumulated in cotton underwear than in aramid underwear. The amount of moisture accumulated in the underwear strongly depended on the characteristics of the neighbouring layer.

1. INTRODUCTION

Moisture accumulation in firefighter protective clothing is a major problem, as it strongly affects the heat transfer properties of the protective garment. Moisture trapped in the clothing layers increases the heat capacity as well as the thermal conductivity of the garment. The effect of the moisture on thermal protection of a garment mainly depends on the amount of moisture trapped in the garment and also on the location of that moisture [1]. An additional problem of moisture accumulated in the protective garment layers is burns due to fast evaporation of such moisture [2, 3], which is thought to emerge especially at low level radiant heat fluxes [4].

Up to now the distribution of moisture in textile layers has been analysed primarily for sportswear in moderate climatic conditions. Weder et al. [5] analysed the distribution of moisture in combinations of hydrophilic and hydrophobic clothing layers by X-ray tomography. They found that most of the moisture was accumulated in the 2 layers next to the skin. Similar observations were made by Rossi [6], who compared in his study the moisture distribution in clothing layers with different underwear.

In order to explore the occurrence of burns due to hot steam it is important to analyse the distribution of the sweat. Therefore we analysed in this study the distribution of moisture in firefighter protective clothing assemblies composed of 2 different underwear, 3 different station uniform layers and a state-of-the-art firefighter jacket.
2. METHODOLOGY

2.1. MATERIALS

Typical firefighter protective clothing assemblies were analysed in this study (underwear, station wear, turnout coat). As material for the underwear we used cotton or aramid, which are commonly used by firefighters and have very different moisture transfer properties, as cotton is hygroscopic and aramid hydrophobic.

In combination with the underwear, the behaviour of 3 different station uniform garments was studied. We chose a hydrophilic and hygroscopic FR-cotton station uniform, a station uniform made of an aramid/viscose FR blend which was treated with a hydrophobic finish, and a hydrophobic aramid station uniform. A state-of-the-art firefighter jacket with a total surface weight of 535 g/m² was used. The jacket consisted of an aramid inner layer (115 g/m²), a thermal barrier consisting of aramid non-woven (100 g/m²), a breathable PTFE membrane laminated on an aramid fleece (135 g/m²) and an aramid outer layer (185 g/m²).

The clothing layers listed above were combined in a total of 8 different samples (see Table 1).

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Underwear</th>
<th>Weight (g/m²)</th>
<th>Station uniform</th>
<th>Weight (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cotton (CO)</td>
<td>175</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>Aramid (AR)</td>
<td>140</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>3</td>
<td>CO</td>
<td></td>
<td>FR-cotton (SCO)</td>
<td>320</td>
</tr>
<tr>
<td>4</td>
<td>CO</td>
<td></td>
<td>Aramid/viscose FR (SAV)</td>
<td>250</td>
</tr>
<tr>
<td>5</td>
<td>CO</td>
<td></td>
<td>Aramid (SAR)</td>
<td>220</td>
</tr>
<tr>
<td>6</td>
<td>AR</td>
<td></td>
<td>SCO</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>AR</td>
<td></td>
<td>SAV</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>AR</td>
<td></td>
<td>SAR</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Combination of 8 different samples analysed in this study in combination with a firefighter protective clothing multilayer ensemble.

The samples were conditioned for at least 24 hours at standard climatic conditions of 20 °C (+/- 2 °C) and 65% (+/- 5%) relative humidity.

2.2. MEASUREMENT METHODS

Measurements were performed on a sweating torso (see Figure 1). The sweating torso is a cylindrical measurement device with the dimensions of a human torso which simulates the thermophysiological behaviour of the human torso. The torso is able to release defined amounts of water in order to simulate sweating, and its surface temperature can be controlled. The surface temperature of the torso can either be kept constant or the torso can be run with constant heating power.
The temperature on the surface of the torso and the weight of the torso are recorded during the measurement. The amount of moisture evaporating out of the clothing combination can be registered during the entire measurement. The temperature on the surface of the torso is a measure of the possibility of thermoregulation by the evaporation of sweat, as will be illustrated below. Further details of this measuring device can be found in [7].

Measurements on the sweating torso were performed under standard climatic conditions of 20 °C and 65% relative humidity. A sequence of 3 phases was run on sweating torso. Each of the phases lasted one hour. The first phase was for acclimation, during which the surface temperature of the torso was kept constant at 35 °C, without sweating. In the second phase, the torso was heated with a constant power of 125 W and sweating of 0.25 l/hour started. This corresponds roughly to a physical activity of a human of 500 W and 1 l/hour sweating. In the third phase sweating was stopped and the supplied power was reduced to 25 W (about 100 W/human).

The torso surface temperature and the weight of the torso were recorded during the entire measurement. Each clothing layer was weighed before and after the measurement. The amount of moisture accumulated in the different layers was determined from the differences.

3. RESULTS

3.1. TORSO SURFACE TEMPERATURE

Figure 2 a) shows the impact of the underwear on the torso surface temperature in measurements with the protective assemblies without the station uniform layer. In the sample using aramid underwear the torso surface temperature reached its maximum of 35.2 °C 3 minutes after the start of the sweating phase. At that point, the evaporative cooling started and the temperature dropped to 33.7 °C at the end of the sweating phase. The temperature of the sample with cotton underwear rose to 35.4 °C at 5 minutes after the beginning of the sweating phase. But after the beginning of the evaporative cooling the decrease of temperature with cotton underwear was larger than with aramid underwear and a temperature of 33.5 °C was reached at the end of the sweating phase.
Figure 2 b) shows the behaviour of the samples consisting of 2 different underwear and 3 different station uniform layers combined with the protective clothing fabric. During the first 4 minutes of the sweating phase, the torso surface temperature of all samples rose at similar rates until sample 8 reached its maximal temperature of 35.3 °C. Six minutes after the start of the sweating phase samples 4, 5 and 6 reached all the same maximal temperature of 35.5 °C. The temperatures of samples 3 and 7 continued rising until they reached maximal values of 35.8 °C for 3 and 35.6 °C for 7 after 8 minutes. In sample 7 the torso surface temperature did not drop after reaching its maximum, but remained constant until the end of the sweating phase. Similarly, the temperature of 6 dropped only by 0.3 °C between reaching the maximum and the end of the sweating phase.

![Figure 2: Surface temperature of the torso during the sweating phase: a) Comparison of the samples in combination with two different underwear layers and without the station uniform layer, b) Comparison of the samples with different combinations of two different underwear and three different station uniform layers.](image)

The samples with the aramid station uniform (5 and 8) showed a similar behaviour as the samples without a station uniform (1 and 2). Sample 3 also showed a temperature course similar to the other curves for samples with cotton underwear. The only sample with cotton underwear that behaved differently was sample 4. In this sample the temperature dropped until a steady-state temperature was reached and stayed constant until the end of the sweating phase.
3.2. MOISTURE DISTRIBUTION

The distribution of the moisture in the textile layers at the end of the third measurement phase is shown in figure 3. More moisture was accumulated in the cotton underwear than in the aramid underwear in the samples with the same station wear and firefighter jacket.

The moisture accumulated in the underwear strongly depended on the second layer of the samples. For example, in samples with the aramid/viscose FR station uniform layer, which was treated with a hydrophobic finish, over 4 times more moisture was accumulated in the underwear than in the underwear of the samples with other station uniform layers or without a station uniform layer. In those samples only about 4% of the moisture moved out to the firefighter jacket, while in samples with the FR-cotton station uniform layer over 30% of the moisture moved out to the firefighter jacket; in samples with aramid station uniform layer as much as 40% - 60% of the moisture accumulated in the firefighter jacket.

In sample 7 only 24 g moisture accumulated in the clothing layers, which was less than in all samples with other station uniform layers. In this sample 40 g of moisture dripped off, and in sample 2 about 10 g dripped off. All samples from which moisture dripped off included aramid underwear. Water drop-off was not observed in any of the samples with cotton underwear.

![Figure 3: Moisture distribution in the textile layers at the end of the third measurement phase](image)

Overall, we found that both layers, underwear and station uniform, affected the distribution of moisture in the clothing system. The two effects of moisture absorption ability of the underwear and wicking properties of the station uniform were superimposed. This means that for corresponding combinations of outer clothing the amount of moisture in the underwear was always greater for cotton than for aramid. However this quantity also varied with the type of outer layers.

4. DISCUSSION

As could be intuitively expected, the samples without a station uniform layer accumulated the least moisture and the torso surface temperature dropped the most until the end of the sweating phase. In the beginning of the sweating phase, the temperature of the sample with cotton underwear rose more than
the temperature of the sample with aramid underwear. This phenomenon is due to the hygroscopic properties of cotton. Heat of sorption was released during absorption of the moisture by the fibres and the temperature therefore rose higher than with aramid underwear. In sample 2, water dripped off. Therefore not all of the moisture could be used for the evaporative cooling of the torso and the temperature did not drop as much as with cotton underwear. The same phenomenon could be observed in sample 7, from which more water dripped off than remained in the clothing. As this moisture could not be used for evaporative cooling, the surface temperature of the torso at the end of the sweating phase was 0.8 °C higher during the acclimation.

The fact that more moisture was accumulated in the cotton underwear corresponds with the findings of the better cooling abilities of samples including cotton underwear. As more moisture is accumulated in the underwear than in the external layers, it is likely that more moisture evaporates near the skin, where the energy used for the evaporation is taken directly from the skin. If the moisture evaporates in an outer layer the energy used for the evaporation is taken from the neighbouring layers and the cooling of the body is not that efficient. However this higher amount of moisture in the underwear might also contribute to an increased risk for steam burns.

5. CONCLUSIONS

The material of the underwear largely influenced the torso surface temperature course. With aramid underwear the temperature decreased faster than with cotton underwear but with cotton underwear the temperature drop was larger than with aramid underwear. The underwear did not dominate the distribution of moisture in the clothing systems; that distribution depended instead mainly on the station uniform layer. The properties of the latter strongly influenced the amount of moisture accumulated in the underwear and also in the firefighter jackets.

REFERENCES


STUDY ON THE PERMEATION RESISTANCE OF GLOVES AGAINST HAIRDRESSING CHEMICALS

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ABSTRACTS

Physical contact with chemicals which are offensive and hazardous to health is unavoidable in many hairdressing activities. Protective gloves – generally disposable sheer film gloves – are frequently supplied with hairdressing chemicals; their protective value is however often questionable and unproven. Certain typical and widely used chemicals are to be used to study the chemical resistance to permeation of both disposable gloves supplied with hairdressing products, and selected certified gloves which enjoy wide user acceptance, against EN 374-3.

Twelve selected glove types (Co-polymer (CPE, polyethylene), PVC, vinyl acetate, nitrile, latex) of varying composition and material thickness are subjected in each case to a permeation test at 33° C according to a practical approach under a triple test arrangement based upon DIN EN 374-3:2003 and employing five common preparations (oxidative hair dye/peroxide solution, bleaching powder/peroxide solution, direct dye, fixing solution, permanent-wave solution).

This study reveals that the best possible protection against the variety of hairdressing chemicals is given by different individual materials. In view to desired recommendations for the practise it is of importance to implement assessment criteria that implicate the toxicological relevance of the single components in the respective mixtures.
A PERSPECTIVE ON REALISTIC MATERIAL CHEMICAL PERFORMANCE REQUIREMENTS: THE NEED TO REDEFINE HOW INDUSTRY CHOoses CHEMICAL PROTECTIVE SUIT MATERIALS

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ABSTRACT

Significant advances have been made in the barrier qualities of protective clothing fabrics. Over the past 25 years, material technology has evolved to now provide a number of multi-film laminates with high levels of permeation resistance to a wide range of chemical classes. The principal driving force has been the permeation resistance test and its manner of application for qualifying candidate clothing materials. The industrial application of the permeation test procedures, as defined in ASTM F 739, EN 369, and ISO 6529, entails testing materials against chemicals at 100% concentration (gas or liquid) over the duration of the test usually for up to 8 hours. However, no specific attempt is made to relate these data to actual wearer exposure or permissible exposure rates. While this practice has yielded excellent barrier technologies, the singly focused objective of permeation resistance often comes at the expense of other material attributes particularly those related to wearer comfort and other human factors properties. This paper describes a more appropriate approach for defining acceptable material performance that is based on the consideration of realistic exposure levels, the measurement of cumulative permeation, and the application of appropriate toxicological-based performance criteria. Approaches used for setting emergency responder suit material requirements for chemical warfare applications are examined and contrasted with current industrial approaches for measuring and reporting chemical permeation resistance. Similarly, the practices associated with choosing respiratory protection and the testing of respirators are compared with industrial clothing selection guidelines. A specific series of recommendations is made for appropriate testing and reporting of clothing barrier performance.

INTRODUCTION

The approach using breakthrough time in evaluating chemical permeation resistance for protective clothing material is based on the time for the chemical's permeation rate to achieve arbitrary levels (0.1 µg/cm²/min in North America and 1.0 µg/cm²/min in Europe – see Figure 1). These levels were set nearly 2 decades ago for the sole purpose of providing a way of normalizing differences between testing laboratory and equipment for consistent reporting of chemical resistance test results. The normalization permeation rates were chosen because they were considered achievable for a large range
of chemicals. The breakthrough time has never been specifically related to the toxicity of the chemical or the actual exposure of the individual wearing the protective clothing.

Figure 1. Practices for determining permeation breakthrough time

CURRENT PRACTICES FOR USING PERMEATION DATA

The use of breakthrough time-based criteria does not reflect a predicted chemical dose to the clothing wearer and instead has only been used in the absence of qualified dermal exposure limits. While in most cases, this approach might be considered as erring on the side of safety, it limits available material technology usually at the expense of ergonomic properties such as moisture vapor transfer and material stiffness. The approach also fails to take into account that in some cases during a chemical exposure, the permeation will reach a peak that exceeds the normalization rate over a relatively short period of time though there is a significant decline following the volatilization of the chemical. The test approach based on breakthrough time characterizes materials based on how fast the concentration reaches the permeation limit. While at first glance it seems overly conservative, it would allow up to 6 ug/cm² of cumulative breakthrough during the test if the North American normalization practice was followed and as much as 60 ug/cm² of permeating chemical under the European system for interpreting breakthrough time. Based on inhalation toxicity for the same chemical (again, using conservative measures) this could be more than a reasonably safe level. The more important point is that toxicity is not just a function of concentration, it is a function of dosage (concentration x time). Thus a perfectly safe material may allow the concentration to exceed the rate limit at some time during the test, but the ultimate (cumulative) dosage could be well below the toxic level. Therefore, it is not an approach that will effectively screen or allow the ranking of chemical protective materials in terms of defining true exposure or protective capabilities.

Industry has become accustomed to the use of breakthrough times as chemical protective clothing manufacturers provide extensive lists of chemical permeation resistance test results. The general practice is to choose appropriate protective clothing based on the breakthrough time where the selected
clothing item has a breakthrough time that is longer than the maximum expected period of protective clothing use. In many cases, end users will opt for clothing materials that show no reported breakthrough over a period of time that is much longer than intended use based on the philosophy that a better barrier material will protect against a large range of conditions. Unfortunately, in the absence of dermal exposure limits (analogous to respiratory exposure limits) no other approach seems possible and industry has maintained the status quo for deciding on the suitability of chemical protective clothing.

**CURRENT USE OF CUMULATIVE PERMEATION**

In contrast, permeation resistance for chemical warfare agents is based on maximum cumulative permeation that can occur through the protective clothing material in a given time period. While the specific origin of the current levels is unknown, this approach is based on the relative dosage of the chemical warfare agents that are considered safe from a dermal exposure perspective. This current practice involves measuring total cumulative permeation of chemical warfare agents over a relevant time period and then comparing the cumulative permeation mass (measured in ug/cm²) to acceptable skin exposure limits. For example, a maximum cumulative permeation mass of 1.25 ug/cm² is used for nerve agents (Sarin, Soman, VX) while 4.0 ug/cm² is used for blister agents (distilled mustard).

Cumulative permeation can also be reported as part of standardized permeation testing. ASTM Test Method F1383 and ISO 6529 establish protocols for intermittent challenge of protective clothing materials with chemical and permit the report of cumulative permeation mass as an effective means of qualifying material results under these conditions. In fact, given the variability in test equipment and set-up, it has been reported that there is likely less variation in cumulative permeation measurements as there is in breakthrough time [1].

**PROPOSED ALTERNATIVE REPORTING OF PERMEATION RESULTS**

The practice for replacing breakthrough time with cumulative permeation mass could easily be accomplished in a variety of ways. In current permeation testing, data are collected periodically at some sampling rate from permeation test cells to establish a permeation curve and ultimately allow the determination of breakthrough time. The use of these data by integrating under the curve will yield the permeation mass meaning that cumulative permeation masses could be calculated from historical data for material-chemical combinations already tested. Alternatively, if the intended period of use is known, the collection medium could be simply analyzed at the end of the test period for a closed loop system or collected in total on a filter without intermediate analysis. The latter approach could greatly simplify the measurement of permeation resistance.

Two specific approaches exist for how cumulative permeation could be reported and classified. In the first approach, the total cumulative permeation mass could be reported at one or more times. For example, where permeation tests are run for 8 hours, the cumulative permeation at the end of 8 hours would be reported. It could also be possible to determine cumulative permeation at intermediate time points under this practice. In the second approach, the time to a specific cumulative permeation could be determined where their relevance to a specific dose or exposure for a particular chemical. This type
of measure would provide a more meaningful assessment of exposure compared to permeation breakthrough times.

**ESTABLISHMENT OF PERMEATION RESISTANCE CRITERIA**

The principal challenge for applying cumulative permeation measurements is determine how these data could be used to set acceptance criteria. This has been one of the primary constraints affecting the reporting of cumulative permeation masses. In order to know an acceptable dose, permissible exposure limits are needed for dermal contact. However, exposure limits of this type are only available for a few chemicals and there have not been consistent practices in place for their determination. The designation of some chemicals as skin toxic further does not provide useful information for establishing an acceptable skin dose.

One approach could be the use of inhalation toxicity levels to define acceptable skin exposure. This approach could use the best available inhalation toxicity limits and then calculate the associated cumulative breakthrough for established test conditions. Given an inhalation exposure limit in mg/m³, the related cumulative permeation can be calculated known the exposure duration, the flow rate of the permeation collection medium, and the exposed surface area of the permeation test cell. In the United States, specific permissible exposure levels for vapor concentrations of certain chemicals have established by the American Industrial Hygiene Association for emergency response. These emergency response planning guidelines (EPRGs) set different maximum airborne concentrations of chemicals for up to 1 hour where specific threshold effects would be obtained. For example, an ERPG-2 is the concentration where nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptom’s that could impair an individual’s ability to take protective action. Applying the ERPG-2 for acrylonitrile, a maximum cumulative permeation for skin exposure could be determined as follows:

- The ERPG-2 for Acrylonitrile is 76 mg/m³
- Maximum exposure duration is 60 minutes, so maximum allowable dosage would be (768 mg/m³)*(60 min) = 4560 mg-min/m³.
- Test flow rate is 1 Liter/min and test sample area is 10 cm².

Cumulative permeation can be calculated as:

\[
\text{Cumulative permeation} = (4560 \text{ mg-min/m³}) \times (1 \text{ Liter/min}) \times (1 \text{ m}^3/1000 \text{ Liters}) \times \left(\frac{1 \text{ µg}}{1000 \text{ mg}}\right) \times \left(\frac{10 \text{ cm}^2}{\text{test sample area}}\right) = 456 \text{ µg/cm}^2
\]

Following a similar logic for the other representative toxic industrial chemicals, the cumulative permeation amounts are shown in the following table (related acute exposure guideline levels are used for most chemicals as the acceptable vapor exposure concentration). The same approach is also applied to the two chemical warfare agents now included in the standard (Soman and distilled Mustard):
Table 1. Cumulative permeation limits for selected chemicals

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Exposure Limit (mg/m³) – Type</th>
<th>Cumulative Permeation (µg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrolein</td>
<td>0.229 (AEGL-2)</td>
<td>1.37</td>
</tr>
<tr>
<td>Acrylonitrile</td>
<td>38 (ERPG-2)</td>
<td>456</td>
</tr>
<tr>
<td>Ammonia</td>
<td>54.3 (AEGL-2)</td>
<td>326</td>
</tr>
<tr>
<td>Chlorine</td>
<td>4.42 (AEGL-2)</td>
<td>26</td>
</tr>
<tr>
<td>Dimethyl Sulfate</td>
<td>0.62 (AEGL-2)</td>
<td>3.7</td>
</tr>
<tr>
<td>Distilled Mustard (HD)</td>
<td>0.018 (AEGL-2)</td>
<td>0.118</td>
</tr>
<tr>
<td>Soman (GD)</td>
<td>0.10 (AEGL-2)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

For comparison purposes, a toxic industrial chemical that immediately permeated a material at the normalization permeation rate of 0.1 µg/cm²-min and remained at that level of permeation would yield a cumulative permeation of 6.0 µg/cm². It is important to point out that based on this analysis, four of the chemicals (acrolein, dimethyl sulfate, distilled mustard, and soman are below what would be predicted as acceptable using the current practice for toxic industrial chemicals. On the other hand, the cumulative permeation values for acrylonitrile, ammonia, and chlorine would establish greater acceptable permeation than currently permitted.

These limits should be considered conservative because it is understood that the skin toxic dosages should (almost always) be less than the inhalation toxic dosages (in some cases much less). Nonetheless, without actual skin toxicity data, these levels should still err on the side of safety. A better understanding could be obtained by examining those chemicals where there are both skin and respiratory exposure levels that can be compared.

**RELATIVE INHALATION TO SKIN TOXICITY OF CHEMICAL WARFARE AGENTS**

A potential next step could be to take the above limits and modify those limits by considering the relative inhalation toxicity to skin toxicity ratio of other chemicals where both skin and inhalation toxicity are known. Using "threshold/severe effects," the following inhalation/skin toxicity ratios can be obtained for various chemical warfare agents [2]:

\[
\begin{align*}
GA &= \frac{2,000}{50} = 40 \\
GB &= \frac{1,200}{25} = 48 \\
GD &= \frac{300}{25} = 12 \\
GF &= \frac{300}{25} = 12 \\
VX &= \frac{25}{10} = 2.5 \\
HD &= \frac{500}{100} = 5
\end{align*}
\]

The first number is the inhalation toxicity concentration (in mg/m³) based on vapor contact, while the second number is the skin toxicity concentration, also based on vapor contact.

These numbers show that the relative inhalation to skin toxicity ratio varies for different chemicals. One approach could be to base maximum acceptable cumulative permeation on inhalation and apply a
ratio of 2.5 (the lowest ratio of the above comparison, and therefore, the most conservative). This approach could serve on an interim basis until the skin toxicity work could be done; however, there is really no basis for following this approach. Nevertheless, it is reasonable to say that the skin vapor toxicity will never be greater than the inhalation vapor toxicity, but to arbitrarily select a ratio could invite criticism of the intent to relate permeation end points to actual skin toxicity.

Another argument could be the consideration of the type of exposure where liquid contact to the skin would present a high toxicity than vapor inhalation toxicity. However, given the levels of protection required, all chemicals will pass through the protective clothing material as vapors (or they will not pass through at all). Thus, this argument is not relevant.

PROPOSED PATH FORWARD

The use of cumulative permeation data offers a more practical and logical basis for establishing permeation resistance performance criteria for chemical protective clothing materials. Very little change in testing practices is needed to accommodate this change and in fact permeation testing could become simpler if only cumulative permeation mass is sought for a specific exposure time. The principal challenge is related cumulative permeation results to acceptable exposure levels. Unless skin toxicity data is specifically present, it is recommended that the use of the inhaled vapor limits based on appropriate permissible exposure levels be used to set specific minimum criteria for each chemical. In this fashion, chemical protective clothing performance could be related to actual needed protection.

REFERENCES

LOAD, RISKS AND THE NEED TO USE PPE IN AGRICULTURAL ENTERPRISES

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ABSTRACT

In animal or plant production, different kinds of load and risk exist for the farmer. It is to distinguish between indoor and outdoor production in livestock buildings, greenhouses and mobile work places in the fields, fruit gardens or vineyards. Farmers and farm workers will be stressed mainly by mechanical load, heat, vibration, noise and airborne contaminants like disinfectants, pesticides or bio aerosols including bacteria or viruses. In all cases the possible risks have to be limited by reducing load or by using different types of personal protective equipment (PPE) to protect the head, whole body or respiration. Risk assessment gives the need and the required performance of protective means.

1. INTRODUCTION

In the present public discussion about possible impacts of agriculture on the environment, farmers health and welfare at the working place should not be neglected. Despite decreasing numbers of farmers and farm workers the branch of agriculture represents a considerable group of gainfully employed persons.

![Figure 1: Numbers of farm workers in the member states of the EU-15, 2004](image)
Figure 1 shows the numbers for the fifteen member states of the European Union (EU-15) in the year 2004. Employment ranges from 99,000 farm workers in Denmark up to 1,017 million in Italy. In the whole nearly seven million persons are working in agriculture. The share from total employment varies between 0.9% in the United Kingdom and 13.6% in Greece. In the average 3.9% of the European people are working in agriculture.

Farmers’ work environment shows large diversity depending on national structures of agriculture in Europe. Farmers’ and farm workers are stressed by different kinds of load which may cause hazards. All possible loads must be diminished to acceptable levels or personal protective equipment (PPE) must be used to ensure most secure working conditions. The paper gives an overview about relevant working places and sources of danger and assesses possible risks for the example of Germany. The main weight lies on protection against airborne contaminants. Examples are given for one working step each in animal and plant production.

2. SOURCES OF LOAD

Mechanical load, heat, vibration, noise and airborne contaminants like disinfectants, pesticides or bio aerosols including bacteria or viruses may affect farmers’ health and welfare. Sources of possible airborne hazards exist in plant and animal production, figure 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Desired conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>airborne pollutants</td>
<td></td>
</tr>
<tr>
<td>inhalable dust</td>
<td>&lt; 10 mg/m³</td>
</tr>
<tr>
<td>respirable dust</td>
<td>&lt; 3 mg/m³</td>
</tr>
<tr>
<td>carbon monoxide</td>
<td>&lt; 35 mg/m³</td>
</tr>
<tr>
<td>nitrogen dioxide</td>
<td>&lt; 9.5 mg/m³</td>
</tr>
<tr>
<td>climate</td>
<td></td>
</tr>
<tr>
<td>fresh air stream</td>
<td>30 – 50 m³/h</td>
</tr>
<tr>
<td>air temperature</td>
<td>17 – 25 °C</td>
</tr>
<tr>
<td>air humidity</td>
<td>35 – 65 %</td>
</tr>
<tr>
<td>air velocity</td>
<td>&lt; 0.5 m/s</td>
</tr>
<tr>
<td>noise</td>
<td>noise level</td>
</tr>
<tr>
<td></td>
<td>≤ 85 dB(A)</td>
</tr>
</tbody>
</table>

Figure 2: Sources of load, possible loads and desired conditions for work in agriculture
It is to distinguish between indoor and outdoor sources. Mobile sources arise from work steps using tractors with or without mountings and other self-propelled machinery. Stationary located sources are livestock buildings, post harvest equipment, machinery of food management on farm level and greenhouses. Concerned parameters are airborne contaminants, climate and noise for which desired conditions are defined. The values given in figure 2 are examples and may vary depending on particular national regulations.

All loads must be diminished by active means to acceptable levels or personal protective equipment must be used to ensure most secure working conditions.

3. RISK ASSESSMENT AND NEED OF PROTECTION

Risk assessment gives the need and performance requirements of protective means. Table 1 shows selected possible hazards for animal keeping and plant protection.

Noise in animal keeping is mainly a problem in pig stables before and during feeding, in plant protection during the application of pesticides caused by the tractor or especially by air-blast sprayer. In both cases hearing protectors may be demanded.

Farmers are exposed to different hazardous materials handled as liquids, sprays or gases. Biological materials are airborne and settled on surfaces in the stable. Both hazardous and biological materials may cause harm after respiration or dermal uptake. Depending on level and duration of exposure and specific effects of the materials respirators and/or protective garments are required.

The German Agricultural Professional Associations created a matrix for risk assessment, table 2, which will be applied to a special working situation /2,3/.

Table1: Selected possible hazards in animal and plant production examples

<table>
<thead>
<tr>
<th>classification of hazard</th>
<th>animal keeping</th>
<th>plant protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>mechanical</td>
<td>mobile operations</td>
<td>mobile operations</td>
</tr>
<tr>
<td>physical</td>
<td>noise</td>
<td>noise</td>
</tr>
<tr>
<td>hazardous material</td>
<td>disinfectants</td>
<td>liquids, aerosols, gases fumigants, pesticides</td>
</tr>
<tr>
<td>biological material</td>
<td>infectious allergenic and toxic micro-organisms</td>
<td>--</td>
</tr>
</tbody>
</table>
Table 2: Matrix for risk assessment

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Nothing</th>
<th>Bagatelle</th>
<th>Injury Sickness</th>
<th>Permanent Harm</th>
<th>Severe Permanent Harm; Death</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very rare</td>
<td>I</td>
<td>I</td>
<td>II</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>Rare</td>
<td>I</td>
<td>I</td>
<td>II</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>Often</td>
<td>I</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>III</td>
</tr>
<tr>
<td>Very often</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>III</td>
<td>IV</td>
</tr>
<tr>
<td>Permanent</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>III</td>
<td>IV</td>
</tr>
</tbody>
</table>

Four classes of risk are defined with increasing order of relevance from class I to class IV, table 3.

Table 3: Risk class, risk potential and need of protection

<table>
<thead>
<tr>
<th>Risk Class</th>
<th>Risk Potential</th>
<th>Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Minor</td>
<td>Hardly necessary</td>
</tr>
<tr>
<td>II</td>
<td>Medium</td>
<td>Necessary</td>
</tr>
<tr>
<td>III</td>
<td>High</td>
<td>Pressing</td>
</tr>
<tr>
<td>IV</td>
<td>Very High</td>
<td>Very Pressing</td>
</tr>
</tbody>
</table>

Class I has a minor potential and needs normally no measures of protection, but requires duly handling of tools and materials. Looking to hazardous materials class IV indicates carcinogenic effects. Chemicals, such as disinfectants and pesticides are labelled according to the Hazardous Substances Ordinance /4/ if they are highly toxic (T'), toxic (T), caustic(C), harmful (Xn) or irritating (Xi). Outgoing from the risk potential these chemicals belong to the classes II and III, with highly toxic and toxic substances in class III.

Depending on the R- and S-phrases for risk and safety appropriate PPE must be selected. According to the EU directives such equipment must be tested and certified. It exist a comprehensive network of testing chemical protective components. For textile material for example, which shall protect against permeation, the test procedure of EN 374 /5/ is used. For penetration jet test, spray test and the gutter test are applicable depending on the kind of exposure /6/. Exposure against sprayed pesticides and performance of PPE concerned gives an exceptional figure for different countries. Germany created a special standard (DIN 32781) for protective suits against pesticides /7/. Core element is a special test procedure which reflects to spray conditions in the reality. Meanwhile this atomizer test is accepted to be an European standard (EN 14786 /8/). Beyond CEN, efforts exist which are in line with German intentions. For example ISO established a new work item for pesticide protective suits.
4. SUCaM PROCEDURE

Nowadays the problems of the use of PPE are seen in general much broader than in the past. Starting from the estimation of exposure and assessment of risk an appropriate protective measure, e.g. gloves, suits or respirator is selected for a special case of work to ensure the correct use from the point of the wearer. This comprises to define how it should be selected, handled, against what it protects and what are the limits for wearing. This leads to the so called SUCaM Procedure:
Selection, Use, Care and Maintenance
This procedure helps to fulfil increased demands of those persons which are responsible for employees protection, the user itself and the manufacturer. The scheme of the procedure is given in figure 3:

![Scheme of the SUCaM procedure](image)

Figure 3: Scheme of the SUCaM procedure

In this guidance the first two items are personal related while the other are targeted mainly to the product that means the textile and the suits. It starts with risk assessment, gives further information to select and how to use PPE and ends with notes for cleaning, repair and disposal. This procedure may be a useful aid for secure working.

5. FINAL REMARKS AND CONCLUSION

Farmers’ work environment shows a large diversity. Farmers or farm workers will be stressed mainly by mechanical load, heat, vibration, noise and airborne contaminants like disinfectants, pesticides or bio aerosols including bacteria or viruses. All parts of the body inclusive respiration must be considered for assessing the risk. Risk assessment gives the need and performance of protective means. More comprehensive information becomes available if the procedure of selection, use, care and maintenance is used. At the present time different groups create special SUCaM guidance papers for particular fields of load. Examples are noise protection, respirators and chemical protective clothing /9,10,11/.

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EN 458 Hearing protectors – Recommendations for selection, use, care and maintenance-Guidance document

prEN 529 Respiratory protective devices – Recommendations for selection, use, care and maintenance-Guidance document

CEN/TR 15419 Protective clothing – Guidelines for selection, use, care and maintenance of chemical protective clothing
PROTECTIVE CLOTHING FOR PESTICIDE APPLICATORS: A COMPREHENSIVE ONLINE SYSTEM FOR DATA MANAGEMENT, ANALYSIS AND DISSEMINATION OF INFORMATION

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ABSTRACT

National and international test standards and performance specifications for protective clothing have increased considerably over the last few decades. Laboratories around the world use these standards to evaluate protective clothing and determine whether performance requirements have been met. Garments that have met the specifications are labeled accordingly. Record keeping at and among laboratories as well as information dissemination to users is often challenging. The purpose of the online system is two-fold: to assist laboratories with data management and analysis, and to provide a source of information for prospective users. This comprehensive system has two major components – the password-protected data management system and the information dissemination component, which has the option for password protection. The data management system includes blank forms that are used to enter the raw data while conducting the test. This information is then keyed into the system and results are automatically computed. Once the data is submitted, it can be edited only by personnel with administrative privileges. The data from the password-protected component can be accessed by authorized personnel for review and to generate detailed and summary reports. The information dissemination component allows PPE users to enter their requirements to obtain information regarding garments that meet the specified criteria. Information related to selection, care, use and maintenance is also included to assist in the selection of appropriate protective clothing for pesticide applications. This system has the ability to present the information in different languages, and can be used as a model for the development of systems for other PPE. The presentation will include a system demonstration.

1. INTRODUCTION

The explosive growth of information technology is having a profound impact on our lives. Web-based databases are used extensively for data collection, analysis and dissemination. The other added advantage to online systems is the ability of sharing information worldwide through a click of a button. At the University of Maryland Eastern Shore, the data was originally stored in Microsoft Excel files. In order to manage the data more efficiently, the results were transferred into an Access database. This database then was developed into a password protected online system entitled “Work
and Protective Clothing for Pesticide Applicators”. In 2005, a new online system was designed and developed that includes data entry and the decision making process. This system serves as a bridge between research and practical applications of the research findings.

2. OBJECTIVES

The objective of the project was to develop a comprehensive, user-friendly online system with the following capabilities:

– Enable lab technicians to enter and manage raw data about the physical and performance characteristics of fabrics and garments
– Allow users with administrative privileges to view reports and approve data entered by the lab technicians.
– Compare the data with the performance specifications to determine if a garment meets minimum specifications.
– Present information to the user in a non-technical format to assist in the selection of appropriate garments.

3. METHODOLOGY

The online system is a password protected system that was designed to allow access to three types of users. The system authenticates the user name and password prior to allowing access to the system. The authentication was designed to allow access to users in the following three categories:

– Laboratory technicians responsible for entering data online.
– Supervisors/administrators with access to laboratory data and with the authority to approve data submitted by the technicians.
– Users who have the ability to access information to assist in the selection of suitable garments.

The modules within the system are grouped into three broad categories: data entry and management, data computation, and data dissemination.

3.1. DATA ENTRY AND MANAGEMENT

Lab technicians/research assistants record raw data on forms that can be printed from the system for use in the lab. The raw data is transferred from the form to the online system and then submitted. Once it has been submitted, the data cannot be changed by the data entry personnel. The administrator has the authority to reject the data and thus allow the data entry personnel to edit the data. Users with admin privileges have access to the data sections of the online system. A sample data entry form is shown in Figure 1.
3.2. DATA COMPUTATION

Upon submission of the data by the laboratory technician, the system computes the results and the raw as well as computed data are saved to the respective tables in the database. The system also allows data entry of computed results through a separate set of forms.

3.3. INFORMATION DISSEMINATION

The homepage of the system provides an overview and links that provide the ability to pull up information based on the user’s needs. This section of the online system has the option of being opened to the public with no username and password. The user enters the selection criteria that include factors such as level of protection, type of garment, and country of use to obtain a list of garments that meet the criteria. Information that is beneficial to decision making, such as cost, type of garment, and size, is provided in a table format to allow comparison of the different garments. Easy to use dropdown menus are used to provide general information regarding fabrics, garment design, pesticides, risk assessment, as well as standards and performance specifications utilized for testing and analysis. The system also allows users to view details about a particular garment if they want to obtain more information.
4. OUTCOMES

The comprehensive system provides a transparent mechanism to collect, manage, and disseminate information on protective clothing for pesticide applicators. The easy data entry form allows the laboratory technicians and research assistants to efficiently enter the data. Data integrity is maintained by checks and balances built into the system. The system allows the administrator the ability to drill down to the raw data level with a few clicks. The reports enable the supervisor to generate detailed and summary reports based on the criteria selected. The reports are also beneficial in managing a large volume of data. The system provides continuity in the manner in which data is saved and sorted when there is a change in personnel. For example, at a university it simplifies the process of data management when graduate assistants working on a project change.

This system addresses a major challenge in transitioning research/testing from the laboratory level to the user. Over the two decades of research on protective clothing for agricultural workers at the University of Maryland Eastern Shore, the projects have transitioned from primarily factorial design-based studies to a broader collaborative approach. The goal is to address the need for performance based recommendations for the availability and selection of protective clothing for pesticide workers. This online system has been developed as a prototype to demonstrate a mechanism that spans from data entry to dissemination of performance based recommendations. This system provides multiple functions to assist in selection. The individuals responsible for the selection of appropriate PPE for pesticide workers have the ability to select garments based on the needs of the applicator. It also provides a mechanism to obtain information about garments that do not meet the performance specifications. If the garment does not meet the performance specification, the reason for not meeting the specification is indicated. This option is included to assist the users and individuals responsible for ordering PPE in making the right selection. In addition to level of protection and comfort, cost and ability to use the garments for different scenarios are often significant factors in choice. Therefore, the system allows the flexibility to search for information for a specific garment in the database.

5. RECOMMENDATIONS FOR FUTURE WORK

The system has the capability to be set up to provide information in different languages as well as the ability to perform selection based on the criteria for the country or region selected. In addition, the prototype can be used as a basis for developing similar systems for PPE required for other sectors.

Acknowledgements: Research on protective clothing for pesticide applicators is funded through University of Maryland Eastern Shore Agricultural Experiment Station. This research is part of the NC-170 project. Several individuals and organizations have contributed to the development of standard methods and proposed performance specifications for PPE that have been incorporated in the development of the prototype system.
CHEMICAL PROTECTIVE GLOVES FROM PERFORMANCES TO SERVICE TIME PREDICTION

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ABSTRACT

PPE performances are determined through standardized laboratory tests whose parameters are defined to be representative of realistic conditions of use, though with the need to ensure the best reproduceability of the test methods.

What help can they bring in selecting the appropriate PPE and define its limitations and conditions of use? This question is always more often posed for chemical protective gloves due to the pressure exerted by the European regulation regarding hand protection (PPE Use directive and 2001/58/CE directive on the safety data sheets for chemicals).

It is attractive to declare that the result of the permeation test – the breakthrough time- defines the service life. But such an assumption is oblivious of the working conditions, risk assessment, and limitations of the permeation test to qualify the chemical resistance of a glove. There are also conflicting and unrealistic interpretations of the test data.

A typical example: the breakthrough time of Glove X has been measured at 62 minutes with a given chemical. What conclusions can I draw regarding the recommendation of use? How safe is Glove X in case of repeated contacts or splashes, and for how long?

This presentation will develop these various interpretations and suggest principles to offer answers that would be both practical and safety oriented.

1. INTRODUCTION

Permeation test data sometimes along with degradation test data is provided to end-users in order to help in selecting chemical protective gloves and determine the appropriate limitation of use. In fact, permeation data being given as a breakthrough time, it may be attractive to directly relate it to a service time in application. But already at this stage, conflicting opinions have arisen in such direct interpretation. As an example, we can quote the case of a glove X which breakthrough time (BTT) is measured at 62 minutes against Butyl acetate. The opinions heard on the suitability for use of such glove from the most optimistic to the most limitative are:

- Glove X may be used and reused without limitation, since there are no applications with continuous contacts as long as this breakthrough time;
- Glove X may be used and reused provided the period of continuous contact with butyl acetate does not exceed 62 minutes;
Glove X may be used for a maximum total contact time of 62 minutes (cumulating all periods of contact), then discarded
- Glove X may be used for a maximum total contact time of 31 minutes, then discarded
- Glove X may only be used to protect against splashes of the chemical
- Glove X is not safe to be used since it shows limited resistance to butyl acetate; an acceptable glove shall have a BTT in excess of 480 minutes.

These various opinions expressed by the protective glove’s experts may become very confusing to the end user, who is responsible to implement the PPE and ensure a safe use of it. It is thus useful to agree on certain principles in order to offer answers that will be practical, realistic as well as safety oriented.

2. TEST DATA AND TEST PARAMETERS

2.1. PRINCIPLES OF CHEMICAL RESISTANCE

Two essential factors are determining the chemical resistance of a given protective glove to a specific chemical:
- Degradation: there are various degradation modes affecting the glove’s physical properties permanently or just for the time of the contact. Thus the glove may be discoloured, swell or shrink, soften and lose its mechanical resistance, harden with surface cracks (usual degradation mode with acids). Degradation is the main factor determining chemical protection of a glove in contact with water-based chemicals, in particular acids. Some degradation modes such as swelling and softening are partly or totally reversible, the glove recovers its original properties after evaporation of the solvent.
- Permeation: breakthrough of a solvent by solubility at a molecular level through a waterproof material. Permeation is typical of solvents.

Both assessments of degradation and permeation are necessary to determine the chemical resistance of a glove, and the exclusive use of the permeation data may result in wrong recommendations in glove selection and use.

2.2. DEGRADATION TEST

Such test is missing from the EN 374 set of standards on chemical resistance of protective gloves, but there are already several standard tests, thus enabling to assess most of the degradation modes:
- ISO DIS 22611: puncture resistance assessment before and after a given contact time
- ISO 1817:1999: dimension swell assessment
- ANSI/ISEA 105-2000: puncture resistance assessment before and after a given contact time
- ASTM D471: weight change assessment

There are other non standardized tests based on similar principles, the assessment (e.g. tensile properties instead of puncture strength) and calculation of result may differ, or they use other principles (e.g. difference in breakthrough time between two successive permeation tests).

The test method and its parameters which are defined in order to ensure the best reproducibility of the test data may result in differences with conditions of use of the gloves. Without being exhaustive, key parameters are including the test device geometry, static test, testing temperature, continuous contact,
and the area of the glove tested. As a consequence, there are numerous limitations of the test methods to properly simulate conditions of use among which the fact that each test assesses only one mode of degradation, it may be impossible to test certain types of gloves, the result is not expressed as a time and the levels of performance are arbitrary without correspondance between the ratings of the various test methods.

2.3. PERMEATION TESTS

Three standards describe test methods for a similar assessment of permeation:
- EN 374-3
- EN ISO 6529
- ASTM F739

On the basis of the already long experience of practising the test methods as well as inter-laboratory tests and studies comparing them such as (1), the key parameters influencing the test result can be quoted: cell geometry, detection limit, flow rate, calibration, testing temperature, area of the glove tested. These tests find natural limits in pretending simulating the conditions in a workplace, e.g. :
- Static test, degradation is minimized compared to the use where the glove is stressed; the test result may be significantly too optimistic for instance with acids, with a poor reproducibility.
- Continuous contact of the chemical onto the glove’s surface; this is difficult to extrapolate to contacts that occur in practice such as intermittent contacts or splashes
- Test limited to 480 minutes
- The weakest part of the glove (finger crotch) is not tested
- High dispersion in the BTT determination may exist with certain chemicals that permeate at a very low permeation rate increase (e.g. alcohols)
- It may be difficult to test complex compounds; the test result may be invalid if the composition is not fully known

Besides, alternative permeation test methods have been developed to cover high molecular chemicals which cannot be assessed through the present tests. But none of them have been introduced in standards yet. They are based on a solid sampling medium as a receptor made of glass fibres (2) or silicon (3) or charcoal (4). A Thermo-Hand method including an indicator pad has been developed to specifically test acid permeation (5). With a purpose to measure permeation in conditions closer to real use, some studies have proposed alternative parameters, such as temperature or specimen stretch (2), but this may have negative consequences on the reproducibility.

2.4. TABLES AND INFORMATION RELATIVE TO CHEMICAL RESISTANCE OF PROTECTIVE GLOVES

The end-users of protective gloves have data bases at their disposal to know the resistance of a given glove to chemicals, usually based on pure chemicals, and very rarely on the compounds that are involved in chemical applications. Apart from the data provided by the glove manufacturers themselves, other sources of information may be the safety data sheets and data bases or studies (6), (7) etc.

Besides, the chemical protective gloves are placed on the market with a marking including pictograms and an information that ought to be read. Unfortunately, such information is not providing the extent and limitation of the chemical protection offered by the glove. The useful information remains
exclusively with the chemical test data. According to the EN 374-1:2003, there are now two pictograms dedicated to chemical protection, that aim at making a difference between gloves of general purpose from gloves offering a higher, broader chemical protection.

### Protection against chemicals

**Requirement:**
- The glove shall be liquidproof according to EN 374-1.

### A K L

**Protection against chemicals**

**Requirements:**
- The glove shall be liquidproof according to EN 374-1
- Permeation performance level at least 2 (> 30 minutes) against at least 3 chemicals taken from a list of 12 in Annex A (representing common classes of chemicals in use)

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### 3. FROM CHEMICAL GLOVE RESISTANCE TO HAND PROTECTION

#### 3.1. PRINCIPLES OF CHEMICAL PROTECTION

Some key data regarding the risks resulting from the dermal contact of chemicals must be known to select the appropriate glove. Of course the chemical(s) in the workplace must be fully described. All chemicals in a compound along with their respective concentrations must be quoted; this is usually available in the safety data sheets. Beyond the chemical hazards thus defined, the risks must be determined. In fact, whether the hands are dipped in the chemical or there are risks of accidental splashes such as found in laboratories makes a significant difference. This will define the possibility to use gloves with limited resistance (according to permeation and degradation test results). The following principles can be quoted:

- **Long duration contacts** (e.g. in cleaning jobs): gloves offering the highest possible performance must be selected, i.e. BTT in excess of 480 minutes, no degradation; the service time will not depend upon chemical resistance but mechanical damages and hygiene considerations

- **Splash protection required**: gloves with limited protection may be used; the user must be made aware of the test data, and decide upon the acceptable service time for the glove accordingly

- Various chemicals are used, risks of splashes or intermittent contacts (e.g. mixing room), where no glove is offering an unlimited protection to all chemicals. The user must be made aware of the test data for the selected glove in order to ensure that the contacts do not exceed the given test performances, and write his working procedure accordingly.

- In case of a multi-component solvent where test data is not available, some approximation may be provided based on the chemical(s) in the compound that is/are in large quantity and also most likely to permeate first; but degradation is a critical factor, since the components in small quantities may also be detrimental to the glove. A test is thus recommended, when there is suspicion of possible degradation.
3.2. SELECTION PRINCIPLES AND GOOD PRACTICES IN USE

It shall be reminded that glove selection is a compromise that ought to accommodate the often conflicting requirements of safety level, functionality (lowest impediment in doing the job, comfort) and of course the cost (figure 1).

![Diagram of glove selection principles]

Figure 1 – Principles for protective glove selection

Recommending the highest chemical protection in all cases is not realistic and does not help the users. Other risks in the workplace such as mechanical ones shall not be forgotten. The first condition for a glove to pretend protecting against chemicals is to be liquidproof and to remain so during use. It is not rare to see users burnt with acids when using gloves offering a total protection according to test results, just because the gloves are mechanically damaged during work!

Besides, accidents may occur if the gloves do not offer sufficient dexterity or grip. Functionality must be considered though without forgetting about the primary function of the glove, which is to protect. Hence the use of thin disposable gloves is an illustration of wrong selection. They are attractive because liquidproof and offering excellent touch sensitivity and ease of movement, but not protective against chemical contacts beyond accidental splashes, which means that their service time is limited to the occurrence of a contamination, when they must be changed.

Beside, good practises are to be implemented in order to preserve the glove from premature failure due to the chemicals. Thus, it must be reminded in the information supplied by the manufacturer that the chemicals that may remain on the gloves must be dried out or rinsed as appropriate after use, so that the chemical attack or permeation is stopped.

All these factors, beyond the mere chemical protection also play a role in determining a safe and acceptable service time for the glove.
4. CONCLUSION

The perfect chemical protective glove offering total protection against all chemicals, i.e. without any permeation and nor degradation does not exist. Besides, the appropriate glove for an application must be a compromise between levels of protection, functionality factors and cost. Thus the most protective glove can only be rarely implemented, at the benefit of more common gloves offering more limited protection but well accepted by the wearers and affordable. The chemical resistance data provided by the manufacturers is thus useful to determine a limitation in use. Of course it results from laboratory tests whose parameters differ from the conditions found in real use. There is no direct mathematical relation between the performance levels and the limitation in use. But the chemical resistance data is an indispensable guideline that ought to be taken into account. Good sense must prevail in the limitations of use implemented accordingly, avoiding extreme interpretations. Besides, other parameters relative to hygiene and mechanical resistance must also be taken into account in determining the optimum service time of the gloves.

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ISO DIS 22611 – Protective clothing – general test methods and performance requirements for hand protection (draft rejected in 2004)
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EN ISO 6529: 1999- Protective clothing – Protection against chemicals – Determination of resistance of protective clothing materials to permeation by liquids and gases
ASTM F739: 1999 – Standard test method for resistance of protective clothing materials to permeation by liquids or gases under conditions of continuous contact
A TRANSIENT THERMAL MODEL OF THE HUMAN BODY-CLOTHING-ENVIRONMENT SYSTEM

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ABSTRACT

This paper reports on a new transient model integrating the heat and moisture transfer through clothing as well as the two-node human physiological model to predict the human physiological responses. In this model, clothing ventilation and moisture accumulation on the inner surface of the underwear are considered for the first time. The numerical results agree well with the experimental data in the literature.

1. INTRODUCTION

Evaporation of sweat from the skin surface has a very effective cooling effect due to the great latent heat of evaporation of water. For clothed human, the clothing contacts skin surface, the sweat accumulation at the skin can be captured by the inner surface of the fabric. Sweat accumulation on the skin and moisture accumulation on the inner surface of the clothing may influence the evaporation of sweat greatly. So far, some work has considered the moisture accumulation on the skin (Jones and Ogawa 1992; Umeno et al. 2001; Li et al. 2004), however, no work considered the moisture accumulation on the inner surface of the clothing system. Ventilation is another effective mechanism to remove heat and moisture from the clothed body, therefore, an important determinant of thermal comfort. However, only few models considered the effect of air penetration and ventilation through openings although a number of theoretical models have also been proposed to model the coupled dynamic heat and moisture transfer through fabrics or simple clothing ensembles (Fu 1995; Umeno et al. 2001; Li et al. 2004).

This paper we developed a new clothing ensemble transient thermal model considering moisture accumulation on the inner surface of the underwear and clothing ventilation, and then integrate a two-node human model with the new clothing model.
2. MATHEMATICAL FORMULATION

In this work, we consider a human body-clothing-environment system as depicted in Figure 1. The system consisted of human body, clothing and environment. Human body is simplified as two concentric cylinders: body core and skin shell. Clothing system includes two parts. Clothing climate, a single fabric layer and an outer surface air layer comprise the first part that covering the unexposed skin. Clothing climate is the confined air sandwiched between the unexposed skin and the fabric layer. Outer surface air layer surrounds the outer surface of the fabric layer and the exposed skin. The air layer outside the unexposed skin is the second part. Ordinarily, during exercise some regions of the skin are in sensible perspiration zone, others are in insensible perspiration zone. Because of the difference of heat and moisture transfer mechanisms in the clothing in these two kinds of regions, we partition the first part of the clothing system into sweating regions and insensible perspiration ones.

2.1. MODELING THE HUMAN THERMOREGULATION

Gagge et al. (1971, 1986) developed a two-node thermoregulatory model. In this work we adopted this two-node thermoregulatory model but the skin model is modified to consider moisture accumulation based on Jones and Ogawa’s model (1992).

2.2. MODELING THE HEAT AND MOISTURE THROUGH CLOTHING

The clothing system is divided into two parts: covered and uncovered parts. For the covered part, heat and moisture transfer from the covered skin to the environment via the clothing climate, the fabric layer and air layer outside the fabric. For the uncovered part, the skin and the environment exchange heat and moisture only through the air layer outside the skin. We established heat and moisture balance equation for the clothing climate and the fabric layer, respectively.
Clothing ventilation takes away heat and moisture from the clothing climate. Sweat accumulated on the skin would be captured by the inner surface of the fabric layer and be wicked into it. In this model the details of them are described as follows.

### 2.2.1. Clothing ventilation

Clothing ventilation can be considered as the heat and moisture exchange between clothing climate and environment. The heat and moisture taken by clothing ventilation may be expressed as follows:

\[ Q_{\text{vent,sw}} = U_{\text{vent}} \cdot C_v \cdot \left( T_{mc,sw} - T_a \right) f_{sw} \]  
\[ Q_{\text{vent,ins}} = U_{\text{vent}} \cdot C_v \cdot \left( T_{mc,ins} - T_a \right) (1 - f_{sw}) \]  
\[ \dot{m}_{\text{vent,sw}} = U_{\text{vent}} \cdot (C_{mc,sw} - C_a) f_{sw} \]  
\[ \dot{m}_{\text{vent,ins}} = U_{\text{vent}} \cdot (C_{mc,ins} - C_a) (1 - f_{sw}) \]  

where \( Q_{\text{vent,sw}} \) and \( Q_{\text{vent,ins}} \) are heat exchange between environment and clothing climate in sweating regions and in insensible perspiration ones, respectively; \( C_v \) is volume heat capacity of air; \( U_{\text{vent}} \) is clothing ventilation index per unit surface area of the body which is proposed by Crockford and Rosenblum (1974); \( T_{mc,sw} \) is temperature of clothing climate in the sweating regions, \( T_{mc,ins} \) is temperature of clothing climate in the insensible perspiration regions; \( C_{mc,sw} \) is water vapour concentration of clothing climate in sweating regions, \( C_{mc,ins} \) is water vapour concentration of clothing climate in the insensible perspiration regions; \( f_{sw} \) is the percentage of body surface area in the sweating regions.

Qian (2005) investigated the clothing ventilation, and he found ventilation is dependent on clothing style, fitness, thickness and air permeability of garment fabrics. He derived the following equations to calculate \( U_{\text{vent}} \):

\[ U_{\text{vent}} = \frac{KVR}{\eta} \left(V_{\text{wind}} + 2V_{\text{walk}} - 0.22\right), \eta = 17.5 \]  

where \( V_{\text{wind}} \) is wind velocity of environment, \( V_{\text{walk}} \) is walking speed, \( KVR \) is a moisture vapour resistance prediction parameter in Qian’s model (2005), which depends on garment fitting, styles of design can construction of clothing ensembles.

For clothing ensemble consisting of jackets and pants without underwear,

\[ KVR = 0.0006 \ln \left( \frac{\text{Fit}^3 \cdot \sqrt{ap}}{\text{th}^{0.2}} \right) + 0.0036 \]  

where \( \text{Fit} \) is a fit index of clothing fitting for the body which is proposed by Qian (2005), can be evaluated by Qian (2005)’s method, \( ap \) is air permeability of clothing fabrics and \( \text{th} \) is the thickness of clothing fabrics.

### 2.2.2. Sweating accumulation on the inner surface of the fabric

During exercise, the fabric layer contacts skin surface frequently, the sweat accumulation at the skin will be captured by the inner surface of the fabric. Sweat captured into the inner surface has three ways to go sway: diffusion into microclimate, diffusion into fabric layer and wicking into the fabric layer. The mass balance equation may be written as:

\[ \frac{dm_{sw}}{dt} = f_{\text{cover}} f_{sw} h_{in} \left( P_{mc,sw} - P_{cl,sw} \right) - f_{\text{cover}} f_{sw} \frac{P_{cl,sw} - P_{sw}}{R_{elc}} - \dot{m}_{sw} \]  

where...
where $m_{eq}$ is the sweat accumulation per unit body surface area, $f_{cover}$ is the percentage of the covered body surface area, $h_m$ is convective mass transfer coefficient at the inner surface of the fabric layer, $P_{mc,sw}$ is water vapour pressure of clothing climate in the sweating regions, $P_{cl,sw}$ is the water vapour pressure on the inner surface of the fabric layer in sweating regions, $R_{elic}$ is water vapour resistance from the inner surface to the center of the thin fabric layer and $\dot{m}_w$ is the liquid water flow rate from the inner surface to the center of fabric layer, which is caused by wicking action.

The accumulation captured by the inner surface is dependent on body motion and clothing factors. For example, higher frequency of body motion, tighter fitting of clothing and the hydrophilicity of inner surface may lead to more sweat accumulation on the inner fabric surface. Without detailed quantification of this phenomenon, we here assume 50% of sweat accumulation at the skin are captured by the inner surface of the fabric layer.

When there is no sweat accumulation on the inner surface, the moisture balance gives the following relationship:

$$h_m (P_{mc,sw} - P_{cl,sw}) = \frac{P_{cl,sw} - P_{cl,sw}}{R_{elic}}$$

This equation can be solved for $P_{cl,sw}$:

$$P_{cl,sw} = \frac{P_{mc,sw} \cdot R_{elic} \cdot h_m + P_{cl,sw}}{h_m \cdot R_{elic} + 1}$$

When there is sweat accumulation on the inner surface,

$$P_{cl,sw} = P_e(1)$$

The wicking process of the sweat from the inner surface into the fabric is complicated, but can be simplified as liquid water diffusion (Gibson 1996), driven by the gradient of fraction of void space occupied by liquid. When there is sweat accumulation on the inner surface, the difference of fraction of void space occupied by liquid makes capillary action occurs. This action can be described as:

$$\dot{m}_w = f_{cover} f_{sw} \rho_l D_l \epsilon \frac{1 - \epsilon_{ml}}{th/2}$$

where $\rho_l$ is density of liquid water, $\epsilon$ is porosity of the fabric layer, $D_l$ is diffusion coefficient of liquid water and $\epsilon_{ml}$ is volume fraction of liquid phase.

### 3. NUMERICAL SIMULATION

In 1998, Kwon et al. conducted some wearer trials to compare the physiological effects of hydrophilic and hydrophobic properties of the fabrics during intermittent exercise in humans under the influence with and without wind. In this work, we attempted to simulate Kwon et al.’s experiments using the new human-clothing-environment model.

### 4. SIMULATION RESULTS

Figure 2 compares the numerical results with the experimental ones from the literature. As can be seen, the numerical results are in very good agreement with the experimental ones from Kwon et al. (1998) in terms of general trend of physiological responses and the effects of water absorption properties and ventilation on them.
Figure 2 Comparison of mean skin temperature predictions of subjects in clothing A and C with experiments

5. CONCLUSIONS

In this chapter, we developed a dynamic clothing ensemble model considering the influence of clothing ventilation. After combining with human thermoregulation model, the new human-clothing-environment model can be used to elucidate the effect of water absorption properties and ventilation on human physiological response. The results were found in good agreement with the experimental ones.

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HEAT STRAIN IN AIR-PERMEABLE AND SEMI-PERMEABLE PROTECTIVE CLOTHING


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ABSTRACTS

It is well documented that protective clothing against chemical and biological agents imposes heat stress on the wearer. For the sustainability of the soldier it is of great importance to reduce heat strain. Air-permeable NBC protective suits made from carbon based filter fabrics are performing better than impermeable NBC protective clothing in respect to thermal comfort. Currently a number of companies are developing semi-permeable membranes which might be able to function as a barrier against NBC agents, but will still transport moist air (with evaporated sweat) from the inside to the outside of the suit. To value the possible impact of these new developments on the thermal comfort in NBC protective suits we investigated the difference in heat stress imposed by air-permeable and semi-permeable clothing.

In a laboratory experiment several types of protective clothing with different levels of air- and vapour permeability were used to investigate the impact on heat strain. Nine human subjects cycled at an ergometer at 1.5 Watt / Kg bodyweight for 90 minutes in a warm, dry (40ºC, 20% rh) and a cool (5ºC, 50% rh) climatical chamber while wearing protective clothing. Wearing the membrane suit resulted in a 2ºC increase in rectal temperature compared to 1-1.5ºC increase in the air-permeable suits. This significant difference in heat strain on the body results in less heat stress and longer performance times in the air-permeable suit.

From this experiment it was concluded that air-permeable protective clothing imposed less heat strain on the user than semi-permeable clothing.
NUMERICAL SIMULATIONS OF HEAT AND MOISTURE TRANSPORT IN THERMAL PROTECTIVE CLOTHING SYSTEM UNDER FLASH FIRE CONDITION

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ABSTRACT

A numerical model of heat and moisture transport in thermal protective clothing during a flash fire exposure was constructed. The changes in thermodynamic and transport properties of the fabric system as the result of the presence of moisture were considered. The numerical model predictions were compared with experimental data from different fabric system configurations. Additionally, numerical simulations predicted by the model were performed to study heat and moisture transport through moist fabric system when exposed to intensive flash fire condition.

1. INTRODUCTION

In developing thermal protective materials, researchers traditionally focus on heat transfer in dry conditions. However, moisture transport in fabrics and its effect on protective performance of the garment has not been studied in sufficient detail. Protective fabric can be treated as a porous medium. Heat and mass transport in wet porous media are coupled in a complicated way. Energy transport in such a medium occurs by radiation and conduction in all phases as well as by convection within the liquid and gas phases. There are many existing models for the analysis of multiphase transport in porous media. Vafai and Sözen [1] summarized and compared these models. One of the models which is suitable for fabrics subjected to intensive heat is Gibson’s model [2]. Gibson performed the analysis of multiphase transport in hygroscopic porous textiles. However, Gibson’s model does not account for radiation heat transfer within the fabric layer. Torvi [3] developed a one-dimensional transient heat transfer model, which accounts for the penetrating radiative heat transfer through a fabric. In this research, a model that couples heat and moisture transport is developed and the effect of moisture transport on thermal protective performance is analyzed.
2. MATHEMATICAL MODEL FORMULATION

Figure 1 shows a multi-layer protective garment exposed to a high intensity flash fire exposure. This garment system consists of three different fabric layers, which are the outer shell, the moisture barrier, and the thermal liner, respectively from the exterior to the interior of the clothing ensembles. An air gap between the fabric inner surface and the temperature sensor can exist.

Fabric can be modeled as a hygroscopic porous media. The porous textile material is a mixture of a solid phase consisting of solid fibers plus bound water absorbed by the solid polymer matrix, and a gaseous phase consisting of a water vapor and dry air. A schematic diagram of porous textile structure is illustrated in Figure 2. Gibson [2] applied Whitaker’s theory [4] of coupled heat and mass transfer through porous media to derive a set of equations for modeling heat and mass transfer through textile materials. Torvi [3] assumed that convective heat flux only applies to the surface of the fabric but radiative heat flux can penetrate through the fabric up to a certain depth. Definitions of the physical properties of the fabric are given in Morton and Hearle’s work [5]. The convective heat transfer in the air gap between the fabric and the sensor is simulated as a natural convection in a horizontal enclosure, which is heated from below [6]. Based on the above assumptions, the energy balance in the infinitesimal element of fabric can be written in the form of a differential equation. In this work, the finite volume method (Patankar [7] and Tannehill, et al. [8]) is used to solve the differential equations, which are the energy equation for the fabric, the solid phase continuity equation, and the gas phase diffusivity equation, respectively. The Crank-Nicholson scheme is adopted to discretize the transient partial differential equations. Due to non-linearities in this system, the Gauss-Seidel point-by-point iterative scheme is chosen to solve these equations.

3. RESULTS AND DISCUSSIONS

3.1. COMPARISON OF MODEL PREDICTION AND EXPERIMENTAL DATA

The shell fabric of the garment system is Kevlar®/PBI 7.5 oz/yd², moisture barrier is ComfortZone™ and thermal liner is Aralite™. The test configuration is shown in Figure 1. The tests were performed with and without air gap. The physical and thermal properties of fabric composite are shown in Table 1.
A model validation was performed. Figure 3 and Figure 4 show the examples of comparisons of computational and experimental results of heat flux histories at the surface of the sensor for 3-layer clothing systems with and without air gap. Both computational temperature and heat flux histories at the surface of the sensor demonstrate a good agreement with the experimental data.

Table 1. Physical and thermal properties of fabrics.

<table>
<thead>
<tr>
<th>Property</th>
<th>Outer Shell: KEVLAR®/PBI 7.5 oz/yd²</th>
<th>Moisture Barrier: ComfortZone™</th>
<th>Thermal Liner: Aralite™</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho ) [kg m(^{-3})]</td>
<td>1210</td>
<td>1210</td>
<td>126.6</td>
</tr>
<tr>
<td>( c_p ) [J kg(^{-1}) K(^{-1})]</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>( k ) [W m(^{-1}) K(^{-1})]</td>
<td>0.0512</td>
<td>0.0512</td>
<td>0.0512</td>
</tr>
<tr>
<td>( L ) [m]</td>
<td>( 0.50 \times 10^{-3} )</td>
<td>( 0.70 \times 10^{-3} )</td>
<td>( 1.88 \times 10^{-3} )</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>0.336</td>
<td>0.336</td>
<td>0.336</td>
</tr>
<tr>
<td>( R_{f, 45%} )</td>
<td>0.080</td>
<td>0.080</td>
<td>0.080</td>
</tr>
<tr>
<td>( r )</td>
<td>2.12</td>
<td>2.12</td>
<td>2.12</td>
</tr>
<tr>
<td>( D_{rad} / d^2 ) [s(^{-1})]</td>
<td>( 3.44 \times 10^{-2} )</td>
<td>( 3.44 \times 10^{-2} )</td>
<td>( 3.44 \times 10^{-2} )</td>
</tr>
</tbody>
</table>

3.2. MODEL PREDICTIONS

A 0.00635 m (1/4\(^{\prime}\)) thickness of the air gap [9] is used in the test. Computations are performed for the duration of a flash fire exposure of 4 seconds. After the fire is off, computations continue until the time reaches 60 seconds. The temperature of the hot gas and the ambient temperature gradually decrease after 4 seconds of burning. From the expression for the Nusselt number, natural convection will contribute to heat transfer across the enclosure when the Rayleigh number is greater than 1708. The maximum Rayleigh number, \( Ra \), for all computed cases of the Thermal Protective Performance (TPP) test was 1123. Therefore, for the case computed in this paper, the Rayleigh number is always smaller than 1708, which means that natural convection is negligible. Therefore, radiation and conduction heat transfer will be dominating heat transfer mechanisms across the air gap.
Figure 5 depicts the temperature distributions in the fabric, the air gap, and the sensor at different moments of time. The temperature at the outer surface of the fabric increases very fast compared to that at the inner surface of the fabric while the garment is exposed to the intensive flash fire. In the same manner, the temperature at the outside surface of the fabric reduces very fast compared to that at the inside surface of the fabric during the cool-down phase of the process (post-burn process).

Figure 6 shows distributions of the relative humidity in the fabric at different moments of time. The relative humidity in the outer layer of garment drops very fast when it is exposed to the flash fire. In the latter layers of the garment, the relative humidity increases. This means that the moisture is pushed from the outside fabric layer to the inside fabric layer and then into the air gap because of the temperature gradient. After the temperatures at the outer surface and the inner surface of the fabric become low enough, the relative humidity starts growing back to its initial distribution.

Figure 7 shows the calculated fabric weight per unit area versus time. The fabric weight decreases because the fabric loses the moisture to the air gap.

Figure 8. Calculated relative humidity in the air gap versus time
Figure 8 presents the calculated relative humidity in the air gap versus time. Because the relative temperature increase is slower than the relative moisture density increase, one can see that the relative humidity in the air gap increases slightly and then drops rapidly. When the temperature increases, the saturation pressure also increases. Therefore, the relative humidity in the air gap reduces even though the moisture content in the air gap increases.

CONCLUSIONS

The coupled heat and moisture transport in firefighter protective clothing during flash fire exposure is investigated numerically. It is shown that the obtained comprehensive model of heat and moisture transport can be used to estimate the thermal response of protective fabric. The distributions of temperature and moisture content in the fabric and the sensor during flash fire exposure can be obtained.

REFERENCES

SAFE&COOL, AN INNOVATIVE PROTECTIVE WORKWEAR INTERLINER

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ABSTRACT

Main objective of the Safe&Cool project is to develop a thermal and moisture management layer to be implemented inside protective workwear. The Safe&Cool layer, usable both for garment interliner and for insulating underwear, is based on warp-knitted fabric constituted from hydrophilic and hydrophobic yarns, with a 3D structure enabling sweat removal from skin surface. Fabric will be integrated with hydrogel polymers in order to absorb excess moisture, and to release it in case of sudden, dangerous temperature increase. For the most demanding applications, the warp-knit structure will be designed with open channels enabling to insert cooling tubes, mimicking the natural cooling obtained from blood circulation. The Safe&Cool layer will be designed according to the specific protection requirements, thanks to a Design Tool, which aim is to select the main injury sources, and to prevent them by the use of the most appropriate structure. Safe&Cool purpose is to replace the thermal layer and moisture barrier in typical three-layered protective clothing fabric. This concept has been validated through a feasibility study performed by the partners, which permitted to obtain 3D fabric samples for performing preliminary testing on mechanical and thermal performance of the fabric. The results insofar obtained account for the assessment of the heat and moisture transfer model for the material under radiant heat, in different configurations, enabling the simulation of the comfort parameters for the wearer. Work has focused also on development of enabling process to allow the cost-effective integration of the hydrogel material in the textile structure.

1. INTRODUCTION

Wearing state of the art protective clothing for indoor work in non-ventilated areas, in hot temperatures or under radiating sources, while performing physically demanding work, hinder a worker ability to remain cool. Workers inability to shed excess heat results each year in many strokes in Europe. Less serious consequences of heat stress are more common, affecting several ten thousands workers per year all over Europe.

The 3D textile structure of the Safe&Cool textile layer is intended at replacing the interliner and moisture barrier in the classical three-layered protective clothing. The materials employed for its
development are hydrophobic thermal comfort fibres (in contact with the body to avoid wet feeling) with hydrophilic fibres (creating suction channels to transport the moisture away from the skin) in appropriate combination. A cooling system consisting of liquid circulation through tubing inserted in the cavities available within the 3D structure will reproduce blood vessels for heat removal. The 3D spacer fabric will also facilitate convective effects due to its singular structure comprising vertical and diagonal spacer yarns, thus enhancing the cooling effect to the whole body surface. Water binding polymer will be added as a coating, or in the form of a powder dispersed inside the fabric thickness, with the purpose of absorbing and binding the excess of moisture migrating through the semi-permeable membrane if the temperature is maintained below the threshold controlled through the cooling system.

Safe&Cool is a cooperative research project co-funded by the European Commission under the 6th Framework Programme. The project started in 2004, and is currently in its 18 months activity.

2. DESIGN PROCEDURE AND FIRST PROTOTYPES

Design of the innovative interliner fabric layer is devoted to the achievement of superior insulation and protection to the wearer – industrial worker or firefighter – to help a safer working shield against heat. Design of the layer has to be performed according to the specific needs of insulation and of protection, keeping also in mind the ergonomics and the conditions of use. The wearer has not to be hindered in his/her tasks by the protective garment.

Specifications for the interliner characteristics can be derived from the thermal load, coming from the outside – exposition to radiant heat, flames or other sources – or from the inside: metabolic heat production. The optimum design is performed with a trade-off between the insulating properties, lightness and flexibility. Main parameters are the fabric layer characteristics, the liquid coolant circulating system and the water binding polymer embedded within the fabric. In the following paragraphs the approach to solve these aspects into a viable protective product is analyzed. A design software tool shall be developed, according to the parameters of use identified during the course of the project. This is expected to help the selection of the most adequate protecting workwear, balancing the apparel protective performance, ergonomics, maintainability, and of course cost.

In Figure 1 the overall Safe&Cool concept is depicted: the moisture uptake channels are highlighted, as well as the water binding polymer layer and the cooling circuit.
2.1. TEXTILE STRUCTURE

The main issue for the fabric constituting the interliner in protective clothing is thermal insulation. However, it has to grant the wearer comfort as well as being lightweight, soft and mechanically resistant. The hydrophobic comfort fibers are to be placed in contact with skin, to ensure good wearability while avoiding wet feeling. The outer layer of the textile material has to be composed of the hydrophilic material, to collect the humidity creating a gradient of water concentration.

The rib warp-knit fabric for this purpose has been selected as the most suitable textile structure. This ensures to stabilize fabric thickness, opposing also to the compression flattening, and therefore enabling enhanced protective capabilities during use. The warp-knit structure furthermore allows designing the 3D structure of the different technical fibers according to the specific requirements of the fabric layer. Ribs are created, ensuring a trade-off between stability of the rib structure, reduction of bending rigidity and sufficient amount of channels for the tubes.

The fabric prototype has been produced according to the abovementioned concept, with a total thickness of 5 mm, and a rib structure with two alternated upper and lower yarns enabling easy accommodation of the cooling pipes. A picture of the fabric layer is provided in Figure 2: it is possible to distinguish the Dacron white material from the black Viafil Polypropylene based product.

![Figure 2: Safe&Cool prototype fabric layer, upper view (left image) and skin-upper layer fabric comparison](image)

2.2. COOLING CIRCUIT

The dimensions and placement on the different body surface areas of the cooling circuit are developed according to the cooling needs, taking advantage of the large space destined to the passage of small tubes by the rib structure. Silicone tubes with maximum diameter 2.5 mm have been selected as the optimum material for cooling, having good resistance to thermal load, thin wall and low bending rigidity, ensuring easy placement in the selected position. It is foreseen that this system is used for the firefighter garment only, where the possibility to rescue human lives justifies to employ this specific application.

In Figure 3 is presented a conceptual sketch for the cooling circuit, enabling to concentrate the cooling effect where the heat generation is more intense, and the discomfort due to wet feeling is more relevant.

First fabric prototypes have been produced to validate the concept of the piping insertion, and performing tests at lab-scale. The cooling unit is designed in order to be as light and compact as
possible, while granting sufficient autonomy (power or phase change material) for the firefighter to complete the mission.

Figure 3: possible configuration of the piping path on the torso

2.3. WATER BINDING HYDROGEL

Different methods have been investigated for the deposition of the water binding polymer on the fabric layer; the most promising techniques are currently under investigation for the purpose of extending the lab-scale trials at industrial scale. In Figure 4 the results for the different methods are presented: Racla deposition method and hydrogel powder embedded with quilted membrane.

Figure 4: Safe&Cool water binding polymer on fabric layer: Racla coating (left image) and quilted membrane powder hydrogel (right image)

The Racla coating has proven to be simpler and easily adaptable to industrial processing. It provides a tough layer, suitable for a reduced water binding rate for application where the lightness and flexibility of the material is a major need. Quilted structure increases the polymer capability of water retention, and the quickness of humidity absorption. Furthermore, the free spaces of the textile layer are sufficient for accommodating the polymeric material also in its swollen state (volume increase up to 900%).
3. FEM SIMULATION

The behavior of the fabric layer in different environmental conditions and garment configurations has been simulated via FEM analysis. The fabric layer has been considered alone, or coupled with a standard layer of protective Nomex. The water binding membrane has been considered in its fully dry and wet state. The thermal load has been simulated both in convective conditions, and in highly demanding conductive heat transfer. Radiant heat transmission has not been simulated, due to the scattering of the radiant exposure under use conditions. The cooling system has been simulated as a tubing section at the constant average temperature of 20°C.

The results of the simulations have provided interesting results on the Safe&Cool performances, in terms of resistance to the most demanding conditions. In Table 1 is collected a resume of the basic resistance parameters under the different conditions: testing method EN 367 under convective conditions has been taken as reference, evaluating the time required for 24°C temperature rise at contact with skin (marked as $t_{24°C}$ in Table 1) starting from the initial level of 20°C. The reference temperature of 120°C has been taken as limit for the integrity of the textile layer – even if the layer still retains some protective capabilities (marked as $t_{\text{integr}}$ in table 1).

Table 1: some significant results from the textile layer simulation under thermal load

<table>
<thead>
<tr>
<th></th>
<th>Convection 80°C No hydrogel No cooling</th>
<th>Convection 80°C No hydrogel With cooling</th>
<th>Convection 600°C Dry hydrogel With cooling</th>
<th>Convection 600°C Wet hydrogel With cooling</th>
<th>Conduction 200°C Dry hydrogel No cooling</th>
<th>Conduction 600°C Wet hydrogel With cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{24°C}$ [s]</td>
<td>&gt;80</td>
<td>&gt;240</td>
<td>50</td>
<td>110</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>$t_{\text{integr}}$ [s]</td>
<td>-</td>
<td>-</td>
<td>70</td>
<td>180</td>
<td>90</td>
<td>35</td>
</tr>
</tbody>
</table>

Figure 5 presents the result of the FEM thermal simulation on the textile layer: it is possible to see the cooling tube and the rib structure in these sections.

Figure 5: Safe&Cool FEM simulation of thermal profile under convection, 80°C with cooling (left image) and conduction, 600°C with cooling (right image) both after 60 seconds

Thermal flux has been estimated as well for the superposed thermal load. Results showed that, even if the wet hydrogel layer has the effect of retarding the thermal uptake inside the fabric due also to the increased thermal capacity, the heat flux is greater for the wet state. This fact enabled to perform
consideration on the need to avoid the presence of liquid water inside the structure of the protective clothing. Hydrogel can be a solution, to bind the excess humidity present in the layer.

4. CONCLUSIONS

Safe&Cool project is aimed at the development of an innovative fabric layer for protective clothing, integrating cooling circuit and water binding hydrogel within a 3D composite engineered textile structure.

The results of the prototypes are encouraging for future possible developments of the different concepts into industrial products. On-going laboratory trials are currently running to validate the superior insulating properties of the Safe&Cool concept, and for defining the effective protective capabilities in the aimed application, for assessing the input to the configuration Design Tool.

5. ACKNOWLEDGEMENTS

We acknowledge the financial support provided by the European Commission under the VI Framework Programme for Research, within the Cooperative Research project N° 508191. We acknowledge the input and contribution of all the project partners, which details may be found at the official Project website: http://www.dappolonia-research.com/safe&cool/home.php.
ABSTRACT

The objective of the investigation was to examine the feasibility of incorporating passive cooling in a high visibility vest for use in selected outdoor activities and light industrial sites to improve thermal acceptability to workers in these workplaces. Selected high visibility fabrics were screened using standard laboratory methods to identify the 'best' candidate fabric. Passive cooling was provided in a high visibility vest and vests used in human field trials in two factories and several orchards. Some differences in the acceptability of the vest based on the type of workplace were identified. High visibility and passive cooling provided simultaneously is feasible.

1. INTRODUCTION

Integration of protection against various workplace hazards which occur simultaneously continues to challenge designers and manufacturers of personal protective clothing and equipment. Although much of the early work on fabrics for protective clothing and indeed many test methods for fabrics deal with protection against one hazard at a time, there is increasing evidence of greater realism in test conditions and methods (e.g. ). This investigation was part of a series on cooling vests: a comparison of the physiological effects of wearing different cooling vests under controlled laboratory trials; UVR protection, high visibility and passive cooling; and the present field trial of passive cooling using the high visibility vest. The objective of this part of the broader investigation was to examine the feasibility of incorporating passive cooling in a high visibility vest for use in selected outdoor activities and light industrial sites to improve thermal acceptability to workers in these workplaces.

2. METHODS

2.1. MATERIALS AND VEST

The cooling vest was based on that developed by the principal author and co-workers and tested under controlled laboratory conditions, details of which have been reported elsewhere. This earlier model
has been available commercially for several years and has been used by a variety of sports persons and teams from New Zealand and several other countries (e.g. Wales, Australia). In sporting applications however, the cooling vest is worn prior to competition (i.e. prior to rather than during ‘work’). The vest had been designed as ‘one size fits all’, low cost, light in weight, portable, all properties desirable for employers/employees in a range of New Zealand workplaces. In New Zealand, workplace protective clothing is provided by the employer5 6 7, but ease of use, garment mass, and general acceptability are all relevant to employees.

Two high visibility fabrics were screened for dimensional stability since matching dimensional stability of different fabrics to be seamed together is required to avoid garment distortion. Standard laboratory test methods were used: preparation and marking8, laundering9, and the more stable of the two selected (Section 3.1). The fabric was a high visibility, plain-woven cloth with 20 warp and 15 weft yarns per 10 mm, 170 g/m², 100% polyamide, and coated with an acrylic lacquer. The lining fabric was of knitted mesh structure, 100% polyamide, 66 g/m², and was identical to that used for the earlier vest. While high visibility was not essential in the two selected factories and the several apple orchards, it was considered an additional desirable feature for those working in and around vehicles.

Selected performance properties of the one fabric were measured, again using standard test methods: resistance to abrasion using the load for work wear (795±5 g, 12 kPa nominal pressure) (fabrics having been pre-treated using 1 and 5 cleaning cycles9, and specimen failure taken when two threads were broken10, high visibility to comply with AS/NZS 4602:1999 High visibility safety garments11, including compliance with requirements for road traffic control12. All testing was conducted under standard (at the time of testing) atmospheric conditions13.

The fabric thus described was selected as the outer for a vest based on the earlier model3, with modified closures and position of the coolant pack. The minimum area for high visibility in a safety garment is 400 mm², distributed evenly across the garment11, and this was achieved by the entire outer layer of the vest being of the high visibility fabric. A non-toxic coolant (468.1g per pack; melting rate of 1.33 ºC/100g) identified in an earlier investigation3 as the best of several options (gels, water absorbing crystals which ranged in rate of melting from 0.44 ºC/100g to 0.97 ºC/100g3) was used.

2.2. HUMAN TRIALS

Passive cooling was provided to participants (n=35 (89.7%) male, n=4 (10.3%) female) during human field trials in two factories in Dunedin, New Zealand (n=22, aged 21-50 years) and several apple-producing orchards in Otago, New Zealand (n=17, aged <20-50+ years) during summer months (November-February). Vests were worn by participants for at least ten days and at least four hours per day, the participants opting to wear them as needed and as convenient. Environmental conditions were monitored at each site, either continuously (as routine monitoring in one factory), intermittently (as in the other factory), or from data provided daily by the New Zealand Meteorological Service.

Assessment of the cooling vest by participants was made using questions as in an earlier evaluation of commercial microclimate cooling systems14. Satisfaction with the garment was established using a 7-point rating scale, and perceived thermal and wetness sensations established by adapting scales from the earlier study on the vest3. Effectiveness, ease of use, acceptability of fit, and overall satisfaction were also assessed using the 7-point rating scale following the trial. A Kruskal-Wallis one-way analysis of variance was used to determine any significant differences between the mean responses of participants at the different workplaces15.
Ethical approval was obtained from the relevant University of Otago Ethics Committee prior to the field trials, and participants, all of whom gave written consent, were permitted to withdraw from the trial at any time without penalty.

3. RESULTS AND DISCUSSION

3.1. MATERIALS AND VEST

Dimensional changes in the two fabrics separately were: outer–lengthwise 1.36%, 1.84%, 1.96%; crosswise 0.52%, 0.99%, 0.64%, after one, five, and ten cleaning cycles respectively; and lining lengthwise 0.69%, 0.12%; crosswise 0.52%, 0.28%, after one and five cleaning cycles respectively. The effect of ten cleaning cycles on the lining fabrics was not examined because its stability evident after the five-cycle treatment, and the fact that this lining was part of an existing product already tested and in production (Cool.1.nz™). Dimensional changes when the two layers were joined remained <1.5% in both directions. The outer fabric resisted >100 000 abrasion cycles both after having been exposed to one and to five cleaning cycles. It complied with AS/NZS 1905.4 – 199712 in colourfastness to washing, to perspiration, and to light (in each case grade >4), and also met the required levels of the daylight colour and luminance factor test when both wet and dry12. However, the type of fabric used for lining needs further investigation since several participants reported snagging as the coolant packs were inserted during the trial, and tears (≥30 mm in length) in the lining adjacent to the coolant pockets were evident following the trials. The outer fabric remained in satisfactory condition after >40 hours use, although staining from unknown origins on some vests was evident.

The vest design was in accordance with general requirements of occupational protective clothing16, specifically dimensional change due to cleaning, colourfastness and ergonomics. The vest when loaded with cooling packs weighed 1900 g. Wide (50 mm) belts inserted between the inner and outer layers and fastened with quick-release clips, held the coolant packs firmly against the wearer's body.

3.2. HUMAN TRIALS

In one factory (A), employees worked near electrical furnaces loading and unloading small, sometimes bulky, but light objects from a conveyor belt. Ambient temperatures were typically 23±2 °C to 36±2 °C in the general work area and at the furnace opening respectively. Employees wore a t-shirt with bib overalls, a face-mask and gloves intermittently depending on specific work conditions and tasks, and worked an 8-hour day with three scheduled breaks. Workers in the other factory (B) were lifting, packing, and continuously walking (Figure 1). Ambient temperatures in that workplace were typically 20 °C to 34 °C. They wore t-shirts, shorts, and earmuffs, worked a 12-hour shift with a 20-minute break every two hours. Of all indoor workers (n=22), 73% (n=16) were involved in various combinations of standing, walking, and lifting. No participant chose to wear a garment over the vest. Participants who worked outdoors were thinning apples (on foot), spraying (from a tractor cab), or harvesting (on foot, with an apron for apple collection). The mean high daily temperature was 27 °C and the maximum temperature 33 °C. Full chemical protective clothing (facemask, gloves, PVC jacket and trousers, boots) was worn when spraying, worn over the cooling vest. Participants worked an 8-hour day with a 15-minute break at mid-morning and mid-afternoon and a 45-minute break at midday. Of the outdoor workers (n=17), most wore shorts (82%, n=14) and a t-shirt (53%, n=9). Two (11.8%) chose to wear a shirt over the cooling vest.
Perceptions of the cooling vest are summarised in Table 1 and show general satisfaction with most aspects of the vest; thermal sensations at the cool end of the scale and perceptions of wetness certainly not dry, but at least in the centre of the scale.

<table>
<thead>
<tr>
<th></th>
<th>Indoors (n=22)</th>
<th>Outdoors (n=17)</th>
<th>Total (n=39)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Factory A</td>
<td>Factory B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mean (s.d.)</td>
<td>mean (s.d.)</td>
<td>mean (s.d.)</td>
</tr>
<tr>
<td><strong>a During trials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceptability of vest</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>with other garments</td>
<td>4.8 (1.35)</td>
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</tr>
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<td>with other equipment</td>
<td>5.2 (0.89)</td>
<td>5.6 (1.06)</td>
<td>5.5 (1.17)</td>
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<tr>
<td>Acceptability re mobility</td>
<td>5.7 (0.53)</td>
<td>5.5 (1.21)</td>
<td>5.8 (1.10)</td>
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<td>5.9 (1.11)</td>
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<td>6.2 (1.17)</td>
<td>6.4 (0.82)</td>
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<td>2.5 (1.04)</td>
<td>2.8 (1.27)</td>
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<td>3.3 (1.90)</td>
<td>3.0 (1.91)</td>
</tr>
<tr>
<td><strong>b End of trials</strong></td>
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</tr>
<tr>
<td>Acceptability of fit</td>
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<td>5.6 (1.17)</td>
<td>5.3 (1.30)</td>
</tr>
<tr>
<td>adjustment of fit</td>
<td>5.3 (1.29)</td>
<td>5.4 (1.51)</td>
<td>5.2 (1.33)</td>
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<td>pack prepn/storage</td>
<td>3.9 (1.54)</td>
<td>4.4 (1.78)</td>
<td>4.5 (1.75)</td>
</tr>
<tr>
<td>pack insertion/removal</td>
<td>2.8 (1.30)</td>
<td>4.3 (1.57)</td>
<td>4.3 (1.70)</td>
</tr>
<tr>
<td>putting on</td>
<td>5.5 (1.21)</td>
<td>5.8 (1.03)</td>
<td>5.9 (1.10)</td>
</tr>
<tr>
<td>taking off</td>
<td>5.6 (1.19)</td>
<td>5.9 (1.10)</td>
<td>5.7 (1.48)</td>
</tr>
<tr>
<td>Overall satisfaction</td>
<td>4.5 (1.79)</td>
<td>5.1 (1.79)</td>
<td>5.2 (1.56)</td>
</tr>
</tbody>
</table>

Scales used: 1=not at all, 7=extremely, * 1=very cold, 7=very hot, ** 1=dry, 7=very wet
Open-ended comments included 'very refreshing, making working in the heat reasonably comfortable', 'coolant pack lasts 90-120 minutes', 'excellent, bring them back please', 'spraying on a hot day the vest lasted around 75 minutes reaching warm by 90 minutes, and this was under PVC clothing.' Some differences in the acceptability of the vest among the three types of workplace were identified (e.g. sensation of wetness $\chi^2=11.07$, df=2, $p \leq 0.01$; convenience of inserting and removing cooling packs $\chi^2=10.57$, df=2, $p \leq 0.01$), in both cases depending on whether working in the factory where tasks were delivered via a conveyor belt (thus providing little freedom for the participant to replace coolant packs) or working outdoors (where participants had greater flexibility in managing the timing of their tasks). Differences in perception of wetness were also attributable to the type of garments worn on the lower body (shorts, trousers, overalls) ($\chi^2=7.92$, df=2, $p \leq 0.05$), with stronger perceptions of wetness when overalls rather than shorts were worn. Information from open-ended questions suggested an easier way to insert the coolant packs could be investigated, as could a different lining fabric because edges of the packs snagged the lining during insertion.

4. CONCLUSIONS

This low cost, portable cooling vest has been shown as feasible in several different types of work environments where the ambient temperature was high – manufacturing plants indoors and orchard activity outdoors. Unlike the earlier model designed for sporting applications and worn for pre-and post-cooling, the present version was worn during work itself, including under impermeable chemical protective ensembles. The low cost, ready availability, sizing options, and non-toxicity of the coolant packs offsets, in part at least, the disadvantage of the need for re-freezing the packs. Although the packs thawed after 1.0-2.5 hours depending on the environmental conditions, a number of participants reported remaining cool for half a day or more, and perceptions of enhanced comfort may in turn enhance performance in the workplace.

ACKNOWLEDGEMENTS

Cooperation of the participating companies/organisations and the participants made this study possible. The fabric tests for fastness to colour, and that for daylight colour and luminance factors were carried out by WRONZ (Christchurch, New Zealand) and AWTA Textile Testing (Melbourne, Australia) respectively.

REFERENCES


ABSTRACTS

Simulator is developed for modeling thermal processes in man wearing various clothing ensembles in different environments. The computer simulator is Information technology and can be used for scientific and practical approach in the development of the protective clothing and equipment. Simulator involves the class of mathematical models of heat transfer and thermoregulatory processes in man that allows simulating dynamics of local temperatures and heat flows, thermoregulatory responses and other physiological parameters. Modeling of protective clothing includes apparel, thickness of textile, thermal insulation and evaporative resistance. Microclimate Cooling System is simulated by ventilation, temperature and humidity of inlet air, underclothes volume, “on” and “off” thresholds. Predicting of thermo-physiological state of man wearing the protective clothing or use of MCS by simulation reduce human injury and improve productivity for development of protective clothing and garment.
INFLUENCE OF DIFFERENT PARAMETERS ON COOLING EFFICIENCY OF LIQUID CIRCULATING GARMENTS

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ABSTRACT

Liquid Circulating Garments (LCG) are used as a component of liquid-based Personal Cooling Systems (PCS). PCS employing LCG have been demonstrated to provide an effective solution in mitigating the heat stress experienced by individuals carrying out physical activities while exposed to thermally hostile environmental conditions and/or wearing insulating protective clothing ensembles. This paper reports the results of a study examining the influence of coolant temperature and flow rate, outer-garment type, LCG fit and moisture condition on the cooling efficiency. Experiments were conducted with both “dry” and “sweating” thermal manikins. The LCG used in the current study consisted of a tubing network sewn into a vest with water used as the coolant. Experimental results show that the LCG cooling efficiency was not significantly influenced by the water temperature and flow rate in both dry and sweating manikin tests. In dry manikin tests, the variation in the cooling efficiency for a given outer-garment was within 5.4% among 9 tests covering 3 levels of cooling water temperature and flow rate. In sweating manikin tests, the variation in the cooling efficiency was within 2.6% among 3 tests at different combinations of water flow rate and temperature for a given outer-garment. The results of the dry manikin tests also showed that the outer-garment type had significant influence on the LCG cooling efficiency. The cooling efficiency was found to be higher with more insulating outer-garments. At the four water temperature and flow rate combinations, the cooling efficiency with a Fire Fighting Garment (FFG) was, on average, 8.1% higher than that with HAZMAT. Fit of LCG was also found to be a significant parameter influencing the cooling efficiency. The increase in the cooling efficiency as a result of a snug fit was, in dry condition, 12% and 18.5% when a HAZMAT suit and FFG suit were worn over the LCG, respectively. Sweating was found to be the most influencing parameter on the cooling efficiency. The average cooling efficiency of the 3 tests in sweating condition with a natural fit was 29.5% higher than in the dry condition.

1. INTRODUCTION

Individuals involved in a number of occupations, such as explosive ordnance disposal, hazardous materials clean-up, combat operations, fire-fighting, crowd management, millwork or welding, are required to wear protective clothing ensembles and often exposed to harsh environmental conditions.
The use of protective clothing ensembles increases thermal resistance to body heat dissipation and reduces vapour permeability. Depending on the application, these harsh environmental conditions may consist of elevated ambient temperatures and/or humidity, possibly coupled with the influence of solar and/or surface radiation. Individuals involved in physically demanding activities require high metabolic efforts that produce high physiological heat. As a result, such individuals may be affected by heat stress.

Personal Cooling Systems (PCS) are designed to mitigate the effects of heat stress resulting from wearing protective clothing ensembles, harsh environmental conditions, and/or high metabolic efforts. PCS employing Liquid Circulating Garments (LCG) have been demonstrated to provide an effective solution to mitigate heat stress [1-3]. LCG integrate a flow network within a fabric material structure, and are used as a component of liquid-based PCS. They function as a heat sink to body heat dissipation and environmental heat sources.

The efficiency of an LCG to remove physiologically-produced heat is influenced by the LCG heat transfer characteristics, clothing configurations worn under and over the LCG, and environmental conditions. The purpose of this study was to investigate how different parameters, such as coolant temperature, flow rate, outer-garment type (insulation level), fit of LCG and sweating condition at the skin surface affect the cooling efficiency.

2. METHODS

The efficiency of an LCG to remove physiologically-produced heat ($E_{LCG}$) is defined as the ratio of LCG heat removal from the body ($Q_b$) to the coolant heat gain ($Q_t$), which is the sum of $Q_b$ and coolant heat gain from the environment ($Q_{en}$):

$$E_{LCG} = \frac{Q_b}{Q_t} = \frac{Q_b}{Q_b + Q_{en}}$$  (1)

Thermal manikins are valuable tools for quantitatively evaluating the performance of various PCS including LCG. Except for tests involving a sweating condition at the manikin surface, all tests were conducted in dry conditions. For the sweating condition case, the manikin surface was kept fully wet throughout the duration of a test.

An LCG vest configuration, consisting of tubing network sewn into the fabrics, was used and supplied with cooling water in all tests. The inlet water temperature ranged from 8 to 24°C and flow rate from 0.25 to 0.65 L/min (LPM), respectively. HAZMAT Level B suit and Fire Fighting Gear (FFG) were used as the outer-garments in the dry manikin tests. The outer-garment for the sweating manikin tests was a Selectively Permeable Membrane (SPM – providing Chemical-Biological protection), which offers similar dry resistance and permeability characteristics as compared to the HAZMAT Level B suit. The parameter “fit of LCG” was examined by putting the LCG on the manikin in two fit configurations. The “Natural” configuration consisted of wearing the LCG on top of the undergarment without any other measures for fit adjustment, whereas the “Snug” configuration consisted of using tape wrapping around the torso area to provide a tighter fit between the LCG and the manikin.

All tests took place with the manikin’s surface temperature and environmental chamber set at 35°C. Setting identical manikin and chamber temperatures eliminates the effect of dry heat exchange between the manikin and the surrounding environment in the areas not covered by the LCG. In the case of dry manikin tests, the power input to the manikin became, at steady state, the direct heat
transfer from the manikin to the cooling water, namely $Q_b$. For the sweating manikin tests, a baseline test was necessary to account for the evaporative heat transfer, even in the absence of cooling from the LCG. This is required as the manikin surface was fully wet at all time whereas the relative humidity of the environment was controlled at 30%. This baseline heat transfer value was subtracted from the manikin power input to isolate the heat removal rate of the LCG. The coolant heat gain was calculated from its flow rate and temperature rise.

3. RESULTS AND DISCUSSION

Figure 1 shows the measured cooling efficiency at 3 water temperature and flow rate levels for a snug-fit LCG on the dry manikin and a HAZMAT as an outer-garment. At any of the 3 temperature levels, the influence of coolant flow rate on the cooling efficiency was negligible, with a maximum difference in the efficiency of 1.8%. At all 3 flow rate levels, the cooling efficiency was not significantly influenced by the coolant temperature either; however, the results presented a higher difference in the cooling efficiency than the influence of flow rate. The maximum difference was 5.4%. The overall difference in the cooling efficiency among the 9 test cases was 5.4%. Figure 2 shows the corresponding measured cooling efficiencies at the 3 temperatures and coolant flow rate levels for FFG as an outer-garment with a snug-fit LCG. At any of the 3 separate temperature levels and flow rates, the maximum difference in cooling efficiency was 3.2% and 3.3%, respectively. Thus, the overall difference in the cooling efficiency among the 9 test cases was 3.8%.

In general, the experimental results showed that the LCG cooling efficiency was not significantly influenced by the coolant temperature and/or flow rate in dry conditions. Similar observations were also found in sweating manikin tests. Figure 3 indicates the measured cooling efficiency at the 3 selected combinations of temperature and coolant flow rate when the LCG was tested on a sweating manikin with a SPM worn over the LCG. The maximum difference in the cooling efficiency among the 3 coolant conditions was 2.6%.

Figure 4 presents the influence of the outer-garment type on the cooling efficiency at 4 different coolant conditions with a snug-fit LCG. It can be seen that, at any given coolant condition, the cooling efficiency with an FFG was slightly higher than that with a HAZMAT outer-garment. The average difference in the cooling efficiency among the 4 test conditions was merely 4.8%. When a more insulating outer-garment is worn over an LCG, the heat gain of the LCG from the ambient is reduced. Hence a higher cooling efficiency can be obtained, according to Equation (1). Since the FFG is a better insulator than the HAZMAT, it is reasonable to conclude that at any given coolant condition the cooling efficiency with FFG would be higher. This observation was validated as the LCG was worn on the manikin naturally, without fit adjustments, as Figure 5 shows. On average, the cooling efficiency with FFG was 11.4% higher than that with HAZMAT.
Fit of LCG on manikin was found to be a significant parameter influencing the cooling efficiency. Figure 6 compares the average cooling efficiency of 9 test cases covering 3 temperature and flow rate levels between the natural and snug fit for both HAZMAT and FFG outer-garment configurations. The difference in the cooling efficiency was 18.5% and 12% when HAZMAT and FFG suits were worn over the LCG, respectively. This occurs as a snug-fit increases the heat transfer rate between the manikin and the LCG [4], thereby resulting in a higher cooling efficiency according to Equation (1). Figure 7 compares the cooling efficiency between 18 respective tests from the natural and snug fit LCG in dry conditions, and the 3 tests conducted in sweating condition with a natural fit. The average cooling efficiency values were 60.6%, 75.9% and 90.1%, respectively. It was obvious that the wet manikin surface significantly enhanced the LCG cooling efficiency. This echoes similar studies whereby the heat transfer rate between the manikin and the LCG was much higher in the sweating condition as compared to the dry condition [5,6].
4. CONCLUSIONS

The experimental results showed that the LCG cooling efficiency was not significantly influenced by the water temperature or flow rate in both dry and sweating manikin tests. In dry manikin tests, the variation in the cooling efficiency for a given outer-garment was within 5.4% among 9 tests covering 3 levels of cooling water temperature and flow rate. The variation in sweating manikin tests was within 2.6% among 3 tests at different combinations of water flow rate and temperature for a given outer-garment. The results of the dry manikin tests also showed that the outer-garment type had significant influence on the LCG cooling efficiency. The cooling efficiency was found to be higher with a more insulating outer-garment. At 4 compared water temperature and flow rate combinations, the cooling efficiency with FFG was, on average, 8.1% higher than that with HAZMAT. Fit of LCG was also found to be a significant parameter in determining the cooling efficiency. The increase in the cooling efficiency as a result of a snug fit, in the dry condition, was 12% for a HAZMAT suit and 18.5% for a FFG suit, when worn over the LCG. Sweating was found to be the most important parameter on the cooling efficiency, where the average cooling efficiency of the 3 tests in sweating condition with a natural fit was 29.5% higher than that in dry condition with a natural fit.
REFERENCES

ACTIVE CLOTHING PROTECTING AGAINST COLD

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ABSTRACT

In the paper “smart” clothing protecting against cold that have been worked out and constructed in CIOP-PIB is presented. Concept of the “smart” clothing that is clothing, which on its own support thermoregulation processes of the body assumes the multilayer system of materials with electrically heated inserts. The inserts are controlled by the smart-control unit that reacts on temperature of the body and temperature of the environment measured by mikrosensors placed in the garment. The construction of the garment and the heating system has been presented. In the paper the results of the performance tests including thermal insulation of the multilayer systems of materials designed for smart clothing protecting against cold as well as the whole suit test results have been introduced. The clothing has been tested on human subjects with two different activities in cooling chamber in -20°C. The human subjective evaluation of users thermal sense according to Fanger scale and both skin and environmental temperature have been recorded.

1. INTRODUCTION

At many workstands with low environmental temperature, when changes of the worker’s activity result in the changes of produced heat quantity, clothing used as a passive shield does not ensure thermal comfort [1]. Appropriate protection and comfort can be obtained only by using an active shield changing its thermal insulation properties according to the climatic changes of the environment and the level of heat produced by the user’s body.

A model of active clothing designed for works in cold environment, responding actively to temperature changes and adjusting accordingly its thermal insulation properties so as to provide conditions approximating thermal comfort for the user, has been developed in CIOP-PIB.

2. CLOTHING CONSTRUCTION

The “active” clothing protecting from cold, developed within the framework of the research project conducted in CIOP-PIB consists of a jacket and trousers with braces. Straight jacket covers upper side of trousers. In the down parts of the jacket sleeves and trouser legs cuffs and turn-ups with Velcro
have been accomplished adjusting their circumference and providing tightness and protection against wind. Fitting the clothing to the body of the user let reduce the movement of the air entering through the clothing openings in the ensemble that lead to diminish the insulation property of the clothing protecting against cold. In the garment six heating fibrous inlays connected with the temperature microsensors, control system and the batteries by means of the wires have been placed (fig. 1).

![Fig. 1 Block diagram of the temperature regulation system](image)

The six heating inlays were put in the following places: two inlays on the chest, two inlays in the sleeves and two inlays in the trouser legs (fig. 3). The places have been chosen on the basis of the test results of the research project conducted in CIOP-PiB.

![Fig. 2 The pictorial diagram of the active garment system](image)

![Fig. 3 Jacket and trousers with the marked heating inlays](image)

Placing of the heating inlays in the sleeves and trouser legs let increase the thermal insulation of the parts of the clothing covering the places of the body mostly exposed to heat loss. The control system
has been inserted in the inner pocket specially designed for that purpose. The system has been designed to be connected either to the external power supply as for example the car battery or to the rechargeable portable batteries. In the second case for ten batteries of 1.2 V voltage the special pocket along the waist have been accomplished as to distribute the weight and to diminish discomfort. The clothing consists of multilayer system of materials that cooperate between each other with synergy effect. The active elements of the clothing are six heating inlays of total 66W power, made with electrocunductive yarn. The control of the heating inlays is accomplished by means of a measurement and control system, collecting information from temperature microsensors placed outside the garment and in two points of the human body under and the clothing. According to a specified algorithm that has been worked out on the basis of test results, the control system makes a decision to switch on or off the voltage supply to the heating inlays.

3. METHODOLOGY

The multilayer system of materials has been selected on the basis of the preliminary numerical simulation and results of the laboratory tests performed in CIOP-PIB. For the purpose of modelling the construction of materials for “active” clothing the numerical model of heat flow based on the Finite Element Methods [2,3,4,5,6] has been worked out. In the experiment the human body model of eliptic roller of axis 100 and 225 mm and 500 mm height, has been introduced. In the model the materials insulation as well as the air layers attached to the outer surface of each material has been considered. The exemplary result of the simulation for ambient temperature of (-25)°C and material thermal insulation of 0.775 m²K/W has been presented on the figure 4.

![Fig. 4 Temperature distribution for the thermal conduction coefficient 0.16 W/mK and ambient temperature (-25)°C](image)

As the result of the numerical simulation the requirements for the multilayer system of materials insulation and power of the heating inlays have been obtained. The laboratory tests of the material system have been performed on the equipment specially designed in CIOP-PIB that is modified skin model according to the standard EN 31092:1998 [7] and let test the materials that changes its thermal insulation, including heating materials. The apparatus let perform the tests of materials that surface temperature is about 35°C degrees and to measure its thermal insulation in terms of heating efficiency. In the tests the multilayer systems of
materials containing heating inlays with conductive carbon and steel yarns have been tested and compared (fig.5).

![Figure 5](image-url)

Fig. 5 Relation between power P [W] and environmental temperature T [°C] for two systems with two heating inlays: with steel yarn (Manufaktura 2) and with carbon yarn (Manufaktura 3) and water vapour permeable membrane.

In the cold environment the multilayer system with steel inlays needs less energy to buffer capacity of heat than the system comprising inlays constructed with the carbon yarn. For the garment designed for use in low temperature the heating inlays with steel yarn were selected. As the result the system composed of textile with water vapour permeable membrane as the external layer, polar knit fabric as the middle layer and cotton-and-wool knit as the internal layer with inlays containing steel yarn has been chosen and used in the garment. On the surface of the heating elements under the external layer of material the textile with membrane reflecting the infrared radiation has been inserted.

For verification of the theoretical calculation and testing of proper work of temperature regulation system the “active” clothing was tested on human subjects in a cold store at -24°C (+2°C). The aim of the tests was both to check the correct function of the measurement and control system and to demonstrate differences between the thermal perception of the user wearing clothing with constant thermal resistance and “active” clothing with the same thermal resistance, equipped with the “active” heating system described above. The system responded to the changes of the user’s skin temperature by 0.2 °C and switched on at external temperature below 0°C. When the tested subject moved from a room with +10 °C temperature to a room with -24°C temperature, the system switched on after ca. 2 min. Then, when the skin temperature increased by 0.2 °C the system switched off, and became active again when the skin temperature decreased by 0.2 °C. In the first version of the experiment, where the user was doing low-intensity physical exercise (metabolic rate – 110 W/m²), at environment temperature of -24°C, differences in body cooling rates were observed between workers wearing electrically heated („active”) and unheated („passive”) clothing.
Analysis of the results of subjective assessment of thermal perception according to Fanger demonstrated considerable differences in thermal perception of the users working in the tested clothing variants. The thermal comfort reported by all six subjects wearing “active” clothing was higher than reported by those wearing passive clothing (fig. 6). After 45 minutes of the test, the users of „active” clothing assessed their condition as „warm” or „natural”, whereas the tests carried out in clothing with stable thermal insulation level were discontinued after a shorter time (ca. 20-30 min) because of the users’ perception of cold.

CONCLUSIONS

The results obtained in the tests confirmed the assumptions of the theoretical model. As follows from the laboratory experiments the “active” clothing provided more thermal comfort than traditional “passive” clothing and in. The model of worked out garment still needs improvement particularly in the scope of energy supply and management. In terms of work in cooling chambers, driving fork-lift trucks or motorcycle when the user can use the car battery the energy supply does not pose a problem but carrying the batteries requires use of the power supply that is light and efficient.

REFERENCES

7. EN 31092:1993 *Textiles – Physiological effects – Measurements of thermal and water vapour resistance under steady-state conditions (sweating guarded – hotplate test).*
THERMOINSULATION PARAMETERS OF MEMBRANE AND WOOL TYPE FABRICS

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Department of Clothing Technology, ul. Żeromskiego 116, 90 – 543 Łódź, POLAND

ABSTRACT

The thermal insulation fabric parameters are significant from the point of view of maintaining the heat balance of the human body. Clothing can aid or make difficult taking off the heat dependably on its thermal insulation. Therefore, the assessment of thermal insulation parameters by a measurement of coefficient of thermal conductivity, thermal transmission, thermal resistance and so on, is very important. In the paper there are presented results of thermal insulation parameters measured for membrane and wool type fabrics. The measurements were carried out on the Alambeta device in the normal climate. The thermal insulation parameters were measured for 6 different clothing membrane materials and for 4 wool type fabrics for the left as well as right side of it. On the basis of measurements presented in figures and literature the influence of some technological parameters describing thermoinsulation properties were discussed.

1. INTRODUCTION

Determination of thermoinsulation parameters is a part of characteristics of textile materials used for clothing production (finally, also the clothing characteristics). The full characteristics enables the assessment of thermoinsulation, vapour diffusion and air flow through the clothing. It enables the conscious designing of clothing in the aspect of choosing the appropriate material for its destination as well as utility conditions with assuring the physiological comfort of the user.

2. MATERIAL AND METHODS

Clothing materials with membranes and wool fabrics were undergone to measurements. Measurements were done on the Alambeta device in the normal climate (temp. 20 °C, the relative humidity 65 %). The measurements were done for 5 membrane, one Osmosis laminated fabrics and 4 wool type fabrics for both sides left and right.
1- heating head,  
2- feeding conductor,  
3- heating element,  
4- heat flow sensor,  
5- measured sample,  
6- metal plate,  
7- quides of head,  
8- thermometer measuring the plate temperature,  
9- thermometer measuring the enviroment temperature.

Fig. 1. Scheme of Alambeta device

Characteristics of clothing materials with membranes are presented in Table 1; whereas analogous parameters of wool fabrics in Table 2.

Table 1. Set of examined clothing materials with membranes

<table>
<thead>
<tr>
<th>Material</th>
<th>A Osmosis</th>
<th>B Gore - Tex</th>
<th>C Gore - Tex</th>
<th>D Gore - Tex</th>
<th>E Gore - Tex</th>
<th>F Gore - Tex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>membrane</td>
<td>PU</td>
<td>PTFE</td>
<td>PTFE</td>
<td>PTFE</td>
<td>PTFE</td>
</tr>
<tr>
<td></td>
<td>outer fabric</td>
<td>PA (plain)</td>
<td>PET (stop tread)</td>
<td>PET</td>
<td>PET</td>
<td>PET (plain)</td>
</tr>
<tr>
<td></td>
<td>lining</td>
<td>-</td>
<td>-</td>
<td>PET (tricot)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Resistance of vapour transmission [m² Pa / W]</td>
<td>83,2</td>
<td>10,6</td>
<td>22,7</td>
<td>10,9</td>
<td>8,2</td>
<td>8,8</td>
</tr>
<tr>
<td>Vapour permeability [g / m² / 24 h]</td>
<td>2352</td>
<td>7224</td>
<td>5400</td>
<td>6144</td>
<td>6459</td>
<td>6408</td>
</tr>
<tr>
<td>Air permeability [dm³ / (m² s)]</td>
<td>-</td>
<td>-</td>
<td>0,308</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Vapour transmission resistance was measured according to PN-EN 31092: 1998, vapour permeability was measured according to PN-P04611: 1971, air permeability was measured according to PN - 89/P –
A horizontal line in the case of air permeability means that the laminate doesn’t transmit the air. In the case of laminate C the given value was obtained at the underpressure 250 Pa.

Table 2. Set of examined wool fabrics

<table>
<thead>
<tr>
<th>Material</th>
<th>G 100% wool</th>
<th>H 40% wool 60% polyester textured</th>
<th>I 100% wool</th>
<th>J 60% wool 40% polyester textured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weave</td>
<td>plain</td>
<td>blended</td>
<td>plain</td>
<td>twill (2/2)</td>
</tr>
<tr>
<td>Yarn linear density [tex]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>warp</td>
<td>16×2</td>
<td>60×1</td>
<td>40×2</td>
<td>36×2</td>
</tr>
<tr>
<td>weft</td>
<td>45×2</td>
<td>100×1</td>
<td>40×2</td>
<td>100×1</td>
</tr>
<tr>
<td>The number of threads per 1 dm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>warp</td>
<td>285</td>
<td>130</td>
<td>140</td>
<td>131</td>
</tr>
<tr>
<td>weft</td>
<td>162</td>
<td>120</td>
<td>100</td>
<td>147</td>
</tr>
<tr>
<td>Air permeability [dm³ / (m² s)]</td>
<td>71,448</td>
<td>211,540</td>
<td>203,137</td>
<td>98,066</td>
</tr>
</tbody>
</table>

3. RESULTS AND THEIR ANALYSIS

Using two factor variance analysis the influence of factors (a kind of fabric or laminate and its side) on the particular thermoinsulation parameters were assessed. Also the interaction between factors were analyzed. It was done using the module ANOVA/MANOVA of Statistics.

The following designation of independent factors was assumed: 1 – a kind of fabric or laminate, 2 – side of material (left or right).

Table 3. Results of two factor variance analysis for the thermal conductivity

<table>
<thead>
<tr>
<th>Factor number</th>
<th>F</th>
<th>level P</th>
<th>Significance of factor influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>850.1341</td>
<td>0.000000</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>4.4881</td>
<td>0.034781</td>
<td>+</td>
</tr>
<tr>
<td>12</td>
<td>8.5125</td>
<td>0.000000</td>
<td>+</td>
</tr>
</tbody>
</table>

Fig. 2. Mean values of thermal conductivity coefficient for the left and right side · 10³ [W/(m³ K)]
Table 4. Results of two factor variance analysis for the thermal diffusion

<table>
<thead>
<tr>
<th>Factor number</th>
<th>F</th>
<th>level P</th>
<th>Significance of factor influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1405.759</td>
<td>0.000000</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>175.306</td>
<td>0.000000</td>
<td>+</td>
</tr>
<tr>
<td>12</td>
<td>37.665</td>
<td>0.000000</td>
<td>+</td>
</tr>
</tbody>
</table>

Fig. 3. Mean values of thermal diffusion for the left and right side \( \cdot 10^5 \) \([m^2 s^{-1}]\)

Table 5. Results of two factor variance analysis for the thermal absorption

<table>
<thead>
<tr>
<th>Factor number</th>
<th>F</th>
<th>level P</th>
<th>Significance of factor influence</th>
</tr>
</thead>
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<tr>
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<td>+</td>
</tr>
<tr>
<td>2</td>
<td>315.8534</td>
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<td>+</td>
</tr>
<tr>
<td>12</td>
<td>52.3961</td>
<td>0.000000</td>
<td>+</td>
</tr>
</tbody>
</table>

Fig. 4. Mean values of thermal absorption for the left and right side \([W m^{-2} s^{1/2} K^{-1}]\)

Table 6. Results of two factor variance analysis for the thermal resistance

<table>
<thead>
<tr>
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<th>Significance of factor influence</th>
</tr>
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<td>+</td>
</tr>
<tr>
<td>2</td>
<td>7.33</td>
<td>0.007083</td>
<td>+</td>
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<tr>
<td>12</td>
<td>0.72</td>
<td>0.693509</td>
<td>-</td>
</tr>
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</table>
Fig. 5. Mean values of thermal resistance for the left and right side $\cdot 10^{-3}$ [K m$^2$ W$^{-1}$]

Table 7. Results of two factor variance analysis for the ratio of maximal and stationary heat flow

<table>
<thead>
<tr>
<th>Factor number</th>
<th>$F$</th>
<th>level P</th>
<th>Significance of factor influence</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.000000</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>58.222</td>
<td>0.000000</td>
<td>+</td>
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<tr>
<td>12</td>
<td>51.968</td>
<td>0.000000</td>
<td>+</td>
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</table>

Fig. 6. Mean values of the ratio of maximal and stationary the heat flow for the left and right side

Table 8. Results of two factor variance analysis for stationary heat flow

<table>
<thead>
<tr>
<th>Factor number</th>
<th>$F$</th>
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<th>Significance of factor influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1697.710</td>
<td>0.000000</td>
<td>+</td>
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<tr>
<td>2</td>
<td>232.413</td>
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<td>+</td>
</tr>
<tr>
<td>12</td>
<td>80.611</td>
<td>0.000000</td>
<td>+</td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

1. Among the laminates the best thermoinsulation properties has the three-layer laminate C, which is different than the others. It can result from the different structure and a fact that it is the thickest laminate. Moreover, it should be added that this laminate has at least minimum air permeability, what can be caused by a lack of oilfobic layer on the membrane surface for providing a wind proofness. Among two-layer laminates the best thermoinsulation parameters has the laminate B, which is also thick.

2. We would like to pay attention on the laminate D, two-layer Gore-Tex. The majority of measured parameters has the values not much worse than the best two-layer laminate. This laminate has characteristic high values of thermal absorption and thermal conductivity coefficient, what influences negatively the general assessment of its thermal insulation.

3. Two-layer laminates have worse thermoinsulation properties for the left side than for the right side. It is not comfortable during wearing the cloths, because the left side of laminate is closer to the human being skin. The value of differences shows that the heat flows in a different way through such a material dependably on the direction. It confirms a lack of isotropic properties of laminates, which are built from two different raw materials. Three-layer laminate has better thermoinsulation properties than two-layer ones. Two-layer laminates need an additional underlining for clothing.

4. The worst thermoinsulation properties has the two-layer laminate A, Osmosis with polyurethane membrane. It is the thinnest from the assortment of measured samples.

5. The best thermoinsulation parameters among the measured fabrics shows a wool fabric made of blended yarn 60 % wool/40 % PES of rough surface, designated by the symbol J. Its thickness is 1 mm. This conclusion indicates the significant influence not only of thickness, but also of the textile surface structure on the thermoinsulation parameters.

6. Among the wool fabrics we can pointed out the 100% wool plain fabrics designated by symbol I. There are clearly seen differences between the values of thermal insulation parameters for right and left side of fabric. The characteristic feature of this fabric is that the majority of parameters takes the higher values for the left fabric side than for the right one. Taking into account the organoleptical assessment, both fabric sides don’t differ practically. The reason of such big differences in parameter values can be, for example, apreting the one fabric side.
7. Less advantageous thermal insulation properties shows boucle fabric made of blended yarn 40% Wo/60% PES of thickness 1,3 mm, designated by the symbol H. This fabric in the cases of majority measured parameter is a little worse than the best fabric. The characteristic shortcoming is much higher coefficient of conductivity than for the other fabrics.

8. Wool fabrics don’t show big differences between values of termoinsulation parameters for both sides. The existing differences allows concluding that left fabric sides have a little better thermoinsulation. This situation results from the small diversity of both side structure of wool fabrics and the uniform raw materials. The wool fabrics show differences in pattern (yarn colors, relief).

9. Among the wool fabrics the worst thermoinsulation properties has 100% wool fabric of thickness 0,4 mm, designated by the symbol G. It is the thinnest from the examined wool fabrics. Moreover, the surface of this fabric is smooth, it doesn’t have a possibility of gathering a lot of air.

10. Comparing two samples of the similar thickness – 0,4 mm: wool fabric (G) and three – layer laminate Gore – tex (C) it can be stated that they show similar values of thermoinsulation parameters. Nevertheless, the mentioned above wool fabric has more advantageous properties. Among the wool fabrics the fabric G is the thinnest and the smoothest one. It has also the smallest air permeability because of the dense structure. The laminate (C) is the thickest one. Similar thermoinsulation parameters for the mentioned materials can result not only from the similar thickness, but also from surface similarities (smoothness).

5. LITERATURE

ZAWARTOŚĆ TESTOWA
EVAPORATIVE COOLING IN PROTECTIVE CLOTHING

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ABSTRACT

As part of the EU funded research project THERMPROTECT (“Thermal properties of protective clothing and their use”) this paper deals with manikin experiments looking at the cooling power provided by moisture evaporating from the skin surface while wearing protective clothing. Protective clothing typically has a diminished vapour permeability compared to normal clothing, and this reduces the cooling capacity. When in addition liquid protection is present in the clothing, vapour permeability and cooling capacity will diminish further, increasing the risk of heat stress. In a series of experiments in different laboratories heat loss from PPC with different permeabilities was studied, which will be presented by Richards et al. at this conference. In addition, an analysis was made of the moisture loss from the clothing (manikins sweating or with wetted skin), and by subtracting the heat loss of the manikin while dry from the heat loss of the manikin while wet, the cooling power of wetting the skin could be calculated and analysed in relation to the amount of moisture evaporated from the clothing system. The ratio of these two gives the ‘apparent evaporative cooling efficiency’ of moisture lost. It includes heat loss changes due to conduction by wet underclothing, as well as heat transport by evaporation and condensation within the clothing. In addition, experiments at 34ºC, where only evaporation takes place were performed, which allowed the calculation of the ‘real evaporative cooling efficiency’.

Results show that apparent cooling efficiency changes dramatically with temperature and with the amount of moisture lost. Real evaporative cooling efficiency is rather stable with temperature however, but the values are much lower than commonly assumed. Both values differ with the garments permeability.

This work was funded by the European Union (project G6RD-CT-2002-00846).

1. INTRODUCTION

Evaporation of moisture, usually sweat, is essential for the maintenance of heat balance under most conditions when personal protective clothing is worn. Evaporation provides cooling where otherwise body heat losses would not be able to match metabolic heat generation. The energy equivalent of evaporating water or sweat from the skin is deemed only to be dependant on the temperature at which
it takes place (1) (with skin temperature ranging typically from 30-36°C), but otherwise not influenced by factors such as clothing. When moisture evaporates from the skin in a person wearing clothing and travels towards the environment, it may be sorbed and subsequently desorbed by textile fibres (2), it may condensate in outer layers if these are colder than the skin (3, 4) and subsequently evaporate again, it may be ventilated from the clothing microclimate through openings in the clothing or may finally diffuse through the outer clothing layer. Each of the phase changes mentioned will cause heat to be released or absorbed. It is mostly assumed that only moisture vapour that actually leaves the clothing ensemble contributes to body cooling.

Most thermophysiological and clothing-related research on exchanges of heat and mass between humans and their thermal environment is based on heat balance analysis (5). This analyses the various avenues for heat generation and heat transfer: Metabolic rate (M), Radiation (R), Convection (C), Conduction (K), Evaporation (EVAP), Respiratory heat losses (RESP) and finally Heat Storage (S) in the body. Most of these parameters can be determined directly, whereas DRY heat loss (R+C+K) is normally calculated as the balance of all other heat gains and losses (DRY=M-EVAP-RESP-S). The latter is often done in clothing research, where the DRY value is used to calculate the thermal insulation of the clothing, and EVAP to calculate the clothing vapour resistance. It should be noted that any errors made in the determination of one of the heat balance parameters will end up cumulated in the value for DRY. Only when DRY can be measured directly, can this be avoided.

The method used to determine EVAP is to weigh the change of the (clothed) person’s mass per unit of time, corrected for respiratory moisture loss and metabolic mass losses. From the weight loss per unit of time, it is possible to calculate the equivalent heat loss, which is the energy required for evaporation of that quantity of moisture. The value commonly used is 2430 Joules per gram of moisture evaporated. Hence evaporative heat loss is determined as

\[ EVAP(W) = \frac{\text{mass loss}}{\text{time}} \cdot \text{heat of evaporation} = \frac{\text{mass loss (g)}}{\text{time (s)}} \cdot 2430(J \cdot g^{-1}) \]  

As mentioned above the mass loss is taken by either continuously weighing the nude or clothed person, or, due to technical difficulties of weighing an active person continuously, by weighing the person before and after a test and from the weight difference calculate the mean mass loss per unit of test time.

All such calculations assume that the evaporative efficiency, i.e. the heat actually lost by evaporation of a certain mass of water is equal to the evaporative heat loss potential (mass loss (in g) * 2430 J/g). It may be questioned whether this is the case when (protective) clothing is worn, especially when this clothing hampers the evaporation of sweat and where sorption and desorption or condensation or evaporation within the clothing takes place.

The present study was designed in an attempt to address the issues discussed above, including the assumption that evaporative cooling efficiency is unity for people wearing clothing. As such an investigation is not possible on human subjects, a thermal manikin was used.
2. METHODS

2.1. MANIKIN

In order to discriminate between and determine all heat exchanges, measurements were made using a thermal manikin (‘Newton’). This manikin has 32 independent zones in which heat input or temperature can be controlled and measured. With a dry skin, the skin temperature of the manikin controlled at 34°C, and a fixed environmental temperature the measured heat loss can be used to calculate dry heat resistance of the clothing worn. This measurement is described extensively in ISO15831:2004 and ASTM F1291-05 (6, 7). All heat resistances were calculated using the ‘parallel method’ as described in the standard (8). To allow measurements with wet skin, the manikin was covered with a cotton stretch ‘skin’, that was wetted and acted as a ‘sweating skin layer’. Apart from heat losses, also the weight change of the clad, wet manikin was determined by continuous weighing of the whole setup. The whole manikin setup was placed on an accurate balance (Sartorius 150, with a resolution of 1g; absolute accuracy to ±10g). This setup enabled the amount of water evaporated from the clothing system and thus the real evaporative heat loss and real evaporative heat resistance to be determined.

Pilot tests have shown that the skin remained fully wet for the duration of the experiments (40 minutes) providing a constant rate of ‘sweat’ loss.

All results presented in this paper are calculated for the clothed area only, excluding data from the head, hands and feet.

2.2. CLOTHING

Different test series were performed, with different combinations of outerwear and temperature.

Three underwear types were used: cotton (Gnägi; CO), polyester (PES) and polypropylene (PP) (Table 1), selected to give a similar material heat and vapour resistance. Results will be presented lumped over the different underwear types.

Three custom-made outer garments were used, with identical design and production, but made of either impermeable (IMP), semipermeable (SEMI) or permeable (PERM) material (relative to vapour resistance; see Table 1). An attempt was made to match the materials for heat resistance, but this was not achieved for the impermeable material.
Table 1. Heat and Vapour transfer properties of materials used determined according to EN31092/ISO 11092. Air permeability was determined according to EN ISO 9237: 1995 (9)

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Air permeability l/(m²s)</th>
<th>Rct (m² K/W)</th>
<th>Ret (m² Pa/W)</th>
<th>imt</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>Gnägi Cotton</td>
<td>0.024</td>
<td>4.2</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>PES</td>
<td>Helly Hansen Polyester</td>
<td>0.029</td>
<td>3.4</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>Lifa Active Polypropylene</td>
<td>0.026</td>
<td>3.7</td>
<td>0.42</td>
<td></td>
</tr>
</tbody>
</table>

2.3. EXPERIMENTAL CONDITIONS

For all climates the same water vapour pressure was used (1 kPa), so that the driving force (humidity gradient) for evaporation was the same in all tests and thus for a certain suit (fixed evaporative resistance) the evaporative moisture loss should be the same for all temperatures.

Three climates were chosen: 34ºC (isothermal conditions where tsk=ta and thus no dry heat loss is present), 20 and 10ºC. The 1 kPa vapour pressure combined with these temperatures resulted in relative humidities of 18.5, 42 and 80% for 34, 20 and 10ºC respectively.

The manikin was placed in front of three fans, mounted in a vertical line, producing a reference wind speed of 0.5 m/s. In terms of heat losses, only evaporative heat loss is present at 34ºC, whereas dry heat loss increases with the temperature gradient for lower temperatures.

From the data obtained, ‘Apparent Evaporative Heat Loss’ is calculated as:

\[
\text{Apparent Evaporative Heat Loss} = \text{Total Heat Loss Wet Manikin} - \text{Dry Heat Loss}
\]  

(2)

Then, the ‘Apparent Evaporative Cooling Efficiency’ was calculated as the Apparent Evaporative Heat Loss of the wet manikin divided by the ‘Evaporative Cooling Potential’ (weight loss * 2430 J/g/time) of the same condition.

\[
\text{Apparent Evaporative Cooling Efficiency} = \frac{\text{Apparent wet heat loss of wet manikin}}{\text{Evaporative Cooling Potential}}
\]  

(3)
3. RESULTS

Fig. 1 shows the results for the ‘Apparent Evaporative Cooling Efficiency’ (equation (3)). For the impermeable suit, at lower temperatures this value goes substantially above one. Thus more heat is lost than would be expected based on the mass loss of the person-clothing system. For the more permeable suits the efficiency remains around one or lower, indicating that heat loss is equal or less than expected based on mass loss.

![Graph showing apparent evaporative cooling efficiency](image)

**Fig. 1.** Apparent evaporative cooling efficiency based the ratio of the calculated ‘wet’ heat loss over the heat loss of the evaporation as determined from weight loss.

4. DISCUSSION

The data presented in Fig. 1 allow two important observations: firstly, for low permeability clothing, the apparent evaporative cooling efficiency can be substantially higher than one, when temperatures are low. This is attributed to the condensation of moisture on the inner clothing surface, which has first cooled the skin by evaporation (3, 4). This extra evaporation-condensation mechanism transports more heat than expected when looking at the mass loss alone (10). Secondly, at high temperature, the cooling by evaporation is actually less than the value deducted from mass loss. This is most evident for IMP, but also observed for SEMI and PERM. This implies that the real evaporative cooling efficiency (not including evaporation-condensation effects) is less than 1 for all suits.
5. ACKNOWLEDGEMENTS

This work was funded as European Union GROWTH programme project “THERMPROTECT, Assessment of Thermal Properties of Protective Clothing and Their Use”, contract G6RD-CT-2002-00846.

REFERENCES

ABSTRACT

In order to avoid heat strain, the human body must lose excess heat when exercising and/or under hot conditions. However Personal Protective Clothing (PPC) tends to hinder the transfer of heat and moisture from the body which increases the possible resultant heat strain.

For work package 2 of the EU funded Project THERMPROTECT (entitled ‘Thermal Properties of Clothing and Their Use’), the effects of moisture in PPC on the heat loss from the body was investigated in relationship to the water vapour resistance of the clothing, type of underwear, location of the moisture and the climate. This paper presents manikin results from different laboratories of dry and wet heat losses for a range of 2-layer clothing with similar dry insulations but different water vapour permeabilities and absorptive properties.

The results obtained from different manikins are generally consistent with each other, in spite of the fact that different experimental methods were used. For each climate, the wet heat losses are predominately dependent on the permeability of the outer layer. The location and quantity of moisture within the clothing also affects the wet heat loss. Particularly for impermeable clothing at low temperatures, the wet heat loss is markedly higher than expected from evaporation alone. This additional heat loss is attributable to increased conductivity of the wet clothing layers and condensation within the clothing.

1. INTRODUCTION

Humans lose excess body heat though several different dry and wet heat transfer processes. Protective clothing tends to hinder these transfer processes and thus reduce the possible heat loss from the body thus increasing the risk of heat strain under hot conditions and/or high physical exertion. Humans increase body heat loss under such conditions by increasing blood flow to the surface of the body and increased sweating. The evaporation of sweat from the surface of the skin is one of the most important methods of loosing excess body heat.

The European funded project THERMPROTECT was set up to study systematically the basic physical properties of various types of protective clothing. Present standards for Personal Protective Clothing (PPC) take little consideration of special issues like effects of radiation or moisture. Work package 2 of this project
investigated the effects of moisture on the heat loss from the body under different climates. The results presented here demonstrate the increased heat loss due to the evaporation of sweat as well as additional heat loss caused by increased conduction due to the clothing becoming wet and to condensation occurring within the clothing.

In this study manikins from four different institutes were used to investigate the dry and wet heat losses for different climates and clothing. Preliminary results from one of these manikins have already been presented (1). Generally adult-sized manikins used to simulate dry and wet heat loss from the human body tend to give a limited reproducibility due to different manikin designs and experimental techniques (2). Nevertheless the results presented here confirm and extend the principle findings of the above-mentioned preliminary results.

2. METHODS

2.1. MATERIALS/CLOTHING INVESTIGATED

The clothing materials investigated in this study had a range of different properties, the underwear being hygroscopic, hydrophilic or hydrophobic and the outer wear having different permeabilities. Intrinsic dry thermal insulation ($I_d$) and water vapour resistance ($R_{wat}$) values for these materials (measured as separate textile layers using EN 31092/ISO 11092 (3)), calculated water vapour permeability values ($i_{wat}$) are listed in tables 1 and 2.

<table>
<thead>
<tr>
<th>Code</th>
<th>Material</th>
<th>Moisture property</th>
<th>$I_d$ (m$^2$ K/W)</th>
<th>$R_{wat}$ (m$^2$ Pa/W)</th>
<th>$i_{wat}$</th>
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<tbody>
<tr>
<td>CO</td>
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<td>PES</td>
<td>100% Polyester</td>
<td>Hydrophilic</td>
<td>0.029</td>
<td>3.4</td>
<td>0.51</td>
</tr>
<tr>
<td>PP</td>
<td>100% Polypropylene</td>
<td>Hydrophobic</td>
<td>0.026</td>
<td>3.7</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table 1: Underwear materials. See text for the definition of the values listed.

<table>
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<tr>
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<th>Moisture property</th>
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<th>$R_{wat}$ (m$^2$ Pa/W)</th>
<th>$i_{wat}$</th>
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<tr>
<td>IMP</td>
<td>PA webbing with outer PVC coating</td>
<td>Impermeable</td>
<td>0.007</td>
<td>$\infty$</td>
<td>0</td>
</tr>
<tr>
<td>SEMI</td>
<td>hydrophilic layer with outer PTFE membrane</td>
<td>Semi-permeable</td>
<td>0.023</td>
<td>18.6</td>
<td>0.07</td>
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<tr>
<td>PERM</td>
<td>hydrophobic layer with inner PTFE membrane</td>
<td>Permeable</td>
<td>0.025</td>
<td>5.6</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 2: Outerwear materials. See text for the definition of the values listed.

The underwear clothing consisted of two pieces with long-arm tops and long johns. The outer garments were one-piece coveralls without pockets, but with a draw-string at the waist and velcro ties at the wrists and ankles. For most tests all openings (at the neck, wrists and ankles) were closed. Clothing fit was kept as constant as possible.
2.2. CLIMATES USED

The climates presented here are for ambient temperatures $t_a = 10^\circ C$ with 80%rh and $t_a = 34^\circ C$ with 18%. Thus both climates have the same water vapour partial pressure of 1 kPa. For $t_a = 34^\circ C$, the measurements were isothermal with the manikin surface temperature $t_{sk} = 34^\circ C$ and so no dry heat loss took place.

2.3. MANIKINS USED

Results from three different thermal manikins are presented here. The manikins are as follows:

1) EMPA manikin (‘SAM’) (4), 26 heated sweating sectors and 8 heated guard sectors
2) TUT (Tampere University of Technology) manikin (‘Coppelius’) (5), 18 heated sweating sectors
3) LU (Loughborough University) manikin (‘Newton’) (6), 32 heated sectors

These manikins were used to measure the total dry heat flux of different protective clothing according to ISO15831 (7). Additionally sweating was simulated using an integrated sweating system (EMPA and TUT manikins; sweat rate of 200 g/(m²h)) or by a pre-wetted wicking skin layer worn tightly around the manikin (LU manikin). All values of dry and wet heat loss presented here are steady-state values for the areas of the body covered by clothing only, excluding heat losses from the head, hands and feet.

3. RESULTS

Comparing results from the sweating manikins at TUT and EMPA in figure 1(a) and (b), the EMPA manikin tended to give slightly lower dry heat losses but similar increases in heat losses caused by sweating (termed the apparent evaporative heat loss). Thus in spite of differing manikin designs, the relative changes in heat losses are comparable. Impermeable clothing gave lower wet heat losses than permeable clothing and the increase in heat loss caused by sweating was greater for synthetic underwear (PES and PP) than for cotton (CO).

![Figure 1](image.png)

**Figure 1** Comparison of results for $t_a = 10^\circ C$ from the sweating manikins (a) Dry heat losses for clothing with permeable and impermeable coveralls, (b) apparent evaporative heat losses from the increase in heat losses when sweating.

Total wet heat losses measured using the EMPA and LU manikins for $t_a = 10^\circ C$ for different outerwear but the same underwear (PP) are presented in figure 2, broken down into heat loss components. The dry heat loss (consisting of radiation, convection and dry conduction) was determined without simulating sweating. The value for actual evaporative heat loss is based on results with sweating obtained for $t_a = 34^\circ C$. As the partial pressure used for $t_a = 10^\circ C$ was the same as for $t_a = 34^\circ C$, the evaporative heat loss should be equal
for both temperatures. It is evident from figure 2 that the results obtained using the LU manikin confirm the results from the EMPA manikin presented previously (1).

![Figure 2](image)

**Figure 2** Total heat loss measured for \( t_a = 10^\circ C \) for different outerwear but the same underwear (PP), broken down into heat loss components. Results from: (a) EMPA manikin, (b) LU manikin.

The moisture collected within the clothing layers measured using the EMPA manikin for \( t_a = 10^\circ C \) is shown in figure 3. As expected the total moisture which collected is strongly dependent on the water vapour permeability of the outer layer, with most moisture collecting in clothing with the IMP outer layer. For a given outer layer, the moisture accumulation within the underwear is dependent on its absorptive properties, with the most moisture collecting in CO (being very hygroscopic) and the least in PP (being hydrophobic). The moisture within the tight-fitting skin on the manikin surface is dependent on the underwear layer, being greatest for CO and least for PP for a given outer layer. For the IMP results, almost all the water sweated in 2½ hours collected within the clothing. Some water dripped down and was collected below the manikin and some evaporated sweat (about 20% of the total 550g sweated) could escape through the collar of the overall which was not completely closed for these manikin tests.

![Figure 3](image)

**Figure 3** Moisture within the clothing layers and evaporated for \( t_a = 10^\circ C \) measured using the EMPA manikin.

### 4. DISCUSSION

Dry heat transfer and evaporative heat transfer of moisture which leaves the clothing are often treated as being the only processes involved in heat transfer through clothing. However this work confirms that there are indeed other heat transfer processes involved for all types of clothing presented here. Additional heat transfer is attributable to increased conduction due to the clothing layers being wet and to evaporation of
moisture from the skin which does not leave the clothing in vapour form but condenses on the inner surface of the outer clothing layer.

5. CONCLUSIONS

Generally the presence of moisture within clothing reduces its total effective thermal insulation and causes an increase in the heat loss from the wearer under cold conditions. The majority of this increased heat loss is due to evaporation for semi-permeable and permeable clothing. However not all of this increase can be accounted for by evaporation. The apparent evaporative heat loss (defined as the increased total heat loss from dry to when sweating is simulated) for \( t_s = 10^\circ C \) is markedly higher than would be expected from evaporation alone. This is particularly true for impermeable clothing with additional heat losses of up to 40%. Thus the total heat loss under cold conditions is greater than expected from the sum of dry and evaporative heat losses.

5.1. ACKNOWLEDGEMENTS

This work was funded as European Union GROWTH programme project “THERMPROTECT, Assessment of Thermal Properties of Protective Clothing and Their Use”, contract G6RD-CT-2002-00846.

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EFFECTS OF HEAT RADIATION ON THE HEAT EXCHANGE WITH PROTECTIVE CLOTHING – A THERMAL MANIKIN STUDY

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ABSTRACT

Within the scope of the European research initiative THERMPROTECT numerous thermal manikin experiments were performed on the transfer of heat through personal protective clothing (PPC) under far infrared radiation (FIR) stress. The influence of the reflectivity and insulation of the clothing, the radiated body surface area, and the interaction with convection and wet underwear were considered. The data showed a decrease in whole body heat loss, i.e. heat gain under radiant heat stress. This heat gain increased with radiation intensity, the slope depending on air velocity and underwear insulation. Except for an aluminised garment that showed minor effects, the influence of the material and colour of the outer layer was negligible, as was the effect of radiation geometry. However, wetted underwear caused differential effects, with FIR induced heat gain depending on water vapour permeability.

1. INTRODUCTION

The work package ‘Heat radiation’ of the EU funded research project THERMPROTECT (“Thermal properties of protective clothing and their use”) studied the effects of long and short wave heat radiation on PPC. A stepwise experimental approach comprising flat plate material tests, manikin experiments and human trials was applied.

Whereas first results of the long wave (1) and solar radiation (2) experiments with thermal manikins have been reported elsewhere and also during this conference (3), this summarising contribution focuses on the effects of far infrared radiation (FIR) that were mainly studied by CEPA and IfADo.

The objective of the manikin experiments was to evaluate the effect of radiation on heat transfer through PPC, considering aspects related to the reflectivity and insulation of the clothing, the radiated body surface area, and the interaction with convection and wet underclothing. Furthermore, the results were to be used as a database for the development of corresponding heat transfer models.
2. METHODS

The electrically heated thermal manikins Heatman (CEPA) and Tore (Lund University, operated at IfADo) were operated with a constant surface temperature of 34 °C standing in climatic chambers (Fig. 1). To ensure proper operation of the manikins’ heating mechanism the experiments were carried out at low air temperatures \( t_a \) of 12 °C (CEPA) or 5 °C (IfADo) with 50% relative humidity (rh) and air velocities \( v_a \) of 0.5, 1 and 2 m/s. Infrared radiation was applied by heating up one wall and the ceiling to 60 °C (CEPA), resulting in mean radiant temperature \( t_r \) of 28.8 °C, or by ceramic panels (IfADo) that generated FIR with \( t_r \) between 41.3 and 88.7 °C, and a condition with \( t_r = t_a \) was included as a reference. The geometry of the effective radiant field was varied by rotating the manikin or changing the position of the FIR source.

Garments with different outer materials (cotton, Nomex®) and colours (black, white, orange) as well as an aluminised reflective suit and a black Nomex® with inside lamination were combined with different layers of underwear (Helly Hansen Bodywear Super™ 140 g/m², HHS; Ullfrotté Original™ 400 g/m², ULF). The effect of wet underwear was studied by pre-wetting ULF with 800 g water.

Steady state values were calculated from the final 10 minute recordings of the power supplied to the manikins as area weighted averages of the local heat losses according to the parallel method (4) for the whole body, and separate for radiated and non-radiated body parts. All calculations excluded the head, hands and feet, that were shielded against high intensity FIR with aluminium foil (Fig. 1). As the application of FIR did not cause changes in \( t_a \) the results are presented as (changes in) measured heat loss averaged over two replications.

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**Figure 1.** Experimental set-up of the thermal manikin Tore from Lund University inside the IfADo climatic chamber (a) with HHS underwear, gloves and socks, (b) with ULF coverall and head, hands and feet covered with aluminium foil, and (c) with the black Nomex® outer layer.
3. RESULTS AND DISCUSSION

3.1. FIR EFFECTS RELATED TO REFLECTIVITY AND INSULATION

The results showed a decrease in whole body heat loss (Fig. 2a), i.e. heat gain for the conditions with radiant heat stress compared to the reference, as shown in Fig. 2b). Except for the reflective suit that demonstrated no effects at CEPA and only minor effects with the higher intensity FIR at IfADo, the other outer garments revealed only a negligible influence of colour and material on this heat gain. This was in contrast to experiments with short wave radiation (2;3;5) showing definite colour effects.

The FIR induced heat gain appeared to be linearly related to radiation intensity expressed as t_r-t_a (Fig. 2a) and showed a flatter slope for a 3 layer clothing compared to a 2 layer combination (Fig. 3).

Extrapolation of these curves suggest that at higher radiation intensities heat gain may be smaller for the 3 layer system with higher insulation, which would be beneficial to the user.

3.2. FIR EFFECTS RELATED TO RADIATED SURFACE AREA

The comparison of the heat losses between three positions of the manikin in the CEPA chamber are illustrated in Fig. 4. The whole body heat loss was very similar between the various conditions, but local differences were observable. Note that even when facing the air (middle part of the figure) one side of the manikin had larger heat losses because a warm wall was still present on the other side. The rotation of the manikin had exactly the same consequences on any side (left and right parts of Fig. 4).

An interesting observation concerns the wind effect, clearly visible as a higher heat loss on the side of the manikin which was directly exposed after rotation.

![Graph](image-url)

**Figure 2.** a) Manikin heat losses at IfADo measured with HHS underwear at t_a=5 °C, v_a=0.5 m/s, rh=50%, and b) Changes in heat loss to the condition with t_r=t_a, i.e. heat gain as measured at CEPA without underwear at t_a=12 °C, v_a=0.5 m/s, rh=50% (radiation via 2 surfaces at 60°C), for the whole covered body area (head, hands, feet excluded) related to the different outerwear.
Also experiments at IfA Do showed (1) that whole body heat gain under radiant heat load \( (t_r=50 \, ^\circ C) \) was similar for frontal, lateral and all-side radiation, but that one-sided radiation affected differently radiated and non-radiated body parts, thus causing an inhomogeneous spatial distribution of heat gain.

These results are concordant with human wear trials showing no effect of radiation direction on the physiological heat strain with light clothing, cf. (1), or PPC (6).

**Figure 3.** Manikin heat loss connected by straight lines as measured at IfA Do for the whole body (left panel) and frontal torso area (right panel) at \( t_a = 5 \, ^\circ C, \, v_a = 0.5 \, m/s, \, rh = 50\% \) in relation to \( t_r - t_a \) for ensembles with 2 layers (depicted from Figure 2a) and with an additional layer (ULF).

**Figure 4.** Manikin heat loss under the radiation effect as measured at CEPA for the whole covered body area (Total) and for the left and right specific area exposed to the radiation field (head, hands, feet excluded). The manikin wore the black Nomex\textsuperscript{®} coverall without any underwear.
3.3. INTERACTION OF FIR EFFECTS WITH WIND SPEED

Fig. 5 illustrates for the *IfADo* experiments, that increasing wind speed also increased heat loss as expected with the adjusted air temperature of 5 °C. An interaction effect of FIR and convection appeared insofar, as the steepness of the effect of FIR was modified by wind speed. Apparently, the FIR related reduction in heat loss (i.e. heat gain) was flatter at higher wind speed. Similar relations were also found in experiments with short wave radiation (2).
3.4. INTERACTION OF FIR EFFECTS WITH WET UNDERWEAR

With dry ULF underwear the change in heat loss, i.e. heat gain was again similar for the non-reflecting materials (Fig. 6, left). However, wetted underclothing caused differential effects (Fig. 6, mid), with FIR induced heat gain depending on water vapour permeability, as indicated by evaporation rate that increased with radiation intensity only for the more permeable black materials (Fig. 6, right).

For an impermeable PVC coated garment, heat gain increase appeared to be steeper with wet than with dry ULF (Fig. 6, blue lines). The reflecting property of the aluminised suit was outweighed by its low vapour permeability, so that with wet ULF its heat loss was nearly identical to that of the black suits, which showed its consequences in wear trials (6).

4. CONCLUSION

The results show that thermal radiation transferred through PPC causes heat gain at the skin surface that (i) increases linearly with radiation intensity \( (t-t_a) \), (ii) depends on the reflecting properties of the clothing with a colour effect evident only in the solar (2;3), but not in the infrared spectrum, (iii) is attenuated by adding clothing layers, (iv) is attenuated with increasing wind speed.

During THERMPROTECT an appropriate model for the effect of radiation on dry heat loss had been developed under the lead of E. den Hartog (TNO), that provided good predictions of the effects of short and long wave radiation measured with the manikins under different conditions in different laboratories.

However, the manikin experiments with wet underwear, as well as wear trials (6) indicate that such models need to be expanded by the modifying effects of (sweat) evaporation, that may outweigh the benefits of reflective, but vapour resistant clothing at low to moderate radiation intensities.

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5. REFERENCES


THE COMPARISON OF THERMAL PROPERTIES OF PROTECTIVE CLOTHING USING DRY AND SWEATING MANIKINS

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ABSTRACT

The thermal insulation of clothing is commonly determined by dry thermal manikins either made of plastic or metal. For the determination of evaporative resistance of clothing ensemble, there exist three types of manikin methods: pre-wetted underwear or “skin” covered on dry manikins, the manikin with regulated constant water supply to the “skin” surface and the sweating fabric manikin based on a water filled body covered with waterproof but vapour permeable fabrics. The purpose of this study was to compare thermal insulation and moisture evaporative resistance of a set of protective clothing measured using different type of manikins. The total thermal insulation of seven EU project ensembles (Subzero A and B, Permeable (PERM), Impermeable (IMP), Nomex coverall (with two types of underwear) and Cotton coverall) were measured using the manikin Tore in Sweden, the sweating fabric manikin Walter in Hong Kong, and the mankin Newton in the UK. The results showed that total thermal insulation is reproducible for the seven clothing ensembles measured on the manikins Walter and Tore. The coefficient of variance is less than 8%. Nomex coverall with cotton underwear has 8-16% higher total insulation than that with polypropylene underwear. The apparent evaporative resistance of the impermeable coverall with cotton underwear measured on Newton was 44.5% lower than the evaporative resistance measured on Walter. The effect of condensation and conduction at room temperature environment and measuring time allowing full accumulation of moisture in clothing ensembles might be two important factors affecting the evaporative resistance

1. INTRODUCTION

Thermal properties of clothing such as thermal insulation and evaporative resistance can be determined using manikins (1). However, different types of manikins developed using different designs, constructions, principles, and calculation methods may show different results for the same clothing ensemble. This is in particular the case in the measurement of evaporative resistance of clothing ensembles using sweating manikins as there has been no standard (2). It is therefore necessary to make interlaboratory comparison measurements in order to evaluate and verify results from different manikins and labs in order to assess reproducibility (2, 3).

The coefficient of variation for dry thermal insulation of cold protective clothing in non-walking conditions was reported within 8% measured using dry thermal manikins among eight European
thermal laboratories (3). The basic construction of those manikins, heating systems, shell materials, dimensions and the measurement principles are similar to each other. The thermal environment lab at Lund University in Sweden is one of them.

The dry thermal insulation is commonly determined by dry thermal manikins. But it can also determined by a sweating manikin (4, 5). To determine evaporative resistance of clothing ensembles is not as common as determining thermal insulation. There are relatively few sweating manikins available for measuring the evaporative resistance of clothing, and the test procedures have not been standardized (5, 6). Sweating manikins design and test methods vary considerably from lab to lab. The variability among labs was reported relatively high in the interlaboratory evaluation of sweating manikins (2). The sweating manikin methods can be categorized into three types: (a) pre-wetted “skin” (e.g., cotton knit suit) covered on dry manikins, (b) manikin with sweating glands with regulated constant water supply to the “skin” surface (microporous suit). These two types are made of plastic or metal with heating and sweating facilities on the “skin” surface. (c) The sweating fabric manikin. The manikin Walter has been developed at Hong Kong Polytechnic University, which is based on heated water filled body covered with waterproof but vapour permeable fabrics (4). Walter was not used in the above mentioned interlaboratory evaluation of sweating manikins (2).

The purpose of this project was to compare reproducibility between labs with dry and sweating manikins in measuring thermal insulation and evaporative resistance of sets of protective clothing used in the EU-projects.

2. METHODS

Two European research projects have been undertaken with the purpose of investigating thermal properties of protective clothing using thermal manikins and human subject tests, i.e., (a) Assessment of thermal properties of protective clothing and their use (Thermprotect), (b) Thermal insulation measurements of cold protective clothing using thermal manikins (Subzero). In this investigation, two cold protective clothing ensembles and three protective ensembles from Thermprotect were selected out of the above two EU projects (Table 1).

Three thermal manikins were used in this study. Thermal manikin Tore was used for measuring dry insulation. Tore is divided into 17 individually controlled zones. The surface temperatures of all zones were kept at 34 °C, heat losses and ambient temperature were recorded at 10 second intervals. Total insulation values were calculated according to parallel method (ENV 342). The manikin Newton has 32 zones applying the same principle as Tore to measure and calculate the dry thermal resistance. It was also used to measure apparent evaporative resistance of clothing ensembles by covering the manikin with a pre-wetted cotton stretch “skin”. A dry and a wet test were carried out separately for the same type of clothing ensembles (Table 2). Apparent Evaporative Heat Loss is calculated as:

\[ \text{The Apparent Evaporative Heat Loss} = \text{Total Manikin Heat Loss (measured during wet test)} - \text{dry heat loss (measured during dry test)}. \]

The apparent evaporative resistance is then calculated as:

\[ R_e = \frac{\text{skin vapour pressure- ambient vapour pressure}}{\text{evaporative heat loss}} \]

Walter simulates perspiration using a waterproof, but moisture-permeable fabric “skin”, which holds the water inside the body, but allows moisture to pass through the “skin”. The water supply rate changes automatically by siphon action depending on the amount of clothing worn and perspiration.
Evaporative heat loss is calculated based on water mass loss (perspiration rate) when a steady state is reached.

Dry heat loss is calculated as:

\[ \text{Dry heat loss (} H_d \text{)} = \text{total heat loss} - \text{evaporative heat loss} \]

Base on \( H_d \) the total thermal insulation is then calculated (4).

### Table 1. Clothing ensembles and garments

<table>
<thead>
<tr>
<th>Ensemble</th>
<th>Garment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perm+CO</td>
<td>Permeable coverall (polypropylene layer with inner PTFE membrane), underwear: cotton (CO) shirt and pants</td>
</tr>
<tr>
<td>Imperm+CO</td>
<td>Impermeable coverall (polyamide with PVC coating), underwear: cotton shirt (CO) and pants</td>
</tr>
<tr>
<td>Nomex+CO</td>
<td>Nomex coverall, underwear: cotton (CO) shirt and pants</td>
</tr>
<tr>
<td>Nomex+PP</td>
<td>Nomex coverall, underwear: polypropylene (PP) shirt and pants</td>
</tr>
<tr>
<td>Cotton+PP</td>
<td>Cotton coverall, underwear: polypropylene (PP) shirt and pants</td>
</tr>
</tbody>
</table>

Testing environment in the three laboratories was not controlled at the same condition (Table 2).

### Table 2. Testing conditions and zone inclusion in the calculation in three labs

<table>
<thead>
<tr>
<th></th>
<th>Ta (°C)</th>
<th>Va (m/s)</th>
<th>R.H. (%)</th>
<th>Zone excluded in calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tore</td>
<td>20</td>
<td>0.2 (0.3 for Subzero A&amp;B)</td>
<td>30</td>
<td>Hands and feet</td>
</tr>
<tr>
<td>Walter</td>
<td>21</td>
<td>0.2</td>
<td>70</td>
<td>No hands and feet</td>
</tr>
<tr>
<td>Newton (wet)</td>
<td>20</td>
<td>0.5</td>
<td>42</td>
<td>Head, hands and feet</td>
</tr>
<tr>
<td>Newton (dry)</td>
<td>5.9</td>
<td>0.5</td>
<td>50</td>
<td>Head, hands and feet</td>
</tr>
</tbody>
</table>

### 3. RESULTS

The results of dry thermal insulation of the seven clothing ensembles measured on Tore and Walter, four ensembles on Newton are shown in Figure 1. The coefficient of variance (SD/average %, CV) was used to indicate the reproducibility (3). The CV of the seven tested clothing ensembles between Tore and Walter was less than 8% (ranging from 0 to 7.4%). The results obtained on Newton were not included in the calculation of the CV since the testing air velocity and zone inclusion were different (Table 2).
Figure 1. The thermal insulation of seven clothing ensembles measured on Walter, Tore and Newton (CV between Walter and Tore: 0-7.4%)

Figure 2. Evaporative resistance of clothing ensembles measured on Walther and apparent evaporative resistance measured on Newton

The evaporative resistance measured on Walter (seven ensembles) and the apparent evaporative resistance measured on Newton (two ensembles) of the clothing are in Figure 2. The evaporative resistance of the ensemble “IMPERM+CO” measured on Walter was calculated after several hours when it had reached stable state. The transient values at the 1st, and 3rd hours were 78.3 and 96.8 m²Pa/W respectively (Figure 2).
4. DISCUSSION AND CONCLUSIONS

Seven ensembles were measured with Walter in Hong Kong with the procedures developed in house. The total thermal insulation is reproducible for the seven clothing ensembles measured on Walter and on Tore even though the constructions, measurements and calculation principles are quite different. The reproducibility for the total insulation measurements are in good agreement with previous European interlaboratory tests with different types of manikins (3). The differences of the total insulations measured on Newton compared to those on Tore and Walter are less than 10% despite of different testing air velocity and zone inclusion in the calculation (Table 2).

The results from Tore and Walter showed that Nomex coverall with cotton underwear has 8-16% higher dry insulation than that with polypropylene underwear. This is consistent with Thermprotect findings (7). The thermal insulation of Nomex coverall with PP underwear showed slightly higher values than that of cotton coverall with PP underwear. The difference is marginal. This difference could be due to the accuracy or repeatability within a laboratory.

The evaporative resistance measured on Walter and the apparent evaporative resistance on Newton varied between permeable and impermeable coveralls. The apparent evaporative resistance of permeable coverall measured on Newton based on total heat loss subtracted by dry heat loss was 15% higher than the evaporative resistance measured on Walter (based on mass loss), whereas the apparent evaporative resistance of the impermeable coverall measured on Newton was 44.5% lower. This is mainly due to the fact that measurement and calculation principles are different between Walter and Newton. The value measured on Newton is apparent evaporative resistance. “Apparent” indicates that it is not only due to actual evaporation (water mass loss), but also includes other heat loss compared to dry such as condensation and conduction, in which the heat loss increases with lowering ambient temperature and reducing clothing vapour permeability (7). The condensation and conduction during test at room temperature environment causes extra heat loss besides heat loss from mass. This is discussed in detail in the report of the latest EU Thermprotect project (7).

Other factors affecting the evaporative resistance could be the measuring time. It took about several hours for Walter to stabilize for the impermeable coverall with cotton underwear. The transient values at the 1st and 3rd hours increase with measuring time (Figure 2). This implies that the perspiration rate (water loss) decreases with time before the accumulation of moisture in the cotton underwear and impermeable coverall reached its maximum. Walter took more than 1 hour to stabilize for the permeable coverall with cotton underwear. The measurement on Newton lasted 40 minutes. The steady-state might have not completely reached (2). The accumulation of moisture in the cotton underwear and the coverall might have not been stabilized. On the other hand, it is not surprising that the evaporative resistance of the permeable coverall between Newton and Walther is about 15% different although there is no or very small condensation and conduction heat loss, as the variability of evaporative resistance among labs has been reported relatively high. The mean evaporative resistance values of chemical protective clothing between labs could differ three times (2).

In conclusion, the total thermal insulation is reproducible for the seven clothing ensembles measured on the manikins Walter and Tore. The coefficient of variance is less than 8%. Nomex coverall with cotton underwear has 8-16% higher total insulation than that with polypropylene underwear. The apparent evaporative resistance of the impermeable coverall with cotton underwear measured on Newton was 44.5% lower than the evaporative resistance measured on Walter. The effect of condensation and conduction at room temperature environment and measuring time allowing full
accumulation of moisture in clothing ensembles might be two important factors affecting the evaporative resistance.

Acknowledgement

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REFERENCES

MODELLING THE METABOLIC EFFECTS OF PROTECTIVE CLOTHING

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ABSTRACT

Protective clothing is worn in many industrial and military situations. Although worn for protection from one or more hazards, protective clothing can add significantly to the metabolic (energy) cost of work. Suggestions put forward as to the mechanisms behind the observed increases include, the additional clothing weight of the protective garments, possible friction between the number of layers that must be worn and restriction of movement due to clothing bulk. However, despite much speculation, these areas have not received much investigation.

Wearing protective clothing from a range of industries and with quite different characteristics for example weight, bulk and stiffness significantly increased metabolic rate when walking, stepping and completing an obstacle course activity. Increases in the metabolic rate of up to 20% above control conditions (lightweight tracksuit and trainers worn) were seen. A number of clothing properties were then investigated to try and understand the causes of these recorded metabolic rate increases. Clothing bulk was measured at 3 sites, upper arm, torso and thigh. The stiffness of the clothing was also calculated, using a method which measured the clothing drape of the sleeve, main body of the garment and trouser leg.

A multiple regression carried out on the data showed body weight to be the best predictor of absolute metabolic increases across all work modes. For the % increase in metabolic rate total clothing weight was the best predictor. Torso bulk was negatively correlated with the increased metabolic rate for walking and stepping and the overall average, whereas leg bulk was a significant predictor of an increased stepping metabolic rate and leg stiffness a significant predictor for the obstacle course work mode.

1. INTRODUCTION

The effects of protective clothing on workers has been studied across a number of industries but most studies have emphasized the thermal effects of clothing, such as heart rate, core temperature responses to different garments and performance decrements in the heat. Few studies have considered the metabolic effects. In those that have, it has been shown that various protective clothing ensembles increase the metabolic cost of performing walking and stepping tasks by adding weight (1, 2, 3, 4).
A ‘hobbling’ effect of clothing due to the interference with movement at the body’s joints, produced by the bulk of the clothing, has also been suggested as a contributing factor to the increased energy costs documented (1, 2, 3, 4).

2. METHODS

Using the data from this lab on increased metabolic rate for a number of protective garments (1), further data was collected on the clothing characteristics. Clothing bulk was measured at 3 sites, upper arm, torso and thigh, Participants wore a pair of work trousers and t-shirt under the protective garments and then measurements of the excess clothing fabric were made at 3 sites; upper arm, torso and upper thigh, using a standard tape measure, by pinching the clothing fabric at each site and measuring the excess fold of material as illustrated in Figure 1.

![Figure 1](image1.png)

*Figure 1.* Photographs showing site and method of measuring clothing bulk.

The stiffness of the clothing was also recorded, using a method which measured the clothing drape of the sleeve, main body of the garment and leg. Measurements were made by supporting the garment on a small platform 20cm above the ground, as illustrated in Figure 2 and allowing the section of the garment to be measured to drape over the edge. A tape was in place on the floor and the distance to the point at which the garment touched the floor was recorded, as shown in Figure 2. For the leg measurements the trousers were laid on the platform with the crotch at the edge of the platform and the left leg of the garment draped off the platform. For the arm measurement the main body of the garment was placed on the platform with the seam of the left sleeve on the edge of the platform allowing the left sleeve of the garment to drape off the platform as in Figure 2. For the torso measurement, the main body of the garment was supported on the platform with the armpits of the garment in line with the edge of the platform allowing the torso section of the garment to drape over the edge.
A stepwise interactive multiple regression was carried out to assess if any of these clothing properties (weight, bulk, stiffness) could be used to predict the metabolic cost of wearing the protective clothing.

3. RESULTS AND DISCUSSION

The results of the regression modelling have been summarised in Table 1. The columns contain headings and units of the variables recorded when protective clothing was worn walking, stepping, completing the obstacle course and overall (average of the 3 work modes). Metabolic rate was measured in watts and subsequently calculated as watts per metre squared to take account of body surface area and as percentage (%) increase from a control condition. Heart rate results have also been analysed. The rows in the table contain the variables that the modelling process showed to be significant predictors of the metabolic rate and heart rate.

When the overall % increase in metabolic rate was analysed, total clothing weight was found to positively correlate with an increased metabolic rate and clothing bulk around the torso to negatively correlate with an increased metabolic rate. The effects of load, in this instance carried as extra clothing weight, on oxygen consumption and metabolic cost of work has been well documented. The modelling suggests that greater increases in metabolic rate are seen in garments with a lower clothing bulk in the torso region. When the absolute results (watts) for overall increase in metabolic rate are considered the best predictor of the increase is body weight.

When the walking work mode is considered, total clothing weight (+) and torso bulk (-) are again the best predictors of the % increased metabolic rate, total clothing weight positively and torso bulk negatively as described above. For the absolute walking results, metabolic rate (watts and watts/m²) and heart rate, body weight is the best predictor of the increase.

For the stepping work mode, the % increase in metabolic rate was best predicted by increased clothing weight (+) and decreased torso bulk (-) as for the overall and walking work modes. Additionally increased leg bulk was positively related to an increased metabolic rate. During the stepping activity, the range of movement in the leg especially in the knee is much higher than when walking so bulkiness of the trousers will have a much larger effect on the energy cost of the activity. Body weight
was the only predictor of the stepping metabolic rate when the absolute values were considered (watts and watts/m²) and total clothing weight the only predictor of heart rate.

When the results from the obstacle course work mode are considered in isolation, the total clothing weight (+) is the best predictor of the % increase in metabolic rate. However when the absolute metabolic rate results are analysed the body weight (+) and leg stiffness (+) are the best correlates of an increased metabolic rate. The obstacle course involved a number of activities including lifting and moving crates, moving over and under wooden hurdles and crawling on hands and knees. Garments with greater material stiffness in the leg clearly made these movements harder and less efficient, as the model predicts the greater the stiffness, the greater the metabolic rate. Total clothing weight and leg bulk were also important correlates of an increased metabolic rate, they can be considered to be equally important predictors of metabolic rate but when one is included in the model the other becomes not significant and vice versa. Heart rate during the obstacle course is best predicted by total clothing weight (+) worn but also by leg bulk (+).
<table>
<thead>
<tr>
<th>Overall</th>
<th>Walking</th>
<th>Stepping</th>
<th>Obstacle Course</th>
</tr>
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<tbody>
<tr>
<td>Met Rate</td>
<td>Met Rate</td>
<td>Met Rate</td>
<td>Heart Rate</td>
</tr>
<tr>
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<td>Met Rate</td>
<td>Met Rate</td>
<td>Heart Rate</td>
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<tr>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>% Increase</th>
<th>Watts</th>
<th>Watts</th>
<th>Watts / m²</th>
<th>BPM</th>
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</thead>
<tbody>
<tr>
<td>Body Weight</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Total Clothing Weight</td>
<td>+</td>
<td>+</td>
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<td>+</td>
</tr>
<tr>
<td>Torso Bulk</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<td>+</td>
<td>+</td>
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</tr>
<tr>
<td>Leg Stiffness</td>
<td>+</td>
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</table>

Table 1. Summary table of results from multiple regression
4. CONCLUSIONS

In summary, the stepwise interactive multiple regression carried out on the data showed body weight to be the best predictor of absolute metabolic rate increases across all work modes. For the adjusted data on metabolic rate (% increase when wearing protective clothing from control) total clothing weight was the best predictor of the increase. Torso bulk was negatively correlated with the increased metabolic rate when walking, stepping and overall. Leg bulk proved to be a good predictor of an increased stepping metabolic rate and leg stiffness a good predictor of an increased metabolic rate when completing the obstacle course work mode.

This modelling was based on data from 12 protective garments and 4 categories of predictors; subject weight, total clothing weight, bulk (measured at 3 sites; arm, torso and leg) and stiffness (measured at 3 sites; arm, torso and leg). Further work on clothing weight distribution and number of layers will hopefully add to the predictive power of the model.

Acknowledgements

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REFERENCES

CARE AND MAINTANCE OF PROTECTIVE CLOTHING. THE VIEW OF TEXTILE RENTAL SERVICES

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ABSTRACT

In a context of greater regulatory complexity and fear of liability claims, professional care and maintenance of protective clothing plays an increasingly important role.

Industrial launderers need realistic manufacturers’ instructions, in particular washing temperatures which allow effective soil removal and restoration of hygiene. Protective clothing intended to be industrially laundered often requires higher physical resistance than garments laundered domestically or non-professionally.

Users need to take into consideration the complexity of proper care and maintenance. Key aspects include inspection, repair, and timely removal from service. Specialised CEN tool exists to help guide users: SUCAM – Selection, Use, Care and Maintenance guidelines for protective clothing against heat and flame, high-visibility, chemicals, and general SUCAM for all types of protective clothing.

A specialised ISO standard (ISO 15797) provides 8 reference washing procedures and 2 drying procedures to test workwear to see whether it is suitable for industrial washing.

Guidelines from laundries also exist: (1) requirements for fabrics for workwear and (2) requirements for workwear garments (accessories, design, assembly and construction). See www.etsa-europe.org
PREDICTION OF CLOTHING THERMAL INSULATION AND MOISTURE VAPOUR RESISTANCE UNDER “WALKING” MOTION AND WINDY CONDITIONS

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ABSTRACT

Clothing thermal insulation and moisture vapour resistance are two important parameters for clothing thermal comfort. These two parameters vary with body motion and environmental conditions. For functional clothing design, selection of clothing for different end uses and environmental engineering, it is important to predict these two parameters under varying body motions and environmental conditions. This paper reports on a new quasi-physical model for the prediction of the dynamic clothing thermal insulation and moisture vapor resistance under “walking” motion and windy conditions from those measured when the wearer is standing in the “still” air condition.

Keywords: thermal insulation, moisture vapour resistance, mechanisms of heat and mass transfer, prediction model, ventilation, clothing physical characteristics.

INTRODUCTION

Clothing thermal insulation and moisture vapor resistance are two most important clothing properties with respect to thermal comfort. The accurate determination of these two clothing properties is crucial to the selection of clothing for different end uses, functional clothing design and thermal environmental engineering. Although these two properties can be measured by tests on human subjects or by using sweating manikins, it is highly desirable to predict them not only because of the variability, cost and danger in using human subjects for measurements and the scarceness of sweating manikins, but also because of the fact that it is practically impossible to measure them for endless clothing ensembles under the different body motions and various environmental conditions.

A number of researchers have attempted to predict the clothing thermal insulation and moisture vapour resistance under various conditions (Spencer-Smith, 1977; McCullough, et al, 1985; McCullough, et al, 1989; Lotens and Havenith, 1991; Holmer et al, 1999; Nilsson et al 2000). Although a number of prediction models have been proposed in the literature, these models have not properly considered the effect of garment characteristics and the interaction of body motion and wind. The data used to derive the prediction models were also limited.
In this study, clothing thermal insulation and moisture vapour resistance of 32 clothing ensembles were measured using the walking-able sweating manikin-Walter (Fan and Qian, 2004) under various environmental conditions and walking speeds. Based on the experimental data and theoretical analysis, we propose a quasi-physical model.

**DESCRIPTION OF THE MODEL**

*Heat and mass transfer through clothing systems*

Considering a typical clothing system which consists of close-fitting inner garment(s) and a loose-fitting outer garment(s) as shown in Figure 1.

When a clothed person is walking in wind, the loose outer garment(s) may flap, pumping out warm air and moisture vapor from the air gap between the tight-fitting inner garment(s) and the loose-fitting outer garment(s) and replacing it by cooler air from the surrounding environment, and at the same time wind may penetrate through the outer garment(s) to create heat and mass exchange. The actual process of the heat and mass transfer through clothing system is generally very complicated. In order to simplify the analysis under steady state, the dry heat flow through clothing is considered as consisting of two parts; the part induced by conduction, convection and radiation, and the other part induced by air ventilation and wind penetration. Similarly the evaporative heat is also regarded as consisting of
two parts; the part induced by diffusion and convection and the other part induced by air ventilation and wind penetration.

As Figure 1 shows, the dry heat \( H_{dt} \) generated by human body will pass through the inner clothing system \( H_{dci} \) and then separated into two parts. The first part \( H_{dcom} \) is lost by conduction \( H_{dcon} \), convection \( H_{dc} \) and radiation \( H_{dr} \) through the outer garments, and the second part is lost by air ventilation and/or wind penetration \( H_{dv} \) directly into the environment, viz.

\[
H_{dt} = H_{dci} = H_{dcom} + H_{dv} = H_{dcon} + H_{dc} + H_{dr} + H_{dv}
\]  
(1)

Since \( H_{dcom} \) must pass through the outer garments and the outer surface of the clothing ensemble, we have

\[
H_{dcom} = H_{dco} = H_{doa}
\]

where, \( H_{dco} \) is the dry heat loss through the outer garments and \( H_{doa} \) is the dry heat loss from the outer surface of clothing ensemble.

Similarly, after passing through the inner garment(s) \( H_{eci} \), the total evaporative heat \( H_{et} \) generated by sweat evaporation will be separated into two parts: evaporative heat loss through the outer garments \( H_{ecom} \) and evaporative heat loss directly into the environment by air ventilation and/or wind penetration \( H_{ev} \), viz.

\[
H_{et} = H_{eci} = H_{ev} + H_{ecom}
\]

(3)

Since the evaporative heat loss by moisture transfer must go through the outer garments and the outer surface of the ensemble, we have

\[
H_{ecom} = H_{eco} = H_{eoa}
\]

(4)

where, \( H_{eco} \) is the evaporative or latent heat transfer through outer garments and \( H_{eoa} \) is the evaporative or latent heat loss from the outer surface of the clothing ensemble.

**The thermal insulation and moisture vapour resistance of clothing**

According to the definition of the thermal insulation of clothing, we have:

\[
H_{di} = \frac{A_s(T_s - T_a)}{I_{dyn}}
\]

(5)

where, \( T_s \) and \( T_a \) are the mean skin temperature and the environment temperature, respectively. \( A_s \) is the surface area of the human body or a manikin. \( I_{dyn} \) is the resultant total thermal insulation of the clothing system when the wearer is walking in the windy conditions;

For heat transfer through inner garments, we assume the temperature of the outer surface of the inner garments is the same as the temperature of the inner surface of the outer garments. This is
justifiable as the air movement within the inner microclimate will make the temperature difference very small. We therefore have

\[ H_{dc} = \frac{A_s(T_s - T_{ci})}{I_{ci}} \]  

where, \( T_{ci} \) is the mean temperature of the air gap in-between the inner and outer garment(s), \( I_{ci} \) is the thermal insulation of the inner garment(s).

\[ H_{doa} = \frac{A_s f_{ci} (T_{ci} - T_{co})}{I_{co}} \]  

where, \( T_{co} \) is the mean outer surface temperature of outer garments, \( f_{ci} \) is the area factors of the inner garments, \( I_{oa} \) is the thermal insulation of the outer garment(s).

\[ H_{dcom} = \frac{A_s f_{ci} (T_{ci} - T_a)}{I_{com}} \]  

where, \( f_{co} \) is the area factor of the outer garments, \( I_{oa} \) is the thermal insulation of the outer surface still air layer of the clothing system.

Assuming all dry heat loss by air ventilation and wind penetration is resulted from the exchange of warm air in-between the inner and outer garments and the cold air in the environments, we have

\[ H_{dv} = h_{dv} A_s f_{ci} (T_{ci} - T_a) \]  

where, \( h_{dv} \) is the equivalent dry heat transfer coefficient induced by ventilation and/or wind penetration.

From the above heat transfer equations, for a clothed person standing in still air, the total intrinsic thermal insulation of the clothing ensemble can be calculated by:

\[ I_c = I_{ci} + \frac{I_{co}}{f_{ci}} \]  

Let \( m \) be the fraction of the intrinsic thermal insulation of the inner garment(s) from that of the total clothing system for a clothed person standing in still air, viz

\[ m = \frac{I_{ci}}{I_c} \quad (0 \leq m \leq 1), \]
We have:

\[ I_{co} = (1 - m) f_{ci} I_c \]  

Let \( I_{mix} \) be the thermal insulation of the outer garments reduced by air ventilation and/or wind penetration, viz.

\[ H_{dv} + H_{dc} = \frac{A_s f_{ci} (T_{ci} - T_a)}{I_{mix}} \]  

From Equation (9), (10) and (14), we can have

\[ \frac{1}{I_{mix}} = h_{dv} + \frac{1}{I_{com}} \]  

From Equation (2), (7), (8) and (9), we have

\[ I_{com} = I_{co} + \frac{f_{ci}}{f_{co}} I_{oa} \]  

From Equation (1), (5), (6) and (14) we have

\[ I_{dyn} = I_{ci} + \frac{I_{mix}}{f_{ci}} \]  

The total thermal insulation of the clothing system can therefore be calculated by

\[ I_{dyn} = I_{ci} + \frac{I_{mix}}{f_{ci}} = mI_c + \frac{1}{f_{ci} h_{dv}} + \frac{1}{(1 - m) I_c + \frac{1}{f_{co} I_{oa}}} \]  

Similarly, we can have the following equations for calculating the moisture vapor resistance:

\[ R_e = R_{ci} + \frac{R_{co}}{f_{ci}} \]  

Let \( n \) be the fraction of the intrinsic moisture vapor resistance of inner garment(s) from that of the total clothing system for a clothed person standing in still air, viz.

\[ n = \frac{R_{ci}}{R_e} \quad (0 \leq n \leq 1) \]
Then:
\[ R_{ev} = (1 - n)f_{ci} R_c \] (21)
\[ R_{tdyn} = nR_c + \frac{R_{mix}}{f_{ci}} \]
\[ = nR_c + \frac{1}{f_{ci} h_{ev}} + \frac{1}{1 - n} R_c + \frac{1}{f_{co} R_{oa}} \] (22)
\[ \text{where, } R_t \text{ is the total moisture vapor resistance of clothing ensemble system in p.m}^2/W; R_{ci}, R_{co} \text{ and } R_{oa} \text{ are } \text{the moisture vapor resistance of the inner garment(s), outer garment(s) and the outer surface still air layer of the clothing system, respectively. } h_{ev} \text{ is the equivalent latent heat transfer coefficient induced by ventilation.} \]

Let:
\[ h_{dev} = h_{de}, f_{ci} \] (23)
\[ h_{eev} = h_{ev}, f_{ci} \] (24)

\[ h_{dev} \text{ and } h_{eev} \text{ are defined as the effective dry heat and latent heat transfer coefficient by air ventilation and/or wind penetration, respectively. We have:} \]
\[ I_{tdyn} = mI_c + \frac{1}{h_{dev}} + \frac{1}{1 - m} I_c + \frac{1}{f_{co} R_{oa}} \] (25)
\[ R_{tdyn} = nR_c + \frac{1}{h_{eev}} + \frac{1}{1 - n} R_c + \frac{1}{f_{co} R_{oa}} \] (26)

Based on analyzing the past and our own experimental data (Qian 2005), it is clear that dry and latent heat transfer by ventilation and air penetration are linearly related to the windy velocity and walking speed. We thus propose the following empirical equation to predict heat and mass transfer coefficients by air ventilation and wind penetration for a clothed person walking under windy conditions:
\[ h_{dev} = KVI(V_{wind} + \beta_V V_{walk} - v_0) \] (27)
\[ h_{eev} = KVR(V_{wind} + \beta_V V_{walk} - v_0) \] (28)
\[ v_f = V_{wind} + \beta_V V_{walk} - v_0 \] (29)
where, $KVI$ and $KVR$ are constants, which depend on garment(s) fitting, styles of design and construction of the clothing ensembles. $v_r$ is an equivalent wind velocity taking into account the effect of walking speed, $\beta$ is an equivalent factor of walking speed on wind velocity. $v_0$ is the air current in the “still air” condition. (In any climate chamber, even at “still air” condition, there is air current. This is essential for the operation of air conditioning system in the chamber). By definition, at the “still air” condition, there is no air exchange by wind and walking motion, viz. $h_{dev}=h_{rev}=0$.

For the model described by Equation (25) and (26), there are four extreme cases as follows:

1. A clothed person standing in still air. Due to no ventilation, the inner and outer garments can be considered as a whole, thus, $V_{wind}=0$, $V_{walk}=0$, $m=1$, $n=1$. Equation (25) and (26) can be re-written as the well known form:

\[
I_{tdyn} = I_c + \frac{I_{oa}}{f_{co}}
\]

\[
R_{tdyn} = R_c + \frac{R_{oa}}{f_{co}}
\]

2. A nude person. In this case, $I_c=0$, $m=0$, $n=0$, $KVI=KVR=0$, hence:

\[
I_{tdyn} = I_{oa}
\]

\[
R_{tdyn} = R_{oa}
\]

3. No inner garment(s). In this case, $m=0$ and $n=0$, $f_{ci}=1$ and $I_{oa}=I_c$, hence:

\[
I_{tdyn} = \frac{1}{KVI(V_{wind} + \beta v_r V_{walk} - v_0) + \frac{1}{I_c} + \frac{1}{I_{oa}}}
\]

\[
R_{tdyn} = \frac{1}{KVR(V_{wind} + \beta v_r V_{walk} - v_0) + \frac{1}{R_c} + \frac{1}{R_{oa}}}
\]

4. No outer garment(s), viz. the inner garment(s) is tightly fit to the body and impenetrable to air (Otherwise, the garment(s) will be considered as the outer garment(s)). In this case, $I_{oa}=0$, $I_c=I_{ci}$, $m=1$, $n=1$, hence:

\[
I_{tdyn} = I_{ci} + \frac{I_{oa}}{f_{ci}}
\]

\[
R_{tdyn} = R_{ci} + \frac{R_{oa}}{f_{ci}}
\]
Thermal insulation and moisture vapor resistance of the outer surface of the clothing ensembles (Ioa and Roa): 

With results of our previous study (Qian and Fan, 2006), the heat loss through the outer surface air layer of clothing ensembles is transferred by convection and radiation. The surface insulation can be estimated using the following equation:

\[ I_{oa} = \frac{1}{h_r + h_c} \]  

(38)

where, \( h_r \) is the radiative heat transfer coefficient (\( h_r = 5 \text{ W/m}^2\text{K} \)) and \( h_c \) is the convective heat transfer coefficient.

Since the convective heat loss varies with body activity level and the wind velocity, the following equations were proposed to calculate \( I_{oa} \):

For a clothed person walking in wind, we have:

\[ I_{oa} = \frac{1}{5 + 8.3\sqrt{0.11 + 0.45V_{walk} + V_{wind}}} \]  

(39)

According to Lewis relation, the surface moisture vapour resistance, \( R_{oa} \), can be obtained by:

\[ R_{oa} = \frac{1}{0.0165 \times 8.3\sqrt{0.11 + 0.45V_{walk} + V_{wind}}} \]  

(40)

Intrinsic parameters of clothing in the model (Ic, Rc, Ici, Rci, fco, fci, m, n):

\( I_{ci}, R_{ci}, I_c, R_c \) are defined as the intrinsic thermal insulation and moisture vapor resistance of the inner garment(s), and the entire clothing ensemble, respectively. They can be calculated from the total thermal insulation or moisture vapour resistance of inner garment tested alone in standing and “still” air condition, and the total thermal insulation and moisture vapour resistance of the entire clothing ensemble tested in standing and “still air” condition, viz.

\[ I_{ci} = I_{cit} - \frac{I_{oai}}{f_{ci}} \]  

(41)

where, \( I_{cit} \) is the total thermal insulation of the inner garments tested alone on a standing manikin in “still air”, \( I_{oai} \) is the surface thermal insulation of the inner garments when tested alone on a standing manikin in “still air”, \( f_{ci} \) is the clothing area factor of the inner garment(s) when tested alone, and

\[ I_c = I_t - \frac{I_{oat}}{f_{co}} \]  

(42)

where, \( I_t \) is the total thermal insulation of the entire clothing ensemble tested on a standing manikin in “still air”, \( I_{oat} \) is the surface thermal insulation of the entire clothing ensembles tested on a standing manikin in “still air”, \( f_{co} \) is the clothing area factor of the outer surface of the clothing ensemble.

\( f_{ci} \) and \( f_{co} \) can be estimated from the insulation value(McCullough et al 1985 and ISO 7933), viz.

\[ f_{ci} = 1 + 1.97 I_{ci} \]  

(43)
Solving Equations (45) and (47) simultaneously, we have

\[ f_{ci} = \frac{1 + 1.97I_{cit} + \sqrt{(1 + 1.97I_{cit})^2 - 7.88I_{oai}}}{2} \]  \hspace{1cm} (44)

Similarly, we have:

\[ f_{co} = \frac{1 + 1.97I_{c} + \sqrt{(1 + 1.97I_{c})^2 - 7.88I_{oat}}}{2} \]  \hspace{1cm} (45)

We can also calculate \( R_{ci} \) and \( R_c \) in the similar way, viz.

\[ R_{ci} = R_{cit} - \frac{R_{oai}}{f_{ci}} \]  \hspace{1cm} (46)

where, \( R_{cit} \) is the total moisture vapour resistance of the inner garments tested alone on a standing manikin in “still air”, \( R_{oai} \) is the surface moisture vapour resistance of the inner garments tested alone on a standing manikin in “still air”,

\[ R_c = R_t - \frac{R_{oat}}{f_{co}} \]  \hspace{1cm} (47)

where, \( R_t \) is the total moisture vapour resistance of the entire clothing ensemble tested on a standing manikin in “still air”, \( R_{oat} \) is the surface moisture vapour resistance of the entire clothing ensembles tested on a standing manikin in “still air”.

With \( I_{ci}, I_c, R_{ci} \) and \( R_c \), the values of \( m \) and \( n \) can be determined according the equations of (12) and (20).

**DETERMINATION OF KVI, KVR AND \( \beta_V \)**

With the experimental data of the thermal insulation and moisture vapour resistances of 32 clothing ensembles tested on the sweating fabric manikin-Walter under different windy conditions and “walking” speeds, the value of \( \beta_V \) can be obtained by regression analysis. We found:

\[ \beta_V = 2.0 \quad (R^2 = 0.95) \]  \hspace{1cm} (48)

With \( \beta_V \), we can then plot the effective dry heat and latent heat transfer coefficients \( h_{dev} \) and \( h_{ev} \) against the equivalent wind velocity \( v_e \) as shown in Figures 2 and 3:
The slopes in Fig. 2 and 3 are the values of $KVI$ and $KVR$. We can see from Fig. 2 and 3, although $KVI$ and $KVR$ are different for different clothing ensembles, they are within a confined range. We also observed that the values of $KVI$ and $KVR$ for clothing ensembles with underwear are very different from those without underwear. The average values of $KVI$ and $KVR$ for clothing ensembles with underwear are 1.72 and 0.0111, respectively. The average values of $KVI$ and $KVR$ for clothing ensembles without underwear are 0.88 and 0.0076, respectively.
THE EVALUATION OF PREDICTION MODEL

Using the average values of $KVI$ and $KVR$ for clothing ensembles with and without underwear, clothing thermal insulation and moisture vapour resistance under windy conditions and walking motion can be predicted by Equations (25) and (26) from those measured when the manikin is standing in “still” air condition. Figures 4 (a) and (b) plot the predicted clothing thermal insulation and moisture vapour resistance against the measured values, respectively.

### Figure 4 (a) Measured thermal insulation vs. predicted values using the quasi-physical model

### Figure 4 (b) Measured moisture vapour resistance vs. predicted values using the quasi-physical model
As can be seen, the model can fit the measured data very well with a correlation coefficient of fit \( R^2 \) of 0.96.

**CONCLUSIONS**

In this paper, a new prediction model has been derived based on the fundamental heat and mass transfer mechanisms, which involve conduction, radiation and natural convection, water evaporation and air ventilation. The model predicts the total thermal insulation and moisture vapour resistance of clothing under body movement and windy conditions from the values of the intrinsic clothing thermal insulation and moisture vapour resistance measured when the body is standing in the still air. Garment design and material properties are taken into account through the parameters of the model \((KVI \text{ and } KVR)\). Very good agreement was found between the predicted values and experimental measurements from the sweating manikin – Walter.

**REFERENCES**

ABSTRACT

PPE specifiers rely on the current standards and regulations in order to define their individual requirements after having gone through a specific risk analysis.

The procured PPE then has to fulfill those requirements during its whole wearlife and needs – as of the European Directives for PPE – to be checked for sustained appropriate performance over time.

The paper will use commonly and less commonly known examples to show the difficulty for a specifier to ensure sustained performance of PPE during its useful life.

Also trends will be discussed how performance levels of different PPE may vary over time due to decosting efforts and better knowledge of producers to not overspecify their designs in markets highly regulated though standard and norms.

The paper will conclude with recent examples of regulation changes to better ensuring sustained PPE performance levels and will reflect on responses of notified CE certification bodies to "unregulated" issues.
ASSESSMENT OF PPE ENSEMBLE COMPATIBILITY: THERMO-PHYSIOLOGICAL METHODOLOGY FOR ASSESSMENT OF FIREFIGHTER PPE ACCORDING TO DRAFT BS 8469

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ABSTRACT

Single items of PPE are rarely used in isolation and are combined into protective ensembles, which may impose significant burdens on the user. A draft British Standard is in preparation to assess complete ensembles of firefighters’ PPE for their effects on wearer performance. This paper examines the draft method for comparing the thermo-physiological stress imposed by such ensembles.

1. INTRODUCTION

The aim of Draft BS 8469\(^{(1)}\) is to define a series of ergonomic and physiological test criteria against which the performance of firefighter ensembles can be evaluated and objectively assessed, either to compare different ensembles, or against predetermined performance limits. When testing to this standard it is important that the whole ensemble from the skin to the outer clothing and ancillary equipments is included.

Table 1 gives a comparison of the requirements of testing to Draft BS 8469 and the experimental conditions and protocol followed in the experiments reported in this paper.

2. METHODOLOGY

2.1. OVERVIEW

A group of volunteers exercised in a thermal chamber wearing in-service firefighting clothing in a controlled environment of 40°C dry bulb and 50% relative humidity for a maximum of 30 min. Each subject wore two ensembles A and B. The time of entry to the chamber was also controlled so that the subjects repeated the experiment at the same time of day on each occasion.
2.2. SUBJECTS

Five fit serving firefighters (four male and one female) volunteered to take part in the studies. The anthropometric details were as follows: mean age 34.8 (+5.4) years, weight 87.0 (+12.6) kg, and height 1.78 (+0.05) m. The subjects were medically screened pre-exposure with a questionnaire based on ISO 12894(2). The experiment was cleared by the HSE Ethics Committee.

<table>
<thead>
<tr>
<th>Test/measurement</th>
<th>Draft BS 8469</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test ensemble</td>
<td>New items to be tested All clothing layers to be worn Ancillary items to be worn e.g. respiratory protection</td>
<td>Due to availability not all clothing tested was new Ancillary items such as breathing apparatus were worn</td>
</tr>
<tr>
<td>Test subjects</td>
<td>6 or more subjects Serving firefighters</td>
<td>5 subjects Serving firefighters</td>
</tr>
<tr>
<td>Statistical testing</td>
<td>For comparative testing either non-parametric sign test or paired t-test</td>
<td>Too few subjects for comparative statistics</td>
</tr>
<tr>
<td>Physiological monitoring</td>
<td>Core temperature measured, with final deep body temperature used for statistical analysis Withdrawal of 38.5 °C</td>
<td>Deep body temperature measured with withdrawal of 38.5 °C. Other measures taken: Skin temperature Heart rate Sweat loss Sweat accumulation in layers of clothing Body heat storage</td>
</tr>
<tr>
<td>Climate1</td>
<td>Ambient: 22 (+1) °C humidity 70 (+5)% Elevated: 40 (+1) °C humidity 50 (+5)%</td>
<td>Elevated only: 40 (+0.2) °C humidity 50 (+1.5)%</td>
</tr>
<tr>
<td>Workload</td>
<td>5 km/hour on level motorised treadmill 30 min or until withdrawal criteria reached – core temperature, gas cylinder, voluntary withdrawal</td>
<td>5 km/hour on level motorised treadmill 30 min or until withdrawal criteria reached – deep body temperature, gas cylinder, voluntary withdrawal</td>
</tr>
</tbody>
</table>

Table 1. Draft BS 8469 test requirements and the experimental conditions used in this study

2.3. ENVIRONMENTAL CONDITIONS

All the experiments were conducted in HSL’s climatic chamber. The dry bulb temperature was 40 (+0.2)°C, with a relative humidity of 50 (+1.5)%. The air speed was minimal (<0.15 m/s). Globe temperature equalled dry bulb temperature.

2.4. EXERCISE

The subjects walked for a maximum of 30 min at 5 km/hour at 0% incline.

2.5. CLOTHING WORN

The subjects wore in-service EN 469(3) firefighting clothing over their day/station wear. The EN 469 clothing worn by the subjects was manufactured by different companies and was therefore tailored and

---

1 Note: Climate and workload listed here are for the climatic chamber assessment option in draft BS 8469 only, and not for the simulation options for climate and workload.
designed differently. The polyester/cotton mixes of the day/station wear also varied between subjects, but was constant for each subject between tests. The total dry weight of the clothing (without breathing apparatus, BA) was 7.58 (+0.54)kg for Ensemble A and 7.59 (+0.47)kg for Ensemble B.

The subjects dressed in the following clothing: underwear and socks, day/station wear, EN 569(4) firefighting gloves, helmet, boots, firehood, BA together with either type A or B tunic and trousers. Type A was the subject’s own in-service PPE (worn state, all same manufacturer and design) and type B was new PPE (all same manufacturer and design). Both designs had a moisture vapour permeable layer within the clothing construction.

2.6. PHYSIOLOGICAL MEASUREMENTS

Deep body temperature was measured with a thermistor placed in the external auditory meatus, with the outer ear well insulated with cotton wool held in place with tape and the in-service firehood. Skin temperature was recorded at 4 sites (chest, arm, calf, and thigh) from which mean skin temperature was calculated(5). Body heat storage(6) was calculated by the method stated in Draft EN 469 Annex F(7). Heart rate was monitored for safety reasons using sports heart rate monitors and is not reported here. Produced sweat was measured by weighing the subjects semi-nude pre- and post-climatic chamber exposure. The different layers of clothing were weighed to give an indication of where the sweat had accumulated within the ensemble. Tolerance times were also recorded (withdrawal criteria reached, air supply exhausted, and voluntary withdrawal).

3. RESULTS

3.1. TOLERANCE TIMES

Table 2 gives the reasons for withdrawal and tolerance times for all subjects.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Ensemble A</th>
<th></th>
<th>Ensemble B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerance time (min)</td>
<td>Reason</td>
<td>Tolerance time (min)</td>
<td>Reason</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>Time limit reached</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>Temperature limit reached</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>Time limit reached</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>Low breathing air</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>Time limit reached</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2. Individual tolerance times for subjects wearing the two ensembles.
3.2. DEEP BODY TEMPERATURE

Figure 1. Mean subject aural temperature (n=5) while wearing Ensemble A and Ensemble B.

Figure 1 shows the different starting temperatures and final aural temperatures of the two groups of subjects wearing the two types of ensembles. The final aural temperatures (at 25 min - first subject withdrawal and 30 min - final mean) are given in Table 3.

<table>
<thead>
<tr>
<th>Ensemble</th>
<th>Aural temperature °C</th>
<th>Experimental time (min)</th>
<th>Aural temperature °C</th>
<th>Experimental time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>A</td>
<td>37.95</td>
<td>0.36</td>
<td>25</td>
<td>38.15</td>
</tr>
<tr>
<td>B</td>
<td>37.54</td>
<td>0.29</td>
<td>25</td>
<td>38.03</td>
</tr>
</tbody>
</table>

Table 3. Final aural temperatures for subjects wearing the two ensembles
3.3. MEAN SKIN TEMPERATURE

Figure 2. Mean subject skin temperature (n=5) while wearing Ensemble A and Ensemble B.

Figure 2 shows the mean 4-point mean skin temperatures of the two groups of subjects wearing the two types of ensembles. The final skin temperatures (at 25 min - first subject withdrawal and 30 min - final mean) are given in Table 4.

<table>
<thead>
<tr>
<th>Ensemble</th>
<th>Mean skin temperature °C</th>
<th>Experimental time</th>
<th>Mean skin temperature °C</th>
<th>Experimental time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Min</td>
<td>Mean</td>
</tr>
<tr>
<td>A</td>
<td>37.92</td>
<td>0.30</td>
<td>25</td>
<td>38.00</td>
</tr>
<tr>
<td>B</td>
<td>37.79</td>
<td>0.35</td>
<td>25</td>
<td>38.04</td>
</tr>
</tbody>
</table>

Table 4. Final mean skin temperatures for subjects wearing the two ensembles.

3.4. SWEAT

Subjects wearing Ensemble A produced a total of 1.12 (±0.13)kg of sweat, and those in Ensemble B 1.03 (±0.19)kg. Table 5 details where produced sweat accumulated within the ensemble.

<table>
<thead>
<tr>
<th>Clothing layer</th>
<th>Ensemble A</th>
<th>Ensemble B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount within layers accumulated during the 30 min exposure</td>
<td>Mean kg</td>
<td>SD</td>
</tr>
<tr>
<td>Total ensemble</td>
<td>1.12</td>
<td>0.13</td>
</tr>
<tr>
<td>Day/station wear</td>
<td>0.80</td>
<td>0.20</td>
</tr>
<tr>
<td>Tunic and trousers (PPE layer)</td>
<td>0.11</td>
<td>0.03</td>
</tr>
<tr>
<td>Boots</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>Firehood, gloves and helmet</td>
<td>0.12</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 5. Sweat accumulation in the ensemble components
3.5. BODY HEAT STORAGE

Subjects wearing Ensemble A had a mean body heat storage increase of 7.38 (±1.11)J/g, and those in Ensemble B 7.91 (±1.03)J/g.

4. DISCUSSION

Draft BS 8469 gives the key criterion for comparative testing of different firefighter ensembles as the final deep body temperature. The results presented in this paper show that, though the clothing is very similar, the final aural temperatures (at 25min) are different (Ensemble A: 37.95 (±0.36)°C, Ensemble B: 37.54 (±0.29)°C), due to the lower starting aural temperature of the subjects wearing Ensemble B. The rates of rise of aural temperature are however very similar which suggests that using final deep body temperature, as the only criterion to compare ensembles could be misleading. The other physiological measures also reinforce that there is little difference between the two ensembles as mean skin temperatures, sweat loss and body heat storage are also similar.

5. RECOMMENDATIONS

These data suggest that other measures should be used to compare ensembles such as: rate of rise of deep body temperature, rate of rise of mean skin temperature, body heat storage increase, sweat rates and accumulation of sweat in clothing layers, rather than final deep body temperature alone.

The levels of heat strain of the subjects are high – as shown by the levels of sweat produced, the elevated deep body temperature reached in a short time frame, and also the high rates of rise of deep body temperature. This high level of strain caused by the clothing and conditions may mask any small effects that differences in the ensembles may have on the physiological responses of the subjects. Therefore it is also recommended that the use of lower ambient dry bulb temperatures, relative humidity or work rate be investigated, thereby reducing the heat strain and maximising the opportunity of discriminating any differences between ensembles.

6. REFERENCES

1. Draft BS 8469 Personal protective equipment for fire-fighters – Assessment of ergonomic performance and compatibility – requirements and test methods. DPC 05/30118212 DC, BSI.

A MANUFACTURER'S REPORT ABOUT TESTING OF GASTIGHT CHEMICAL PROTECTION SUITS

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ABSTRACT
As a supplier and manufacturer for approved PPE we are heavy involved in special customer requests about functions and capabilities the products are not approved for- or approved but not tested for. This seems to be an antagonism, but it is the reality. For example CPS ace. EN 943-2 or NFPA 1991:2000 are permeation tested against 15 or 21 different classes of chemicals, but the chemical industry knows more than 450000 standard chemicals where most of them are harmful, toxic or hazardous. Very often it is impossible to transfuse the standard testings results to other chemicals.
And not even the chemical itself could be critical, its also possible that their conditions are critical (hot, cold, liquid, gaseous). This presentation is a short introduction in testings we were asked for by CPS customers over the last two years. The testings includes ClF3, cold liquid ammonia, Fluor, cold liquid Chlorine and standard works at -40°C and behavior of CPS in a burning test house.

1. INTRODUCTION
Due to the experiences our company made over the last twenty years as a manufacturer and supplier of reusable gastight chemical protective clothing, we dare say that it is easy to design and assemble a reusable suit that meets the standards esp. EN 943-1 or that meets higher specifications according to EN 943-2.
A much higher obstacle to take is to fit to the customer’s specifications. Due to this fact, support does not end with the suit’s approval, or the delivery to the customer. Very often it is necessary to provide the customer with special information, accessories or approvals which surpass the typical approvals.
Usually a customer specifies the standard the suit should meet and the customized demands he has. Especially when he uses reusable suits, he does not always know from the very beginning which chemical accidents or working situations will occur during the suit's lifetime. Therefore it is possible that he needs additional support from the manufacturer.
2. SUIT HISTORY AT DRAEGER

Almost 10 years ago Draeger launched the TeamMaster pro suit. This is a “Type 1a” or “Level A” protection suit that covers the complete user including his “tools” the breathing apparatus, full face mask and helmet. The Material is called HIMEX®; it is a special elastomer-coated fabric with an internal gastight barrier film.

We provided the TeamMaster pro in a blue colour and in two sizes, with two different boot sizes, one type of gloves, with or without antifog visor, or with or without suit ventilation. So we offered 16 different versions, which especially satisfied the needs of the German fire brigades. At that time ventilation units were not permitted and suits were ordered only in the biggest available size due to “vfdb2” regulations.

After only a few years time we were successful with this type of suit, but several times we missed the customer specifications due to the few variances in our product range and not due to pricing.

What were these customer specifications? And why didn’t we meet those right from the start of the approval process? The simple answer: “Every variation has to be approved by the official approval authority, and this means initial costs. And as long as we don’t know, if the product will be a success we have to keep the costs on an acceptable level. But first of all we have to listen to the market to learn what has already been accepted and what needs to be improved.”

Today, we offer an improved model of these suits as TeamMaster pro ET in 28,800 different versions (and these are only the ET approved versions in accordance with EN 943-2). If we would additionally count the versions of this range that only meet the lower standard we would end up with more than 150,000 different variants.

2.1. What has changed, since market launch?

- One simple thing to name is that we do no longer offer suits in Germany only, but almost world-wide except for the NAFTA region.
- Due to this fact the body sizes of the potential users are not only men from heights of 176 cm to 190 cm, but women and men from heights of 1,56 to 2,05 cm with boot sizes from 37-50 (French stitches).
- Blue is a very good company identity colour, but for example if you are working on a vessel in a blue CPS and you slip on deck and fall into the water no one will be able to see you, therefore we offer the suits in 4 different colours today (blue, orange, oliv and beige).
- We can only approve Draeger BA sets in combination with our suits. But we also support users who work with competitor's devices with e.g. enlarged backpack or sleeves for bigger BA sets than ours. Therefor we had approved wider suits, than the standard sizes.
We are able to test suits on the resistance to special chemical substances that are not covered by the standards, e.g. if a customer needs information, if the suit is resistant to ClF₃, cold Liquid Ammonia, cold liquid Chlorine, or chemical mixtures we can provide it. Additional accessories were not part of the initial approval; therefore we had no adapter for security or guiding lines or for distress safety units on the outside of the suits at the time of the initial approval. Customers increasingly ask for special adjustable ventilation units to dehumidify their suits or they ask for devices to cool down the suit's inside.

Customers are looking for suits that can be worn in cold environments. Customers ask for pockets or loops to fix their push to talk button from their voice radio. Customers are looking for suits with integrated gastight socks that do not influence the suit's ergonomics. Customers are looking for tight suits to enter manholes on a ship. Customers are looking for taller suits for persons up to a height of 215 cm. Customers are looking for suits that fit for persons of 150-160 cm body height. Customers ask for suits approved according to the latest European Standards. Customers are looking for possibilities to clean suits in industrial washing machine without loss of chemical and physical performance.....

Enclosed please find a report about one of the most interesting tests we performed in 2004.

3. **COULD HIMEX® SUITS BE USED FOR CLF₃ INCIDENTS?**

3.1. **ClF₃ CAS 7790-91-2,** Molecular weight: 92,45 g/mol, gaseous, colourless to light yellow at room temperatures. The substance itself does not burn, but in contact with combustible substances it increases the risk of fire. Especially with rubber compounds it reacts in a very destructive way.

3.2. Pre-test of burning behaviour, if this test was passed subsequent testing according to EN 6529

3.3. Testing Institute “University of Dortmund” in Germany

3.4. Components to test:
   - Suit material (HIMEX®)
   - Sieve printed suit material
   - PVC boot material
   - Viton® gloves
   - PVC visor
   - alternative suit material Viton®/Butyl
   - alternative suit material (Laminate)
   - Suit barrier material PVF
   - NBR boot material
   - Butyl glove material
   - Hydal® boot material
3.5. Pre-test Chamber\(^1\) out of 1.4571 and Kel-F\(^\circledast\)

![Diagram of pre-test chamber with labels: ClF\(_3\) inlet, Vacuum, Reaction chamber, Kel-F\(^\circledast\), Sample.]

3.6. Permeation Chamber\(^2\)


Material stainless steel 1.4571

3.7. Visual material results

![Visual material results with images labeled 1 and 2.]
1. HIMEX®
2. PVC boot material
3. PVC visor
4. Barrier PVF
5. FKM glove material
6. Screen-printed HIMEX®

3.8. Pre-Test Results

During pre-tests small material samples were tested in a test chamber (see 3.5). Materials that showed heavy reactions on the test gas, were excluded from the following permeation tests.

These materials were Butyl glove material, NR- boot material, CRNR mixtures, loop and hook fixings.

3.9. Permeation Results

Samples 1, 2, 3, 5 and 6 had a permeation period of more than 8 hours without any breakthrough. Sample 4, the PVF film alone has a breakthrough time of only 0-11 minutes. The alternative materials Viton®/Butyl, laminate, Hypalon boots and the NBR had a breakthrough time of less than 100 minutes or showed heavy degradation or burning during pre-tests with the test gas. The degradation was too high and would in case of use cause distrust in the material by the user. The best materials are highly chlorinated or fluorinated compounds. Hardened PVC is better than softened PVC. Laminates cannot be used at all.
4. CONCLUSIONS

As a result of these tests, we decided to use HIMEX® for the suits and to substitute all natural rubber compounds or all blends with high contents of natural rubber. Parts whose materials cannot be substituted will be covered by HIMEX® flaps or covers (valves; Viton zipper). The standard approved NBR boots were changed against PVC boots in accordance with EN 345-2. Gloves have to be made of pure Viton elastomer with PVC over gloves. Velcro hook and loop tapes have to be replaced by metal snap fasteners. The suit must have a “Type 1 a” approval in accordance with EN 943-1. Suits with an outer mask or with a BA worn on the outside cannot be used when handling this chemical substance. Because of all these changes the complete customized suit had to be recertified with an official approval authority.

1 Draeger Review No 78; February 1997
2 vfdb 08/01:1999-01; vfdb 08/02:2002-11
3,4 CLF₃ Material Test Report for Draeger Safety by Dr. A Kornath University Dortmund
ABSTRACT

For more than 25 years, DuPont Personal Protection (DPP) is active in the fire fighter market with NOMEX® and KEVLAR® fibres. So, DPP is in direct contact with many fire fighters in most European countries and has gained many years of field experience.

Over the years, the range of tasks of the fire fighters in Europe has increased steadily. In addition to traditional fire fighting, their duties now include activities around car accidents, flooding, rescue, etc. And their equipment should protect them not only against heat and flame – the main risk in this job –, but also against the hazards related to their additional activities. The list of requirements for PPE has been enlarged and includes heat and flame protection, moisture barrier, foul weather protection, chemical protection, higher visibility.

As it has been recognised that lack of comfort can also result in heat stress and so represent a danger to the fire fighters, modern PPE requests furthermore aspects like wear comfort, moisture management, ergonomics and aesthetics as well as economics.

For all these technical requirements, norms and standards have been created and adequate testing infrastructure developed. However, there are only very few testing facilities that allow assessing PPE in garment form meeting the whole spectrum of requirements. Therefore, the presentation will deal with mannequin testing like SAM and DuPont Thermo-Man®.

The examples discussed will show that holistic solutions have to be a balance between heat protection, comfort/ergonomics and value-in-use. Modular/layered systems and their impact on comfort will be shown. Other novelties regarding innovative fabrics will be presented.
REFERENCE MATERIALS FOR TEST METHOD OF RESISTANCE TO RADIANT HEAT PENETRATION

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Department of Personal Protective Equipment
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ABSTRACT

The paper presents the results of preliminary studies aimed at selection of appropriate reference materials designed for testing resistance of clothing fabrics to the effects of radiant heat according to EN ISO 6942. Taking into consideration the properties that should characterise the reference material and specific features of the analysed research method, in particular the type and mode of exposure to the thermal factor and the resultant classification of the protective parameters defined in the applicable standards, the requirements for the reference materials were established.

Acid-resistant steel plates, characterised by thermal stability, which, after bending, could be shaped to fit the calorimeter surface, were selected for the study. The level of heat permeation was regulated by adjusting the number of openings in the plates. The tests were also carried out on samples of special purpose fabrics including glass fibre materials, glass fibre materials covered with aluminium foil and vermiculite, as well as ceramic and fireproof cotton fabrics. Depending on the intended function of protective clothing, the exposure of the tested material samples to heat was differentiated: 20 KW/m² for protective clothing designed for industrial workers and 40 KW/m² for protective clothing designed for firemen.

On the basis of the completed preliminary studies, it was concluded that the following materials seem to be the most appropriate as reference materials for testing resistance of clothing fabrics to permeation by radiant heat: steel plates with openings and glass fibre fabrics covered with vermiculite or aluminium foil.

The next phase of the research works will involve further testing in order to determine the repeatability of measurements carried out with the use of the selected reference materials.

1. INTRODUCTION

The variety of thermal factors and differentiation of their effects at worksites in metallurgy, iron works and fire fighting may be a problem when appropriate protective clothing is to be selected. The protective properties of clothing are tested according to methods addressing the particular type of exposure to thermal factors, e.g. resistance to radiant heat, convective heat, contact heat, large and
small molten metal splashes. In order to facilitate the selection of protective clothing, the currently revised standards specifying requirements concerning the particular parameters characterizing the protective properties of clothing against thermal factors present them divided into some classes, or levels, or protection. Reference materials provide help in classification of clothing fabrics into particular classes of protection. Reference materials should be characterized by constant, unchanged properties with respect to protection and performance under actual conditions of use. Moreover, reference materials should correspond to different levels of protection. In view of the above, a research project aimed at development of reference materials for the method of testing protective clothing for resistance to thermal radiation was initiated in the Central Institute for Labor Protection – National Research Institute. The reference materials have been adjusted to different classes of protection and will allow to obtain reproducible test results in various laboratories. They will be used for checking appropriate performance of the test stands [1].

2. METHODOLOGY

2.1. METHOD OF TESTING MATERIAL RESISTANCE TO RADIANT HEAT AND CLASSIFICATION OF MATERIALS

The resistance of protective clothing materials to radiant heat is currently determined according to PN-EN ISO 6942:2005 [2] (which has replaced PN-EN 366:1995 [3]) and is cited as the testing method in the latest regulations presenting requirements for protective clothing.

The testing procedure involves exposure of the tested material sample to a stream of thermal radiation of particular intensity (20 or 40 KW/m²). The time of temperature increase in a copper calorimeter located behind the sample and remaining in direct contact with it by 12 and 24 °C is recorded. The calorimeter applied in this method is made of copper, rectangular in shape, with the longer side of the rectangle arched, which allows good contact between the front of the calorimeter and the material sample.

The result of the test is expressed as the levels of radiant heat transfer RHTI 24 (time of calorimeter temperature increase by 24 °C, in seconds) and RHTI 12 (time of calorimeter temperature increase by 12 °C, in seconds).

The classification of materials consistent with heat transfer levels according to the method described for protective clothing designed for industrial workers exposed to thermal factors is presented in pr EN ISO 11612:2004, with respect to protective clothing for fire fighters in EN 469:2005, with respect to protective clothing for fire fighters for entering the areas on fire in pr EN 1486:2003.

2.2. REQUIREMENTS FOR REFERENCE MATERIALS

Considering the general properties which should characterize a reference material and the specific features of the analyzed testing method, and in particular the type of thermal factor and exposure to it, as well as classification of the protective parameters presented in applicable standards, the requirements for reference materials for the method of testing material resistance to radiant heat have been elaborated.
The general requirements for reference materials concern:

- material durability during storage,
- preservation of material properties and stability of its structure at the same protection level during the test (for multiple use pattern),
- resistance to effects of high temperature,
- stable, reproducible quality of the material,
- easy identifiability,
- common availability.

The special requirements for reference material are associated with the testing method and concern:

- mode of exposure of the reference material to heat radiation,
- density of the heat stream directed to the material,
- method of mounting of material sample in the measuring device,
- representation of a particular protection level.

Considering the requirements presented in tables 1-3 it was assumed that the reference materials for the method of determination of resistance to heat penetration under exposure to radiant heat according to PN-EN ISO 6942:2005 [2] should comply with the following requirements with respect to heat transfer level:

\[
\begin{align*}
\text{for heat stream density } & 20 \text{ KW/m}^2: \\
10 \leq \text{RHTI}_{24} < 20 \text{s}, & 20 \leq \text{RHTI}_{24} < 50 \text{s} \\
\text{for heat stream density } & 40 \text{ KW/m}^2: \\
10 \leq \text{RHTI}_{24} < 18 \text{s}
\end{align*}
\]

Because of the specificity of the method of testing material resistance to radiant heat, reference materials should have a surface making possible contact with the curved surface of the copper calorimeter used in the test.

2.3. MATERIALS USED IN TESTS

Considering the presented objectives, acid-resistant steel plates and specialist textiles were selected for testing. The selected materials were characterized by thermal stability and the possibility of adjustment to the calorimeter surface. The level and quantity of penetrating heat was regulated with the size and number of openings in the plates. The tests utilized also specialist fabrics, including glass fiber fabrics coated with aluminium foil and covered with vermiculite, ceramic fabrics and cotton fabrics with fire-resistant finish [7]. Stability and homogeneity of fabric structure was taken into consideration on selection.

Steel sheets with bored openings with B1-B4 symbols and specialist fabrics marked with symbols T1-T6 were tested. The materials are characterized in tables 1 and 2.

3. TESTING RESULTS

The tests were carried out according to PN-EN ISO 6942:2005 [2] for two heat radiation levels: 20 kW/m² and 40 kW/m². The results of heat penetration tests for different radiant heat intensities are presented in figures 1-2.
The results for the lower intensity heat stream (20 kW/m²) the values of heat penetration levels RHTI24 oscillated within a broad range from 14.9 s (T1 fabric) to 722 s (T3 fabric). For metal plates with specified numbers and diameter of openings, intermediate RHTI24 values were obtained: 36 s – B3, 41 s- B2 and 64 s- B1.

For the higher intensity heat stream (40 kW/m²), RHTI24 values fell within the range from 8 s (T4 fabric) to 172 s (T3). Analogically to the lower heat intensity, intermediate RHTI24 values were obtained for metal plates with bored openings of varied diameter and number (B1- 45 s, B2- 23.24 s, B3- 19.4 s, B4 – 42.1 s).

The obtained results were analyzed with respect to utilization of the tested samples as reference materials for checking the correct performance of test stands for determination of material resistance to heat penetration. For this purpose, the obtained RHTI24 values were compared with the requirements set for reference materials. Six of them were found to meet the criteria. The desired levels of RHTI 24 were obtained for the following samples:

- 10 ≤ RHTI 24 < 20 s at heat stream density of 20 KW/m²: fabrics T1, T4, T6
- 20 ≤ RHTI 24 < 50 s at heat stream density of 20 KW/m²: fabric T5, perforated steel plates B2 and B3
- 10 ≤ RHTI24 < 18 s at heat stream density of 40 KW/m²: fabric T5

The utility values of materials proposed as reference were also analyzed. It was decided to abandon the use of glass fiber fabric T1 because of unfavorable dimension stability characteristics. In turn, glass fiber fabrics covered with aluminium foil - T2 and T3, characterized by good utility values, demonstrated very high RHTI24 values, far beyond the limits, acceptable for the protection classes, and were also discarded.

4. CONCLUSIONS

The results of the completed tests have demonstrated that the materials meeting the accepted criteria for reference materials for the method of testing protective clothing resistance to the effect of radiant heat include appropriately selected glass fiber fabrics coated with vermiculite or aluminium foil, as well as perforated metal sheets with the number of perforations appropriately adjusted to the level or class of protection.

It will be possible to use these materials for checks of correct performance of measurement stands.

5. REFERENCES

1. G. Bartkowiak, S. Krzemińska Report concerning realization of task. 03.8, „Development of reference standards for tests of materials protecting against thermal factors”. Stage 1 „Elaboration of requirements for reference materials with differentiated levels of protective properties and selection of materials for reference standards”, Warsaw 2005, CIOP-PiB.
4. pr EN ISO 11612:2004 Protective clothing – Clothing to protect against heat and flame
5. EN 469:2005 Protective clothing for firefighters – Performance requirements for protective clothing for firefighting.
6. pr EN 1486:2003 Protective clothing for fire-fighters – Test methods and requirements for reflective clothing for specialised fire-fighting.
7. Information materials of PABIANTEX company.

**Figure 1.** Results concerning resistance to heat penetration for exposure to radiant heat (heat stream $Q_0 = 20 \text{ kW/m}^2$)

**Figure 2.** Results concerning resistance to heat penetration for exposure to radiant heat (heat stream $Q_0 = 40 \text{ kW/m}^2$)
<table>
<thead>
<tr>
<th>Variant</th>
<th>Fabric type</th>
<th>Surface mass [g/m²]</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Glass fiber fabric</td>
<td>390 ± 20</td>
<td>0.52</td>
</tr>
<tr>
<td>T2</td>
<td>Glass fiber fabric coated with aluminium foil</td>
<td>234 ± 11</td>
<td>0.24</td>
</tr>
<tr>
<td>T3</td>
<td>Glass fiber fabric coated with aluminium foil</td>
<td>638 ± 31</td>
<td>0.70</td>
</tr>
<tr>
<td>T4</td>
<td>Glass fiber fabric coated with vermiculite</td>
<td>650 ± 50</td>
<td>0.60</td>
</tr>
<tr>
<td>T5</td>
<td>Glass fiber fabric coated with vermiculite</td>
<td>1200 ± 50</td>
<td>1.2</td>
</tr>
<tr>
<td>T6</td>
<td>Glass fiber fabric coated with aluminium foil</td>
<td>535 ± 30</td>
<td>0.64</td>
</tr>
</tbody>
</table>

**Table 1** Characteristics of fabrics selected for testing

<table>
<thead>
<tr>
<th>Variant</th>
<th>Number/diameter of openings [mm]</th>
<th>Thickness [mm]</th>
<th>Characteristics of steel sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>16/2</td>
<td>0.50</td>
<td>Symbol: OH18N9</td>
</tr>
<tr>
<td>B2</td>
<td>41/3</td>
<td></td>
<td>Surface finish : matt</td>
</tr>
<tr>
<td>B3</td>
<td>25/2 + 16/4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>25/2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2** Characteristics of steel plates selected for testing
DETERMINING TEMPERATURE REGULATING FACTOR OF APPAREL FABRICS CONTAINING PHASE CHANGE MATERIAL

Wiesława BENDKOWSKA\textsuperscript{1}, Marta GONCIARZ-WACH\textsuperscript{1}, Janusz TYSIAK\textsuperscript{2}, Leszek GRABOWSKI\textsuperscript{2}, Albert BLEJZYK\textsuperscript{2}

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ABSTRACT

In order to characterise the temperature regulating ability of fabrics containing microencapsulated phase change materials (PCM), the test instrument has been designed and built in Textile Research Institute. This instrument simulates an arrangement: skin – apparel – environment. Fabric sample is sandwiched between a hot plate and two cold plates, one on either side of the hot plate. These cold plates at constant temperature simulate the environment outside the apparel. Sinusoidally varying heat input to the hot plate is simulating human activity. All energy inputs and temperatures are recorded by computer data acquisition system. To measure the steady state thermal resistance of the fabric, the controlled heat flux is constant and the test proceeds until steady state is reached. To assess temperature regulating ability, the heat flux is varied sinusoidally with time and temperature regulating factor (TRF) is determined. TRF value defined by Hittle as quotient of the amplitude of the temperature variation of the hot plate and the amplitude of the heat flux variation, divided by the steady state heat resistance of the fabric.

The test instrument can be useful in quality control during manufacture of fabrics containing PCMs. Temperature regulating factor (TRF) can be used in clothing industry to establish criteria for comfort parameters of textiles.

INTRODUCTION

The manufacture and properties of intelligent textiles containing phase change materials (PCM) have been extensively studied at Textile Research Institute (Łódź) since 1999. Phase change materials is able to absorb, store and release large amounts of latent heat over defined temperature range when the material changes phase or state. By application of PCM to the fabric thermoregulating effect, resulting from either heat absorption or heat emission of the PCM can be obtained.

The heat absorption by PCM results in a delay in microclimate temperature and hence a substantial decrease of the sweat amount produced by the skin of wearer. Both lead to an enhancement of the wearing comfort and a prevention of heat stress.
In the manufacture of thermoregulating textiles the most important PCMs are linear chain hydrocarbons (octadecane, nonadecane, hexadecane, eicosane etc.) called paraffin waxes. Microencapsulated PCMs are incorporated into acrylic fibers, or polyurethane foams, or coated on the surface of the fabric substrate.

In the past few years, apparel fabrics containing microencapsulated PCMs have appeared in outdoor garments, particularly sportswear. In the case of traditional fabrics, the thermal properties are investigated by standard steady state procedures involving the use of guarded hot plate apparatus. Because PCM is a highly productive thermal storage medium, steady state procedures are inadequate for testing fabrics containing PCM. Hence it is necessary to work out a test method and instrument for assessing the temperature regulating ability of these fabrics. Basing on a model of heat transfer through textiles containing PCM formulated by Hittle and Andrew, the test instrument has been designed and built in Textile Research Institute. Last year this test method has been standardized by ASTM.

**TEST INSTRUMENT DESCRIPTION**

The most important element of the test instrument is the hot plate that has a sandwich structure. The heater layer is placed between two insulation layers made of epoxy-glass laminate. The construction of plate provides the uniformity of temperature distribution on its surface and as small as possible heat capacitance. A thin (1.0 mm), flexible hot plate is situated in the center of the test stand. Directly above the hot plate there is a rod from which a fabric sample is hung. The sample (0.65 m × 0.25 m) is large enough to cover the hot plate on both sides. A controlled heat flux, either constant or varying, is maintained for the hot plate. On both sides of the hot plate cold plates are situated. The cold plates were designed as the thinwalled tanks, which are cooled to specified temperature by constantly circulating water from thermostat. Temperature of cold plates is measured by thermoresistant sensor. The hot and cold plates can be displaced on guide bars. The cold plates can be pressed against the fabric sample at constant pressure (200 Pa) provided by a compression spring.

PC computer provided with the measuring chart and the application software LabView (National Instruments) realizes all control and registration functions.

These cold plates at constant temperature simulate the environment outside the apparel. Sinusoidally varying heat input to the hot plate is simulating human activity. To measure the steady state thermal resistance of the fabric (R), the controlled heat flux is constant and the test proceeds until steady state is reached. To assess temperature-regulating ability, the heat flux is varied sinusoidally with time and temperature-regulating factor (TRF) is determined.

In order to characterize thermoregulation effect Hittle and Andrew\(^2\) have proposed to use the quotient of the amplitude of the temperature variation and the amplitude of the heat flux variation. The smaller the quotient the better the regulation effect. Dividing this quotient by the value of steady state thermal resistance of the fabric (R) they obtained TRF value:

\[
TRF = \frac{(T_{\text{max}} - T_{\text{min}})}{(q_{\text{max}} - q_{\text{min}})R}
\]

TRF is a dimensionless number varying in range (0,1). TRF shows how well a fabric containing microPCM moderates the hot plate temperature. TRF value of 1 means the fabric has no heat
capacitance and poor temperature regulation. TRF equals zero, means that fabric has infinite heat capacitance and that a body being in contact with it will remain at constant temperature. It is obvious that all fabrics fall somewhere between these extreme values.

TRF is a function of the frequency of the sinusoidal variation of the heat flux into the hot plate. The temperature regulation increases with increasing frequency. Hence TRF increases with increasing cycle time of sinusoidal variation, going exponentially from 0 to 1.

SUMMARY

The test instrument presented here was intended to use for testing steady state and transient state characteristics of apparel fabrics containing

REFERENCES

Heat transfer characteristics of 10 motorcycle helmets were measured. Each helmet was tested three times on a manikin headform placed in a climate chamber (22 °C and 50% RH) at the exit of a wind tunnel (50 ± 1.1 km·h⁻¹). In every measurement a helmet was evaluated with the ventilation openings closed and open. Heat transfer (\( \dot{Q} \)) in the scalp and face sections, along with temperature measured with 10 thermocouples on different locations, were registered in a 20 min steady state period. The heat transfer ranged from 0 < \( \dot{Q} \) < 4 and 8 < \( \dot{Q} \) < 16 for the scalp and face sections, respectively. Closing or opening the ventilation openings did not have a significant effect on heat transfer for most of the helmets. Similar results were found for temperature.

1. INTRODUCTION

The head is one of the body’s strongest thermal comfort sensors (Cotter and Taylor, 2005). Not surprisingly, a common complain about headgear in warm environments is impairment of thermal comfort, as investigated for industrial (Liu, 1997) and bicycle helmets (Ellis et al., 2000). This has motivated a number of studies of the heat transfer characteristics of headgear (Liu, 1997; Brühwiler et al., In press). In the presence of wind, optimizing headgear ventilation has been shown, e.g., for bicycle helmets to improve heat loss and increase thermal comfort in a warm environment (Brühwiler et al., 2004).

A COST 327 survey suggested that physiological aspects associated with motorcycle helmets, e.g., microclimate heat stress and/or CO₂ concentration in the re-breathed air might affect the safety of the wearer (Chinn et al., 2003). Optimizing the ventilation of motorcycle helmets could address both of these concerns, and is therefore a traffic safety issue. A manikin study of two motorcycle helmets (Brühwiler, 2003) showed that ventilation of the scalp section of the head can be very poor (for both motorcycle helmets, in that case), whereas 20% variations were observed for the face. The present study was carried out in order to evaluate the heat transfer characteristics of 10 modern full-face motorcycle helmets, using a thermal manikin headform augmented by local temperature measurements.
2. METHODS

Ten full-face motorcycle helmets from 7 manufacturers (4 flip-up and 6 integral models) were examined on a thermal manikin headform described previously (Brühwiler, 2003). The surface temperature of the headform was set to 35 °C, and the power needed to maintain this temperature in steady state was recorded. This heating power corresponds to the heat transfer (\( Q \)). Values for the scalp and face sections were obtained separately. The neck section of the headform was also heated to prevent conductive heat transfer to the support. The headform was placed at the exit of a wind tunnel with air speed set to 50 ± 1 km·h\(^{-1}\) (14.0 ± 0.3 m·s\(^{-1}\)), and which was in turn located in a climate chamber at 22 °C and 50% RH.

A scarf covered the neck section to reduce an unnecessarily large convective heat loss in this section and to simulate a realistic situation. The headform was instrumented with 10 K-type thermocouples (figure 1); 6 on the face section (forehead, eye, nose, cheek, ear and chin) and 4 on the scalp section. In the text the temperature measured by a thermocouple will be referred to as T1, T2, … T10, corresponding to the numbers shown in figure 1. These temperatures were measured in an attempt to characterize the airflow between headform and helmet.

![Figure 1: Thermocouple location on the thermal manikin headform. The locations of the 10 thermocouples are indicated with squares and corresponding numbers. The three sections are also indicated. In the right most picture the headform is shown with a motorcycle helmet.](image)

Each helmet was tested with all ventilation openings alternately closed and opened in random order. Three such measurements were carried out, with fresh helmet placement between the measurements; each subsequent measurement of a given helmet was interceded by a measurement on at least one other helmet. After every intervention the headform was allowed to reach steady state, usually taking 30 min. From the following 20 min period the steady-state power and temperature values were extracted. All helmets were placed according to a broadly-used impact test standard (ECE324, 2002), with a specified gap of about 3 cm between the bridge of the nose and the upper edge of the helmet facial opening. In order to ensure anonymity, numbers have been assigned to the helmets. ANOVA was used for statistical analysis, with a Tukey test for post hoc comparisons if a significant difference was found (p < 0.05). The statistical analysis was carried out with SPSS 13.0.1 for Windows.
3. RESULTS AND DISCUSSION

3.1. HEAT TRANSFER

The heat transfer data are shown in figure 2. As could be expected based on the construction of such helmets, large differences in heat transfer were observed between the face and scalp sections, ranging roughly from $0 < \dot{Q} < 4$ W for the scalp section and $8 < \dot{Q} < 16$ W for the face section. Also immediately apparent is the large variability among the different models. Strikingly, closing or opening the ventilation openings is unimportant for heat transfer for most of the helmets. For the scalp section, only helmet 110 ($\Delta \dot{Q} = 3.5 \pm 0.1$ W) and helmet 201 ($\Delta \dot{Q} = 0.8 \pm 0.1$ W) display a significant effect of closing/opening the ventilation openings. Only helmet 132 ($\Delta \dot{Q} = 2.2 \pm 0.2$ W) shows a significant effect of closing/opening the ventilation openings in the face section. The combined heat transfer ranged from 8.0 to 18.9 W.

![Figure 2: Steady state heat transfer for the scalp and face sections as indicated, measured for all motorcycle helmets with ventilation openings closed and open. A * indicates a significant difference (p < 0.05) upon changing the ventilation openings](image)

3.2. TEMPERATURE

The temperatures show similar trends for inter-helmet variability, as well as a generally weak role for the ventilation openings. A representative set of temperature measurements (T3) is visualized in figure 3 for all helmets and conditions. Variations in temperature on the different locations showed an average standard deviation of 1.8 ºC. In the scalp section helmet 110 and 212 showed significant differences for closing and opening the ventilation opening for locations T2 / T3 and T3, respectively. Only helmet 110 showed a significant difference in the face section (T5). In two of these cases the temperatures were higher with the ventilation openings open. Because the manikin is constructed to maintain an average constant surface temperature, we cannot determine if the present observations reflect compensation for lower temperatures elsewhere in the same section of the headform, or transport of heated air under the helmet, or a combination of the two.
4. CONCLUSION

The large variations in heat transfer observed among the tested helmets show that there are different strategies being used for ventilation. Furthermore, the small effect of closing or opening all the ventilation openings for most helmets is clearly not an ideal result. It is yet to be determined if the airflow patterns change even if the heat transfer remains the same, or if closing or opening individual ventilation openings would induce greater differences in those cases. Further analysis of the temperature variations might provide insight into this question.

5. ACKNOWLEDGMENTS

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6. REFERENCES


SOL-GEL COATINGS OF PLASMA MODIFIED POLYPROPYLENE FABRIC FOR GAS DEFENCE

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ABSTRACT

Activated carbon has been widely used as an adsorbent in the separation and purification of gas mixtures. In this study, we coated the plasma modified polypropylene fabric and cotton fabric with sol-gel derived carbon xerogel at low temperature. Since polypropylene has no functional groups in its’ structure, it is difficult to deposit oxide or oxide-based coatings directly. Polypropylene needs a surface treatment or modification for improved wetting behavior and adhesion. With this regard, oxygen plasma etching was used to increase oxygen content of the surface of the fabric. Our ultimate purpose is to prepare a specific fabric separating and protecting the breathing air from volatile organic compounds (VOCs). In the first part of our study, oxygen plasma modified polypropylene fabric and cotton fabric surfaces were coated by the sol-gel derived carbon xerogel at low temperature. The effect of these treatments on the surface characteristics of the polypropylene and cotton fiber was investigated. The samples were characterized by surface area analysis as The Brunauer-Emmett-Teller (BET) and scanning electron microscopy (SEM) and water vapour permeability testing.

Keywords: VOCs, Activated carbon, Sol-gel, Plasma treatment

INTRODUCTION

Volatile organic compounds released from organic solvents (VOCs) (toluene, 1,2-dichlorobenzene and 1,1,1-Trichloroethane, ethylbenzene, cyclohexane, dichlorobenzene, benzaldehyde, etc.), used in various industrial fields, cause pollution in various media such as air, water, and soil. Many of these VOCs are hazardous to human health and environment. VOCs contribute to brown, hazy smog that surrounds many urban areas and are a leading cause of respiratory problems. VOCs are the monocyclic aromatic hydrocarbons and the volatile chlorinated hydrocarbons. Both groups of these compounds are considered as priority pollutants in view of their high toxicity and volatility. Industrial processes and the combustion of fossil fuels mainly emit monocyclic aromatic hydrocarbons, while...
chlorinated hydrocarbons are widely applied as solvents for cleaning, as degreasing agents in metal industries, and as fumigants [1].

Adsorption has been recognized as one of the most practical regenerative methods for separating and recovering VOCs. In recent years, new adsorbent materials and sorption methods have been actively studied for the efficient separation of VOCs from polluted air. Activated carbons are the most commonly adsorbents applied for VOCs removal.

In general, inorganic aerogel can be fabricated by the sol-gel polymeric condensation of metal alkoxides (e.g. tetramethoxysilane, tetraisopropoxy titanate, and tantalum ethoxide) through high temperature supercritical solvent drying with alcohol [2] or supercritical solvent drying with carbon dioxide [3]. However, despite their variously unique properties of inorganic aerogels has been hindered due weak mechanical strength, and thus the fragility. Hence, in order to improve mechanical strength, attention has been placed on the fabrication of mechanically strong organic aerogel. R.W. Pekala [4] invented an organic aerogel for the first time. A resorcinol-formaldehyde (RF) aerogel was fabricated by sol-gel polycondensation of resorcinol or melamine with formaldehyde. In addition, by calcination of the organic aerogel, R. Saliger et al [5] obtained a pure carbon aerogel from the RF aerogel as well as R. W. Pekala and co-workers [6, 7] developed a synthetic carbonized RF resin via a sol-gel route [8].

These unique and controllable properties are attributed to the sol-gel process, which is quickly becoming one of the most promising material synthesis techniques. It readily allows control of the texture, composition, homogeneity, and structural properties of the resulting materials [9]. Numerous studies have recently been devoted to understanding how the synthesis conditions affect the porous structure of sol-gel derived materials [10-13]. C. Lin et. al [14] modified the carbon aerogel sol-gel synthesis procedure to make high surface area carbon xerogel with controlled pore structure. Their method was used to only produce carbon xerogel. Nonetheless, carbon xerogel was not applied to coat on the fabric surface using the same technique.

Polymer surfaces prove technically difficult to deposit oxide or oxide-based coatings directly, leading to necessary surface treatment or modification for improved wetting behavior. As a result, a variety of surface treatment techniques have been studied to achieve good wetting and adhesion for deposition of oxide coatings by changing the polymer surface chemistry. Plasma technology is shown to be effective for modifying the polymer surface [15, 16]. Oxygen plasma has been widely used for polymer surface treatment for improved wetting properties [17-24] and for adhesion of sol-gel-derived coatings [15, 25, 26]. Functional groups such as carboxyl groups (-COOH) and hydroxyl groups (-OH) can be introduced, increasing the oxygen content on the polymer surface.

Our ultimate purpose is to prepare a specific fabric separating and protecting the breathing air from volatile organic compounds (VOCs). In the first part of our study, polypropylene fabric was exposed to oxygen plasma etching. Cotton fabric was not exposed to oxygen plasma etching, because cotton is an inherently hydrophilic fiber. Both fabrics were coated by the sol-gel derived carbon xerogel at low temperature. The effect of these treatments on the surface characteristics of the polypropylene and cotton fiber was investigated. The samples were characterized by surface area analysis as The Brunauer-Emmett-Teller (BET) and scanning electron microscopy (SEM) and water vapour permeability testing.
MATERIAL AND METHOD

Preprocessing

**Fabrics:** 100% polypropylene three layer face masks (Sterillife, Turkey) were used in our study. All layers were spunbonded polypropylene. Moreover, scoured and bleached %100 plain-weave cotton fabrics (weight 126 g/m², 17 picks/cm, 21 ends/cm) were used in this study.

**Surface Preparation:** Since polypropylene needed a surface treatment or modification for improved wetting behavior and adhesion for coating, low frequency (40 kHz) oxygen plasma treatment at different power levels (20, 40, 60 W) and exposure periods (15, 30, 45 min) was applied to the masks.

**Sol-gel Coating Process**

Reagent-grade resorcinol (99%, Fluka), formaldehyde (39%, Iron Chemistry, Turkey), sodium carbonate (Kimetsan Chemistry, Turkey) and nitric acid (HNO₃, 50-55%, Birpa Chemistry, Turkey) were used. A solution containing 5 w/v % solids was prepared, in which the R/F (resorcinol/formaldehyde) mole ratio was fixed at 1:2. Sodium carbonate was used as catalyst, and the R/C (resorcinol/sodium carbonate) mole ratio was fixed at 50:1. The initial pH 5.35 of the solution was adjusted with dilute HNO₃ [14]. The solution was sealed in a flask and magnetically stirred for 30 minutes.

A 10x10 cm nonwoven polypropylene three layer face mask and cotton fabric, which was conditioned at standard atmospheric condition was dipped in the solution for 30 seconds and then padded twice using an Rapid Fulard (Model P-A1, Labortex, Taiwan) at a nip 2.8 kg/cm². Firstly, the padded substrates were six times cured at 85 °C for 30 min and then were cured at 85 °C for 24 hours in a preheated oven (Nüve KD400 Oven, Turkey) for gelation of solution on fabric. Typically, gelation on fabric was occured in several hours. After curing, the fabric was removed from the oven and cooled to room temperature. It was then washed and vacuum filtered three times with acetone over a period of three days. Fresh solvent was replaced daily after vacuum filtration. The washed fabric was dried at 65 °C for 5 hours and then at 110 °C for 5 hours. The method of solution preparation was achieved according to the previous study of C. Lin et al [14]. The flow chart of the present study was denoted in Figure 1.
Figure 1. The flow chart for sol-gel coating process

**Characterization**

**Wettability:** The wettability of fabrics was determined by means of wetting time (absorbency) measurements before and after plasma polymerization according to AATCC Test Method 79 [27]. Distilled water was dropped on the fabric and the time required for the specular reflection of the water drop to disappear was recorded as wetting time. The shorter wetting time indicates better wettability.
**BET Analysis:** An Autosorb-1-C/MS manufactured by Quantachrome Corp. was used to obtain the specific surface areas based on the formula of multilayer adsorption by BET. The adsorption isotherms were measured using 0.028-0.066 g polypropylene fabric material, which was dried in vacuum at 100 °C for 5 hours in order to remove all adsorbed water [28].

**Scanning Electron Microscopy:** The surface images of treated and untreated fabric were taken by scanning electron microscopy (JSM–6060 JEOL Model) operating at 3 kV with X2000 magnification.

**Water Vapour Permeability:** Water vapour permeability tester (SDL Int. Ltd., England) was used to determine structural permeability properties of the samples. A test specimen is sealed over the open mouth of a test dish which contains water, and the assembly is placed in a controlled environment. Successive readings of the assembled dish are made before and after 5 hours and the rate of water vapour permeation (WVP) through the specimen is calculated as Equation 1.

$$WVP = \frac{24M}{At}$$  \hspace{1cm} \text{(Equation 1)}

Where M is the loss in mass of the assembly over the time period t (in g). T is the time between successive weighings of the assembly in hours. A is the area of exposed test specimen (equal to the internal area of the test dish (in m²)). In this case A = 0.0054113m².

The water vapour permeability index is calculated by expressing the water vapour permeability of the fabric as a percentage of the water vapour permeability of a reference fabric which is tested in a similar manner. The water vapour permeability index (L) is given by means of the following Equation 2:

$$L = \left( \frac{(WVP)_{\text{test}}}{(WVP)_{\text{ref}}} \right) \times 100$$  \hspace{1cm} \text{(Equation 2)}

Where \( (WVP)_{\text{test}} \) is the mean water vapour permeability of the fabric under test, \( (WVP)_{\text{ref}} \) is the water vapour permeability of the reference fabric.

**RESULTS AND DISCUSSIONS**

**The wettability of samples**

The results of the wettability tests of the polypropylene samples are listed in Table 1. Only three samples showed hydrophilic property. The effectiveness of plasma conditions was verified through water-absorbency tests. Because the water-absorbency must be below 60 sec for hydrophilicity, the sample that signed with star in Table 1 was selected for treatment by sol-gel coating.
Table 1. The wettability properties of the plasma treated and untreated samples.

<table>
<thead>
<tr>
<th>Plasma Processing Conditions</th>
<th>Absorbency (wettability) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inner Surface</td>
</tr>
<tr>
<td><strong>Power (W)</strong></td>
<td><strong>Time (min)</strong></td>
</tr>
<tr>
<td>40*</td>
<td>15*</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>60</td>
<td>15</td>
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<tr>
<td>60</td>
<td>30</td>
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<tr>
<td>60</td>
<td>45</td>
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<tr>
<td>80</td>
<td>15</td>
</tr>
<tr>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td>80</td>
<td>45</td>
</tr>
</tbody>
</table>

* the selected fabric for sol-gel coating

**Specific surface area and adsorption properties**

The total specific surface areas of fibers were determined with nitrogen as adsorbate applying the Brunauer-Emmett-Teller (BET) technique [28, 29]. Figure 2 shows the isotherms obtained for the coated and uncoated polypropylene fabric with carbon xerogel by sol-gel process. For both samples, the isotherms are of type II and III. Type II and III approach the P⁰ line asymptotically; experimentally, such behavior is observed for adsorption on powdered samples, and the approach toward infinite film thickness is actually due to interparticle condensation, although such behavior is expected even for adsorption on a flat surface if bulk liquid adsorbate wets the adsorbent [30].

![Figure 2. The volume versus relative pressure (P/P₀) curves for treated and untreated fabrics.](image-url)
Measured data points in the range of $0.15 < P/P_0 < 0.30$ were used for the fitting procedure. The BET method is widely used in surface science for the calculation of surface areas of solids by physical adsorption of gas molecules. A total surface area $S_{total}$ and a specific surface area $S$ are evaluated by the following Equation 3 and 4 [29]:

$$S_{total} = \frac{V_m N_s}{M} \quad \text{(Equation 3)}$$

$$S = \frac{S_{total}}{a} \quad \text{(Equation 4)}$$

Where $N$ is Avogadro's number, $s$ is adsorption cross section, $M$ is molecular weight of adsorbate and $a$ is weight of sample solid. In Table 2, the values of specific surface area ($S_{BET}$) and the adsorbed volume ($V_m$) were showed for treated and untreated fabric samples.

**Table 2. Textural properties of treated and untreated samples.**

<table>
<thead>
<tr>
<th></th>
<th>$S_{BET}$ (m²/g)</th>
<th>$a$ (g)</th>
<th>$M$ (g/mol)</th>
<th>$s$ (Å²/molec)</th>
<th>$V_m$ (cc/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated fabric</td>
<td>4.970</td>
<td>0.0279</td>
<td>28.0134</td>
<td>16.2</td>
<td>0.3270</td>
</tr>
<tr>
<td>Treated fabric</td>
<td>0.101</td>
<td>0.0656</td>
<td>28.0134</td>
<td>16.2</td>
<td>0.0192</td>
</tr>
</tbody>
</table>

$S_{BET}$- specific surface area, $V_m$- the adsorbed volume

The surface area of unit weight of the polypropylene was found to be 4.97 m²/g and this value is in a good agreement with literature. It is quite expected that, after treatment the raw material with physicochemical modification (oxygen plasma) and further with chemical coating (sol-gel processing), the specific surface area should be reduced. This reduction was observed in the order of 1/50. But it should be noted that, the magnitude of the reduction in the surface area has no meaning if carbon xerogel film formed on the fabric surface has enough activity for the adsorption of VOCs.

**Surface analysis**

The treated cotton fabric has smoother surface than untreated cotton fabric surface as it was seen Fig 3. So, SEM images show that thin film layer was evenly produced on coated cotton fabric by sol-gel polycondensation. As it was seen fig 4, the diameter of the cotton fiber unchanged due to the acetone washing step as approximately 13.7 µm.

![Figure 3. The images of a) coated cotton fabric by sol-gel process b) blank fabric.](image-url)
Acetone washing step of the sol-gel coating process was affected the structure of coated polypropylene fiber, as it is seen on Fig 4. The diameter of the treated polypropylene fiber with acetone washing for 1.5 days was increased 3.4 µm from 16.6 µm to 20 µm in respect to the treated polypropylene fiber without acetone washing step.

![Figure 4. The images of coated polypropylene fabric by sol-gel a) with acetone washing b) without acetone washing.](image)

**Water vapour permeability**

The used test method conforms to the BS7209 specification [31]. On Table 3, the rates of water vapour permeation (WVP) were given. It was resulted that the permeability of the treated cotton fabric decreased in respect to untreated cotton fabric. In contrast, the permeability of the untreated polypropylene fabric, which has higher specific surface area, decreased in respect to treated polypropylene fabric.

**Table 3.** The rates of water vapour permeability and the water vapour permeability index of treated and untreated cotton and polypropylene fabric.

<table>
<thead>
<tr>
<th>Samples</th>
<th>The rate of water vapour permeability (g/m²/day)</th>
<th>The water vapour permeability index (L) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treated cotton fabric</td>
<td>944.75</td>
<td>96.71</td>
</tr>
<tr>
<td>Untreated cotton fabric</td>
<td>1009.94</td>
<td>103.38</td>
</tr>
<tr>
<td>Treated polypropylene fabric</td>
<td>1015.78</td>
<td>103.98</td>
</tr>
<tr>
<td>Untreated polypropylene fabric</td>
<td>968.51</td>
<td>99.142</td>
</tr>
</tbody>
</table>
CONCLUSIONS

In this study, we showed that, polypropylene fabric could be treated by oxygen plasma exposure to increase the wettability of the surfaces for better processing by sol-gel method. Cotton fabric was not exposed to oxygen plasma etching, because cotton is an inherently hydrophilic fiber. Both fabrics were coated by the sol-gel derived carbon xerogel at low temperature. A very thin and homogeneous sol-gel derived carbon xerogel film was observed on the substrate fabrics. These films were characterized by means of surface area, topography and permeability.

Although a sol-gel derived carbon xerogel film was observed, the surface area could not be obtained high enough due to the nature of the wet chemistry for sol-gel processing. In future studies, we will test the adsorption capacity of sol-gel derived carbon xerogel film against VOCs. If the results would be unsatisfactory, powder form of carbon xerogel will be employed by the same procedure. To increase the performance of the sol-gel process, the several types of substrate fabric will be modified by plasma polymerization of acrylic acid to obtain carboxyl groups on the surface. The study to reach our ultimate purpose “a specific fabric separating and protecting the breathing air from volatile organic compounds (VOCs)” is still under investigation.

ACKNOWLEDGEMENTS

Middle East Technical University (METU) Central Laboratory (Turkey) where BET surface area analyses were carried out was greatly acknowledged.

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A PROPOSED HEAT TRANSMISSION TEST FOR SINGLE LAYER FABRICS – RESULTS OF INTERLABORATORY TRIALS

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ABSTRACT

In developing a test method for potential adoption as an ISO Standard it is essential to show that the test method can produce acceptable inter and intra laboratory test results. In this study a new approach to heat transmission testing of single layer fabrics subjected to an open flame is investigated using round robin testing. The tester uses a cylindrical geometry with an air gap between the test specimen and the heat sensor. The construction is such that if shrinkage or stretching of the test specimen occurs during the exposure the size of the air gap will change, affecting the time it takes to reach the end point of the test.

1. INTRODUCTION

Thermal protective clothing is worn by structural and wildland firefighters and workers in the oil, gas and petrochemical industries. The latter often wear a single layer coverall made of flame resistant (FR) fabrics. The coverall is designed to provide protection against accidental exposure to flash fires/fire balls that might occur when gas leaks are ignited accidentally. Wildland firefighters also tend to wear single layer coveralls. Most of their activity involves working on the perimeter of the fire to contain and starve it by removing combustible material from its path, and doing mopping up exercises. Thus most of their exposure is to radiant energy from the fire. However, as with the oil, gas and petrochemical workers, the wildland firefighters can be engulfed in flames due to shifting winds and rapidly advancing fires.

Selecting appropriate materials and garment designs for single layer FR coveralls involves many facets. Included are flame spread resistance, comfort, seam strength, durability etc. Resistance to heat transmission due to direct flame exposure and/or radiant exposure is also an important issue.

Several ISO standard tests are available for evaluating heat transmission characteristics of single and multi layer fabrics when exposed to a high intensity heat source: Protective clothing against heat and flame - Determination of heat transmission on exposure to flame (ISO 9151); Protective clothing against heat and flame – Evaluation of materials and material assemblies when exposed to a source of radiant heat (ISO 6942); and Clothing for protection against heat and flame – Determination of heat
transmission on exposure to both flame and radiant heat (ISO 17492). In all these test methods, the fabric layer(s) are suddenly exposed to the energy source on one side. The heat transmission through the fabric layer(s) is determined by measuring the temperature rise in a copper disk of prescribed dimensions and mass. The test methods stipulate a particular value of exposure heat flux, usually 80 kW/m². With the radiant tester two exposure levels are listed for use, 20 kW/m² and 80 kW/m². The radiant energy wavelength characteristics of the flames specified in ISO 9151 and ISO 17492 are different from those of the lamps or resistance heaters used in ISO 6942 and ISO 17492. Thus the time measured to attain the end point is different depending on the particulars of the apparatus. The end point used is a 24 °C rise in the copper disk. Different fabrics are usually ranked in the same order when tested according to any of these present ISO test methods.

During these ISO tests the fabric layers that are directly exposed to the energy source can attain temperatures of several hundred degrees Celsius in a few seconds. At these temperatures FR fabrics that are not dimensionally stable may soften and droop or shrink. When placed in a flat horizontal position or held across the copper sensor under tension due to an applied weight, such characteristics have little effect on the outcome of the test unless the fabric softens and droops so as to produce an air gap between it and the copper sensor or the fabric breaks open. As air is an excellent insulator this can affect the outcome of the test. If the fabric shrinks it will not affect the outcome unless it breaks open.

When testing garments and garment systems on mannequins under simulated flash fire situations it is observed that the predicted percentage area receiving 2nd degree burns or worse increases when fabrics shrink against the surface of the mannequin. Having a bench scale apparatus that mimics this effect is an obvious approach to take. This lead to the development of the present cylindrical tester used in this study.

2. THE CYLINDRICAL GEOMETRY TESTER

Figure 1 shows the assembled tester, while Figure 2 provides details of the cylindrical section that houses the copper heat sensor and how the 6.4 mm air gap is built into the system. Figure 3 gives the dimensions of the copper heat sensor which has the same surface area and mass as that used in ISO 9151 and ISO 17492. The unit is designed to fit into the existing ISO 9151 apparatus, using the same exposure system, calibration method and end points.

The tester and its development have been described in an earlier publication [1]. Comparisons with other testers and correlations with mannequin test results have also been reported [2]. These latter results showed reasonable correlations between the percentage of the surface area of the mannequin receiving 2nd degree burns or worse with full single layer garments and exposures of similar fabrics (not from the same bolts of material) on the cylindrical tester. These correlations were better than those with a planar geometry unit for all tests.

While the initial work [1] with the unit looked promising in that fabrics that shrank during exposure were found to reach the end point sooner that the planar cases, the mounting of the fabric is more complex and this could lead to higher variability than existing test methods. Round robin testing was a logical next step.
3.  ROUND ROBIN PROCEDURES, PARTICIPANTS AND MATERIALS

The approach taken was first to construct the necessary number of testers and draft a test method in ISO format. Several groups in Asia, Europe and North America were asked if they were willing to participate. These groups were sent a tester, the draft document and five specimens of one fabric for preliminary trials. In addition to the test results, laboratories were asked to provide feedback on the draft test method. It should be mentioned that one of the participating laboratories had never done testing of this nature before.

As the preliminary test results looked promising, the draft test method was revised and a second set of five specimens of one fabric were sent for a second preliminary round. The second set of specimens was the same fiber content as the first, only a lighter mass per unit area. The results from the second preliminary round also looked good, so a third set of specimens was prepared. This latter set included several different fabrics for the official round robin testing.

The specimens for the official testing were all sampled from one bolt of material using ASTM D 2904 Standard Practice for Interlaboratory Testing of a Textile Test Method that Produces Normally Distributed Data. These were randomized and sent to the participants. Included were two weights of one aramid fiber, two weights of one FR cotton fiber and one weight of an aramid/pbi blend. The mass per unit area ranged from 204 g/m² to 340 g/m².

A two way analysis of variance was performed on the data (ANOVA).

4.  RESULTS OF ROUND ROBIN TESTS

Table 1 lists the results from the round robin for the six laboratories and the analysis of variance. The superscripts a, b, c etc. show which results with a particular set of specimens (one vertical column) are essentially equal. All the information is presented anonymously.

Only the primary result, average time to reach a 24 ºC rise in the copper heat sensor, is listed for each set of test specimens and laboratory combination. Note that laboratories 1 and 2 are actually the same laboratory and same equipment, but with two different operators giving a measure of intra laboratory repeatability as well as inter laboratory repeatability.

The two way analysis of variance indicated significant differences between fabrics, as expected, but also differences between laboratories. Ideally the laboratories should produce nearly the same result with each set of test specimens.

5.  DISCUSSION

Examination of Table 1 suggests the following. Four of the six laboratories ranked the test fabrics in the same order on the time to attain a 24 ºC rise in the copper heat sensor. The ones that did not agree with the others in this regard were laboratories 1 and 3. When examining the vertical columns, the superscripts indicate which results are essentially the same. Thus with specimens A, laboratories 1 and 2 agree, while laboratories 3 and 5 have essentially the same result and laboratories 4 and 6 have essentially the same result for this material. For the data presented in Table 1, specimens C shows the most variation between laboratories, specimens E were next while the remaining three sets of
specimens, A, B and D produced the least variation for the particular choice of materials. Ideally all the laboratories should agree, the question is why did this not happen?

All of the apparatus were made by one machine shop. Before shipping to the testing laboratories they were all exposed to a single test laboratory flame to see if the temperature rise in the copper heat sensor was the same for each, which it was. All the laboratories had the same instructions which were modified to make the procedures clearer based on feedback from the laboratories after testing the preliminary fabrics.

Possible reasons for the larger than expected variations are not setting correctly the initial exposure energy, not mounting correctly the specimens on the apparatus and not starting with the exposure with the copper heat sensor within the specified initial temperature range.

6. CONCLUSIONS

Preliminary round robin testing with the cylindrical geometry tester shows that the technique has promise for testing single layer specimens. However based on these results it seems that improvements are still necessary in the written test method, especially in the description of how to set the initial exposure energy and mounting the specimens.

REFERENCES

Table 1. Test results for six different laboratories testing five different fabric samples. Values listed are average times in seconds to reach the end point for 5 samples of each fabric. End Point was a 24 °C rise in the copper sensor.

<table>
<thead>
<tr>
<th>Lab/Fabric</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>6.0&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>2&lt;sup&gt;1&lt;/sup&gt;</td>
<td>7.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>5.0&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>5.6&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>3</td>
<td>7.8&lt;sup&gt;b&lt;/sup&gt;</td>
<td>5.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.2&lt;sup&gt;c&lt;/sup&gt;</td>
<td>4.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.3&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>4</td>
<td>8.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>6.1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>6.6&lt;sup&gt;d&lt;/sup&gt;</td>
<td>5.2&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>6.3&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>5</td>
<td>8.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>5.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.4&lt;sup&gt;c,d&lt;/sup&gt;</td>
<td>4.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.6&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>6</td>
<td>8.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.3&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>5.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5.9&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

1- Laboratories 1 and 2 were the same laboratory, but with two different operators a,b,c,d and e - In each fabric column the same superscript means that there is no significant difference between test results.

Figure 1. Cylindrical Geometry Test Device
Figure 2. Details of Cylinder Used in Cylindrical Geometry Tester (All Dimensions in mm)

Figure 3. Cylindrical Geometry Heat Sensor (Dimensions in mm, may vary slightly, mass = 18 ± 0.05 grams)
OPTIMIZING FABRIC CHARACTERISTICS FOR BALANCED PROTECTION IN CLEANROOM GARMENTS

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\textsuperscript{2}DuPont Engineering, USA

ABSTRACT

Garments for personal protection are, by necessity, a compromise. Garment designers often balance conflicting desires for durability, comfort, performance and cost. Fabric strength, abrasion resistance and resistance to laundering are all elements of durability. Wear comfort includes heat and moisture transport properties of the clothing, as well as skin sensation and fabric softness and pliability in movement. Performance can also require a complicated compromise, depending on the nature of the protection desired. A design study of cleanroom garments required balancing durability, comfort, and barrier properties. Mechanical properties such as breaking load, tear resistance, abrasion resistance, and effect of washing and sterilization were used to quantify durability. Air and water vapor permeabilities were used to quantify comfort. Barrier properties were measured using filtration efficiency and fabric pore size. Regression analysis was used to model the relationship between measured performance characteristics and fabric characteristics. Weighting and desirability functions were constructed for each measured property in order to balance product needs. This approach is both powerful and simple to use, and greatly facilitates fabric selection for protective garments.

1. INTRODUCTION

Modern manufacturing industries, such as pharmaceuticals and electronics, often require exceptionally clean environments to satisfy product quality requirements. In these environments the protective garment and the worker himself can be a source of undesirable pollution as dust, microbes, particles of peeled epidermis, and fibers. The microflora of human skin includes numerous bacteria, including the genera Micrococcus (0.5-2 μm), Staphylococcus (0.5-1 μm), and Corynebacterium (0.5-8 μm). These bacteria usually agglomerate into masses of size 1 to 10 μm, but are carried on the particles of peeled epidermis of size above 10 μm. One of the most important requirements of fabrics used for cleanroom garments is good barrier behavior.

Cleanroom protective garments must do more than simply provide a good barrier, however. Mechanical properties such as breaking load, elongation at break, and tear resistance must be high enough to maintain garment integrity. The garment must also be able to tolerate repeated washing and sterilization without falling apart, or substantially losing barrier protection. Workers spend a large
amount of time is these garments, and must be reasonably comfortable. Air and water vapor permeability and electrical surface resistibility are often used to assess potential comfort of a fabric. All of these factors need to be considered when choosing a fabric for cleanroom use.

2. MATERIALS AND METHODS

A number of fabrics designed at the Institute of Engineering of Textile Materials, Łódź, are intended for use in microelectronics and pharmaceutical industries. One set of fabrics, detailed in Table 1, was chosen as candidates for a garment offering a balance of environmental protection, worker comfort, garment strength, and durability.

Table 1: Fabrics included in the first study

<table>
<thead>
<tr>
<th>FABRIC WEAVE</th>
<th>AERIAL MASS G/M²</th>
<th>RAW MATERIAL</th>
<th>TWIST [TURNS/M]</th>
<th>THREADS PER DM</th>
</tr>
</thead>
<tbody>
<tr>
<td>70/3 Twill 2/1</td>
<td>125</td>
<td>Torlen 84/36</td>
<td>PE Trevira CS 167/32</td>
<td>300 0 740 305</td>
</tr>
<tr>
<td>70/5 Twill 2/1</td>
<td>113</td>
<td>Torlen 84/36</td>
<td>Torlen 110/96</td>
<td>300 0 750 350</td>
</tr>
<tr>
<td>96/5 plain</td>
<td>85</td>
<td>Torlen 84/85</td>
<td>Torlen 110/96</td>
<td>200 0 540 300</td>
</tr>
</tbody>
</table>

All fabrics were tested using conventional methods. Mechanical strength was characterized with breaking load and elongation, and tear resistance in warp and weft directions. Worker comfort was characterized using air and water vapor permeability and electrical resistance. Barrier properties of fabrics were assessed by measuring fabric pore sizes and counts, and by filtration efficiency of sodium chloride and silicon dioxide aerosols\(^\text{1}\). Durability was assessed by measuring fabric properties after repeated washing and sterilization cycles.

3. RESULTS

Figure 1 presents the basic mechanical parameters of the fabrics. Diagrams represent mean values of parameters for samples of fabric in weft and warp directions. All properties are seen to decrease significantly after fifty washing and sterilization cycles. For all fabrics, the breaking load and tear resistance are higher for calendered fabrics and in the warp direction.

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\(^1\) NaCl: sizing apparatus TSI 3030 for measurement time 10 min and flow velocity 3 cm/s; SiO₂: particle counter ROYCO for the same flow velocity. The particles of aerosols had the diameter from 0 to 0.75 μm for sodium chloride and from 1 to 10 μm for silicon dioxide.
Fabric comfort characteristics are shown in Figure 2. Note that air and water vapor permeability increase after washing and sterilization, and are lower for calendered fabrics. Higher air permeability for fabric 70/3 is due to use of lower number of filaments and textured yarns. All fabrics show good surface resistivity, which increases with washing and sterilization. Lower resistivity of fabric 96/6 is due to higher number of conductive warp threads.

**Comfort**
Barrier properties were measured using two aerosols. The results, shown in Figure 3, are conflicting. Further study found that the NaCl aerosol was breaking up during the filtration process, creating smaller particles that easily penetrated the fabric. For this reason, these data are of questionable validity. Another approach to barrier protection is the direct measurement of pores in the fabric. Average pore diameter and number of pores greater than two microns were measured using microscopic image analysis. Those data are summarized in Figure 4. Note that there is a relationship between fabric porosity and filtration efficiency of silicon dioxide. Fabrics with large average pore size and a large number of pores do not offer a good barrier against the aerosol.

**Figure 3.** Barrier properties of test fabrics

**Figure 4.** Fabric porosity of test fabrics

### 4. ANALYSIS

A simple linear model was fit to the test fabric properties. The three model terms were fabric, calendering, and washing and sterilizing (treated here as “none” or zero, and “yes”, or 50 cycles). The simple model explained a good deal of the property behavior, with adjusted R² values mostly above 0.9. The prediction profiler is shown in Figure 5. The prediction profiler displays prediction traces for each of the measured variables. A prediction trace is the predicted response as one variable is changed.
while the others are held constant at the current values. The three fabrics behave similarly for break and tear strength. All properties show a strong change with washing and sterilization.

The three characterized fabrics were used as candidates for an optimal cleanroom garment. The desired value of each property of interest was considered along with its relative importance. Numerical optimization was used to balance those considerations. Barrier properties were considered of the highest importance. It was assumed that lower numbers of pores and smaller pores offer better barrier protection, so that characteristic was minimized. The filtration efficiency data, discussed above, were not included in this optimization. Comfort was considered of medium importance, and air and water permeability and surface resistivity were maximized. Fabric strength is of low importance in this case, as all of the three fabrics possess sufficient strength for the application.

Optimization of the unwashed fabric data found that calendered fabric 70/3 gave the most balanced set of barrier properties, comfort and strength, with 70/5 a close second. After fifty cycles of washing and sterilization the optimum fabric is uncalendered 70/3.
<table>
<thead>
<tr>
<th>Material</th>
<th>BS warp</th>
<th>BS weft</th>
<th>EB warp</th>
<th>EB weft</th>
<th>Tear warp</th>
<th>Tear weft</th>
<th>Water vapor</th>
<th>SurfRes</th>
<th>AirPerm</th>
<th>NaCl Eff</th>
<th>SiO2 Eff</th>
<th>PoreDia</th>
<th>No_pores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>140.358</td>
<td>79.28333</td>
<td>14.69167</td>
<td>125.9083</td>
<td>±14.449</td>
<td>±12.156</td>
<td>±2.4503</td>
<td>±0.7931</td>
<td>±0.6789</td>
<td>±102.28</td>
<td>±11.438</td>
<td>±13.328</td>
<td>±28.964</td>
</tr>
<tr>
<td></td>
<td>51.5</td>
<td>27.8</td>
<td>13.34</td>
<td>3.1</td>
<td>3.514167</td>
<td>3.1</td>
<td>4.2386</td>
<td>3.596667</td>
<td>0.55614</td>
<td>69.1933</td>
<td>3.514167</td>
<td>3.389771</td>
<td>3.2621</td>
</tr>
<tr>
<td></td>
<td>79.28333</td>
<td>27.8</td>
<td>13.34</td>
<td>3.1</td>
<td>3.514167</td>
<td>3.1</td>
<td>4.2386</td>
<td>3.596667</td>
<td>0.55614</td>
<td>69.1933</td>
<td>3.514167</td>
<td>3.389771</td>
<td>3.2621</td>
</tr>
</tbody>
</table>

Figure 5. Prediction profile for three test fabrics.
5. EXTENDING THE STUDY

Eleven additional fabrics were created to join the three candidates discussed in this paper. Five of those fabrics were included in calendered and uncalendered forms. Optimization of the expanded fabric set found a superior candidate to 70/3. Pore counts and diameters were not measured for these additional fabrics, so filtration efficiency was used to quantify barrier protection. The optimal unwashed fabric was calendered p72, with 70/3 a very close second. The optimal fabric after fifty wash and sterilization cycles was uncalendered p71, with p72 a close second. Those fabrics are similar to 70/3 and 70/5, as shown in Table 2.

Table 2. Optimal fabrics from initial fabrics and expanded fabric set

<table>
<thead>
<tr>
<th>FABRIC</th>
<th>WEAVE</th>
<th>AERIAL MASS</th>
<th>warp</th>
<th>conductive warp</th>
<th>weft</th>
</tr>
</thead>
<tbody>
<tr>
<td>70/3</td>
<td>Twill 2/1</td>
<td>125</td>
<td>PES 84/36</td>
<td>Torlen 60% 56/20 PES 40% silvered 37/1 PA</td>
<td>PES Trevira text 167/32</td>
</tr>
<tr>
<td>70/5</td>
<td>Twill 2/1</td>
<td>113</td>
<td>PES 84/36</td>
<td>Torlen 60% 56/20 PES 40% silvered 37/1 PA</td>
<td>PES Torlen 110/96</td>
</tr>
<tr>
<td>p71</td>
<td>Twill 2/1</td>
<td>108</td>
<td>PES 84/36</td>
<td>Torlen 60% 56/20 PES 40% silvered 37/1 PA</td>
<td>PES Trevira text 110/128</td>
</tr>
<tr>
<td>p72</td>
<td>Twill 2/1</td>
<td>123</td>
<td>PES 84/36</td>
<td>Torlen 60% 56/20 PES 40% silvered 37/1 PA</td>
<td>PES Torlen 167/256</td>
</tr>
</tbody>
</table>

6. SUMMARY

This paper demonstrated the use of multi-variable optimization to aid in selecting fabrics for cleanroom garments. A set of fabric candidates was used to create mathematical models relating fabrics to various protection, comfort, and strength measures. Weight functions were used to include the relative importance of different garment characteristics. Barrier protection is the most important property for cleanroom garments, although comfort is also important. All of the fabrics considered in this study had adequate mechanical strength, so its importance was considered low. In a broader study, the optimization would include some minimum required value for tensile and tear strength, with little advantage given once the minimum was achieved. The logical extension of this modeling is to include fabric characteristics such as those shown in Table 2 as predictor variables, rather than simply including specific fabrics as a candidate set. This will provide a better understanding of the influence of fiber characteristics and fabric structures on garment performance, and will help guide us in creating optimal fabrics for specified conditions.
DEVELOPMENT AND APPLICATION OF ASTM F2371-05 - STANDARD TEST METHOD FOR MEASURING THE PERFORMANCE OF PERSONAL COOLING SYSTEMS USING SWEATING MANIKINS

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ABSTRACT

Thermal manikins are valuable tools for quantitatively evaluating the performance of protective clothing ensembles and Personal Cooling Systems (PCS). This paper presents the development of an ASTM standard test method (F2371-05, [1]) for measuring the heat removal rate and corresponding cooling duration of personal cooling systems using a sweating heated manikin. This standard is used to quantify and compare the cooling provided by different PCS worn with an outer-garment (standard or specified). The key elements of the standard test method include: (1) The standing manikin surface must remain fully sweat-wetted; (2) The manikin surface temperature is maintained at a constant uniform temperature of 35°C; (3) The ambient temperature and humidity are controlled at 35°C and 40%; (4) A baseline test with the PCS not activated is required to obtain the baseline cooling rate as a result of evaporative heat transfer in 35°C isothermal condition; (5) The heat removal rate is defined as the total cooling rate of the performance test less the baseline cooling rate; (6) The average heat removal rate is defined as the time-averaged power obtained from the numerical integration of the power input with respect to the time until the effective cooling rate has decreased to 50 W minus the baseline cooling rate; (7) The cooling duration is the time required for the heat removal rate to decrease to 50 W; and (8) Three independent replications of the cooling test are required. This standard method is currently being validated through round-robin testing, as required by ASTM.

1. INTRODUCTION

Personal Cooling Systems (PCS) are used by individuals exposed to conditions that render the body’s thermoregulatory system unable to maintain the body’s core temperature within a safe range. Such conditions include high metabolic rates required by physically demanding activities in elevated ambient temperature/humidity environments. These conditions may include solar and/or surface radiation also. In addition, protective clothing that is impermeable to moisture vapor transport will increase the probability that a worker will suffer from heat stress under these conditions. The use of PCS can reduce the possibility of heat stress related physiological disorders and provide increased comfort, as well as higher productivity. The PCS should be selected such that it is best suited for the specific application.
Heated manikins provide a convenient tool to directly compare and assess the cooling rate and cooling duration provided by the PCS while eliminating the variables associated with human physiology. This paper reports the development and application of a standard test method for measuring the heat removal rate of PCS using a sweating heated manikin.

2. STANDARD TEST METHOD

2.1. SWEATING MANIKIN

At the onset of the standard development, the Human Factors Subcommittee in the F23 Protective Clothing Committee considered using dry heated manikins, as most heated manikins currently in use worldwide, do not have a sweating capability. In addition, there was already an existing standard that used dry manikins, ASTM F1291 [2], and it had successfully undergone inter-laboratory comparison testing. It was therefore anticipated that an earlier adoption of a dry manikin method for the evaluation of PCS would be possible.

However, a major drawback of dry manikins is that they cannot be used to test PCS that rely on evaporative cooling. Systems involving vortex tube air systems, liquid air systems, desiccant air drying systems, amongst others, require a wet testing methodology. Moreover, significant differences in cooling rates have been observed using dry and sweating manikins for the same PCS in the same conditions [3]. This occurred even for PCS that do not rely on evaporative cooling (Fig. 1). The sweating manikins were found to generate cooling rates about 3 times higher than those obtained with dry manikins, for the cases tested. By selecting an apparatus that yields the highest cooling rates (and most likely the most meaningful from a physiological standpoint), one avoids the possibility of manufacturers quoting cooling rates that are more advantageous to them, using a test method that differs from the standard. Some examples of a sweating system include a cotton body suit saturated with water or water fed capillary body suit worn over a thermal manikin.

The manikin must have the ability to evaporate water from its surface, which must remain saturated throughout the test period. The water added to the sweating surface must first be brought to the manikin’s skin temperature, to avoid any dry heat transfer effects. The surface area from which water is evaporated must include the chest, back, abdomen, buttocks, arms and legs. Manikins without sweating heads, hands or feet cannot be used to evaluate PCS that provide cooling to these areas. Finally, the manikin must be able to maintain a constant uniform temperature over its entire surface, with no local hot or cold spots. The skin temperature of the manikin was selected to be 35°C.

2.2. THE ENVIRONMENTAL CHAMBER

To obtain repeatable and meaningful results, the manikin is placed in a temperature-controlled environmental chamber. The environmental chamber and the manikin surface are set at the same temperature (35°C), to limit the importance of direct dry heat transfer between the manikin and the environment. Otherwise, at different temperatures, dry heat transfer would occur irrespective of the presence of PCS. In addition, given that some PCS only cover a fraction of the body (e.g. vests only cover the torso), it was not considered to be practical to let heat transfer take place on regions where no PCS is worn. Thus, all heat transfer, with the exception of the evaporative heat transfer taken into
account through the baseline test, is solely due to the presence of the PCS. This standard also provides temperature, humidity, and wind control requirements.

2.3. PCS AND PPE CONFIGURATIONS

In previous studies, deviations in garment fit have also been shown to significantly affect the performance of the PCS (see Fig. 2), with tighter fits resulting in higher cooling rates [4]. The size of the PCS garment that best fits the manikin should therefore be selected. The outer-garment can consist of standard coveralls having a “clo” value of 1. Alternatively, any other specified outer garment can be used, allowing the measurement of PCS effectiveness in specific PPE configurations such as firefighting, combat, explosive ordnance disposal, etc. It is critical to specify, in the test results, which outer-garment was employed, as noticeable differences in cooling rates have been observed when testing manikins wearing different outer-garments in otherwise identical configurations (Fig. 3 [5]).

2.4. BASELINE TEST

A baseline test without cooling must first be carried out to quantify the evaporative cooling taking place irrespective of the PCS. The effective cooling rate (final output of the standard method) is then obtained by subtracting the baseline power from the performance test power. It is therefore critical that the baseline test be carried out in the same configuration as the performance test. As such, tests involving Phase Change Material (PCM) vests must be first conditioned to the chamber environment and then donned on the manikin, during baseline testing. In such a case, the PCM vests do not provide cooling, but still provide the same water permeability and insulation properties, ensuring that the baseline test is representative. For similar tests involving Liquid Circulating Garments (LCG), the cooling must be turned off for the baseline tests.

2.5. CONSIDERATIONS RELATED TO THE COOLING POWER

Through previous manikin testing [6], it was found that some PCS provide a very high cooling rate, but for a very short duration (only a few minutes). Such PCS are not deemed effective, from the user’s standpoint. The PCS exhibiting that behavior typically rely on the evaporation of water to provide the
cooling effect. When these PCS are placed on the heated manikin, there is initially a large power spike, as the thermal manikin responds to the increased evaporation at its surface (see the power vs. time traces in Fig. 4). In a short period of time however, the power generally drops to a much lower level. Such an initial spike in power is also observed with other PCS, but does not tend to dominate the overall performance of the system. The ASTM method therefore had to take into account these particular cases, to guide potential users/buyers with PCS selection.

To address this issue, it was therefore decided to add in the standard a clause that states that the PCS must provide a minimum of 50 W of cooling, for at least 30 minutes. A 50 W cut-off was determined because any cooling rate below that value has very little practical value (for activities lasting less than 30 minutes, one could question the need for a PCS). Therefore, measurements of heating power are made until the effective cooling rate has decreased to 50 W, up to a maximum of 2 hours. Steady state may be reached for PCS with "infinite" cooling source (such as vapor compression cooling). Otherwise, the cooling rate will vary with time.

The cooling rate is thus calculated as the time average of the power input to the manikin, until the effective power has decreased to 50 W, for a maximum of 2 hours. The effective cooling rate is determined by subtracting the average power input value and the baseline power value. The duration of cooling is determined as the time required for the net cooling power to decrease to 50 W. If such a decrease was not observed within the two-hour maximum testing period, the duration is defined as "more than 2 hours".

Finally, as a consequence of the power spike observed at the beginning of the test, for many PCS, the requirement for constant manikin surface temperature included in the standard is relaxed for that initial highly transient state; this is needed as thermal manikins cannot respond instantaneously to sudden boundary condition changes.

2.6. TEST REPLICATIONS

Three independent replications of the performance test must be conducted. The PCS shall be removed from the manikin at the end of each test, and donned again at the beginning of the next one. In this way, normal variations in dressing and instrumentation are taken into account. It is deemed sufficient to test only one sample personal cooling system, with replicate measurements made on that single sample.
3. ROUND-ROBIN TESTING

ASTM requires that round-robin testing be carried out at 6 different laboratories (if possible), no later than 5 years after standard approval. To provide a validation of the proposed ASTM standard method for measuring the effectiveness of PCS, three types of PCS were chosen for the purpose of inter-laboratory round-robin testing. The first one is a Liquid Circulating Garment (LCG) which uses ice as a cooling source. The other two are Phase Change Material (PCM)-based PCS.

At the time of publication, only one laboratory had completed the validation testing: the Institute of Textile and Clothing, Hong Kong Polytechnic University. Their sweating manikin, referred to as “Walter”, is depicted in Fig. 5. The clothing configuration used in the testing was, starting from the manikin skin: 100% cotton under shirt and pants, the PCS under test, with flame-resistant long sleeve shirt and trousers as outer-garment. Figure 5 shows the 3 PCS worn on the manikin without outer-garment. The tests followed the procedures given in the standard.

For the PCS 1 case (LCG-type), very repeatable results were obtained from the 3 test replications, with the standard deviation value amounting to less than 1% of the cooling rate. For the Phase-Change-Material (PCM) based PCS, larger variations were observed, respectively 3.8% and 11.1%. Standard deviations amounting to 16% and 12% of the total duration values were observed for PCS 1 and PCS 2, respectively. For the PCS-3 case, the duration was longer than 2 hours, and thus not exactly evaluated.

The preliminary results obtained so far provide an estimate of intra-laboratory test variations, for one particular laboratory. It is observed that a higher variability might be expected from the measurement of cooling duration, as compared to cooling rate. It is also observed that LCG-based PCS seem to provide a more repeatable performance, as compared to PCM-based PCS.

![Figure 5: Three test PCS worn on the manikin (without outer-garment).](image)

4. CONCLUDING REMARKS

A standard test method (ASTM F2371-05) for measuring the heat removal rate of personal cooling systems using a sweating heated manikin has been developed. It is to be used to quantify and compare the cooling provided by different PCS worn with a standard outer-garment or one that is specified in an isothermal condition. The standard has been formally approved by ASTM, and it is available for purchase at ASTM.org. The interlaboratory testing is continuing.
5. ACKNOWLEDGEMENT

The authors thank the Hong Kong Polytechnic University for its participation in round-robin testing activities. Contributions to the development of the standard test method from the U.S. Army Natick Soldier Center, the Kansas State University Institute for Environmental Research, W.L. Gore & Associates, North Carolina State University, Measurement Technology Northwest and Système Vêtement (France) are also acknowledged.

REFERENCES

ABSTRACT

This study is part of the EU ThermProtect project and investigates the effect of solar radiation on heat strain in personal protective equipment (PPE). Eight subjects walked for 60 minutes at 4.5 km/hr on a treadmill in two different PPE coveralls made of reflective materials (A) and black nomex (B). They walked without radiation and with one sided (AR and BR respectively) and two sided (BR2) radiation in both coveralls.

Core temperature increased about 0.3°C during walking, no significant differences were found between the five conditions.

Mean skin temperature increased by about 1°C in the impermeable A condition, while it remained essentially unchanged in B. The hampered heat loss in A due to impermeability for water vapour likely explains the differences. This is supported by the relatively low sweat efficiency in the reflective suit. No difference in mean skin temperature was observed between AR, BR and BR2. Mean skin temperature in the irradiated part was higher in BR than in BR2, but irradiated surface area was larger in BR2.

The dry heat loss component was significantly smaller in the radiation conditions with the black nomex coverall compared to the reflective coverall. This was compensated by significantly more sweat evaporation in these conditions. No differences were found in heat balance between BR and BR2.

In conclusion, the impermeable reflective suit caused a higher heat strain in the conditions without radiation. When radiation was applied, the reflective properties caused the differences between the two suits in heat strain to disappear. No differences were found between one and two sided radiation.

1. INTRODUCTION

The use of personal protective clothing (PPC) is often studied, but less is known about the effects of radiation on PPC. In this experiment the heat transfer through PPC with different radiant properties will be studied to investigate the heat transfer that takes place when wearing the protective clothing in thermal radiation.
The experiment is a part of work package 1 of the ThermProtect project. In this work package a stepwise approach was followed, starting with measurements on material samples, followed by evaluations on manikins to obtain a general model of the effects of radiation and on heat transfer in protective clothing. The effects found on the manikins and incorporated into the model have to be verified in human experiments. The objective of this experiment was to obtain data in human wear trials that can be used to validate the model to be derived from manikin measurements, and to provide additional information on special situations.

In this experiment two questions of work package 1 were addressed. One question was about the effect of short wave radiation on protective clothing in relation to the reflectivity of the garment material. The other question was about the radiation angle and area in relation to the reflectivity of the garment material.

These two questions can be answered by executing a single experiment, thereby addressing the following question: “What are the effects of short wave radiation and radiation angle and area on protective clothing in relation to the reflectivity of the garment material?”

In this experiment with human subjects two garments, selected from the manikin measurements, were tested: a black nomex suit and a reflective suit. Both garments were tested in subjects walking on a treadmill with and without radiation from two lamps. Thereby, the black nomex suit was also tested with two sided radiation to see the effect of the radiation angle and area.

2. MATERIALS AND METHODS

Eight healthy, male, 22 ± 2 years old, subjects participated in the study. They were informed of the nature of the experiments and signed an informed consent for participation.

The subjects visited the research laboratory of TNO five times. Prior to each visit, participants were asked to refrain from vigorous exercise for at least 24h and eating for 1h.

All experimental sessions were executed in an environmental chamber. The temperature in the neutral climate was set at 20.0°C and the relative humidity at 42.0%. There was a continuous air flow of 0.2 m/s in the environmental chamber.

Subjects wore polypropylene underwear (Helly Hansen Super Bodywear). They wore two kinds of suits as outer layer. One was a black nomex coverall, the other one was a reflective coverall. The black nomex material has a thickness of 0.55 mm and a weight of 265 g/m². The reflective material has a thickness of 1.02 mm and a weight of 366 g/m².

Before the start of the experiment, subjects stayed about 20 minutes in a neutral climate to get into a stable thermal condition. During each session subjects had to walk on a treadmill for 60 minutes. The velocity of the treadmill was set at 4.5 km/h. All subjects executed the following five exercise sessions in a balanced order:

B - Black nomex suit, no radiation
A - Reflective suit, no radiation
BR - Black nomex suit, one sided radiation
AR - Reflective suit, one sided radiation
BR2 - Black nomex suit, two sided radiation
In the conditions with one sided radiation, two lamps (Thorn OQI 1000, England) were positioned in front of the subject. The lamps were directed to the subject’s chest. The distance between the subject and each lamp was on average 120cm, while the distance between the two lamps was 87cm. Radiation angle was 9°. The same two Thorn lamps with the same height and radiation angle were used in the conditions with two sided radiation. The distance between the two lamps was 250cm, the subject walked in the middle between the two lamps. No significant differences were found between the black globe temperatures of the conditions with one sided and the condition with two sided radiation.

To determine core temperature (15-s sample), participants inserted a rectal probe (YSI 701, Technomed, Beek, The Netherlands) approximately 10 cm into the anus. Skin temperature (1-min sample) was measured by eight iButtons (DS1921 H High Resolution Thermochron iButton, Dallas Semiconductor, USA). The iButtons were placed on the right upper chest, left abdomen, right anterior thigh, left upper arm, right upper arm, left scapula, right paravertebral and left posterior thigh. The temperature of the clothing was measured (15-s sample) using thermocouples (Tempcontrol, Voorburg, The Netherlands). The temperature of the outside of the underwear was measured at four locations: right upper chest, right anterior thigh, left scapula and left posterior thigh. The outer surface of coverall temperatures were measured at the right upper chest and the left scapula. Oxygen consumption was determined during the last five minutes of every fifteen minutes. This was done by analysing the expired gases using an Oxycon Pro (Mijnhardt, Bunnik, The Netherlands). The subject and clothing were weighed separate and together at the beginning and at the end of the exercise period using a balance (Sartorius F300S, Germany) with a resolution of one gram.

Respiratory exchange ratio (RER) was calculated by dividing VCO₂ by VO₂.

The body surface area (A) in m² was estimated using the formula of DuBois and DuBois (1916):

\[
A = 0.202 \cdot \text{body weight}^{0.425} \cdot \text{stature}^{0.725}.
\]

Mean skin temperature (Tₘₖ) was calculated as the simple mean of the eight simultaneous skin temperature measurements.

Mean body temperature (Tₜₚ) in °C is most accurately estimated by measuring Tₘₖ and Tₜ and make a weighed mean. It was calculated using the following equation: Tₜₚ = 0.8Tₜ + 0.2Tₘₖ.

The heat balance equation was defined as:

\[
M = E \pm S \pm \text{Resp} \pm C \pm K \pm R
\]

In which:

- M (metabolic heat production) = ((4940 \cdot \text{RER} + 16040) \cdot \text{VO}_2)/60
- E (evaporative heat loss) = \delta \text{body weight} \cdot 2430/\delta t
- S (heat storage) = (\delta T_t \cdot \text{body weight} \cdot 3.49)/\delta t
- \text{Resp} (respirative heat loss, only dry component since evaporative component is included in E) = 0.0014 \cdot M \cdot (34 – 20)
- C (convective heat loss) \pm K (conductive heat loss) \pm R (radiant heat loss) is dry heat loss. Dry heat loss was defined as: \text{Dry heat loss} = M – E – S – \text{Resp}

Where (4940\cdot\text{RER}+16040) the thermal equivalent of oxygen is, corrected for fuel composition. 2430 is the heat of evaporation of water in J g⁻¹, \delta t is the time span in seconds, 3.49 is the specific heat of
body tissue in J g⁻¹ °C⁻¹, 34 is the temperature of the exhaled air and is 20 is the ambient air temperature.

The statistical analysis was performed for the whole exercise period as well as for the last 15 minutes of exercise. Means and standard deviations were reported for dependent variables. A two-way (session x time) repeated measures ANOVA was used to determine whether there were significant differences for session and time. If significant effects were observed, a Tukey HSD post hoc analysis was performed for the five most relevant comparisons: A vs. B, A vs. AR, B vs. BR, AR vs. BR and BR vs. BR2. Statistical significance was accepted at p<0.05.

3. RESULTS

All eight subjects completed the entire protocol. Table 1 shows the mean and standard deviation (SD) for all measured variables at the beginning (first minute) and at the end (last five minutes) of the exercise period. For all variables the values presented are averages of all subjects.

Table 1. Mean and SD values at the beginning (b) and end (e) of the exercise period of core temperature, skin temperature, outer and under clothing temperature, oxygen consumption, total and evaporated sweat loss for five experimental conditions.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Period</th>
<th>B Mean ± SD</th>
<th>A Mean ± SD</th>
<th>BR Mean ± SD</th>
<th>AR Mean ± SD</th>
<th>BR2 Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tcore (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>37.25±0.44</td>
<td>37.25±0.27</td>
<td>37.26±0.29</td>
<td>37.35±0.25</td>
<td>37.30±0.38</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>37.47±0.32</td>
<td>37.54±0.24</td>
<td>37.51±0.13</td>
<td>37.59±0.27</td>
<td>37.61±0.20</td>
<td></td>
</tr>
<tr>
<td>Tskin (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>31.67±0.82</td>
<td>31.98±1.05</td>
<td>33.58±0.64</td>
<td>33.58±0.61</td>
<td>33.54±0.86</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>31.79±0.45</td>
<td>33.05±0.50</td>
<td>34.08±0.52</td>
<td>34.18±0.60</td>
<td>34.39±0.59</td>
<td></td>
</tr>
<tr>
<td>Touter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>24.38±1.50</td>
<td>19.03±7.65</td>
<td>30.66±7.44</td>
<td>28.92±7.52</td>
<td>37.35±5.35</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>23.33±1.73</td>
<td>21.87±4.04</td>
<td>31.90±11.96</td>
<td>29.76±5.48</td>
<td>38.22±4.91</td>
<td></td>
</tr>
<tr>
<td>Tunder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>27.16±1.99</td>
<td>27.63±2.58</td>
<td>31.64±3.69</td>
<td>31.12±2.25</td>
<td>33.62±4.68</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>26.14±1.92</td>
<td>28.07±2.03</td>
<td>32.22±6.73</td>
<td>29.76±2.21</td>
<td>33.83±5.41</td>
<td></td>
</tr>
<tr>
<td>VO₂ (ml/min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>1065±158</td>
<td>1138±173</td>
<td>1175±232</td>
<td>1170±215</td>
<td>1097±150</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>1049±147</td>
<td>1102±129</td>
<td>1110±185</td>
<td>1129±169</td>
<td>1085±151</td>
<td></td>
</tr>
<tr>
<td>Sweattot (ml)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>309±70</td>
<td>309±107</td>
<td>444±57</td>
<td>425±101</td>
<td>457±72</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>297±64</td>
<td>253±70</td>
<td>431±52</td>
<td>334±51</td>
<td>443±61</td>
<td></td>
</tr>
</tbody>
</table>

In all five conditions a significant increase in core temperature was seen during the exercise period. No significant differences were found between the five experimental conditions.

During the last 15 minutes of exercise, when subjects were in a stable situation, mean skin temperature was significantly higher in A than in B. In the conditions with one sided radiation no significant differences were seen between AR and BR. Also no differences were found between one and two sided radiation in the black nomex suit. Mean skin temperatures in all radiation conditions were significantly higher than in the conditions without radiation.

In the BR and BR2 conditions the irradiated part of the skin had a significantly higher temperature than the non-irradiated part. In AR no differences were found between irradiated and non-irradiated...
Comparing BR and BR2 mean temperature of the irradiated skin was higher in BR, but condition BR2 had a larger irradiation area. Therefore, the temperature of the scapula and paravertebral were significantly higher in BR2 than in BR, but chest and abdomen temperature were significantly higher in BR compared to BR2.

In condition B as well as in condition A temperature of the outside of the coverall was significantly lower than the temperature of the underclothing. No differences were found in underclothing as well as in coverall temperature between B and A during the last 15 minutes of exercise. Comparing the conditions with one sided radiation, no differences were found in the non-irradiated part of the suits. Clothing temperatures of the irradiated part of the suits, anterior thigh and chest (under and outer clothing), were significantly higher in BR than in AR.

In condition BR2 no significant differences were found between underclothing and coverall temperature of chest and scapula. Underclothing temperatures of posterior and anterior thigh were significantly lower. Under and outer clothing temperature of the irradiated part in BR was significantly higher compared to BR2, but irradiation area in BR2 was larger than in BR.

See Figure 1 for the mean values of core temperature and chest temperature on the skin, underclothing and outer clothing during the last 15 minutes of exercise.

**Figure 1.** Mean core, chest skin, chest underclothing and chest outer clothing temperature during the last 15 minutes walking in five different conditions

The heat balance was calculated over the stable last 15 minutes of the walking period. Body weight was only measured at the beginning and end of the exercise period. Based on the assumption that evaporation was a linear process, this values were used. Table 2 shows the results of the mean and standard deviation values of evaporation, dry heat loss, respirative dry heat loss and heat storage. No significant differences in heat storage were found between the five conditions. The dry heat loss component was significantly smaller in the radiation conditions with the black nomex suit. This was compensated by significantly more sweat evaporation in these conditions.
Table 2. Mean and SD values of metabolic heat production, heat storage, evaporative heat loss, respirative heat loss (dry) and dry heat loss during the last 15 minutes walking in five different conditions

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>A</th>
<th>BR</th>
<th>AR</th>
<th>BR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolic production</td>
<td>353 ± 36</td>
<td>368 ± 35</td>
<td>373 ± 45</td>
<td>377 ± 48</td>
<td>363 ± 42</td>
</tr>
<tr>
<td>Heat storage</td>
<td>4 ± 14</td>
<td>7 ± 9</td>
<td>11 ± 11</td>
<td>5 ± 13</td>
<td>11 ± 16</td>
</tr>
<tr>
<td>Evaporative loss</td>
<td>201 ± 43</td>
<td>171 ±47</td>
<td>291 ±35</td>
<td>225 ± 34</td>
<td>299 ± 41</td>
</tr>
<tr>
<td>Respirative heat loss (dry)</td>
<td>7 ± 1</td>
<td>7 ± 1</td>
<td>7 ± 1</td>
<td>7 ± 1</td>
<td>7 ± 1</td>
</tr>
<tr>
<td>Dry heat loss</td>
<td>141 ± 31</td>
<td>182 ± 42</td>
<td>64 ± 55</td>
<td>138 ± 35</td>
<td>46 ± 39</td>
</tr>
</tbody>
</table>

4. DISCUSSION

The five most interesting comparisons will be made. The two conditions without radiation can be compared (A versus B). The conditions with radiation can be compared to the conditions without radiation in the same suit (A versus AR and B versus BR). The two radiation conditions can be compared to each other (AR versus BR) and one sided radiation can be compared to two sided radiation (BR versus BR2).

The mean skin temperature increased by about 1°C in the impermeable A condition, while it remained essentially unchanged in B. Core temperature and heart rate did not differ between the two conditions. Metabolic heat production was higher in A. No differences were found in fluid loss, but subjects could sweat more efficient in the black nomex suit since the water vapour barrier of the reflective material is much higher that that of nomex.

Since there were no significant differences in heat storage as well as in heart rate, metabolic heat production, core and mean skin temperature between condition AR and BR, we may conclude that there are no major differences in heat strain between wearing the black nomex suit or the reflective suit with one sided radiation. Compared to BR, in AR the heat is more equally distributed over the body, because in AR no differences were found between non-irradiated skin and irradiated skin and clothing temperature. In BR irradiated skin and clothing temperature were significantly higher. The subjects’ opinion on comfort of the suits differed. Some subjects preferred the reflective suit, since they appreciated the good heat distribution over the body; others preferred the nomex suit for its weight and flexibility.

It is shown that the reflective suit lowers the temperature of the underclothing. The temperature of the outer clothing layer is also lower in AR, but due to the heating of the tape on top of the thermocouples, the real effect may have been underestimated.

The results of the heat balance show that in BR more sweat was evaporated than in AR, but total fluid loss was not different between both conditions. In AR the dry heat loss component was larger, because
of the temperature difference between skin and underclothing. Therefore, the disadvantage of a higher vapour resistance in the reflective suit was compensated by the reflectivity of the material.

No significant differences were found between BR and BR2. Core temperature, mean skin temperature and heart rate did not differ. Also, no differences were found in evaporative and dry heat loss. In the condition with two sided radiation skin and clothing temperature in the irradiated part of the body were lower than in the condition with one sided radiation, but radiation area was larger. Some subjects preferred two sided radiation, because radiation is applied more equally over the body, other subjects preferred one sided radiation, because of the relatively cool backside of the body.

For methodological reasons the BR2 session was always performed in a later session than the BR experiments.

In conclusion, the impermeable reflective suit caused a higher heat strain in the conditions without radiation. When radiation was applied, the reflective properties caused the differences between the two suits in heat strain to disappear. No differences were found between one or two sided radiation.
EFFECTS OF THE PROPERTIES OF T-SHIRTS ON WEARERS’ COMFORT SENSATIONS

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ABSTRACT

This study is aimed at investigating the relationships between human comfort sensations and clothing properties. 14 types of T-shirt materials were included in the investigation. The thermal, moisture transport and other physical properties of T-shirt fabrics were tested using the instruments and methods including Thermal Labo II, Contact Angle Meter, Moisture Transmission Test, Air Permeability Test and Moisture Regain Test. The T-shirts made of such fabrics were also tested using the sweating manikin-Walter in terms of thermal insulation and moisture vapour resistance.

Four male subjects were invited to conduct the wearer trials of the T-shirts in the climatic chamber of 20°C and 65% RH. The wearers were asked to perform a cycle of activity including running for 30 minutes at 6.0 km/hr and resting for 10 minutes. The comfort sensations at the start, in the middle, at the end and after the running exercise were recorded. Principle Component Analysis was applied to correlate the comfort sensations with the properties of T-shirt fabrics and the measurements of T-shirts from the sweating manikin-Walter.

1. INTRODUCTION

Subjective comfort preference decisions of garment, which are important for modern clothing manufacturers, are dependent on individuals’ psychological and physiological responses and the objective physical properties of the clothing materials\(^1\). Thus, the relationship and predictability between subjective thermal comfort sensation and objective heat and moisture transfer properties of clothing materials are valuable to investigate.

Based on the previous studies, many researchers\(^2,3,4,5,6\) had only examined the relationship between the comfort sensation and an individual specific property such as air permeability and thermal insulation under specific condition. However, it’s not sufficient to identify subjective comfort sensation by limitation of the objective physical factors of the fabrics. Besides, there are some new developed instruments such as thermal manikin\(^7\) which can be used to predict the thermal comfort by evaluating heat and mass transfer of the overall clothing systems in a relevant, reliable and accurate way. It is
therefore valuable to carry a research to investigate such relationship with consideration of any wide important clothing properties which could affect the subjective sensation.

The purpose of this study is to investigate the relationship and predictability between human comfort sensations and clothing properties by means of Principle Component Analysis and Multiple Linear Regression.

2. METHODOLOGY

2.1. SAMPLES

Seven interlock and seven single jersey functional T-shirts fabrics were chosen from commercially available samples, representing T-shirts that are typically worn by consumers in environmental conditions similar to those in this study. The fabrics were sewn into long-sleeved T-shirts for the wearer trial experiments. Table 1 shows the characteristics of the fabrics used in this study.

Table 1. Characteristics of T-shirt samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Compositions</th>
<th>Construction</th>
<th>Thickness (mm)</th>
<th>Mass per unit area (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55% Polyester 40S/2</td>
<td>Single Jersey</td>
<td>0.6962</td>
<td>199.27</td>
</tr>
<tr>
<td></td>
<td>45% Combed Cotton Jersey</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>62% Combed Cotton 40S</td>
<td>Single Jersey</td>
<td>0.8318</td>
<td>284.23</td>
</tr>
<tr>
<td></td>
<td>31% Nylon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7% Lycra Jersey</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>100% Polyester</td>
<td>Single Jersey</td>
<td>0.644</td>
<td>193.43</td>
</tr>
<tr>
<td>4</td>
<td>60% Cotton 40S Polyester</td>
<td>Single Jersey</td>
<td>0.6266</td>
<td>192</td>
</tr>
<tr>
<td>5</td>
<td>44% Combed Cotton 40S Polyester</td>
<td>Single Jersey</td>
<td>0.7036</td>
<td>200.87</td>
</tr>
<tr>
<td></td>
<td>45% Spun Polyester 11% Lycra</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>93% Nylon 7% Spandex</td>
<td>Single Jersey</td>
<td>0.613</td>
<td>229.7</td>
</tr>
<tr>
<td>7</td>
<td>100% Cotton</td>
<td>Single Jersey</td>
<td>0.556</td>
<td>150.93</td>
</tr>
<tr>
<td>8</td>
<td>63% 50S Interlock</td>
<td>Interlock</td>
<td>0.772</td>
<td>148</td>
</tr>
<tr>
<td>Material Properties</td>
<td>Testing Methods</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Permeability</td>
<td>ASTM D737-96 Air Permeability Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>KES-F7 Thermo Labo II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial warm/cool feeling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat keeping property (thermal insulation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact angle</td>
<td>Contact Angle Meter Test (Model CAM-MiCRO)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Initial angle of dropping a water droplet on the fabric surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time of water droplet absorption</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Time of absorbing a water droplet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content / Moisture regain</td>
<td>Moisture Regain Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal insulation of whole garment</td>
<td>Sweating Manikin (Walter)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water vapor resistance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2. OBJECTIVE PHYSICAL MEASUREMENTS

To investigate the heat and moisture transfer properties of the T-shirts/T-shirt fabrics highly related to human comfort perception the following physical experiments were conducted, which are the testing methods commonly used in previous researches.3,4.

Table 2. Summary of measuring methods
2.3. SUBJECTIVE COMFORT SENSATIONS OF HUMAN

Four healthy males served as subjects for the wearer trials in order to collect the subjective data by filling in the questionnaire. During the tests, the wearer(s) wearing T-shirt sample was( were) asked to run on a running machine at a speed of 6.0 km/h in a conditioned chamber with the temperature of 20°C and the relative humidity of 65%. Each subject tested each sample once under the same condition. Each trial consisted of a short period of rest before and after the exercise. The procedure of the wearer trial was shown in Fig. 1.

Figure 1. Procedure of Wearer Trial

![Time (mins)](-10-5 0 5 10 15 20 25 30 35 40)

Figure 1. The questionnaire of the sensory test

- = running
- = filling in different sections of questionnaire

The subjective evaluation was conducted by rating their sensation in different period of time. The warm/cool sensation, skin wetness sensation and overall comfort sensation were evaluated at a scale range from -3 to 3 whereas 0 means normal. The questionnaires were shown in Fig. 2. Figure 2. Questionnaires for the evaluation of subjective sensation

Section 1: Temperature Sensation

<table>
<thead>
<tr>
<th>Extremely Cool</th>
<th>Very Cool</th>
<th>Cool</th>
<th>Normal</th>
<th>Slightly Hot</th>
<th>Very Hot</th>
<th>Extremely Hot</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Section 2: Humidity Sensation

<table>
<thead>
<tr>
<th>Extremely Dry</th>
<th>Very Dry</th>
<th>Dry</th>
<th>Normal</th>
<th>Slightly Damp</th>
<th>Very Damp</th>
<th>Extremely Damp</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Section 3: Overall Comfort Sensation

<table>
<thead>
<tr>
<th>Extremely Uncomfortable</th>
<th>Very Uncomfortable</th>
<th>Slightly Uncomfortable</th>
<th>Normal</th>
<th>Slightly Comfortable</th>
<th>Very Comfortable</th>
<th>Extremely Comfortable</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>
3. **RESULTS AND DISCUSSION**

3.1. **PRINCIPAL COMPONENT ANALYSIS**

The quantitative data of objective measurements and subjective ratings were analyzed by a statistic tool (SPSS version 12.0) to study the interrelationship between the heat and moisture transfer properties of T-shirts and subjective comfort sensations. By principal component analysis, three factors were extracted from the twelve material properties as mentioned in Table 3.

For the first component, moisture regain/content and contact angle (0.894/0.896 and 0.870) have relatively higher predictive power. It represents that the first component is highly related to the ability of the sweat absorption and the moisture which the fabric contain. Moreover, it is also closely dependent on the thermal conductivity of fabric (0.761), but the other objective properties are almost useless for predicting subjective sensation.

It can be observed from Table 3 that thermal insulation of whole garment (0.828) and insulation value of T-shirt fabric (0.764) have a significant predictive power in the second factor. As a result the second component is mainly dependent on the thermal insulation of the materials. The periods of water absorbency (-0.771) and initial warm/cool feeling are also fairly good predictors.

For the third component, mass per unit area and thickness of fabric are relatively higher predictors (0.717 and 0.700), so this component is mainly dependent on the construction and structure of the material. In addition, water vapor resistance of the whole garment also has a higher predictive power (0.765) and air permeability is fair important (-0.527), so the third component is also related to the air and moisture transfer properties of the fabric.

**Table 3.** Three components of twelve material properties by principal component analysis.

<table>
<thead>
<tr>
<th></th>
<th>Component 1</th>
<th>Component 2</th>
<th>Component 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass per unit area (g/m²)</td>
<td>.322</td>
<td>-.380</td>
<td>.717</td>
</tr>
<tr>
<td>thickness (mm)</td>
<td>.208</td>
<td>.531</td>
<td>.700</td>
</tr>
<tr>
<td>Air Permeability (cm³/s/cm²)</td>
<td>-.532</td>
<td>.346</td>
<td>-.527</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mk)</td>
<td>.761</td>
<td>-.221</td>
<td>.556</td>
</tr>
<tr>
<td>q-max (W/cm²)</td>
<td>.555</td>
<td>-.742</td>
<td>-.085</td>
</tr>
<tr>
<td>insulation value (clo)</td>
<td>.011</td>
<td>.764</td>
<td>.301</td>
</tr>
<tr>
<td>contact angle</td>
<td>.870</td>
<td>-.369</td>
<td>-.088</td>
</tr>
<tr>
<td>Period of absorbent (second)</td>
<td>.214</td>
<td>-.771</td>
<td>.126</td>
</tr>
<tr>
<td>Moisture Regain (%)</td>
<td>.894</td>
<td>.219</td>
<td>.302</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
<td>.896</td>
<td>.216</td>
<td>.302</td>
</tr>
<tr>
<td>Thermal insulation by Walter (m²oC/w)</td>
<td>.224</td>
<td>.828</td>
<td>-.103</td>
</tr>
<tr>
<td>Water Vapour Resistance by Walter (m²Pa/w)</td>
<td>.062</td>
<td>.181</td>
<td>.765</td>
</tr>
</tbody>
</table>

(Statistic Significant <0.05 )
3.2. CORRELATION BETWEEN THREE COMPONENTS AND SUBJECTIVE PERCEPTIONS

Table 4. Multiple correlations between three components and subjective sensations.

<table>
<thead>
<tr>
<th></th>
<th>At the beginning of exercise</th>
<th>In the middle of exercise</th>
<th>At the end of exercise</th>
<th>After exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm/Cool Sensation</td>
<td>Thickness (0.712)</td>
<td>Factor 3</td>
<td>Thickness (0.588)</td>
<td>Factor 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&amp; Factor 2 (0.752)</td>
<td></td>
<td>(0.727)</td>
</tr>
<tr>
<td>Skin Wetness Sensation</td>
<td>Thickness (0.626)</td>
<td>Factor 2</td>
<td>Factor 3</td>
<td>Factor 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.592)</td>
<td>(0.561)</td>
<td>(0.639)</td>
</tr>
<tr>
<td>Overall Comfort Sensation</td>
<td>Factor 2</td>
<td>Factor 3</td>
<td>Factor 3</td>
<td>Factor 3</td>
</tr>
<tr>
<td></td>
<td>(0.788)</td>
<td>&amp; Factor 2 (0.774)</td>
<td>(0.748)</td>
<td>(0.768)</td>
</tr>
</tbody>
</table>

Multiple Linear Regression was used to investigate the relationship between three components and the subjective perceptions of human in different periods of exercise as illustrated in Table 4. However, the relationships of the three factors were not observed for the warm/cool sensation at the beginning and at the end of exercise, and skin wetness sensation at the beginning of exercise. It could be explained that the subjective perceptions in these three periods were related to an individual property of T-shirt fabric. Thus, only a single clothing property has a great predictive power for the sensation.

At the beginning of exercise, it shows that the thickness is major predictor of warmth and skin wetness sensation. The physiological changes of the human body are not significant in this period (shown in Fig. 3 - 6). It demonstrates that fabric properties have a relatively weak effect on human subjective preference. The result demonstrates that the wearers obtained the warmth and wetness perceptions by thickness directly when there is no obvious increase of skin temperature and no sweating.

For the overall comfort sensation, Factor 2 and Factor 3 are observed as the good predictors of subjective perception. The overall comfort sensation is not only dependent on the warmth and wetness sensations at the beginning of exercise. This result shows that comfort perception is closely related to the initial warm/cool feeling, thickness and mass per unit area. The first two fabric properties carry an initial uncomfortable feeling to the wearer because of the influence of his warmth perception. In addition, it is no doubt that the heavier the T-shirt, the greater wearing uncomfortableness is. Thus, the mass per unit area is a relatively good predictor of judging the comfort of a T-shirt.

**Fig. 3.** Average skin temperature of wearers by wearing different kinds of single jersey T-shirts

**Fig. 4.** Average skin temperature of wearers by wearing different kinds of interlock T-shirts
In the middle of exercise, the skin temperature and the sweating rate increase rapidly. Table 4 shows that Factor 2 has a significant positive correlation with warmth, wetness and comfort sensations. It indicates that thermal insulation is the main factor of the subjective perception in this period of time. A garment with a high thermal insulation value enhances the increase of skin temperature and sweating because it resists the release of the heat and moisture to the environment. As a result, the uncomfortable sensation is obtained from the garment with high thermal insulation.

Besides, it is observed that Factor 3 also has a high predictive power for warmth and overall comfort sensations but not for wetness perception in the middle of exercise. It’s no doubt that thickness is an important factor of the thermal sensation because of the influence of the heat transfer. Air permeability is also viewed as more essential factor of the heat transfer in this period as a garment with higher air permeability increases the efficiency and effectiveness of hot air release, especially during the period with a high increase of the metabolic rate and the skin temperature.

At the end of the exercise, the skin temperature and skin wetness had increased to the highest value during exercise. The results states that the thickness is highly related to the subjective perceptions. The heat and moisture are more difficult to transfer through a thicker fabric from the skin surface to the environment. It is an important factor for maintaining thermal comfort especially when the human body is the hottest and wettest at that moment.

In addition, it can be observed that Factor 3 is also a good predictor to skin wetness and overall sensations. It shows that the water vapor resistance is also considered by the wearer for the comfort of the garment. Wearer may feel uncomfortable if the sweat presents on his skin surface. If the garment has a better water vapor transmission rate, the sweat can be transformed to moisture and then transferred to the surrounding faster. The sweat does not condense on the skin and results in uncomfortable feeling.

After exercise, the skin temperature increased to a peak and then dropped rapidly. The skin humidity decreased gradually because of no metabolic heat produce. It is found that Factor 3 is the most important component in any comfort judgment. It demonstrates that the thermal and comfort sensation are highly influenced by the air and moisture transfer properties of the T-shirt. The fabric with a high water vapor transfer coefficient and a high air permeability could allow much hot air to flow through the fabric in order to release heat and moisture effectively. Otherwise, the heat and sweat would be trapped under the garment which results in an uncomfortable.
4. CONCLUSIONS

In this study, objective physical measurements of thermal properties of T-shirt fabrics show good relationship with the subjective preference (warmth, skin wetness and overall comfort sensations) of human at different periods of exercise. It was found that the warm/cool sensation in the middle of the running exercise is strongly related to thickness, thermal insulation and air permeability properties of the T-shirt materials. The warm/cool sensation after running exercise is highly related to water vapor resistance and air permeability of the T-shirt materials. The skin wettedness sensation in the middle of the running exercise is closely related to the thermal insulation of the T-shirt fabrics only. The skin wettedness sensation at the end of and after the running exercise is highly related to the water vapor resistance, air permeability and thickness of T-shirt materials. With regard to overall comfort, it was found that the thickness, thermal insulation and air permeability of the fabric materials had great predictive power at the start and in the middle of the running exercise whereas thickness, air permeability and water vapor transmission properties are the predictor of comfort at the end and after running exercise.

REFERENCES


EVALUATION OF DEXTERITY TESTS FOR GLOVES


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CANADA

ABSTRACT

The impairing effects of protective gloves on manual dexterity have been largely studied. However, few studies have aimed at defining a standardized test battery for assessing the effects of gloves on manual performance. This kind of test battery would make possible the comparative analysis of glove evaluation studies, the classification of products and, based on this classification, would allow users in a workplace environment to select gloves meeting their specific needs. The objective of this study was to evaluate twelve dexterity tests in their capacity to discriminate different glove models, in order to identify the most efficient and reliable tests to serve in a standardized test battery. An experiment was conducted with thirty voluntary subjects who performed twelve dexterity tests, including those proposed by standards ASTM F2010 and EN 420, under four conditions – barehanded and wearing 3 different gloves. Nine glove models were selected for the experiment, covering a wide spectrum of thickness, adherence, flexibility and type of protection. Each subject tested a different set of 3 glove models among the nine pre-selected ones. The results show that the Crawford-Screws, the O’Connor Finger, the Grooved Pegboard, the Purdue-Pins Dominant and Non-Dominant Hand, the Purdue-Assembly, the ASTM F2010, the Minnesota-Two-Hand Turning&Placing, and the Minnesota-Turning dexterity tests were more discriminative than the Crawford-Pins&Collars test, the O’Connor Tweezer and the EN 420. None of them was able to discriminate all glove models, but some tests showed a sensitivity within a specific range of manual dexterity.

INTRODUCTION

The use of protective gloves can protect workers in terms of frequency and gravity of hand lesion from various hazards. However, workers often prefer not to wear gloves which hinder the completion of their tasks. The effects of protective hand wear on manual performance have been largely studied through dexterity testing. The Minnesota-Turning test (1-3), the O’Connor Finger test (1-4), the Purdue Pegboard test (3-6), the Crawford-Screws test (2), and the O’Connor Tweezer test (7) were used to evaluate the dexterity of chemical, biological or thermal protection gloves. However, few studies have aimed at defining a standardized battery of tests which would make possible the classification of existing products, and the comparative evaluation of new ones. Such a classification
would allow users in a workplace environment to select gloves meeting their specific needs. Ervin (8, 9) pointed out that the tests must be sensitive to glove types, representative of the tasks expected to be performed in a workplace environment and have the potential to be standardized. To satisfy these requirements, a test battery could be composed of different tests, each test being sensitive within a limited range of manual dexterity (coarse, medium or fine). Few studies aimed to compare several tests, as well as to compare existing dexterity tests with existing standards ASTM F2010 (10) and EN 420 (11). The objective of this study was to evaluate twelve existing dexterity tests and to identify the most efficient and reliable ones to serve in a standardized test battery.

**METHODOLOGY**

The study was conducted with nine glove models that were evaluated using twelve existing dexterity tests on thirty voluntary subjects (15 men and 15 women). All the subjects were recruited among the staff of our organization. The age range of the subjects was 28 to 62 years (mean age : 45). Twenty-one subjects were right-handed, and 9 were left-handed.

The glove models were selected based on differences of thickness, adherence, flexibility, design and type of protection. Based on a priori estimation of their dexterity capability, they were categorized in three groups (3 gloves per group): fine, medium or coarse dexterity. The glove models and associated category are described in Table 1.

<table>
<thead>
<tr>
<th>Category</th>
<th>Id</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Fine</td>
<td>A1</td>
<td>Inspection cotton glove.</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>Disposable nitrile glove, puncture resistant.</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>Dyneema glove, cut resistant.</td>
</tr>
<tr>
<td></td>
<td>B5</td>
<td>Nitrile dipping of a fine gauge knit liner, abrasion resistant, oil repellent.</td>
</tr>
<tr>
<td></td>
<td>B6</td>
<td>White Polyurethane palm coating on a cut resistant Dyneema glove</td>
</tr>
<tr>
<td>C) Coarse</td>
<td>C7</td>
<td>Neoprene coating with dipped rough finish on an interlock knit cotton lining, chemical protection.</td>
</tr>
<tr>
<td></td>
<td>C8</td>
<td>Wrinkle finish flat dipped rubber, Kevlar® Aramid shell, general purpose.</td>
</tr>
<tr>
<td></td>
<td>C9</td>
<td>Seamless knit, loops out, heat and abrasion resistant.</td>
</tr>
</tbody>
</table>

Table 1. Description of the nine glove models

Each subject was asked to perform all twelve dexterity tests under four conditions: barehanded and wearing one pair of gloves taken from each of the three glove categories (A, B and C, see Table 1). Therefore, each glove model was tested by 10 subjects among the 30 volunteers. The tests were performed over 3 sessions of 4 tests per session. The subjects performed 16 trials per session (4 tests times 4 conditions) in a randomized order. Three repetitions of each trial were done, and were averaged for the analysis. At the beginning of a session, six practice trials were imposed for each dexterity test (except for the two standards), in the following order of increasing difficulty: two trials barehanded, two trials wearing glove from category A (the easiest) and two trials wearing glove from category C (the hardest) (8, 9). A practice trial consisted of one complete testing, or up to one minute of practice with tests that last 2 minutes and over.

Modifications were made to the instructions of dexterity tests from their original version (8, 9, 12): the number of practice trials was increased, a starting position was specified, and for some tests, the scoring procedure was simplified. The twelve existing dexterity tests are summarized in Table 2.
This study evaluated the capability of dexterity tests to discriminate between different glove models regardless of each subject’s dexterity level. For each subject, the scores obtained while wearing gloves were normalized by the mean score obtained barehanded. Therefore, a normalized performance close to 1.0 corresponds to a fine dexterity, whereas a normalized performance close to zero represents a coarse dexterity. To evaluate the sensitivity of each dexterity test to gloves, a two-way ANOVA (9 gloves, 2 sexes) and a Tukey-Kramer multiple comparison test were used. The maximum number of significant differences found between pairs of glove models (A1-A2, A1-A3, A1-B4, …, C8-C9) is 36 for nine glove models. The degree of sensitivity for each test was defined by the number of significant differences the test found divided by 36.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Crawford–Pins&amp;Collars</td>
<td>Use tweezers (dominant hand) to place pins into holes, and collars over the pins. Score (simplified): number of holes filled in 2.5 minutes.</td>
</tr>
<tr>
<td>2) Crawford–Screws</td>
<td>Use the fingers (dominant hand) to pick up screws and thread them into holes, and use a screwdriver (both hands) to turn them through. Score (simplified): number of holes filled in 2.5 minutes.</td>
</tr>
<tr>
<td>3) Grooved Pegboard</td>
<td>Insert pegs into holes by rotating them to align the key of the peg with the slot of the hole (dominant hand). Score: time needed to complete the board.</td>
</tr>
<tr>
<td>4) EN 420 Standard</td>
<td>Pick up a pin by its circumference between the forefinger and thumb. Five pins of different diameters are to be picked up, in the following order: 11, 9.5, 8, 6.5 and 5 mm. The result corresponds to the smallest diameter pin that can be picked up three times consecutively without undue fumbling within 30 seconds. To compare this test with all the others tests which record the performance speed, the time needed to complete the manoeuvre for each pin was recorded.</td>
</tr>
<tr>
<td>5) Minnesota–Two-Hand Turning &amp; Placing</td>
<td>Pick up plastic disks from a top board, two at a time (one in each hand), turn them over and place them into the holes of a bottom board. Score: time taken to complete the board.</td>
</tr>
<tr>
<td>6) Minnesota–Turning</td>
<td>Pick up plastic disks with one hand, turn them with the other hand, and replace them back into the holes. Score: time taken to complete the board.</td>
</tr>
<tr>
<td>7) O’Connor Finger</td>
<td>Pick up three pins at a time and insert them into one hole (dominant hand). Score (simplified): number of holes filled in 2 minutes.</td>
</tr>
<tr>
<td>8) ASTM F2010</td>
<td>Pick up pins and place them into holes (dominant hand). Score: time needed to complete the board.</td>
</tr>
<tr>
<td>9) O’Connor Tweezer</td>
<td>Use tweezers (dominant hand) to pick up pins and place them into holes. Score (simplified): number of holes filled in 2 minutes.</td>
</tr>
<tr>
<td>10) Purdue–Pins Dominant Hand</td>
<td>Pick up pins and place them with the dominant hand in the column closest to this hand. Score: number of holes filled in 30 seconds.</td>
</tr>
<tr>
<td>11) Purdue–Pins Non-Dominant Hand</td>
<td>Pick up pins and place them with the non-dominant hand in the column closest to this hand. Score: number of holes filled in 30 seconds.</td>
</tr>
<tr>
<td>12) Purdue–Assembly</td>
<td>Use both hands in an alternating fashion to assemble a pin, a washer, a collar, and another washer, in each hole of the board. Score: number of parts assembled in one minute.</td>
</tr>
</tbody>
</table>

Table 2. Description of the twelve dexterity tests
RESULTS AND DISCUSSION

The gloves have a significant effect on the dexterity measurements with all tests (p<0.05), except with the EN 420 standard. The pairs of glove models which were detected by the Tukey-Kramer test to be significantly different are presented in Table 3. In cases where two tests or more were able to detect a significant difference between two glove models, all tests ranked the glove models in the same way (except for the case A1-B6, with Crawford-Screws and O’Connor Finger tests).

<table>
<thead>
<tr>
<th>Dexterity test</th>
<th>Gloves order in term of normalized performance</th>
<th>Sensitivity degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>Medium</td>
<td>Coarse</td>
</tr>
<tr>
<td>1) Crawford-Pins&amp;Collars</td>
<td>A3 A2 A1 B5 B6 C9 B4 C8 C7</td>
<td>25%</td>
</tr>
<tr>
<td>2) Crawford-Screws</td>
<td>A2 B6 A3 B5 A1 B4 C9 C8 C7</td>
<td>67%</td>
</tr>
<tr>
<td>3) Grooved Pegboard</td>
<td>A2 A3 A1 B6 B5 C9 B4 C8 C7</td>
<td>58%</td>
</tr>
<tr>
<td>4) EN 420 (smallest diameter pin)</td>
<td>B6 B5 A2 C7 C8 B4 A1 A3 C9</td>
<td>3%</td>
</tr>
<tr>
<td>5) Minnesota-2Hand Turn&amp;Plac</td>
<td>A2 A3 A1 B6 C9 B5 B4 C8 C7</td>
<td>58%</td>
</tr>
<tr>
<td>6) Minnesota-Turning</td>
<td>A1 A3 A2 B6 B5 C9 B4 C8 C7</td>
<td>56%</td>
</tr>
<tr>
<td>7) O’Connor Finger</td>
<td>A3 A1 A2 B5 B6 C9 C8 B4 C7</td>
<td>67%</td>
</tr>
<tr>
<td>8) ASTM F2010</td>
<td>A2 A1 B6 A3 B5 C9 C8 B4 C7</td>
<td>64%</td>
</tr>
<tr>
<td>9) O’Connor Tweezer</td>
<td>A2 B5 A3 A1 B6 B4 C9 C8 C7</td>
<td>17%</td>
</tr>
<tr>
<td>10) Purdue-Pins Dominant Hand</td>
<td>A2 A1 A3 B6 B5 C9 C8 B4 C7</td>
<td>64%</td>
</tr>
<tr>
<td>11) Purdue-Pins Non-Dom. Hand</td>
<td>A2 A1 A3 B6 B5 C9 C8 B4 C7</td>
<td>67%</td>
</tr>
<tr>
<td>12) Purdue-Assembly</td>
<td>A2 A3 A1 B6 B5 C8 C9 B4 C7</td>
<td>58%</td>
</tr>
<tr>
<td>Combination of tests 2, 3, 5 to 8, and 10 to 12</td>
<td>A2 A3 A1 B6 B5 C9 B4 C8 C7</td>
<td>92%</td>
</tr>
</tbody>
</table>

Table 3. Results of Tukey-Kramer test. Gloves underlined by the same line are not significantly different from each other (α=0.05). The degree of sensitivity indicates how many significant differences were found between pairs of glove models out of all possible combinations.

The Crawford-Pins&Collars test and the O’Connor Tweezer test were not very sensitive, as reported in literature (8). This is probably due to using tweezers, which are motionless within the hand during all manoeuvres. A study carried out among dental professionals indicates that the O’Connor Tweezer test has the capability of measuring a reduction in manual dexterity for latex gloves only in the case of improper fitting (7).

The use of different diameters pins for the EN 420 test would have been expected to be discriminative in assessing the dexterity of gloves. However, this test shows the weakest sensitivity of all tests. A couple of uncommon aspects of this test could impede its standardization. It is recommended to have a trained operator performing the test, which is not required for other dexterity tests if a minimal practice period is allowed to the subject. The subjects were inexperienced in this study but they followed the directive to hold each pin between the forefinger and thumb. The manoeuvre of picking up each pin three times consecutively took less than 10 seconds for all the subjects (except for 2 subjects with glove C9) while a 30 seconds period is allowed. Moreover, this test is the only one of all
12 tests studied not measuring the speed of execution. Instead, a judgement must be made on whether the manoeuvre was carried out with or without undue fumbling. The Crawford-Screws test, the Grooved Pegboard test, both Minnesota tests, the O’Connor Finger test, the ASTM F2010 and the three Purdue tests have similarly good capability to discriminate between different glove models (56% to 67% of sensitivity). Taken together, they detect all differences between gloves except three, as it can be seen in the bottom of Table 3. No single test was able to discriminate all gloves. However, the tests which require fine dexterity were more sensitive to fine-medium dexterity gloves (e.g. Crawford-Screws and O’Connor Finger with gloves A1, A2, A3, B5 and B6). In the opposite, the tests requiring coarse manipulation of bigger parts were more sensitive to medium-coarse dexterity gloves (e.g. both Minnesota tests and ASTM F2010 with gloves B4, C7 et C8). The results for the three Purdue tests revealed that the Assembly test, which is more complex, does not provide any substantial additional information compared to the Pins tests, which are much simpler and shorter.

CONCLUSIONS

An experiment was driven to compare the discrimination capability of twelve existing dexterity tests to different glove models. It was shown that nine of these tests have a fair sensibility to gloves, namely the Crawford-Screws test, the O’Connor Finger test, the Grooved Pegboard test, the Purdue-Pins Dominant and Non-Dominant Hand test, the Purdue-Assembly test, the ASTM F2010, the Minnesota-Two-Hand Turning&Placing test, and the Minnesota-Turning test. The first two were more sensitive to gloves offering fine to medium dexterity range, and the last three were more sensitive to gloves offering medium to coarse dexterity range. Several tests could be selected based on their sensitivity to fine or coarse level dexterity to be part of a comprehensive dexterity test battery.

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UV PROTECTIVE COTTON FABRICS

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ABSTRACT

Transparent titanium dioxide (TiO2) nanocoatings prepared from alkoxide solutions at room temperature by the sol-gel method were applied on cotton fabrics to protect them against UV radiation. SEM images show the formation of uniform continuous lays of titanium dioxide on the cotton fabrics. Titania-coated cotton fabrics showed a high Ultraviolet Protection Factor (UPF) of 50+ or excellent UV protection rating according to the Australian/New Zealand Standard AS/NZS 4399:1996 even after 30 times of repeated washing, indicating a high level of adhesion between the titania nanocoatings and the cotton fabrics. Therefore, the UV absorption of the titania nanocoatings were quite substantial to promote durable excellent UV protection to cotton substrates, which provided a promising commercialization of UV protective clothing.
The main goal of the article is to answer the question about the degree to which protective clothing manufactured in Poland meets European standards and whether it can compete in the Single European Market after Poland has joined its structures. Based on a questionnaire survey (2003), a general description of the Polish protective clothing market was prepared and the main barriers hindering the export of clothing manufactured in Poland identified. The survey helped indicate the best opportunities and the biggest threats faced by the domestic manufacturers of protective clothing.

A separate analysis concentrated on the marketing activities, a very important component of preparedness of the Polish protective clothing manufacturers to intra-Community operations.

Innovation is believed to be the basic prerequisite for firms to gain and maintain sustainable competitiveness in the global market. Consequently, a very important part of the survey is analysis of the innovation-related needs among the Polish protective clothing manufacturers and evidencing an extremely positive influence of innovation on firms’ competitiveness.

1. CHARACTERISTICS OF THE POLISH PROTECTIVE CLOTHING MARKET

The conducted research and analysis of its findings revealed that the examined group of Polish protective clothing manufacturers is relatively homogenous, regarding both turnover and types of ownership. Their breakdown into small-sized, medium-sized and large-sized organizations according to the EU criteria showed that none of them had a turnover exceeding the threshold of 50m Euro; in other words, all of them fitted in the SME sector. As for the types of ownership, two types definitely prevailed, i.e. privately-owned enterprises with a majority share of Polish capital (64%) and co-operatives (23%).
The most frequent types of products were protective clothing against heat and fire, cold, mechanical risks, chemical risks and the high visibility protective clothing. Only every fourth of the examined manufacturers produced clothing protecting against the inclemency of weather. Clothing protecting against electrical risks, biological risks and the anti-static protective clothing represented only a fraction of the range of products offered by the surveyed enterprises. None of them, however, produced clothing protecting against the UV radiation.

2. INTERNATIONAL COMPETITIVENESS OF THE POLISH PROTECTIVE CLOTHING

The following indicators were used to assess the competitive position of the Polish export of protective clothing to the Community’s markets:

**Branch specialisation indicator**

This indicator shows the percentage share of Poland’s surplus (or deficit) in international trade in product i (where i stands for industrial and occupational clothing – IOC). In other words, the indicator describes the directions and intensity of specialisation processes taking place in the Polish economy with respect to Poland’s major trading partners.
Figure 2 clearly indicates that Poland’s branch specialisation in industrial and occupational clothing is very high (the indicator’s value is close to 1). The indicator is much higher than for all Section XI (textiles and textile materials). However, it somewhat dropped after 2003.

Regarding the IOC trade with the third countries Poland’s branch specialisation is also very high, but slightly lower than for trade with the EU. As before, Polish IOC has an advantage over all textile articles, as well as compared with the indicator’s value for Germany being a EU15 member state (see Fig. 3).

**Index of revealed comparative advantage**

This index represents the relation between the portion of Polish IOC export in the total export of IOC to the Community and Poland’s share in the export of textiles and textile articles to the EU markets. It does not have the cap, but its lower limit is zero. For individual product groups, index values exceeding one point to the appearance of a comparative advantage [2].
The industrial and occupational clothing RCA presented in Figure 4 shows that Poland is capable of competing in the Single European Market (SEM) as an IOC producer (in all the years in question the index value exceeded 1). It is quite alarming, though, that the analysed index started visibly declining after 2002.

**Unit values**

This index illustrates the level of unit values in the Polish export and in one EU15 country, i.e. Germany. Figure 5 markedly points to the considerable difference between unit values of the Polish and German IOC exported to the third countries. Polish clothing is exported at significantly lower unit values. At the same time, however, the gap and the related price competitiveness of the Polish IOC are clearly diminishing. This trend has two sources: one is the gradually increasing unit values in Poland and the other significant price reductions in Germany after 2002.

![Graph showing unit value index in Poland and Germany, years 1999-2004; Source: author’s calculations based on Eurostat data](image)

**Figure 5.** IOC unit value index in Poland and Germany, years 1999-2004; Source: author’s calculations based on Eurostat data

### 3. MAJOR BARRIERS TO POLISH MANUFACTURERS’ EXPORT OF PROTECTIVE CLOTHING – AN ANALYSIS

Besides, the survey found that the Polish manufacturers were concentrated primarily on the domestic market. Only every fifth organization in the sample exported its products to foreign markets. The findings served as a context for analysing barriers to export in terms of their power.

An examination of the questionnaire surveys made it possible to select and then rank export barriers according to their impact. Using values of Wilcoxon test Z statistics and the significance level for individual pairs of export barriers, four groups of such barriers were identified (Table 1).

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1 Most exporters sell their products in EU member states (75%); other export destinations mentioned by the respondents were Russia (25% of indications), as well as Switzerland and Latvia – 13 % each.
Impact | Type of barrier
--- | ---
Strongest | Unavailability of an extended network of outlets  
Low knowledge of the market  
Strong competition
Large | Insufficient marketing activities  
Lack of funds to finance pro-export investments
Moderate | Technical norms and standards  
Quotas
Low | Low quality of products  
Customs duties

Table 1. Breakdown of export barriers in the Polish protective clothing market with regard to their impact

Marketing barriers emerged as the most burdensome for the protective clothing manufacturers, resulting in their weak preparedness to entering the foreign markets.

4. OPPORTUNITIES AND THREATS FACED BY THE DOMESTIC MANUFACTURERS OF PROTECTIVE CLOTHING

As the opportunities arising from Poland’s accession to the European Union, the interviewed representatives of the manufacturers indicated predominantly the spread of information technologies, stabilisation of laws and administrative procedures, access to new sources of supplies, potentially better co-operation with firms established in the member states. In the same context, growing competition and changes in the costs of production factors were put on the list of the largest threats. Regarding the major lacking pieces of information necessary to ensure enterprise’s competitiveness in the Single European Market, the manufacturers typically pointed to the level of prices, market entry conditions and ways of selling products in that market. However, over 80% of the manufacturers believed to have sufficient knowledge of laws regulating business operations.

5. MARKETING ACTIVITIES AS AN ELEMENT OF PREPAREDNESS OF THE POLISH PROTECTIVE CLOTHING MANUFACTURERS TO FUNCTIONING IN THE SEM

Typical actions planned by the manufacturers to strengthen their position in the new circumstances included the improvement of product quality (almost 30% of firms) and enhancement of their brand (almost every fourth respondent). Also plans to extend the range of products and to enter new market segments, as well as every fourth producer’s intentions to expand into new geographical markets should be viewed positively. It is worrying, though, that only 14% of the interviewed firms intended to apply new technological solutions in the manufacturing processes and to initiate co-operation with the domestic R+D centres and fabric manufacturers.

Regarding the major obstacles that the firms faced in the process of their legal adjustment to intra-Community trading, those related to tax laws, financial laws and competition rules were mentioned. Adjustment to the new industrial safety and environmental protection requirements turned out to be the least troublesome. Among the economic and business-related problems, the most severe seemed to
be finding partners/co-operating parties, costs involved in marketing activities and the distribution of clothing articles. Price competitiveness was assessed as a relatively minor problem.

According to the findings provided by the analysis, the frequency of marketing surveys run by the manufacturers deserves a positive opinion. Unfortunately, the least frequently investigated area was competing products and producers’ market shares. The weak knowledge of especially foreign competitors whose would probably build up after 1 May 2004 can soon result in the bankruptcy of some Polish firms. Logically, this is the area that the Polish manufacturers should start emphasising as soon as possible.

6. AN ANALYSIS OF INNOVATION-RELATED NEEDS OF THE POLISH PROTECTIVE CLOTHING MANUFACTURERS

This part of the survey purposed to identify manufacturers’ main needs and their levels of competence in pre-determined areas. This approach allowed to find gaps, i.e. spots where competence and skills did not match the needs².

![Figure 6. Manufacturers’ needs versus competence (average of indications)](image)

Areas where the gap between competence and needs was the largest were the following: foreign cooperation (1.5), marketing (0.9), use of patents, licenses and know-how (0.8). Other identified problem areas were access to capital (0.7), internal development of new technologies (0.7), and introduction of innovations (0.7).

The above brings to light apparent cracks in the broadly understood marketing sphere in the enterprises. Realising their insufficient competence in the indicated areas, organizations were also aware that it was necessary for them to bridge the existing gaps, which should be viewed positively.

² Respondents characterised their needs using the following scale: 1. unimportant, 2. rather unimportant, 3. moderately important, 4. very important, 5. crucial. Averaging of the results for each area made it possible to indicate the largest needs.
Yet, it is disconcerting that Polish manufacturers in the protective clothing industry did not feel the need to improve their cooperation with the R+D centres, even though the self-evaluation of their skills in the area was the lowest. This attitude may prove that they do not quite understand the role of research and development work.

6.1. INNOVATION AND ITS INFLUENCE ON FIRMS’ COMPETITIVENESS

In addition, the conducted survey confirmed the positive influence of innovation on competitiveness. A favourable relationship was found between the level of firms’ innovation and their propensity to export, their financial results, numbers of certificates held (both obligatory and optional), and the directions of changes planned to improve firm’s competitiveness in the future. Both the frequency and targets of actions planned allow to conclude that it is the group of the most innovative firms that faces the best opportunities of not only surviving in the demanding Community market, but also of gaining a strong competitive position there.

6.2. INNOVATIVE PRODUCTS ON THE POLISH PROTECTIVE CLOTHING MARKET

As revealed by the survey’s results, a definite majority of the responding firms (over 70%) planned to introduce a new type of protective clothing in 2005. Additionally, the examined manufacturers showed a considerable degree of adaptability to customers’ varying demands. Every second respondent needed less than 14 days to comply with his or her customers’ requirements and 37% of the firms around one month.

7. FINAL REMARKS

The analysis presented in this chapter has disclosed certain shortcomings suffered by the Polish protective clothing producers in some areas. Over time, the shortcomings may gradually erode the organizations’ competitiveness and, consequently, make them lose their market shares. There exists, however, a group of enterprises within the industry that, being perfectly aware of their weaknesses, started to adjust themselves to the new operational circumstances before 1 May 1 2004 and have continued the process since then. The survey has proved that in many respects the best prepared to compete in the Single European Market are:

- highly innovative organizations;
- private enterprises;
- the medium-sized organizations.

The performance of cooperatives and large-sized enterprises is inferior in many aspects.

In addition, our analysis of indices allowed to assess the competitiveness of the Polish IOC manufacturers and to formulate the following conclusions:

- As an IOC-manufacturing country, Poland has achieved a very high level of branch specialisation, which proves a strong position of her manufacturers against their foreign competitors.
- Poland holds a comparative advantage in the IOC export to the EU that buys 80% of the Polish IOC export (representing ca 6% of all IOC import to the Community).
• Unit values of Polish IOC exported to the EU are higher than in the export from third countries to the Community.
• Unit values of Polish IOC exported to the third countries are below German unit values and lower than average unit values in the EU export. Consequently, Polish exporters are price competitive in the markets of the third countries.

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NEW FILTERING MATERIALS INCLUDING NANOFIBRES

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ABSTRACT

This paper presents new textile materials for environmental protection of respiratory tracts composed of one layer of melt-blown PP nonwoven and one layer of electrospun polyacrylonitrile nanofibres. Characteristics of filtering materials contains description of following parameters: diameter of electrospun nanofibres, the filtering efficiency of sodium chloride aerosol and paraffin oil mist, breathing resistance and filtering efficiency of bio-aerosols. The analysis of the filtering parameters is carried out in relation to values of technological parameters of electrospinning process, such as: concentration of polymer solution, the value of applied voltage and distance between electrodes. The discussion on the influence of the technological parameters of electrospinning process on the improvement of filtering efficiency especially of bio-aerosols is presented.
DETERMINATION OF THE BARRIER MATERIAL RESISTANCE TO PERMEATION BY ORGANIC MIXTURES

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ABSTRACT

The paper presents the results of testing the resistance of butyl rubber vulcanizate membranes to permeation by organic solvents commonly used in the production of paints and lacquers.

The aim of the study was to assess the effect of properties of the ingredients and their content in the mixture, as well as of the thickness of the tested samples, on the changes of parameters characterizing the level of protection, i.e. the breakthrough time of the material by the substance and the permeation velocity under specific, constant testing conditions.

Model systems of butyl rubber vulcanizates, commonly used for the production of clothing and gloves protecting against chemicals, were prepared for the study. The individual variants of the material differed in thickness: 0.2 and 0.4 mm.

During the tests, the breakthrough times were determined for acetone, toluene and n-butyl acetate separately, and then for acetone + toluene and toluene-n-butyl acetate mixtures (proportion 1:1).

The chemicals permeating the barrier material were detected using the technique of gas chromatography.

The results of vulcanized butyl rubber membrane permeation tests carried out for acetone + toluene and toluene + n-butyl acetate indicate that the breakthrough times for individual substances differ significantly from those noted for the same substances in mixtures. Increasing the content of toluene (which demonstrates a very short breakthrough time individually) contributed to an increase of permeation velocity of the acetone and n-butyl acetate, and, consequently, to a reduction of breakthrough time.

1. INTRODUCTION

The aim of the paper was to investigate the resistance of the tested polymer material to permeation by solvents commonly encountered at worksites and to determine whether there are any differences between permeation of a single solvent and a mixture of solvents. It is very important because materials protecting against chemicals are selected mainly on the basis of determination of
breakthrough time. According to the applicable standards, this parameter is determined individually for a system consisting of the tested material and a single chemical substance [1, 2]. It is defined as “time elapsing between the moment of contact of the tested material sample with a chemical substance and the moment the substance appears on the other side of the tested material sample with the velocity specified in the standard” [1, 2]. Depending on the breakthrough time values, polymer materials used for protective devices are characterized by different classes of resistance. Longer breakthrough time indicates higher resistance of the tested material to a given chemical compound. The studies in this field carried out to date suggest that the breakthrough times of a substance acting on polymer materials individually and in mixtures may differ significantly [3-5].

2. METHODOLOGY

2.1. MATERIALS

Butyl rubber vulcanizate membranes, manufactured in two variants of thickness: 0.2 mm and 0.4 mm (specific weight of the membranes was 1.31 g/cm³, vulcanizate crosslinking density 0.38 x 10⁻⁴ mol/g polymer).

2.2. CHEMICAL SUBSTANCES

Organic solvents: acetone, toluene and n-butyl acetate (individual substance and acetone + toluene and toluene + n-butyl acetate mixtures in the following volume proportion of the ingredients 1:1) commonly encountered at worksites in paint and lacquer industry.

Main criterions for the selection of substances:
- common use,
- occurrence, individually and in mixtures, in actual working conditions,
- physical and chemical properties such as (table 1): dipole moment, molecule size, three dimensional solubility parameters of the chemicals and butyl rubber.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Molecule size [Å]</th>
<th>Dipol moment [D]</th>
<th>Three dimensional solubility parameter [MPa⁰.⁵]</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetone</td>
<td>4.34</td>
<td>2.76</td>
<td>20.0</td>
</tr>
<tr>
<td>toluene</td>
<td>5.88</td>
<td>0.39</td>
<td>18.2</td>
</tr>
<tr>
<td>n-butyl acetate</td>
<td>9.13</td>
<td>1.84</td>
<td>17.4</td>
</tr>
</tbody>
</table>

Table 1. Selected parameters characterizing the components of the tested mixtures [6, 7]

2.3. APPARATUS

The following equipment was used in the study:
- gas chromatograph, FID flame ionisation detector, capillary chromatographic column (Rtx-5, length 7m, internal diameter 0.32 mm),
- injecting valve (gaseous sample of 1 ml volume),
- two-chamber permeation cell (construction according to PN-EN ISO 6529:2003(U)),


- thermostate,
- thickness gauge o średnicy stopki 10 mm i nacisku 4.9 Pa.

Chromatographic analysis parameters were adjusted so that individual substances (acetone, toluene, n-butyl acetate) and their mixtures (acetone+toluene, toluene+n-butyl acetate) were analyzed under the same conditions. The analysis was carried out under isothermal conditions: (column temperature – 40°C, dispenser temperature – 110 °C, detector temperature –180 °C, nitrogen flow velocity – 1 ml/min).

2.4. TEST METHOD

Samples (40 mm diameter) were placed in the permeation cell. Then the permeation cell and the chemical substance were conditioned (30 min., 20±1 °C). After that time, 10 ml of an individual substance or mixture was poured into the upper chamber and recorded the test. The lower chamber was ventilated with pure air passed next to the bottom side of the text sample, which collected the solvent molecules diffused and desorbed at the bottom side of the membrane. The air was then directed to the automatic injecting valve in the gas chromatograph. The experiment was conducted until the steady state of the substance permeation process through the vulcanizate was reached. Setted time interval (5 min.) allowing periodic dispensing of samples (1ml) by the injecting valve and good separation of the substances.

As a result of the experiments, chromatograms. Using the calibration curves, the concentration at which the threshold velocity of compound permeation through the material was reached (according to PN-EN ISO 6529:2005 standard, the breakthrough time occurs when the permeation velocity reaches the value P=1µg/cm² min.)

Knowledge of the concentration corresponding with the threshold permeation velocity allows to determine the breakthrough time, which was read directly from the chromatograms.

3. STATISTICAL ANALYSIS

The obtained results were subjected to statistical analysis in order to find out whether there were statistically significant differences between the breakthrough time values for pure substances and the same substances as mixture components (e.g. breakthrough time for acetone as an individual substance and as a component of 1:1 acetone-toluene mixture). The analysis took into account differentiated material sample thicknesses.

On the basis of statistical analysis (bidirectional analysis of variance ANOVA – Test F, then Scheffe’s Multiple Comparisons Test), it was established that, there is a significant difference between the breakthrough time of pure substance and substance in mixture for sample thicknesses 0.2, 0.4 mm. For these samples, the values of F statistics were lower than the critical values of F distribution at the significance level α = 0.05; therefore, there were no grounds for discard the zero hypothesis concerning the lack of differences between breakthrough times for pure substances and breakthrough times for the same substances constituting mixture components. The value of Anova statistics was 95.110, and type I error probability was lower than 0.0001.
In case of these statistically significant differences Turkey multiple comparison test was used to determine between which variants they occurred. Scheffe’s Multiple Comparisons Test indicated the pairs of results differing with statistical significance, for which the values of type I error probability ranged from 0.0001 to 0.021847, whereas for those not differing statistically they ranged from 0.120428 to 1.0000.

4. TEST RESULTS

The results obtained in the tests are presented in figures 1-2.

Figure 1 The breakthrough time results for acetone +toluene mixture (1:1)
The analysis of permeation test results for acetone-toluene 1:1 mixture demonstrated that there is a significant difference between the breakthrough time of acetone alone (e.g., 335 min. for 0.2 mm thickness) and acetone in mixture with toluene (25 min. for 0.2 mm thickness). With respect to toluene, there is also a significant difference between the breakthrough time of toluene alone (5 min.) and toluene in acetone-toluene 1:1 mixture (22 min. for the same thickness of material sample).

The analysis of the effect of tested material sample thickness on breakthrough times demonstrated that they did not differ significantly for acetone alone with sample thicknesses of 0.2 and 0.4 mm (335 min and 360 min., respectively). An analogical conclusion was made for toluene (5, 10 min.). The above is interesting because the breakthrough times of the particular single substances are very differentiated (toluene alone: depending on sample thickness from 5 to 26 min, and acetone alone: depending on sample thickness from 335 to over 360 min).

For toluene–n-butyl acetate 1:1 mixture, similarly as in case of acetone–toluene 1:1 mixture, it can be noted that the breakthrough times obtained for single substances differ significantly from each other (toluene: 5 min for 0.2 and 10 min for 0.4 mm sample thickness, and n-butyl acetate: 55 min for 0.2 mm and 158 min for 0.4 mm). There is a statistically significant difference between the breakthrough time of toluene alone and toluene in 1:1 mixture with n-butyl acetate. An analogical situation was observed for n-butyl acetate.

When toluene and n-butyl acetate occur in mixtures, it can be seen that their breakthrough times, like for the previous mixture, are very similar (e.g. for 2 mm thickness: 7 min. toluene, 10 min. n-butyl acetate).

The analysis of the effect of tested material sample thickness on breakthrough times demonstrated that there are differences in toluene breakthrough time for various sample thicknesses (e.g. 7 min. for 1:1
mixture proportion with 0.2 mm. sample thickness, 30 min. for the same proportion with 0.4 mm). An analogical conclusion was made for n-butyl acetate.

5. CONCLUDING REMARKS

The acetone-toluene mixture represents the variant, in which the constituents are characterized by extreme values of the analyzed parameters (except for molecule size), because acetone as a substance possessing low solubility, high dipole moment and long breakthrough time as an individual compound makes up a mixture with toluene, which has high solubility, low dipole moment and very short breakthrough time. The toluene-n-butyl acetate mixture is a variant where the values of the selected parameters are different, but to a lesser degree than in case of acetone-toluene mixture. N-butyl acetate is characterized, in comparison with acetone, by moderate solubility, average dipole moment and breakthrough time as an individual substance.

As it follows from the tests, permeation for mixtures composed of substances characterized by differentiated values of the above parameters occurs in such a way that the permeation by the constituent with lower solubility (and therefore with lower dipole moment) and longer breakthrough time is accelerated in the mixture and, consequently, the breakthrough time is shortened in comparison with that of the individual compound. It can be supposed that this is associated with the solubility of the mixture-material system, because the quantity of liquid substances which can be absorbed by polymer structure is limited. These substances cannot cause material swelling beyond the material flexibility limits. Therefore, it is observed that increased permeation of one mixture ingredient (acetone, n-butyl acetate) is accompanied by decreased permeation of the other one (toluene).

REFERENCES

EFFECTS OF NATURAL SOLAR RADIATION ON MANIKIN HEAT EXCHANGE

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ABSTRACT

The main objective was to compare solar radiation to short wave radiation from Thorn lamp on clothing that were tested in lab on the manikins and on the subjects. In sun all manikin front zones get more or less evenly radiated but in the lab the radiated power reaches some zones more than others.

Tests were carried out on the thermal manikin Tore under clear sky in a building corner facing the sun. Basic tests without radiation were carried out in homogenous conditions in the climatic chamber. 4 sets of coveralls were tested with polypropylene underwear. Thermocouples were fixed at chest on underwear and outer layer inner and outer surfaces for textile surface temperature measurements.

From basic tests there were estimated the heat losses for particular outdoor conditions. The insulation values were corrected for air velocity according to EN 342 (1). The difference between the calculated heat losses for no sun and actual measured heat losses outdoors gave heat gain from sun for those particular conditions. There was a clear difference between black coverall and the other suits and reflective coverall and the other suits. The highest textile temperatures were recorded for black and lowest for reflective coverall. The curves followed the same pattern as observed from the material tests with solar lamps in the climatic chambers: underwear had often the highest temperatures.

1. INTRODUCTION

Several studies have evaluated the effect of solar radiation by means of tests on human subjects (2, 3, 4), manikins (2, 5) or other instruments (6). Various models (7) have been developed in order to consider human solar heat load both for exposure to cold and heat (5, 8). Also, several authors have looked on the effect of colour of the clothing (4, 9, 10) or skin (11) or animal fur (12). It was also shown that material (fur) tests do not need to match the results from living animals (12).

Within the THERMPROTECT project (13) tests on materials, manikins and subjects were carried out. Temperature curves in material tests were acquired at different power levels / lamp distances. The main objective of the present measurements was to gather data that allows comparing short wave radiation of Thorn lamp to solar radiation on our chosen garment ensembles. It was important to be able to compare different ensembles with each other, and look at general trends, e.g. if temperature curves followed the same pattern outdoors and in lab.

In common laboratory tests on manikin the radiation power was chosen in a way that did not increase the surface temperature over the set point, and thus allowed evaluating the changes in heat loss. Another difference between natural and lamp radiation was that in sun whole
Table 1. Experimental conditions.

<table>
<thead>
<tr>
<th>Garment 1</th>
<th>Date</th>
<th>Time</th>
<th>Solar angle (°)</th>
<th>T&lt;sub&gt;a&lt;/sub&gt; (°C)</th>
<th>Vertical surf radiation (W/m&lt;sup&gt;2&lt;/sup&gt;)&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Plane Radiant Temp (°C)&lt;sup&gt;4&lt;/sup&gt;</th>
<th>Air velocity (m/s)</th>
<th>Heat loss&lt;sup&gt;5&lt;/sup&gt; (W/m&lt;sup&gt;2&lt;/sup&gt;)</th>
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<tr>
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<td>09:55</td>
<td>61.76</td>
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<td>74.3</td>
<td>1.10</td>
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<td>ON3a</td>
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<td>12:05</td>
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<td>15.4</td>
<td>811 747</td>
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<td>811 747</td>
<td>74.3</td>
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<td>718 842</td>
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<tr>
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<td>51.30</td>
<td>21.3</td>
<td>718 842</td>
<td>74.3</td>
<td>1.58</td>
<td>0.70</td>
</tr>
</tbody>
</table>

1 In test codes (Garment) 1, 2 and 3 mean different tests, while a and b come from the same run with 10 minute difference in order to minimize environment dependent difference and for control.
2 Solar angle from vertical surface in degrees.
3 Radiation intensity on vertical surface: sensor standing between the sun and Tore with front side turned the sun [A (Sun)] and backside towards the manikin [B (Tore)]; A-background was measured between the manikin and the glass background behind him (reflection from wall).
4 Plane radiant temperature corresponds to the radiation intensity: sensor standing between the sun and Tore with front side turned the sun [A (Sun)] and backside towards the manikin [B (Tore)]; A-background was measured between the manikin and the glass background behind him (reflection from wall).
5 Heat loss excluding non-covered areas, i.e. head, hands and feet (area of covered body parts was 1.43 m²).
manikin front got more or less evenly radiated but in lab the radiated power reached some zones, e.g. chest, more than others depending on the lamp position. Thus, an aim for the outdoor tests was to look on realistic temperatures in textiles and total heat loss reduction from manikin / gain from sun. Also, the outdoor data could serve as a link between material tests with high radiation power and manikin tests with relatively moderate power levels, but also in order to relate to subjects’ data.

Figure 1. Tore outdoors and the Sun position at the end of each test

2. METHODS

Tests were carried out on the thermal manikin Tore under clear sky in a building corner facing the sun (Figure 1). The manikin was turned so that in the end of each trial the sun faced manikin front (Figure 1). All outdoor conditions are given in Table 1 and some parameters drawn in Figure 2. Tests without radiation in homogenous conditions were carried out in a climatic chamber.

Figure 2. Ambient conditions for some tests.

Figure 3. Manikin’s back and chest, and textile surface temperatures at chest (underwear inner (UWi) and outer (UWo), and outer layer inner (OLi) and outer (OLo) surface) for some conditions. Point UWi for ON3 is estimated because of missing value due to sensor error.

After pre-tests 4 sets of clothing were chosen for further testing: black Nomex (BN, reflectivity 0.23), orange Nomex (ON, reflectivity 0.26), white cotton (WC) and reflective Nomex (RN, reflectivity 0.78). Black laminated Nomex (BL) was skipped due to close values to BN. Helly-Hansen underwear
(super stretch, polypropylene) was used under all coveralls. Thermocouples were fixed at chest on underwear inner (UWi) and outer (UWo) surfaces and outer layer inner (OLi) and outer (OLo) surfaces for textile surface temperature measurements. Data was recorded each 10 seconds.

3. RESULTS AND DISCUSSION

Figure 3 shows manikin’s back and chest surface temperatures, and textile surface temperatures at chest (facing the sun). As expected, the highest temperatures were recorded for BN and lowest for RN. Difference between ON and WC was present, too. The temperature curves followed the same pattern as observed from material and the manikin tests (13) with solar lamps in the climatic chambers: underwear surfaces just under outer layer had often the highest temperatures. Figure 4 illustrates heat losses from the whole manikin body and from the areas totally covered with the coveralls (head, hands and feet excluded). The figure confirms the results from surface temperatures (Figure 3). RN differed from others somewhat more due to lower air temperature (Figure 2), although, even at higher ambient temperature the difference would have anyway been considerable, e.g. RN3 at 21 °C with air velocity of 1.6 m/s (Table 1) had heat losses of 51 W/m² from covered parts. Vice versa, difference between ON and WC might have been slightly less if they have had the same air velocity and temperature.

![Figure 4. Heat loss for one particular test of each coverall. Test with each coverall was chosen to be carried out under as close environmental conditions as possible with others.](image)

From homogenous chamber test results (insulation values) there were estimated the heat losses for particular outdoor conditions without solar load. Insulation values were corrected for air velocity according to Annex C, EN 342 (1):

\[
I_e / I_t = 0.54 \cdot e^{(-0.15v - 0.22w)} + 0.5
\]

(1)

for \(v = 0.4 \text{ m/s to } 2.0 \text{ m/s}\). The difference between the calculated heat losses and actual measured heat losses outdoors gives us heat gain from sun for those particular conditions (Figure 5). These values for various colours lay in the same range as reported in earlier studies (3, 4, 5, 6). Also, the results from Thermprotect study (13) carried out on human subjects point towards the same direction. There is a clear difference between BN and the other suits, and RN and the other suits, however, ON and WC are quite similar. It might depend on solar load (not available for WC, Table 1) that in its own turn is related to solar angle (highest for WC, i.e. bigger surface radiated), and clearness of the sky (the test days were very clear with practically no clouds observed). In spite of higher relative heat gain values...
for WC, the surface temperatures of ON are higher in all layers (Figure 3). It might be related to that in actual conditions ON had somewhat higher temperature and lower wind speed than WC (Table 1 and Figure 2) but also on transmission through textiles.

Based on outdoor tests the following relationship ($R^2=0.89$) was acquired:

$$Q=177+26.85*r-5.18*T_a+16.21*v_a-0.11*P_i$$  (2)

where $Q$ is heat loss (W/m$^2$); $r$ is reflectivity; $T_a$ is air temperature (°C); $v_a$ is air velocity (m/s); $P_i$ is incident power (W/m$^2$).

Figure 6 shows linear relationship between manikin heat loss, ambient air temperature and incident power for reflective and black garment at air velocity of 0.8 m/s. The outdoor tests were relatively limited in count and in clearly defined conditions, e.g. varying air velocity at low level (0.4-1.5 m/s), commonly high incident power levels outdoors or low indoors (chamber tests), clothes with similar insulation only (0.22-0.26 m$^2$°C/W) and solar angle (from vertical from 50-70°, from horizon 20-40°), thus the relationship should be treated with care for only specified range. Obviously, more defined manikin tests in chamber can be the base for the better model, and then the outdoor tests may be used for validation. However, some manikin tests of Thermprotect (13) were not in agreement with this study. That may be due to that even high radiation level measured there (507 W/m$^2$) was lower than the lowest incident power measured up in this study and thus was outside the scope of the linear relationship given above.

**Figure 6.** Linear relationship between manikin heat loss (W/m$^2$), ambient air temperature (°C) and incident power (W/m$^2$) for reflective (upper/red area) and black (lower/blue area) garment at air velocity of 0.8 m/s.

### 4. CONCLUSIONS

The temperature curves followed the same pattern as observed from the material and manikin tests in the climatic chambers: underwear had the highest temperatures. Thus, laboratory tests with solar lamp are representative for short wave radiation tests on garments and textiles on manikin. Heat losses depend on environmental conditions (air temperature and velocity). These are impossible to standardise outdoors. Thus, laboratory conditions are to be preferred for textile/garment testing on thermal manikins. Due to overheating of the zones facing the sun only (chest and stomach) it is not correct to use insulation values from outdoor tests for estimation of heat losses in order to compare manikin tests with solar lamps in the climatic chambers, where conditions were kept so that the heat losses stayed minimal even in the radiated zones, although, calculated heat gain was in the same range.
as in other studies. However, it might be possible to model outdoor conditions based on the chamber tests. In that case validation tests should be carried out.

5. **ACKNOWLEDGEMENTS**

This work was funded as European Union GROWTH programme project “THERMPROTECT, Assessment of Thermal Properties of Protective Clothing and Their Use”, contract G6RD-CT-2002-00846.

6. **REFERENCES**

HEAT AND MOISTURE TRANSFER FROM SKIN TO ENVIRONMENT THROUGH FABRICS: A MATHEMATICAL MODEL INCLUDING RADIATION AND SURFACE DIFFUSION

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Goong-dong, Yusung-gu, Daejeon 305-764, KOREA

ABSTRACT

In this study we set up a mathematical model for the heat and mass transfer from skin surface to environment through fabrics. The model consists of skin, microclimate, fabric and environment. In the model we included the radiation heat transfer between skin and fabric and fabric and environment. We also included the surface diffusion along the fiber surfaces to account for large vapor flux in the case of cotton. The governing equations were solved numerically both at the steady and transient states. The result shows that the boundary layer thickness outside of the fabric is about 10mm and the time scale of the temperature change is about 3 seconds. It has also been found that the radiation has a significant effect on heat transfer while the surface diffusion does not contribute much to the total rate of heat transfer due to the resistance in the microclimate. At the transient, the temperature response shows underdamping characteristics while the moisture response shows overdamping characteristics.

1. INTRODUCTION

The transport of heat and moisture through fabrics is one of the major concerns in the design of functional clothing such as sports wear and military uniforms for extremely cold or hot conditions. To understand the heat and moisture transfer in clothing systems, we need to have the proper mechanism for heat and moisture transport from skin to environment through fabrics. Until now, the mathematical models developed for the heat transport through fabrics have been restricted to the cases of conduction through fabrics, conduction and convection within the microclimate (a space between skin and fabric, see Fig. 1) and heat transfer concomitant with the vapor transport. In the case of vapor transport, only the diffusion of vapor through pores of fabrics together with the adsorption and desorption of vapor onto fabrics was considered (Hong et al., 1988). The radiation term was considered already (Lotens, 1993), but systematic studies have been still lacking. In this study, we consider a more realistic model for the transport of heat and moisture through fabrics by including the effect of radiation of heat from the skin-fabric-environment and the effect of surface diffusion along fiber surfaces. Even though the
importance of surface diffusion was raised from many years ago (Hong et al., 1988), there has been no attempt to include the effect quantitatively. In this research we have included the surface diffusion term in the model.

Fig. 1. Pathways of the heat and moisture transfer from skin to environment through fabric.

2. FORMULATION OF THE PROBLEM

Let us consider a system that consists of human skin, fabric and an air layer between the skin and fabric as shown in Fig. 1. The outer surface of fabric is exposed to the environment extended to infinity. The fabric and the skin are placed perpendicular to the direction of gravity. The air layer between the skin and fabric will be called microclimate. The gap distance of microclimate has an order of millimeters while the size of fabrics and skin is sufficiently large compared to the gap distance of microclimate. Hence it is assumed that the heat and moisture transport are basically one-dimensional. In this lay-out, the air layer between skin and fabric (microclimate) when the temperature difference is small is stagnant without natural (Benard) convection. The fabric is essentially a porous medium with porosity $\varepsilon$.

The heat and moisture originated from human skin are delivered to environment through the microclimate, the fabric and the boundary layer adjacent to the fabric. In the microclimate moisture is transferred to the surface of the fabric according to Fick’s law. The route of heat transfer is more complex. Heat is transferred by conduction, radiation between surfaces and moisture transfer. The governing equations for the transfer of heat and moisture are basically the heat and diffusion equations (Bird et al., 2002). The total heat flux through the microclimate and fabric are written as follows:

$$q_{MC} = -k_{MC} \frac{dT}{dx} + \frac{\sigma(T_S^4 - T_{MF}^4)}{(1/e_S + 1/e_{MF} - 1)} + j_{MC}(-\Delta H_{vap})$$

(1)

$$q_F = -k_{F,\text{eff}} \frac{\partial T}{\partial x} + j_F \Delta H_{vap},$$

(2)

where $j_{MC} = -\rho D_{vap} \frac{dw}{dx}$, $j_F = -D_{F,\text{eff}} \frac{dw}{dx}$ and $D_{F,\text{eff}} = \left(D_{vap} \frac{\varepsilon}{\tau} + D_{sur}\right)$.

At the skin and the fabric-environment interface, the boundary conditions are set as follows:

$$T_{\text{Skin}} = \text{const}, \quad w_{\text{Skin}} = \text{const}$$
\[ q_E = h(T_{FE} - T_E) + j_E \Delta H_{vap} + \sigma e_f (T_{FE}^4 - T_E^4) \]  

(3)

where \( j_E = K_w (w_{FE} - w_E) \). Here we assume that temperature and moisture concentration are constant at the skin surface, and the Howard model applies at the fabric-environment surface (Turner, 1973). The equations were solved numerically by using a finite difference scheme. We chose three different types of fabrics and their physical properties are listed in Table 1.

<table>
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<tr>
<th></th>
<th>Cotton</th>
<th>Wool</th>
<th>PET</th>
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<td>0.691</td>
<td>0.707</td>
</tr>
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<td>Tortuosity</td>
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<td>2.35</td>
<td>1.5</td>
</tr>
<tr>
<td>Emissivity</td>
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<td>0.95</td>
<td>0.8</td>
</tr>
<tr>
<td>( D_{surr}(m^2/s) )</td>
<td>( 10^{-4} )</td>
<td>( 10^{-5} )</td>
<td>( 10^{-6} )</td>
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<tr>
<td>Thermal conductivity (mW/m/K)</td>
<td>29.45+27Wc</td>
<td>44.1+63Wc</td>
<td>40.4+23Wc</td>
</tr>
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Table 1. Numerical parameters used in the simulation. The data are adopted from Layton (2001)

### 3. RESULTS AND DISCUSSION

We performed the numerical calculation at the steady state first. To do this, we set a reference condition for the numerical simulation as listed in Table 2. In Fig. 2, we show that the cumulative heat fluxes through the microclimate due to conduction, radiation and moisture transport for PET, wool and cotton. Roughly, regardless of fabric type, one half is due to moisture transfer, one quarter is due to radiation and the remaining one quarter is due to conduction. Next we examined the contribution of surface and pore diffusions of moisture transfer through fabrics as shown in Fig. 3. The contribution of surface diffusion is very large in the case of cotton. However the total moisture flux is not much different for different fabrics. This is due to the resistance of microclimate. This means that even though a highly permeable fabric to moisture transfer is used, the amount of heat and moisture fluxes is still mostly dependent on microclimate thickness.

Next we performed calculations for unsteady state transports by changing the environment conditions simulating an abrupt exposure to a new environment. First we investigate the case of changing the environment condition from 293 K, 81 % to 283K, 77.5 % for cotton. In Fig. 4, we plot the changes in temperature profiles with time. As the environment conditions change, the change begins to penetrate into the microclimate region and finally the system reaches a new steady state. In this case the boundary layer thickness is approximately 10 mm. In Fig. 5, we have plotted the temperature profiles for some sets of changes in the environmental conditions. It takes about 3 seconds to reach the steady state. During the change there is an overshoot in the temperature profile and the maximum occurs at 0.3 seconds after the change is imposed. This is a typical response to the change in the environmental variables. In Fig. 6, we have plotted the temperature changes at the microclimate-fabric interface when there is a change in temperature only, moisture content only and both temperature and moisture of the environment. At the
transient, the temperature response shows an underdamping characteristic while the moisture response shows an overdamping characteristic. In Fig. 7, we have plotted the transient characteristics for different fabrics. All the fabrics show the similar response upon the changes in the environment regardless of the steady state value.

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Cotton</th>
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<tr>
<td>Environment temperature</td>
<td>298(K)</td>
</tr>
<tr>
<td>Environment moisture fraction</td>
<td>0.012</td>
</tr>
<tr>
<td>Thickness of fabric</td>
<td>0.002(m)</td>
</tr>
<tr>
<td>Thickness of microclimate</td>
<td>0.005(m)</td>
</tr>
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Table 2. Reference condition for the numerical simulation

Acknowledgment

This work was supported by grant No. R01-2003-000-10423-02004 from the Korea Science & Engineering Foundation.

REFERENCES


Fig. 2. Cumulative heat fluxes due to conduction, radiation and moisture diffusion for PET, wool and cotton fabrics.
Fig. 3. Contributions of pore and surface diffusions of moisture through PET, wool and cotton.

Fig. 4. Temperature profiles at several time steps when a step change in temperature and moisture content of environment is imposed on cotton.
Fig. 5. Temperature profiles at the fabric-microclimate interface when some step changes in the environmental conditions are imposed on cotton.

Fig. 6. Temperature profiles at the fabric-microclimate interface when a step change in the environmental temperature, environmental moisture content or both are imposed on cotton.

Fig. 7. Comparison of the temperature profiles at the fabric-microclimate interface when the same step change as in Fig. 4 is imposed on different fabrics.
THE EVALUATION OF THE EFFECT OF USE OF HIGH VISIBILITY CLOTHING ON PRESERVATION OF ITS PROTECTIVE PROPERTIES

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ABSTRACT

The report presents the effect of factors associated with actual use on photometric properties of background material in high visibility clothing.

On the basis of investigations of chromaticity coordinates and luminance factor of the selected woven and knitted fabrics in orange and yellow colour, exposed to a number of factors under actual or simulated usage conditions, the effect of these factors on preservation of protective properties was assessed. It was established that the following factors have a predominant effect on properties determining enhanced visibility of background materials of protective clothing:

− type, level and size of soiling and staining,
− time of exposure to atmospheric factors, especially natural sunlight,
− maintenance, cleaning and washing processes and extent of staining elimination.

The correlations between the effect of actual and simulated usage conditions on photometric properties of the materials were determined.

1. INTRODUCTION

The main symptom of civilization progress is increasing number of motor vehicles and other devices transported on all kinds of roads and highways. The manual, technical, engineering and supervising staff are and will more and more often be at risk of being knocked over by vehicles, particularly if there is low visibility, heavy traffic and limited space. There are also many worksites at which there are hazards associated with impact, pressure or knocking over by moving machines and transported loads (fork-lift trucks, cranes, travelling cranes, machines used at construction sites, etc.). Because of severe consequences, the effects exerted on man by vehicles and machines in motion are a serious problem [1,2].

Therefore, it is necessary to improve the safety of workers and other subjects, such as traffic participants, by improving their visibility by using protective clothing with a warning function. The primary function involves visual signalling of the user’s presence at all times of the day as well as in darkness under artificial lighting conditions. High visibility is provided by the protective properties of
high visibility garments – appropriate size, fluorescent colour areas of garment material by day and reflective tapes visible under artificial lighting conditions by night. Visibility is influenced to a large extent by the state of material surface, which is, in turn, dependent on several factors such as conditions of use, number and course of maintenance processes, appropriate selection of protective clothing type, etc [3].

As far as material properties are concerned, the standards currently applicable to protective clothes: PN - EN 471: 2004 [4] and PN-EN 1150: 2001 [5] are focused on determination of parameters of protective properties only for new background materials, not exposed to specific factors present at worksites and other factors present during job-unrelated uses. There are no testing methods and assessment criteria allowing to conclude whether warning protective garments will maintain their high visibility properties and adequately protect the workers at worksites after use. A few studies in this field conducted by manufacturers’ research centres are limited to the analysis of selected phenomena [2]. Therefore, a research project concerned with the effects of natural factors, such as repeated and long-term exposures to sunlight and temperature differences, effects of various mechanical factors (abrasion) and multiple maintenance processes (washing or cleaning) on the durability of protective properties of high-visibility warning protective clothing materials was undertaken in the Central Institute for Labour Protection – National Research Institute.

2. METHODOLOGY

2.1. ESSENTIAL FACTORS INFLUENCING DETERIORATION OF PROTECTIVE PROPERTIES OF TEXTILES WITH RESPECT TO HIGH VISIBILITY

Many factors, exerting their effect on the material, usually in combinations with one another, may influence the fabric colour and the perception of fluorescence [6].

The most important factors include:

− light-related factors, associated with natural, and, to a lesser extent, artificial light sources. They cause so-called fading of fabrics, a permanent change involving decreased colour intensity or colour change as a result of reduction or oxidation of dyes on the material of single fibres;

− factors forming transparent microcoating on the surface of single threads, permanent or temporary in character, depending on the magnitude of adhesion forces and method of fixation on the fibre surface, causing a colour change of colour filter type, without obscuring the original colour completely,

− factors which change the colour of fibre material (foreign dyes present in particular types of stains) causing changes permanent or temporary in character and often fixed during material maintenance procedures carried out incorrectly;

− opaque solid particles (dust) forming microscreens obscuring the background material completely, of different colours, sizes and physical structure determining the method and duration of anchorage in thread and weave structure. The colour change results from additive, point-like coverage of the background material;

− factors completely covering large areas of background material (big spots of paint, grease, mud, etc.).

The effects of mechanical and thermal factors, as well as wetting, may also interfere with material colour and perception of fluorescence.
2.2. TESTED MATERIALS

The tests were carried out on background materials used for high-visibility warning protective clothing for occupational use. The analysis of warning protective clothing types currently available in the market demonstrates that ca. 90% of these garments are made of woven and knit fabrics, whereas PVC-coated knits and woven fabrics coated with various membranes permeable for steam account for the remaining 10% of materials.

The most common background materials used for high-visibility warning protective clothing are polyester knits most commonly used for warning vests. Woven fabrics characterized by more stable shape are more often used for construction of high-visibility warning suits (jackets and trousers). For the above reasons, to types of materials, orange-red and yellow, meeting the requirements of the PN-EN 471:2004(U) standard, were selected for the tests:

- knit fabric (100% PES),
- woven fabric (80% PES / 20% CO),

The tests were carried out on new materials and material samples collected from warning vests used at liquid fuel and oil intermediate pumping stations and road construction worksites.

2.3. TESTING METHODS

In order to assess photometric properties, both of new materials and after exposure to extrinsic factors, their photometric parameters, i.e. chromaticity coordinates and luminance factor were measured [7]. A Mini Scan XE type reflectometer was used for this purpose. Its optic system allows to perform measurements with the use of a polychromatic beam and 45/0 measurement geometry.

Photometric parameters were determined for materials new and previously exposed to the following factors:

- washing in water according to PN-EN ISO 6330:2002 [8] using a standard commercial washing agent, at the temperature consistent with the manufacturer’s recommendations, up to 50 cycles (inclusive);
- irradiation with a xenon lamp according to ISO 105-B02:1994 [9] until chromaticity coordinates change to the values exceeding the range specified in PN-EN 471:2004(U), Table 2;
- open-air irradiation with sunlight (solarization) until similar changes of chromaticity coordinates took place;
- abrasion with a Nu-Martindale device according to PN-EN ISO 12947-1:2000 [10], in two variants: with the abradent made of the same material as the tested one and of glass paper;
- application with a laboratory method of artificial stains of dry and oily type;
- wetting of the material,
- ironing of the material at the temperature recommended by the manufacturer;
- application of anti-stain finish on the material.

For research purposes, a laboratory method of simulation of actual stains was developed. It allows repeatable application of stains with particular composition onto the material and obtaining an even layer of stain on the whole material sample. Taking into account the specificity of actual conditions, two models of laboratory staining simulation were designed:

- dry staining (applied under normal temperature and humidity conditions) with powder mixture containing of talcum, graphite, quartzite sand and coal, with mechanical impact, directly onto the surface of the tested materials (model I);
- staining with suspension of powdered graphite and coal in mixture of gear oil and methylene chloride (model II).
3. RESULTS

The measurements results of chromaticity coordinates and luminance factor of the tested materials indicate that:

- washing in water – 50 cycles (under standard conditions with a commercial washing agent) does not change the colour properties and consequently the protective properties of high visibility warning protective clothing materials. The values of photometric parameters remain consistent with the requirements of PN-EN 471:2004(U). The selection of washing method must take the type of staining into consideration so that the values of photometric parameters of the material could be reproduced at the required level,
- irradiation with a Xenon lamp, and natural sunlight irradiation for the given material type causes identical characteristics of changes of chromaticity coordinates and luminance factor. No correlation has been found between the values of irradiation time intervals, both under natural conditions and with the Xenon lamp, causing, for the given colours, the respective changes of chromaticity coordinates beyond the range acceptable according to PN-EN 471:2004(U) (fig. 1,2),
- after the application of stains using the developed laboratory methods and single washing of the material, the results of photometry are repeatable. Thus, they may be used for the determination of susceptibility of new material for staining to the extent which is possible to eliminate during a single washing cycle, maintaining the required values of chromaticity coordinates and minimal values of luminance factor.

According to organoleptic assessment, the developed methods cause staining of the material similar in character to staining under actual conditions of use,

- for some tested material types, the values of luminance factor after wetting fall below the values acceptable according to PN-EN 471:2004(U) (fig. 3),
- abrasion does not affect significantly the colour properties of the tested materials,
- material processing such as ironing and anti-stain finish does not affect the photometric parameters of the tested materials.
Figure 1. Chromaticity coordinates and luminance factor after xenon test – woven fabric, yellow color.

Figure 2. Chromaticity coordinates and luminance factor after natural light – woven fabric yellow color.

Figure 3. Luminance factors of dry and wet materials, 1- dry orange knitted material, 1a – wet orange knitted material, 2 – dry yellow knitted material, 2a – wet yellow knitted material, 3 – dry orange woven material, 3a – wet orange woven material.
4. CONCLUSIONS

As a result of the performed tests, it was established that the following factors have a predominant effect determining high visibility of background materials of warning protective clothing:

- time of exposure to atmospheric factors, and in particular to natural light,
- type and size of stains,
- processes of maintenance by washing in water and degree of staining elimination

The developed methodology for assessment of the effects of the above factors on high-visibility protective clothing materials will allow to evaluate the protective properties of new materials after simulated use under model conditions.

It should take into consideration:

- investigation of chromaticity coordinates and luminance factor after irradiation with a xenon lamp, with simulation of actual conditions of high visibility warning protective clothing use (after repeated cycles of irradiation, wetting and environment temperature changes),
- investigation of chromaticity coordinates and luminance factor after application with laboratory methods of dry type and oil suspension stains and single washing in water,
- investigation of chromaticity coordinates and luminance factor of wet materials.

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PROTECTIVE CLOTHING AND OTHER PERSONAL PROTECTIVE EQUIPMENT (PPE) AGAINST HIGH TEMPERATURE LIQUID SPLASHES FOR RECOVERY BOILER WORKERS

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ABSTRACT

One of the aims of this study was to design protective clothing and gear, which meet the demands set by the recovery boiler workers for safety and ergonomics. Secondly, the aim was to select other types of needed personal protective devices from the market, which could provide the best compromise between protection and comfort. The target group consisted of pulp mill workers in Finland. The users’ preferences were identified by interviews in person, and by postal questionnaires. The face-to-face interviews and the questionnaires provided detailed information about the target group's types of injuries, near accidents and actual accidents, as well as their opinions and preferences for the clothing design. Samples of currently available materials and personal protective equipment (PPE) appropriate for protection against high temperature liquid splashes were selected from the materials available on the market and the protection level was tested in the laboratory. Protection against hot splashes in the face, neck and head area were the most often presented demands for the design. Single-layer protective clothing, as well as flame retardant fabrics is ineffective in protecting against splashes of high temperature liquid. Because of the risk of burns, flame retardant underwear with protective clothing and protective gear are also needed to provide sufficient protection. We will recommend a combination of PPE types, which provide the best compromise between protection and comfort.

1. INTRODUCTION

The employees in pulp manufacturing mills working in recovery boiler areas are potentially exposed to liquid splashes, at temperatures up to 800-900°C. In a typical recovery boiler accident, the clothing has caught on fire, and the employee has suffered serious skin burns, despite the use of flame retardant clothing in accordance with EN 531 standard (1). Specifications of requirements and test methods for heat protective clothing are defined by the European Standard EN 531 (1). However, this type of high temperature liquid splash hazard has not been taken into account in the European standardization work for protective clothing.
The aims of this study were to design protective clothing and gear, which meet the demands set by the recovery boilers workers for safety and ergonomics. The second aim was to select other types of needed personal protective devices, which could provide the best compromise between protection and comfort. Additionally, this study aims to give guidelines to the end user's for the correct use of protective clothing, and other PPE. Figure 1 illustrates the product development process for protective clothing and PPE against high temperature liquid splashes. This paper is concerned with identifying demands for use, to study materials, and to design garments. An earlier FIOH study carried out research on protective fabrics against high temperature liquid splashes (2).

Figure 1. Product development process for protective clothing and PPE against high temperature liquid splashes
2. METHODS

2.1. STUDY OF THE DEMANDS FOR USE

The target group consisted of recovery boiler workers in the pulp and paper industry in Finland. The first phase included an analysis of the work demands and working conditions, as well as types of injuries, criticalities, causes of accidents, and types of contact events. During the second phase, the users’ needs were identified by questionnaires. Information was gathered by interviews and by postal questionnaires. Interviews were conducted in seven different mills in Finland (Stora Enso, Botnia, UPM). Sixty-one employees were interviewed in person and 25 employees filled out a postal questionnaire. The questionnaire asked about the employees’ opinions and preferences regarding work and protective clothing design details, as well as other personal protective equipment. Furthermore, this questionnaire examined the recovery boiler workers' near and actual accidents.

2.2. STUDY OF MATERIALS

In the third phase, samples of currently available materials and personal protective equipment (PPE) appropriate for protection against high temperature liquid splashes were selected from the market and their suitability was tested in the laboratory. The development of a test method against hot alkaline chemical splashes is described in another paper also presented at this conference (3).

2.3. GARMENT DESIGN

During the personal interviews the target group's protective clothing was observed and profiled. Required protection level against the hazards has been assessed and the target group's work was observed to form the basis of the garment design.

3. RESULTS

3.1. DEMANDS OF THE WORK AND WORKING CONDITIONS

The temperature and air humidity values in recovery boiler areas were measured in seven different factories during the spring and the autumn of 2005. The range of temperatures was 14 °C to 35 °C, and the relative humidity (RH) was 10.5% to 47 %.

3.2. ACCIDENTS

The results show that the workers are exposed to high temperature liquid splashes and to alkaline solutions, but sometimes also to hot water splashes. The high temperature liquid splashes were considered
a hazard at the highest [most serious] level. The workers reported hazards, which are often caused by high temperature liquid splashes during maintenance tasks, as well as during routine work tasks. Nearly 31% of the employees are exposed to burn injuries of liquid splashes, when they were cleaning up a blockage in a recovery boiler. In these cases, the resulting injuries were 10% serious burns and 28% minor burns. Near accidents show that the job involves a high risk of high temperature liquid splashes, which can cause serious injuries. Thus, 64% of the employees account for near-accidents when they were cleaning up a blockage in a recovery boiler.

### 3.3. DEMANDS FOR PROTECTION

To protect the body, about 70% of the employees used face shields, less than 80% used goggles or ear shields, 90% used ear protection, and nearly 90% used safety shoes, protective clothing and gloves and other PPE (e.g., helmets). The traditional clothing worn by recovery boiler workers consists of 59% of two-piece work- or protective clothing (3% of which are fire retardant), and 44% overalls (31% of which are fire retardant). The results show that, the most important factors are that the types of PPE models should match together, and be useable together e.g., face mask, hearing protector, and eyeglasses. Figure 2 shows, that the face, front of the neck area, the head area, and the front area were the most vulnerable areas.

![Figure 2. Recovery boiler employee's opinions of the most vulnerable areas.](image-url)
3.4. STUDY OF MATERIALS

Different types of flame retardant materials, coated and uncoated have been tested, aiming to find a balance between protection and comfort. In total, 23 different fabrics and about 26 different kinds of fabric combinations were tested in the laboratory. Tested materials included: Aramid, Aramid/Polyacrylonitrile (PAN), O-Pan/P-Aramid, Fibreglass (with double silicone coating), Viscose FR/WO/PES/R-Stat/Modacrylic (MAC)/CO, and WO/CO/PPNAN-fr/PE, FR PES/Cotton.

In this case, typical flame retardant (FR) fabrics did not provide sufficient protection against hot sodium hydroxide solution, the fabrics ignited and continued to burn. The best protection level was provided by the following combination of protective wear, and therefore selected as the prototype materials:

1. Underwear: 55/45% Modacrylic/ Cotton,
2. Middle-layer: 50/30/17/3% Viscose FR, Wool, PES, R-stat,
3. Protective gear: 30/70% Kevlar(R), Polyacrylonitrile (PAN), with silicone coating.

In addition, 21 different types of PPEs for head- and hand area protection have been tested, aiming to find the best protection against splashes.

3.5. GARMENT DESIGN

Within the project, protective clothing, underwear, and special protective gear were designed and the collection consisted of different models. The traditional clothing worn by recovery boiler workers consists of work- and protective clothing, which are typically made from flame retardant fabrics. This single-layer protective clothing is ineffective in protecting against splashes of high temperature liquids. Protection against hot splashes in the front of the neck, breast area, thigh area and lower limbs were the most often presented demands for the design. The clothing combination prototype consisted of long underwear, protective clothing (middle-layer), as well as protective gear. The middle-layer clothing is a two-piece design, because employees also work in ambient conditions in the control room. The protective gear design to provide the required protection level against splashes. Prototypes were manufactured of the underwear, protective clothing and the extra protective gear. In this study, 12 recovery boiler workers will take part in wear trials in six different factories during 2006 in Finland. Also, better design models of face shields were designed against flying splashes, as well as extra neck area protective gear.

4. DISCUSSION

The traditional clothing worn by recovery boiler workers consists of work- and protective clothing, which are most often made of flame retardant fabrics as defined by the standard EN 531 (1). These single-layer protective fabrics are ineffective in protecting against high temperature sodium hydroxide solution splashes given that the sodium hydroxide solution is a very alkaline chemical. There are many alterative fabrics available for heat and fire protection on the market. However, there is no single fabric that provides a good balance between being lightweight and comfortable in addition to protecting against high temperature liquid splashes. Flame retardant underwear and protective clothing, as well as protective gear are needed to provide sufficient protection. In this case, a 3-layer combination is more likely to produce
heat stress for the end users, because of the high ambient temperatures in the work environment. For this reason, it is recommended that this combination be used only for demanding work in danger situations, such as when employees are cleaning a jam in a recovery boiler and during exceptionally hazardous situations. Finally, a combination of different types of PPE, which provide the compromise between protection and comfort will be recommended. However, protective clothing alone cannot guarantee the safety of recovery boiler workers. For this reason, a guidebook to identify and describe work hazards, protective clothing and practices, as well as the correct way to use personal protective equipment will be provided to the end users.

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ABSTRACT

This paper presents the results of the study of physiological responses of volunteers performing a light exercise in a hot environment wearing one of two kinds of protective clothing or a cotton garment, pointing to the necessity of shortening work time in protective clothing.

1. INTRODUCTION

At many work stands workers have to use personal protective equipment to protect body against physical or chemical agents. In the case of chemical danger it is necessary to use chemical protective clothing which disturbs the heat exchange between human body and the environment (1, 2, 3). The aim of the study was to assess physiological and subjective responses of humans wearing one of two kinds of chemical protective clothing made of the same materials, but of different design, or a cotton outer clothing as a control condition.

2. METHODOLOGY

2.1. SUBJECTS

Six fire-fighters participated in the study. Descriptive characteristics of the subjects (mean ± SD) were age (29,0 ± 3,7 years), height (183 ± 7 cm), weight (80,3 ± 4,8 kg) and physical fitness (40,3 ± 2,1 mlVO₂ · kg⁻¹ · min⁻¹). The subjects were fully informed of the purpose and procedures, and signed a statement of informed consent.

2.2. PROTECTIVE CLOTHING TESTED IN THE STUDY

Two kinds of chemical protective clothing (L1 and L2), made of the same materials, but of other design, were studied. The mentioned models of protective clothing were designed for the protection of
workers against pouring with acids or alkalis during temporary work. They were made of polyamide fabric weighing 300 ± 20 g · m², covered on both sides with a rubber mixture based on a butyl rubber. Protective clothing L1 consisted of two parts: a hooded top and trousers, while clothing L2 consisted of a boiler suit with a hood. Both kind of clothing had wellingtons glued permanently to the trousers. A common cotton working outer clothing (C) was applied as control clothing. All kinds of outer garment were accompanied by cotton underwear.

2.3. THERMAL AND PHYSICAL LOAD

The study was conducted in a climatic chamber in conditions of the air temperature of 40 °C, air relative humidity of 30 % and of wind speed of 02 m · s⁻¹, while participants were walking on a treadmill with the speed of 3 km · h⁻¹.

The exercise was continued until one of the following limits was reached: core temperature of 38.0 °C, heart rate of 80 % of individual maximum heart rate, 100 % of relative humidity measured at two places (under the garment), or subjective signs of fatigue. For the cotton outer garment, the study lasted 55 minutes.

2.4. MEASUREMENTS

Core temperature in the external auditory canal ($t_{ac}$), skin temperature ($t_{sk}$) at four places (4), heart rate (HR) as well as the temperature and relative humidity under clothing at four places (right chest, left shoulder, left arm, right thigh) were monitored every one minute. Mean weighted skin temperature ($\bar{t}_{sk}$) was calculated according to EN ISO 9886:2004 (4). Body and clothing weights were determined before and after exposure. Sweat loss was calculated as a difference between body weight after and before the exposure to heat. Subjective ratings of climate (5), skin wetness (6) and perceived exertion were collected every 10 minutes.

3. RESULTS

Increases of core temperature were statistically significantly higher in protective clothing L1 and L2 than in the cotton outer garment (p< 0,05), and were as follows: 1,37 ± 0,25 °C, 1,27 ± 0,45 °C and 0,58 ± 0,13 °C for L1, L2 and the cotton outer clothing (C), respectively. Changes of core temperature are presented in Fig. 1.

Changes in mean weighted skin temperature were similar and statistically significantly higher for experiments in protective clothing L1 and L2 then in a cotton outer clothing (p<0,05). They were 4,7 ± 1,1 °C, 4,8 ± 0,9 °C and 3,1 ± 0,8 °C for L1, L2 and for the cotton clothing C, respectively.

Increase in heart rate after 30 minutes of exposure in a hot environment for L1 and L2 was two times higher than for the cotton outer garment and was statistically significant (p<0,05). Changes in HR amounted to: 73,7 ± 12,8 beats/min 73,7 ±17,7 beats/min and 35,2 ± 5,1 beats/min for L1, L2 and C, respectively.

As the duration of exercise varied depending on the subject, sweat loss in the participants was expressed per time unit. Mean values of sweat rates were 24,2 ± 8,7 g · min⁻¹, 20,9 ± 3,0 g · min⁻¹ and 13,6 ± 5,8 g · min⁻¹ for L1, L2 and C, respectively. Sweat rate was statistically significantly higher in experiments in L1 than in C (p<0,05). Also, in experiments with both kinds of protective clothing the
weight of sweat accumulated in all parts of clothing was statistically significantly higher than for experiments with the set C (p<0.05). Accordingly, for both kinds of protective clothing sweat evaporation was statistically significantly lower than for the cotton outer clothing (p<0.05), as presented in Fig.2.

![Core temperature (t_{ac})](image1.png)

**Figure 1.** Changes of core temperature during light exercise in a hot environment in protective clothing L1, L2 and in a cotton outer garment (B). * p<0.05 between experiments in protective clothing L1, L2 and in cotton outer clothing C.

![Sweat distribution](image2.png)

**Figure 2.** Percentage of sweat evaporated and accumulated in clothing for three kinds of studied clothing L1, L2 and C. * p<0.05 compared to L1 and L2.

The highest temperature under the clothing was on the shoulder and reached 39.2 ± 0.5 °C, 39.3 ± 0.2 °C and 37.0 ± 0.2 °C in L1, L2 and in C, respectively. Average relative humidity for the four measured spots under clothing L1 was between 90 and 100 %. It was close to 95 % and between 75 and 85 % in L2 and C, respectively.
Subjective ratings of climate and skin wetness were statistically significantly worse for protective clothing L1 than for cotton outer clothing C (p<0.05) in the 10th, 20th and in 30th minute of the exposure to heat. Subjective ratings of perceived exertion had similar trends but were not significant.

4. DISCUSSION

The results presented in the study indicate that because of physiological limits low-intensity exercise in chemical protective clothing cannot last longer than 30 minutes. Exercise in cotton clothing is not so tiring and can last much longer. The design differences in protective clothing made it possible to extend safe exposure by only 11%.

The results also indicate that impermeable protective clothing disturbs, to a high extent, heat dissipation from the body to a surroundings during exercise in a hot environment.

Many authors who carried out studies with different kinds of impermeable protective clothing indicate a necessity to limit the duration of work while wearing such clothing (7, 8). Earlier research carried out by this author (7) indicates that the use of light-weight, but totally impermeable clothing causes a physiological load similar to that observed for a three-times heavier, but semi-impermeable, clothing, indicating that the clothing weight is less significant than the level of permeability of the fabric.

The present study also indicates that the hygienic characteristics of protective clothing L2 are slightly better, because the mean work time before the physiological limits were reached was several minutes longer (11 %) than for L1.

In the present study, during work in a hot environment in a study with cotton outer clothing there was observed a continuous, though small, increase of physiological parameters (tac and HR) and especially the deterioration in subjective ratings. This situation indicates that the garment with a cotton outer clothing was not suitable for the designed environmental conditions because of the level of warmth retention. However, it was necessary to compare sets of clothing with the same number of layers with different properties.

The results presented here constitute the first stage of the study. In the future, new construction solutions will be applied to improve hygienic properties of chemical protective clothing of that kind, and the results will be studied again.

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ABSTRACT

Many places of work involve workers in lengthy periods away from facilities necessary for refurbishing/cleaning of their clothing (e.g. army personnel, aid workers, maritime workers). Inevitably, the clothing worn by such workers will need to be worn for long periods of time without cleaning. Which fabrics and fibres are appropriate for use in such situations is one question, but a related underlying question is how to determine the tendency for body odour to be retained on apparel fabrics. The objective therefore was to develop a method for screening fabrics to be worn next to the skin in places of work which preclude normal access to facilities for refurbishing garments. The paper describes two standard procedures (one for odour-deposition, one for detecting odour), and highlights challenges and solutions in implementing the methods. Difficulties associated with human variation are addressed in the method, and the importance of using human participants discussed. The method provides a basis for development toward an international standard. Ethical approval was obtained prior to carrying out the trials.

1. INTRODUCTION

In many cultures cleanliness and hygiene are considered important in terms of good social behaviour and wellbeing. Strong body odours associated with an individual’s physiology are often considered undesirable and can be embarrassing for the individual concerned and those with whom they are in contact. However, many places of work involve workers in lengthy periods away from facilities necessary for refurbishment/cleaning of their clothing (e.g. army personnel, aid workers, maritime workers). Inevitably, the clothing worn by such workers will need to be worn for long periods of time without cleaning. The human axilla contributes to high amounts of body odour due to the high density of apocrine sweat glands which secrete initially odourless products but become malodorous through degradation by certain gram-positive bacteria present on the axillary skin surface \(^1\). Even after removal of a garment from the body, clothing can continue to remain odorous, possibly even intensifying, due to the transfer of axillary secretions, odour causing bacteria and other skin debris from the skin surface onto the adjacent garment \(^2\). When garments are not able to be refurbished between subsequent wearing this could cause a problem.
Most attempts to reduce odour in fabrics has been associated with applying antimicrobial finishing treatments to the textiles fibres or fabrics \(^5\-^8\). This focuses on reducing the bioactivity to a level at which anti-odour properties of fabrics are sustained, and quantitative and qualitative measurements of microorganisms are taken. Rarely has this also been related to sensory measurements of odour, yet sensory analysis of odour is common in the cosmetics and food industries.

A procedure for collecting odour on fabrics and a method for sensorial evaluation of odour is outlined. Difficulties associated with human variation are addressed in the method, and the importance of using human participants discussed.

2. METHODS

Nine experimental fabrics were used and are described in Table 1. Fabric specimens (225 mm x 225 mm) were folded in half along the course direction, and a shallow arc stitched to facilitate fit into the t-shirt underarm area. Fabric specimens were hand-stitched to the inside, underarm area of 100% cotton, interlock t-shirts in a location where the centre of the fabric specimen was adjacent to the axillae when the t-shirt was worn. Ethical approval from the Ethics Committee of the University of Otago was gained prior to beginning the experiment. Five male participants employed in non-sedentary jobs from the Property Services Department of the University of Otago took part in the study (age range 18-55 years).

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<th>Fibre content (100%)</th>
<th>Fabric structure</th>
<th>Wales/cm*</th>
<th>Courses/cm</th>
<th>Mass g/m²</th>
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</tr>
<tr>
<td>PR</td>
<td>polyester</td>
<td>1x1 rib</td>
<td>24.1</td>
<td>18.0</td>
<td>192</td>
<td>0.80</td>
</tr>
<tr>
<td>PJ</td>
<td>polyester</td>
<td>single jersey</td>
<td>14.1</td>
<td>19.0</td>
<td>128</td>
<td>0.74</td>
</tr>
</tbody>
</table>

*Counts of visible loops are doubled for 1x1 rib and interlock fabrics

NB. Each fabric length was laundered six times and laid flat to dry prior to cutting (ISO 6330: 2000)\(^9\)

Participants were asked to refrain from wearing antiperspirants, deodorants or other cosmetic or antibacterial products in the axillae for seven-days prior to and during the testing, and not to consume spicy foods, (including garlic and onions) forty-eight hours before the test phase. Participants were provided with a non-perfumed soap to use during the conditioning phase and throughout the test period. Participants wore t-shirts for two consecutive work days (approximately 8 hours per day) and carried out their normal work-day routine. The experimental design involved allocation of the fabrics
so that during each two-day wear period all nine fabrics were worn by each of the five participants (fabrics being randomly assigned to either the left or right axilla). Five wear-periods were required for each participant to wear each fabric; a tenth fabric specimen (an additional cotton 1x1 rib fabric) was used as a reference sample for sensory analysis. Following wear each fabric specimen was cut into an 8x8 grid of 20 mm x 20 mm specimens (Figure 1). Two groups of eight specimens were pooled and placed in Petri dishes and stored in one of two relative humidity environments (40±5% R.H. and 65±5% R.H.) at 20±2°C, for 1 day, 7 days or 28 days prior to sensory analysis being carried out. (Remaining specimen groups were kept aside for microbial analysis but this is not discussed in this paper). Fabric specimens were uncovered for approximately 12 hours to allow any residual moisture retained from participants sweat or the outside environment to dissipate on the first night following collection. Sensory analysis was conducted 1 day (between 16 – 22 hours), 7 days and 28 days following removal of the fabric specimens from the body. An hour prior to sensory analysis fabric specimens were placed in a glass vessel (150 mL volume) and a glass Petri dish placed over the mouth of the glass to contain the volatiles. The same group of fabric specimens were used during each of the three time periods.

Thirteen assessors (each of whom had earlier shown good reliability and discrimination) participated in the study. Eighteen test samples were used (nine fabrics, each at two different % R.H.) and two reference samples (spare CR fabric). The reference sample (blind) was always presented as the first sample, whilst the order of presentation of all other specimens was based on the 18-factor Williams’ design to reduce order effects 10. Intensity of odour for the reference and nine test samples were rated on a 150 mm unipolar line scale with low intensity indicated on the left of the scale and high intensity on the right. Assessors were requested to allow at least thirty seconds between sniffing samples (to reduce the effects of adaptation) and to assess each sample only once. Assessors carried out assessment in two sessions. Ten scales were printed on the same response form and all test samples had a random three-digit identification code. The panel mean of odour intensity was calculated and a repeated measures analysis of variance was carried out with time (i.e. number of days) as the repeated measures on odour intensity. Tukey’s tests were performed where significant values were found.

Figure 1  Sampling of fabric specimen for sensory analysis
3. RESULTS AND DISCUSSION

3.1. DIFFERENCES ATTRIBUTABLE TO FABRIC AND PARTICIPANT

Intensity of axillary odour detected on fabrics following removal of the fabric from the human body was clearly affected by the type of fibre from which the fabric was constructed ($F_{2,56}=94.23$, $p \leq 0.001$), with wool and cotton fabrics resulting in very low intensity ($\bar{x}=24.36$ and $\bar{x}=33.79$ respectively) and polyester fabrics high in intensity ($\bar{x}=71.80$). A small effect of fabric structure was also detected ($F_{2,56}=4.17$, $p \leq 0.05$), mostly in relation to the polyester fabrics where an interaction between fibre and structure was detected ($F_{4,56}=3.751$, $p \leq 0.01$) and intensity of polyester single jersey ($\bar{x}=65.16$) was less than that of polyester 1x1 rib (the latter rated highest ($\bar{x}=78.71$)) (Figure 2).

Although a difference in intensity among the participants was identified ($F_{4,56}=5.70$, $p \leq 0.001$) the effect of fibre type was dominant. Polyester fabrics were most frequently rated the highest in odour intensity regardless of the wearer, yet for each fibre group fabrics worn by Participant 4 were rated the highest (Figure 3). Hence, even although variation among the participants was apparent, the effect that the fabric type had in intensifying (or reducing) the odour could be detected sensorially.

The relative humidity in which fabrics were stored following wear did not affect odour intensity ($F_{1,56}=1.55$, NS), nor did the number of days fabrics were stored for ($F_{2,112}=1.65$, NS).

3.2. CHALLENGES AND SOLUTIONS IN THE USE OF HUMAN PARTICIPANTS

Many problems arise from relying on human participants as odour sources. Intensity and quality of odour that is produced in the axillae is variable from day to day for an individual and variable from one individual to another $^{11}$. Another obvious limitation is two armpits per individual, when more than two fabrics are to be tested. This excludes the possibility that odour intensity in the left and right axillae could also differ for some individuals. But despite these shortcomings, the complex interaction between odour-producing bacteria, nutrient rich apocrine and moist eccrine secretions, combined with the mechanical action and pressure from the underarm, which may facilitate transfer of odour and soils on to the fabric, cannot be easily replicated and controlled in a laboratory. So use of human participants was deemed most suitable for odour deposition on fabrics. Investigations involving human wear trials (e.g. thermoregulatory responses, perception of comfort) often control or monitor physiological responses by carrying out trials in controlled humidity and temperature environments.
(e.g. \textsuperscript{12}), where a certain level of physical activity is sustained and monitored (e.g. heart-rate, VO\textsubscript{2} max). This level of control, however, may not be appropriate (or indeed practical) when production of odour is the primary intention. For example, a number of hours of intermittent physical activity and rest periods may be required to develop sufficient ‘intense’ level of odour, and as excessive eccrine sweating is not necessarily associated with intense axillary odour \textsuperscript{13} physical activity alone may not provide satisfactory levels of intensity. Human wear trials often entail a number of additional issues surrounding them such as increased costs, ethical requirements and participant compliance which, although still exist, are less considerable when the investigator does not require participants to carry out activities they would not otherwise be doing. Therefore, this method called for human participants to wear t-shirts and fabric specimens during two consecutive work-days, not only ensuring that adequate amounts of axillary odour could be collected, but with minimal cost and ethical requirements.

Unlike instrumental test methods sensory testing is highly prone to bias and errors associated with individual subjective measures and inconsistencies. Despite training and familiarisation with test samples, it is virtually impossible to have all assessors use the scale in exactly the same way, because each assessor has his/her own internal measure or frame of reference which is often affected by the first test sample. Because the experimental was carried out over a number of days the experiment was designed so that all fabrics were allocated among the five participants in each wear period so assessors evaluated all nine test fabrics each test session, and each participant wore each test fabric over the course of five wear periods. A reference fabric was used and collected by using the ‘tenth’ armpit. This reference sample was presented as the first test sample for all assessors during every sensory session. Results from the reference samples were excluded in the analysis.

At least ten panellists is recommended for sensory testing \textsuperscript{14}, yet often even more are desirable. A greater number of assessors will increase the time needed to complete the sensory test, and this poses a problem when the test sample, or odour source, is limited in quantity and where the odour changes with time. In the current study a sampling procedure was used to divide the worn fabric specimen into a number of smaller specimens and pooling specimens evenly distributed across the original fabric specimen in groups of eight. This technique enabled other testing (microbiological) to be carried out on some groups of specimens while allowing test samples to be made available for sensory analysis. In the current study, worn fabrics were stored in one of two relative humidity environments and no differences in odour intensity was observed. This sampling method produces a sufficient number of specimens to make up eight test samples representative of the worn fabric, thus permitting a maximum of eight assessors to complete evaluations at the same time. This makes the test procedure more time efficient and creates the possibility for a larger panel to be used than in the current study.

4. CONCLUSIONS

A method to collect axillary odour on fabrics was developed which addressed human variation both in depositors of odour and in the assessors of odour. A simple method of stitching fabrics into t-shirts to be worn by workers of non-sedentary jobs over two work days enabled sufficient levels of odour to be produced and deposited on the fabric. Differences in odour on the fabrics could be perceived, as polyester fabrics were considerably more intense than either wool and cotton fabrics, and even small differences such as that between polyester single jersey and polyester 1x1 rib fabrics could be detected. The sampling procedure allows more test samples to be generated creating the potential for a greater number of assessors to be used on the panel, with testing to be carried out simultaneously.
This is especially important when the ‘object’ (i.e. in this case odour) changes with time. The problem of human variation was acknowledged, through including participants as a factor in the design, and having a panel of at least ten assessors, selecting those who had previously shown good discrimination and reliability with the test method and samples.

REFERENCES

ABSTRACT

In the prioritisation of research topics, CEN/TC 248 (Textiles and Textile Products) has identified the thermoregulatory properties as a topic to be introduced as a possible new standardisation item. The existing international standard methods are considered quite complicated and mainly related to protective clothing and footwear. A task group has therefore been formed with the objective to review existing methods and examine the feasibility of developing simpler methods for evaluating these properties. National standardisation bodies from 11 European countries have nominated participants to the task group.

The poster presents the preliminary work of the task group, i.e. the test methods which are chosen for consideration in the standardisation work. Thermal insulation, water vapour permeability and liquid water transmission assessment of textiles for clothing and footwear applications will be handled, as well as special methods for e.g. phase change materials.

1. INTRODUCTION

The clothing acts as a thermal barrier between the human body and the environment, forming a resistance for both the dry and the evaporative heat loss from the body. Appropriate thermoregulatory properties of the clothing are essential for thermal comfort and well-being of humans in most wear situations. In the case of protective clothing, a compromise between the protective and the thermal comfort properties has to be found in many cases. Several PPC standards define requirements for both aspects, and the respective performance classes are marked in the product labels. On the other hand, in many e.g. sport and leisure type of clothing there is a clear need to give this type of information to the consumers in an easily understandable and commonly accepted way, to be able to compare products from different producers.
New interactive thermoregulatory materials, e.g. phase change materials (PCM), are being introduced on the clothing markets. The conventional test methods do not necessarily give measure on their specific properties, and special test methods are therefore also being introduced.

2. TEST METHODS

A large number of physical test methods are used to assess the thermoregulatory properties of textile materials and garments or clothing ensembles. Some of the methods are standardised, either in international or in national standards, whereas many are laboratory specific. The most important properties are the thermal insulation and the water vapour permeability or resistance, but other related properties are also considered.

2.1. THERMAL INSULATION

Two international standards exist for the thermal insulation measurements of textile materials, ISO 5085-1:1989 /1/ and ISO 11092:1993 /2/. The results from the tests are considered to be comparable. The application of ISO 5085-1 is restricted to materials up to 20 mm thick, and it has been completed with ISO 5085-2:1990 /3/ for high thermal resistance, which however was withdrawn in 2005.

2.2. WATER VAPOUR PERMEABILITY / RESISTANCE

Two international and a number of national standards exist for the water vapour transmission or “breathability” measurements. A review of the test methods is published in reference /4/.

In the cup methods (upright or inverted cup) water vapour is transmitted through the test specimen either from the cup to the environment or from the environment to a desiccant in the cup, and the transmission rate WVP (g ·m⁻²·Pa⁻¹·h⁻¹, g ·m⁻²·24h⁻¹ or g ·m⁻²·h⁻¹) is determined by weighing the cup at specified intervals. ISO 15496:2004 /5/ and the national BS, ASTM, JIS, CAN, AS and DIN standards are variations of cup methods. As the test conditions (temperature, relative humidity, reagent, air gap, air flow and measuring interval) however vary between the standards, the results from tests according to different standards are not comparable.

In ISO 11092:1993 /2/ the water vapour resistance is measured with the same apparatus as the thermal resistance. The hot plate generates water vapour, which due to the humidity gradient across the specimen is transferred to the environment. Water vapour resistance R_{e} (m²·Pa/W) and water vapour permeability index i_{mt} (ratio of thermal and water vapour resistance, dimensionless) are determined.

2.3. COMBINED THERMAL INSULATION AND WATER VAPOUR PERMEABILITY

The total heat flux through textile materials or their combinations can be simultaneously determined with the sweating cylinder apparatus, used in two European laboratories /6, 7/. Thermal insulation and water vapour permeability values are defined for specific test conditions (sweating levels, ambient conditions). The test method is not standardised, and it has mainly been applied for research purposes.
2.4. AIR PERMEABILITY

The international standard ISO 9237:1995 /8/ defines the generally applied test method for air permeability R (mm/s or m/s). Different test surface areas (5, 20, 50 and 100 cm²) and different pressure drops (50, 100, 200 and 500 Pa) may be used, which lead to differences in the test results.

2.5. LIQUID WATER TRANSMISSION

No international standard exist for testing the liquid water transmission through clothing textiles. ISO and other standards for non-woven fabrics might be applied also on clothing fabrics or combinations. The Polish sorptionmeter SORP-3 measures several absorption / desorption values.

2.6. OTHER MATERIAL TEST METHODS

The thermoregulatory properties of PCM materials, which absorb and release heat at certain temperature changes due to phase changes between solid and liquid, cannot be assessed with conventional textile test methods. A special ASTM test standard /9/ has therefore been developed for this type of materials. The steady state thermal resistance R is defined at a constant heat flux between a cold and two hot plates, and the temperature regulating factor TRF at a heat flux which is varied sinusoidally with time. A method for testing the thermal efficiency of PCM materials, expressed through the time of protection $\tau_{pc}$, has been also been described /10/.

2.7. TESTING OF GARMENTS AND CLOTHING ENSEMBLES

The international standard ISO 15831:2004 /11/ defines test methods for the measurement of thermal insulation of clothing ensembles using a movable thermal manikin with the dimensions of an adult human. Two different test procedures are described: the total thermal insulation $I_t$ is measured with a stationary manikin, and the resultant total thermal insulation $I_r$ with the legs and arms of the manikin mechanically moved. The thermal insulation values can be calculated using either the serial (surface area weighed) or the parallel (surface area averaged) model, which particularly for ensembles with unevenly distributed insulation give different results. Sweating thermal manikins are used to measure the simultaneous dry and evaporative heat flux through clothing ensembles /12/, but the method is not standardised.

3. DISCUSSION

The feasibility of developing simple test methods for evaluating the thermoregulatory properties of textiles, i.e. the heat and moisture fluxes from the human body through the textile layers to the environment, is to be investigated by a new CEN TC 248 standardisation task group. Existing methods are being reviewed, and feedback from all experts on protective and other types of clothing will be gratefully accepted.
4. REFERENCES

EXAMINATION OF DOMESTIC AND COMMERCIAL WASHING MACHINES FROM THE POINT OF VIEW OF EFFECTS ON WASHING OF PPE’S

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Textilní Zkušební Ústav, Brno, CZECH REPUBLIC

ABSTRACT

New standard EN ISO 15797 – Industrial washing and finishing procedures for testing of workwear – was compared with domestic washing procedures from the point of view of keeping quality of PPE and ensuring its long-life period. Possibilities and common equipment for domestic washing was compared with industrial washing machine developed according to EN ISO 15797 requirements and laboratory washing machine for textile testing according to EN ISO 6330. Also monitoring of temperature program “temperature calibration” of domestic washing machines was performed and compared with today’s possibilities of commercial laundries. The results obtained compare advantages and disadvantages of both washing procedures and offer new view on aspects of washing of PPE under professional and individual washing procedures.

1. INTRODUCTION

The washing procedure is intended to remove impurities from textiles and damage as little as possible the washed textiles, i.e. to change negatively their performance in use. The overall result of washing is influenced by a number of factors: mechanical effects, temperature of washing and rinsing baths, water quality, composition and performance of detergents. In order to compare particular procedures of commercial and domestic washing procedures from the point of view of their effects on textiles, standard conditions of washing procedures described in international standards were selected, thus securing acceptable approximation of the equipments and testing procedures. The assessment and comparison of the washing procedures was carried out based on a comparison of changes of selected properties of work-protective clothing both prior to and after the washing. The effect of twenty-fold washings on the dimension changes, colour fastness, appearance after washing and puckering of work-clothing was assessed.
2. PROCEDURES

**EN ISO 15797** Textiles – Industrial washing and finishing procedures for testing of workwear. The Standard specifies testing procedures of washing, drying and finishing, including testing facilities, which may be used for assessment of work-clothing made of cotton, or of a cotton/polyester blend, intended for commercial washing. Depending on the material composition and clothing style (white or coloured), it is possible to select several washing procedures differing in composition and temperature of the washing bath. According to the above standard, the influences of commercial washing on important properties of work-clothing were assessed. They include dimensional stability, colour fastness, creasing, puckering and appearance after washing.

**EN ISO 6330** Textiles – Domestic washing and drying procedures for textile testing. The Standard specifies procedures of domestic washing and drying for testing the textiles. The selected properties of the textiles are tested after washing and drying by a specified procedure.

**EN ISO 105-C08** Textiles – Tests for colour fastness - Part C08: Colour fastness to domestic and commercial laundering using a non-phosphate reference detergent incorporating a low temperature bleach activator. The Standard specifies the procedures intended for assessing colour fastness of textiles of all types and all forms against procedures of domestic and commercial washing. The test equipment and standard detergent are used, adding activating bleaching agent. The test specimens are washed under relevant conditions of temperature, alkalinity, bleaching and rubbing effect, so that the results should be obtained in a reasonably short period of time.

**EN 340** Protective clothing - General requirements. The Standard specifies general conditions for workmanlike finish, concerning the views of ergonomics, health-hygienic properties, size designation, ageing, compatibility and marking of protective clothing. The Standard also specifies the information submitted by the producers together with the protective clothing. Also incorporated into the Standard were the testing procedures pertaining to the commercial washing because this way of washing is often used for many types of protective clothing.

3. DESCRIPTION OF TEXTILE MATERIALS, PRODUCTS AND TEST EQUIPMENT

3.1. TEXTILE MATERIALS

**Woven fabric NORD 235 (sample 1 - colour: dark blue; sample 2 - colour: dark green)** intended for production of work clothing to provide a protection against increased mechanical surface strain and against soiling.

Construction parameters: material composition: 100 % cotton, twill weave 2/2, mass per unit area of 235 g/m², permitted mass deviation of ±3 %, woven fabric width of 150 cm, warp set of 44 yarns/cm, pickage of 20 yarns/cm.

**Woven fabric PESTERN (sample 3 - colour: orange-red)** with fluorescent properties intended such as base material for production of clothing with a high visibility.

Construction parameters: material composition: 88 % polyester/22 % cotton, satin weave 4/1, mass per unit area of 280 g/m², woven fabric width of 150 cm, warp set of 38 yarns/cm, pickage of 21 yarns/cm, yarn in warp: 100 % polyester of 42 tex, yarn in weft: 65 % polyester/35 % cotton of 42 tex.
3.2. PRODUCTS

Work trousers were manufactured: from a woven fabric in green and blue colours. A warning jacket was sewed from the blended woven fabric. The products were subjected to the following tests:

Care symbols for the products:
Work trousers: 🛑 ▲ ✰ ✠ X Warning jacket: 🛑 ▲ ✰ ✠ ✠ X

3.3. TEST EQUIPMENT

A commercial washing machine with uncushioned motion, made by PRIMUS, type XS 35 with a horizontal turning drum having front loading, capacity of 35 kg, corresponding to technical specification according to EN ISO 15797.
Laboratory washing machine for simulation of domestic washing made by Electrolux, type FOM 71 MP, with a horizontal turning drum having front loading, capacity of 5 kg, corresponding to technical specification according to EN ISO 6330.
Laboratory equipment for washing LINITEST, in which the test specimens are washed under conditions identical with both commercial and domestic washing in accordance with EN ISO 105-C08.
Spectrophotometer SPECTRAFLASH SF 300 made by Datacolor International for measurement remissive properties, shown by both the new and washed woven fabrics.
All the specimens were washed using the same commercial laundry detergent for both commercial and domestic washing procedures at a loading ratio of 1:4, a liquor ratio of 1:14 and at washing temperature of 60 °C.
Washing according to C08 conditions was carried out in line with the prescribed standard detergent at the loading ratio of 1:4 and temperature of 60 °C. The products were dried in a tumble drier at 50 °C, in contradiction with the quoted care symbols because another means of drying, other than machine drying, is not acceptable for a commercial laundry.

4. DESCRIPTION OF TESTS AND THEIR EVALUATION

The effects of the particular technologic procedures of washing were compared using the work trousers from the above mentioned cotton blue and green woven fabrics and the warning jacket from the blended woven fabric polyester/cotton of the orange-red colour. The following changes of the selected properties were evaluated:

- dimensional changes
- colour fastness in washing
- appearance after washing
- puckering.

4.1. DIMENSIONAL CHANGE EXPRESSED IN PERCENTAGE

<table>
<thead>
<tr>
<th>Article (warp/weft)</th>
<th>after 10 washing cycles</th>
<th>after 20 washing cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EN ISO 6330</td>
<td>EN ISO 15797</td>
</tr>
<tr>
<td>1 blue trousers</td>
<td>-6 / -2</td>
<td>-6,5 / -3</td>
</tr>
<tr>
<td>2 green trousers</td>
<td>-5,5 / -2</td>
<td>-6,5 / -2,5</td>
</tr>
<tr>
<td>3 orange-red jacket</td>
<td>0 / -1</td>
<td>0 / 0</td>
</tr>
</tbody>
</table>

The requirement of EN 340:2004 from the point of view of general material requirement is max.±3 %.
4.2. COLOUR FASTNESS IN WASHING EXPRESSED IN LEVELS OF GREY SCALE

<table>
<thead>
<tr>
<th>Article (warp/weft)</th>
<th>new material</th>
<th>after 1 washing cycle</th>
<th>after 10 washing cycles</th>
<th>after 20 washing cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 blue trousers</td>
<td>5</td>
<td>4-5</td>
<td>4-5</td>
<td>4-5</td>
</tr>
<tr>
<td>2 green trousers</td>
<td>5</td>
<td>4-5</td>
<td>4-5</td>
<td>4-5</td>
</tr>
<tr>
<td>3 orange-red jacket</td>
<td>5</td>
<td>--</td>
<td>--</td>
<td>4</td>
</tr>
<tr>
<td>reflective strip</td>
<td>5</td>
<td>--</td>
<td>--</td>
<td>3-4</td>
</tr>
</tbody>
</table>

Colour fastness in washing according to EN ISO 105-C08:

<table>
<thead>
<tr>
<th>Article</th>
<th>new material</th>
<th>change of shade after 10 washing cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 blue trousers</td>
<td>5</td>
<td>3-4</td>
</tr>
<tr>
<td>2 green trousers</td>
<td>5</td>
<td>3-4</td>
</tr>
</tbody>
</table>

The products have a poor colour fastness when the detergents with bleaching agents are used. The colour bleeds into the washing bath and the change of colour shade is more intensive as compared to both the domestic and commercial washing. The evaluation of the shade change was carried out according to EN 20105-A02 Textiles - Tests for colour fastness - Part A02: Grey scale for assessing change in colour. This scale has five levels; the samples exhibiting non-observable colour shade change in the test are assigned as level five on the scale.

4.3. CHANGE OF FLUORESCENT PROPERTIES OF THE WARNING JACKET

<table>
<thead>
<tr>
<th>original coordinates</th>
<th>EN ISO 15797</th>
</tr>
</thead>
<tbody>
<tr>
<td>X 0,5918</td>
<td>X 0,5923</td>
</tr>
<tr>
<td>Y 0,3588</td>
<td>Y 0,3602</td>
</tr>
</tbody>
</table>

Change of fluorescent attributes after 10 cycles of commercial washing

Change of fluorescent attributes after 20 cycles of commercial washing

The commercial washing of the warning jacket caused a change of the orange-red colour shade, but the fluorescent properties of the product were nearly preserved.
4.4. APPEARANCE AFTER WASHING, PUCKERING

The appearance of the products tested in 20 cycles was not different whether the washing was of domestic or commercial procedure. The following table describes the changes observed on the washed products.

<table>
<thead>
<tr>
<th>Article</th>
<th>appearance after 20 washing cycles</th>
<th>puckering</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 blue trousers</td>
<td>Increasing number of washing cycles cause abrasion mainly on borders (seams, pleats) and pilling. After 10 washing cycles there is no significant difference in appearance of fabrics depending on type of washing</td>
<td>no change</td>
</tr>
<tr>
<td>2 green trousers</td>
<td>no change</td>
<td></td>
</tr>
<tr>
<td>3 orange-red jacket</td>
<td>fabric pilling</td>
<td>no change</td>
</tr>
</tbody>
</table>

5. MONITORING OF TEMPERATURE CONDITIONS OF WASHING IN DOMESTIC WASHING MACHINES

A part of the research it was also monitoring the temperature conditions in the domestic washing machines. The aim of this was to check the temperature calibration of the domestic washing machines, considering obeying the recommended care and gentleness in washing of work-clothing.

For this purpose, a measuring sensor T-BUG developed in the Textile Testing Institute specifically for the purpose of measuring the temperature profile of the washing bath was employed. The measurement was attended by a group of 21 volunteers, carrying out washing at home in their washing machines, using the above described sensor. The age of the washing machines was not taken into account, the only emphasis was given to correct setting of the actual temperature washing bath during the washing procedure. The actual state and a practical variability of the washing bath temperature in the domestic washing procedure were monitored. Most of the users did not know the information on the washing bath temperature and were dependent exclusively on information pertaining to correct calibration setting made by the manufacturers.

Sensors with the temperature profiles were returned to the Textile Testing Institute. The temperature curves obtained were processed and evaluated after the test cycles have been finished.

5.1. TECHNICAL PARAMETERS OF THE T-BUG SENSOR

It is in principle an aluminium disc, being located during the washing procedure in the washing machine drum together with the textiles being washed. The washing bath temperature was monitored continuously by the integrated memory of the sensor. The temperature record was initiated automatically upon reaching the "starting temperature".

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature range</td>
<td>25 - 100 °C</td>
</tr>
<tr>
<td>Time interval between measuring</td>
<td>30 s , temperature time constant 90 s</td>
</tr>
<tr>
<td>Start recording condition</td>
<td>t &gt;25 °C (hysteresis 5 °C)</td>
</tr>
<tr>
<td>Memory capacity</td>
<td>14 308 records, rewritable</td>
</tr>
</tbody>
</table>
**5.2. RESULTS OBTAINED – MAXIMUM WASHING TEMPERATURE REACHED**

<table>
<thead>
<tr>
<th>Model of washing machine</th>
<th>30 °C</th>
<th>40 °C</th>
<th>50 °C</th>
<th>60 °C</th>
<th>70 °C</th>
<th>80 °C</th>
<th>90 °C</th>
<th>95 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEG Elektrolux</td>
<td></td>
<td>56,5</td>
<td></td>
<td></td>
<td>81,0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AEG Lavamat 1046</td>
<td></td>
<td>46,5</td>
<td></td>
<td></td>
<td>83,5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AEG Lavamat W1260</td>
<td>37,5</td>
<td></td>
<td>52,5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARDO</td>
<td>30,0</td>
<td></td>
<td>47,0</td>
<td></td>
<td>83,5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARDO TL 600x</td>
<td></td>
<td>49,5</td>
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**6. CONCLUSIONS**

An evaluation and a mutual comparison of effects of domestic and commercial washing procedures according to EN ISO 15797 (commercial washing procedure), EN ISO 6330 (domestic washing procedure) and EN ISO 105-E08 (colour fastness in domestic and commercial washing procedures) for work-clothing was carried out. The following useful characteristics were assessed: dimensional changes, colour fastness, appearance after washing and puckering.

The results obtained have proved a slightly higher wear of the woven fabrics during the commercial washing procedure and slightly higher change of colour of the fabric during the commercial washing procedure. The change of colour was influenced primarily by the commercial washing machine...
loading (a higher probability of coloration from the bath, even though the conditions of EN ISO 15797
were respected).
A slightly higher dimensional changes appeared during the commercial washing procedure. This effect
can be assigned to a higher strain (due to higher loading) in the tumble washing machine. The change
obtained corresponds to 0.5 % - 1 % as compared to the domestic washing procedure.
The washing procedure using detergents containing bleaching agents under conditions of
EN ISO 105-E08 confirmed the assumption of a substantial influence of the change in colour of the
coloured washed specimens.
When comparing the washing procedures, it can be stated that no substantial differences have been
observed between washing procedure in the commercial washing machine under conditions of
EN ISO 15797 and under conditions of the domestic washing procedure according to EN ISO 6330.
Approximately from the tenth washing cycle, the fabric washed via the domestic washing procedure
got the appearance of the fabric washed using the commercial washing procedure. The colour shade is
rubbed from the thicker places of the product (e.g. seams) and a propensity to pilling appears.
The results obtained proved that washing according to the standards for domestic and commercial
washing procedures provided comparable results.
This observation can be utilized in the assessing of the PPE’s characteristics within evaluation of
conformity.
Investigation of the temperature conditions setting in domestic washing machines has shown that a
majority of the washing machines complied with the temperature tolerance of ±10 %. However, the
results obtained also showed that in certain cases, the setting of the washing bath temperature of
domestic washing machines entirely differ from the required value!
This observation should be a challenge for manufacturers to offer commonly within the frame of
services of their products also a calibration check of the washing bath temperature.
ABSTRACT

A speed-march is a form of movement for quick withdrawal from a dangerous area. Speed-marching might be the option a unit chooses to get out of an area which is under (chemical) attack. However it is unclear if wearing NBC protection will result in a substantial loss of speed. A field trail was performed in a tropical climate to obtain more knowledge about working in the field under NBC protection. This investigation was performed within the framework of the Anglo Netherlands Norwegian Cooperation on Chemical Protection (ANNCP) on the island Curacao in the Netherlands Antilles. Earlier research showed that speed-marching on the Island of Curacao is a very heavy task due to the extremely high metabolic rate which results in high levels of heat stress. During the trails the effects of wearing a respirator on the soldiers physiological strain and performance during a speed-march were studied.

Although we could only use four subjects which not enough to generate significant results the data indicates that wearing a respirator during a speed march results in a increased heart rate, a rise in core temperature and a reduction in speed. This might have serious consequences for soldiers who are escaping from a contaminated area. The increased blood flow and skin permeability as indicated by body temperature and heart rate can make the human body more vulnerable for CW-agents while a reduction in mobility might increase the time the soldier is exposed to CW-agents.
A MANNED TEST FOR EVALUATING SLIPPERINESS FOR BOOTS ON ICY SURFACE

Hannu RINTAMÄKI¹, Juha OKSA¹, Tero MÄKINEN¹, Arvid PÅSCHE²

¹Finnish Institute of Occupational Health, Oulu, FINLAND
²Thelma AS, Trondheim, NORWAY

ABSTRACT

A new manned test method provides means of combining both subjective evaluation and objective results for the performance of walking boots on icy surfaces at different temperatures and with the boots and the soles cooled to the same temperature as the ice. A shallow water basin, 266 cm long, 99 cm wide and 10 cm deep, is being water filled and frozen to a preferred temperature. The rectangular piece of ice created is positioned on a treadmill in the cold room test facility. For the actual testing only the slope adjustment of the treadmill is being used. The testing includes two sequences. In the first sequence the test person dressed in the test boots attempts to walk up the icy surface at a pre-established constant walking speed, with the slope of the treadmill set at a low angle. The slope is then step wise being increased until the test person no longer can walk up the ice, but keep sliding down. The highest slope the test person has successfully managed is considered the maximum performance for this particular boot. In the second sequence the test person, still wearing the same test boots, is being positioned standing on both feet facing downwards the ice surface with slope of 5°. The slope of the ice is then steadily and continuously being increased until the test person starts sliding. The test procedure produce very repeatable results, and it is concluded that this method provides an additional valuable means of evaluating the performance of boots on icy surface.

1. INTRODUCTION

Accident caused by slipperiness and fall on icy surfaces is one of the common health problems during winter activities. Means of evaluating slipperiness of boots on icy surface are of great importance to be able to select proper footwear for this environment. The developed test method using test subjects provides means of combining both subjective evaluation and objective results for the performance of walking boots on icy surfaces at different temperatures and with the boots and the soles cooled to the same temperature as the ice.
2. METHODS

A shallow water basin, 266 cm long, 99 cm wide and 10 cm deep, was filled with water and frozen to a preferred temperature. The rectangular piece of ice created was positioned on a treadmill in the cold room test facility. For the actual testing only the slope adjustment of the treadmill was used.

The testing includes two sequences. In the first sequence the test subject dressed in the test boots adequate winter clothing attempted to walk up the icy surface at a pre-established constant walking speed, with the slope of the treadmill set at a low angle (Fig. 1). The slope was then stepwise increased until the test person could no longer walk up the ice, but was sliding down. The highest inclination the test person has successfully managed was considered the maximum performance for this particular boot. Three repetitions were done, and the average value was calculated for each boot. One test subject (height 175 cm, mass 70 kg) performed all measurements.

![Figure 1. A test person walking up the inclined icy surface.](image)

In the second sequence the test subject, still wearing the same test boots, was standing on both feet facing downwards the ice surface with slope of 5°. The slope of the ice was then steadily and continuously being increased until the test person starts sliding down (Fig. 2). Three repetitions were done, and the average value was calculated for each boot.

The samples of test boots included a variation of boots for leisure activities as well as working boots. The soles of the boots also varied considerably regarding material composition and structure. The exact material composition for the different soles was not available.
3. RESULTS

Figures 3 and 4 show the results from testing including 22 different boots using the method described. The tests were performed in different ambient temperatures, -5.0 °C and -14.0 °C, with ice temperatures of -4.8 °C and -13.5 °C respectively. Prior to the tests at the two different ambient temperatures all test boots were kept in the climatic chamber at the actual temperature for 24 hours. The test boots were donned in the climatic chamber.

The results shown in Figure 3 are from the testing with the test subject walking up the inclining ice surface. It was found a considerable difference regarding to the slipperiness on the icy surface for the 22 pairs of boots tested. The differences in slipperiness were found both on -4.8 °C and -13.5 °C ice temperature. In general the highest slipperiness (lowest ice inclination) was found at the higher ice temperature (-4.8 °C). At lower temperatures the friction between the sole of the boot and the ice surface increased, higher inclination was reached and the variation between the boots were smaller.

In the sliding test, starting with the test subject standing on the ice, resulted in a similar variation between the boots tested as for the walking tests at -4.8 °C. However, a higher inclination was reached resulting from the increase in total sole area in contact with the icy surface compared to the walking situation. At the lower ice temperature (-13.5 °C) most of the boots tested reached the highest inclination possible for the treadmill (16°) without sliding.

Repeated tests for selected boots, tested with 24 hours interval, showed results for inclination angel that differed by only 0.5 °. These results indicated a good reproducibility for repeated tests.
Figure 3. Average results for maximum inclination the test person can walk up the ice surface, tested at ice temperature of -4.8 and -13.5 °C.

Figure 4. Average results for maximum inclination of the ice surface before the test person in a static position with both feet on the ice starts sliding. The tests were performed at -4.8 °C and -13.5 °C. Maximum possible inclination was 16.0 °.

4. CONCLUSION

The test procedure produced very repeatable results, and it is concluded that this method provides an additional valuable method for evaluating the performance of boots on icy surface. Some (6) of the boots had been tested earlier mechanically with an artificial foot, and that test put the boots in the
same friction/performance order. The results show that the performance of the boots was better at
colder temperatures in all boots except one (number 22), which had smaller friction in walking test at
the colder temperature, probably due to hardening of the sole material.
GASTIGHT CHEMICAL RESISTANT ELASTOMER SOCKS

Klaus-Michael RÜCK, Chemistry Engineer

R&D Draeger Safety AG & Co. KGaA, Lübeck, GERMANY

ABSTRACT

Integrated Socks for CPS are known since several years. Contrary to the NFPA Standard 1991:2005 the European Standard EN 943-2:2002, only knows socks from same material like the CPS main material. In 2004 Draeger Safety developed an elastomer- sock that could be integrated gastight to CPS. These 100% elastomer socks provide excellent chemical protection (comparable to Viton/Butyl gloves) and excellent wearing comfort in comparison to socks out of coated textile, because they fit excellent to the feet and they don't have any seams at the sole or ankle area like a sock from standard CPS material. In combination with boots acc. EN 345-2 S5 FPA they are a benefit for every user of CPS with socks. The poster presentation should inform especially standard association members to think about changes in the international esp. European standards and to introduce this development to customers and/or suit manufacturers.

1. INTRODUCTION

Integrated Socks for CPS are known since several years. Contrary to the NFPA Standard 1991:2005\textsuperscript{1} the European Standard EN 943-2:2002\textsuperscript{2}, only knows socks from same material like the CPS main material. In 2004 Draeger Safety developed an elastomer- sock that could be integrated gastight to CPS. These 100% elastomer socks provide excellent chemical protection (comparable to Viton/Butyl gloves) and excellent wearing comfort in comparison to socks out of coated textile, because they fit excellent to the feet and they don't have any seams at the sole or ankle area like a sock from standard CPS material. In combination with boots acc. EN 345-2 S5\textsuperscript{3} FPA they are a benefit for every user of CPS with socks. The poster presentation should inform especially standard association members to think about changes in the international esp. European standards and to introduce this development to customers and/or suit manufacturers.
2. METHODOLOGY

2.1. ACTUAL SITUATION

Existing integrated socks are already known by several suppliers. Especially suits for the limited use market out of laminates are usually equipped with integrated socks (for this reason the US market prefers this sort of suits). Some suits especially suits out of viton butyl coated textiles are equipped with socks out of the main suit material too. For this reason we bought several different suits from the market and started a comparison.

2.2. COMPARISON

All these suits have similar disadvantages.

- they have seams and all seams a areas with potentially leakages
- the seam areas are thicker than the standard suit material
- the user has to wear boots with a size minimum 3 sizes bigger than the own boot
- the stepping into the over boot with the integrated socks is difficult, due to wrinkles and/or static friction
  - wrinkles at the foot area especially of laminates are very disturbing during mission
  - you can’t step into a container that is filled with liquids higher than the bootleg, because liquids could spilled in the bootleg (this could be problematic even when the material isn’t influenced physical or chemical by the substance, due to weight or temperature)
  - assembling a boot is easier than assembling a sock (sock layout, sewing, gluing is more complex than fixing ready boots via steel cable, thrust ring, and sealing compound)

The advantages of integrated socks this way are

- The user can use the standard boot of the operating unit (but bigger than your own sizes)
- Reusable suits with socks are lower stressed during cleaning procedures in machineries than suits that are assembled with fixed boots.
  - The suits are lighter
  - Due to lower weight they can be easier handled during care and maintenance
  - The suits are easier to store
  - Socks are usually easier to repair than complete boots.

2.3. DEVELOPMENT SPECIFICATION

As a result of this comparison of existing suits with integrated socks we decided to define following technical/customer requirements for the development of an own integrated sock by Draeger Safety

- High chemical permeation resistance
- High flexibility
- Easy adaptation
- Minimum three sizes
- ankle or bootleg flap to prevent splashes to rinse into the bootleg
- approval acc. EN 943-2:2002
- And some others not of general interest.
2.4. MATERIAL SELECTION

Regarding the different materials the market can provide the suit suppliers with, we very soon found out that coated fabrics which provide the user on a high permeation level are usually not as flexible as they should be for a user's feet. Therefore the coated fabrics or laminates very soon were out of the track. We decided to go for elastomer directly. The best elastomer for chemical protection suits you can get are fluoro elastomeres FKM, butyl IIR or FKM/IIR double layers or EPDM. These materials are usually in use for gloves at CPS or full face masks and they seemed to be the right for socks too. Special blends of CR/NR/SBR/NBR/CSM would perhaps work too.

2.5. SELECTING THE RIGHT COMPOUND AND TOOLING

Depending on the amount of nature rubber NR, elastomers can show to heavy ageing or degradation at UV light or ozone or organic compounds. For this reason we excluded NR mixtures very soon.

A tool to inject or a compression moulding tool for EPDM, which would be excellent at thicknesses > 1.5 mm regarding the permeation resistance, would cost more than 100 T € per sock size. 300 T € only for the tooling were unacceptable for this project. Thicknesses higher than 1.5 mm seemed to be too strong for a flexible sock.

The CPS market is not comparable to a full face mask market where more than 100,000 a year are normal to sold. The market share even when we would gain some shares with these new socks wouldn’t justify these expenses.

Due to these facts and due to the long ongoing contacts to glove manufacturers we very soon decided to go for socks that were manufactured in a dipping process. The best gloves for CPS are the ones out of Butyl Base with a FKM coating. So the decision was clear to create socks with this two layer design.

2.6. PROTOTYPING

First prototypes shown following:

− A sock has to have an ergonomic form, because flat forms get wrinkles on the wrong feet areas
− Its better to have a left and a right sock, than an ambilaterial sock
− Adaption with a thrust ring is possible but the ring disturbs the donning with the over boot
− Minimum thickness has to be the thickness of our FKM/IIR glove to get the correct permeation resistances acc EN 943-2:2002

2.7. DECISIONS

During development process we added following requirements to the specifications

− Direct sewing and taping to the suit legs
− Ergonomic left and right foot design
− FKM/IIR as main material
3. REALISATION AND DISCUSSION

All these requirements are fulfilled now.

We created a soft permeation resistant ergonomic elastic sock in three different sizes. The socks are so elastic that e.g. the sizes 44 can be worn by users with a foot size from 41 to 47 without disturbing wrinkles or uncomfortable pressure on the feet.

A problem was the approval acc. EN 943-2:2002, because this stated in § 5.3.2 that “an integral sock or bootee shall provide at least the same level of protection as the fabric from which the chemical protective suit is manufactured”.

This is a thing that no boot or glove worldwide fulfil (e.g. there is no boot that fulfils same permeation classes than Tychem TK® which always fulfil class 6, or our own HIMEX® Material). As soon as you don’t use the same material like the suits material you will not achieve same values. You can find on any elastomer or coated fabric a chemical that will not have same permeation resistance than the other. Regarding the aspect that a sock always has to be combined with an outer boot, there is no risk for the user when the sock fulfils the permeation requirements acc. § 5.2 of that standard EN 943-2:2002. The approval authority Force Technology Institute5 in Denmark decided to accept these new developed socks. Under the aspect that §5.3.2 is not fulfilled, but that the suits fulfil the requirements when they are in use in conjunction with a boot acc. EN 345-2 Version FPA.

We think that existing standards should not interfere new solutions for ergonomic developments, as long as these solutions are safe for the users. This restriction is only to find in the European Standards the NFPA Standard NFPA 1991:2005 is a little bit more progressive in this case, and we hope that for the future this part will be revisioned.

4. PICTURES

![Suit with socks at donning procedure. Separate boot at the left side.](image-url)
Suit with socks after donning the right boot.

Suits with integrated socks at pressure drop test procedure acc. EN 464

2) EN 943-2:2002 Protective clothing against liquid and gaseous chemicals, including liquid aerosols and solid particles
3) EN 345-2 Sicherheitsschuhe für den gewerblichen Gebrauch
4) Tychem TK® is a Trademark of DuPont; HIMEX® is a Trademark of Draegerwerk AG
5) FORCE Technology: Park Allé 345, DK-2605 Brøndby Phone: +45 43 26 70 00 Fax: +45 43 26 70 11 E-Mail: force@force.dk
6) EN 464 Protective Clothing – Protection against liquid and gaseous chemicals,…,Test method: Determination of leak-tightness of gas-tight
ABSTRACT

Body armor, both military and civilian, often carries a minimum “no penetration” velocity specification. Fiber, fabric, and garment manufacturers associated with body armor design typically use $V_{50}$, the velocity giving equal probability of stopping or not stopping the projectile, as the measure of body armor performance. Logistic regression provides a useful model for relating impact velocity and the probability of projectile penetration. The velocity difference between any two penetration probabilities ($V_1$ and $V_{50}$, e.g.) is a simple function of the regression slope. Standard ballistics testing protocol does not provide a good estimate of that slope, however, so two products can appear similar in standard testing, but differ substantially in customer protection. In addition, $V_{50}$ variability, which depends among other things on test design, is often confused with variability in projectile penetration probability. Proper characterization of ballistic performance of a protective garment requires a thorough understanding of the penetration probability function for that system, as well as the mapping function between variability in penetration probability and $V_{50}$ test results.

1. MODELS FOR QUANTIFYING BODY ARMOR PROTECTION

Ballistic testing yields a dichotomous outcome: pass or fail (“partial” or “complete” penetration). This outcome is modeled as a function of projectile impact velocity. Regression analysis, usually in the form of logistic regression or probit analysis, is used to estimate model coefficients.

The logistic regression model is $\pi(x) = \frac{e^{\alpha + \beta x}}{1 + e^{\alpha + \beta x}}$, where $\pi(x)$ represents the probability of penetration at velocity $x$. The logit transformation, $\text{logit}(x) = \ln[\pi(x)/(1-\pi(x))]$, plays a central role in logistic regression since $\text{logit}(x) = \alpha + \beta x$ has many of the desirable properties of a linear regression model.

- $\frac{\partial \pi(x)}{\partial x} = \beta \pi(x)[1-\pi(x)]$. The curve has its steepest slope at the $x$ value where $\pi(x) = \frac{1}{2}$, which is $x = -\alpha/\beta$. This is the $V_{50}$. The line tangent to the logistic curve at that point has slope $\beta/4$. 
The value \(1/\beta\) approximates the distance between \(x\) values where \(\pi(x) = 0.25\) or \(0.75\) and where \(\pi(x) = 0.5\). In ballistic testing application, \(1/\beta\) approximates the velocity difference between \(V_{25}\) and \(V_{50}\). Figure 1 shows the impact of \(\beta\) on the slope of the probability curve. In this example, \(1/\beta = 91\) and 59 fps, respectively. The velocity difference between any two penetration probabilities can be calculated as \([\text{logit}(\pi_1) - \text{logit}(\pi_2)]/\beta\).

Figure 1. Two ballistic test curves having identical \(V_{50}\)s but different penetration behaviors (blue: \(\beta = 0.0111\); purple: \(\beta = 0.0171\)).

Probit analysis arose in connection with bioassay, although it can be effectively used to model ballistic resistance test data. The probit model is \(\pi_x = \Phi(\alpha + \beta x)\) where \(\Phi\) is the cumulative normal distribution function (normit link), and \(\alpha\) and \(\beta\) are unknown parameters to be estimated. The probit model response curve for \(\pi(x)\) has the appearance of a normal cdf, with mean \(\mu = -\alpha/\beta\) and standard deviation \(\sigma = 1/|\beta|\). Since 68% of the mass in a normal distribution falls within a standard deviation of the mean, \(1/|\beta|\) is the distance between the \(x\) values where \(\pi(x) = 0.16\) or 0.84 and where \(\pi(x) = 0.50\). The rate of change in \(\pi(x)\) at a particular \(x\) value is \(\partial\pi(x)/\partial x = \beta\phi(\alpha + \beta x)\), where \(\phi\) is the standard normal density function. That rate is highest when \(\alpha + \beta x = 0\) (i.e., at \(x = -\alpha/\beta\)), where it equals \(\beta/(2\pi)^{1/2} = 0.40\beta\) and at which point \(\pi(x) = 1/2\).

The logit and probit functions are almost linearly related over the interval \(0.1 < \pi < 0.9\). For this reason, it is usually difficult to discriminate between them on the grounds of goodness of fit. Experience shows that bias between the two functions increases as variability increases, is most pronounced in the distribution tails, and is not of practical importance from the perspective of model fit or model predictions. The probit model, however, provides an explicit estimate of the penetration probability standard deviation, which is useful in considering specifications and safety margins, and in comparing products.
2. RELATIONSHIP BETWEEN $\sigma$ AND $V_{50}$ VARIABILITY

More than a decade of body armor testing has shown $V_{50}$ to have standard deviation of 30 to 35 fps (9.1 to 10.7 mps) for bullets (3-pair estimates). $V_{50}$ tests typically follow a form of the “up-and-down” method:

“The first round to be fired in this method is prepared with a propellant charge estimated to give a striking velocity equivalent to the ballistic limit of the target. If the resulting impact is a partial penetration, the second round is prepared with a propellant charge estimated to increase the velocity by 30 m/s (100 fps) (or more if a large jump is obviously needed). If this round results in a complete penetration, the third round is loaded with a propellant charge estimated to decrease the velocity by 15 m/s (50 fps). The velocities of subsequent rounds are increased by 15 m/s each time a partial penetration occurs, and decreased by 15 m/s each time a complete penetration occurs, until the conditions of the test are satisfied. If the first round had been a complete penetration, the second round would be prepared with a propellant charge estimated to reduce the velocity by 30 m/s (or more, if required), etc. Increments (or decrements) of no less than 30 m/s are used at the beginning until a reversal occurs (from partial to complete or vice versa), after which 15 m/s increments or decrements are used.”

The ballistic limit ($V_{50}$) is determined:

“Three complete penetrations and three partial penetrations within a spread of 27, 38, or 46 m/s (90, 125, or 150 fps): A ballistic limit determined by this method is reasonably accurate. This type (referred to as a six-round ballistic limit) is used most in that it generally is used in all tests involving small arms projectiles. Firing is discontinued as soon as three complete and three partial penetrations are obtained with a velocity spread of 27, 38, or 46 m/s, as specified. These six striking velocities are then averaged to estimate the ballistic limit. The velocity spread employed will depend on specifications or other requirements.”

$V_{50}$ variability is a function of the underlying penetration probability slope ($\beta$), as well as elements of test structure such as number of data points, test design, and velocity window restriction. A set of macros was written to simulate the typical ballistic test sequence. The macros incorporate the quality of the initial guess at ballistic limit (usually within 100 fps), the variability in projectile velocity (usually 15 to 25 fps), and slope of the penetration probability curve. The relationship between $V_{50}$ standard deviation (3-pair, 125 fps velocity spread restriction) and penetration probability $\sigma$ ($1/|\beta|$ in the probit model), is shown in Figure 2.

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We have historically seen $V_{50}$ standard deviation for bullets in the range of 30 to 35 fps. This implies a penetration probability $\sigma$ (probit model) of roughly 55 to 65 fps. Those values were used to generate penetration probability versus velocity curves, using a probit model with mean equal 1400 fps. The curves are shown in Figure 3.

A quick method for approximating velocities associated with small percentiles can be constructed:

- Estimate $V_{50}$ by shooting $k$ panels. The quality of the estimate will depend on the number of panels tested. For example, if the $V_{50}$ standard deviation is 35 fps, the standard error associated with an average of four $V_{50}$s will be $35/\sqrt{4}$, or 17.5 fps. The standard error of a ten-panel average would be $35/\sqrt{10}$, or 11 fps.
- Estimate the $V_{50}$ standard deviation. This is best done using a large number of test panels, so an historical estimate may be the best.
- Convert the $V_{50}$ standard deviation into corresponding standard deviation of the penetration probability function, using the graph shown in Figure 2.
• Multiply the model standard deviation by the appropriate z-value for a standardized normal distribution. For example, $z = 0.67, 1.28, 1.64, 1.96,$ and $2.32,$ for $V_{25}, V_{10}, V_{5}, V_{2.5},$ and $V_{1},$ respectively.
• Subtract the value above from the $V_{50}$ estimate.

For example, assume that eight panels were tested and gave an average $V_{50}$ of 1625 fps. If the $V_{50}$ standard deviation is 35 fps, the standard error of the average $V_{50}$ is 12.4 fps, and a 95% confidence interval on the average $V_{50}$ is $[1596, 1654]$. The simulation results shown in Figure 2 indicate $\sigma$ to be roughly 68 fps. Using the 99% multiplier we get a $V_{1}$ prediction of 1468 fps. We might feel comfortable using this product if the pass/fail specification is 1400 fps.

3. DIRECT ESTIMATION OF $\sigma$

The standard ballistic limit test designs are stepwise-sequential in nature, where each trial is predicated on the results of the previous trials. There has also been a large body of work on optimal allocation of the total number of trials in single- and multi-stage experiments. That type of experiment may not be particularly useful in routine ballistic limit testing, but it can prove useful when a more complete material characterization is required.

In single-stage testing, the variance of $V_{50}$ is minimized by placing all of the observations at the 50th percentile. That is the intent of the standard up-and-down test. Similar calculations for the probability slope show that the observations should be placed in two equal groups of $n/2$ at about the 0.085 and 0.915 probability levels. For estimation of both $V_{50}$ and slope, the optimum placing of the two groups is at approximately the 0.176 and 0.824 levels, a design termed "D-optimal."

Multi-stage testing, where an initial pilot study is used to direct optimal placement of a second set of trials, is a more interesting option. The purpose of the first stage is to provide a good estimate of $V_{50}$ for properly locating the second stage velocities. The goal of the second stage is to minimize the two-stage generalized asymptotic variance of both $V_{50}$ and probability slope. For a small total sample size of 30, one should use somewhere between 40 and 50% of the sample in the first stage. For a large sample size of 300, the recommendation ranges from 15 to 30% depending on the situation.

A good application of two-stage optimal test design is the comprehensive characterization of a new product. In that case, we may choose to test 16 panels for ballistic limit. With 3-pair estimates the total number of shots will be approximately 120. A two-stage test was simulated by using $k$ panels for the initial estimate of $V_{50}$. Those panels were tested using the standard up-and-down method. The second stage used the remaining panels divided evenly at estimated $V_{15}$ and $V_{85}$ velocities. The second stage is optimized to estimate the penetration probability slope, but also contributes to improving the first stage estimate of $V_{50}$. The results showed minimum variance of $\sigma$ with three to five panels in the first stage (19 to 31% of the total number of shots), which agrees with previous work. Overall $V_{50}$ variance was not significantly changed by the allocation, so there appears to be no drawback to using a two-stage design in this type of situation.
4. SUMMARY

Logit or probit regression models are useful for quantifying probability of projectile penetration through body armor as a function of impact velocity. The most common measure of protection is $V_{50}$. $V_{50}$ variability is a function of test size, test structure, estimator type, and the slope of the penetration probability curve. $V_{50}$ may be the single most valuable measure of ballistic performance, but it is not sufficient to characterize body armor performance. A relationship was found between $V_{50}$ variability and the penetration probability slope, which provides an easy way to examine velocities associated with low penetration percentiles. Direct estimation of the penetration probability slope requires a special set of test velocities, which can be obtained as part of a two-stage test.
ABSTRACT

Nowadays, though many apparel industries employ automated machinery in their production process, some firms still rely on a large number of labors to produce their products, where the performance of operator greatly determines a plant’s productivity. The variance of operator efficiency is also the main factor that causes production line imbalance. As many decisions in apparel manufacturing are still made based on supervisor’s experience and knowledge about the operators, the prediction of operator efficiency is therefore significant in providing accurate information to support the production control. The operator efficiency is revealed to be greatly influenced by such factors as working environment, operator’s emotion, motivation, health, skill level and experience of doing the similar operation previously. Five possible situations of the change of operator efficiency are brought forward in this paper, among which, increasing trend and horizontal situations are much common but seldom studied. Using historical efficiency data collected from the apparel manufacturing sector, a time series based artificial neural network (TSANN) operator efficiency prediction process is proposed in this paper to establish a practical and reliable method to forecast the work efficiency of human being.
END-OF-SERVICE-LIFE INDICATORS FOR CHEMICAL PROTECTIVE GLOVES

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ABSTRACT

At this time, the performance of gloves protecting against chemicals is determined by means of normalized permeation method based on determination of the breakthrough time. This is a period of time after which a particular concentration of a test chemical is detected on the other side of tested material. The material is exposed to continuous contact with test chemical in the laboratory test conditions. Such a test method does not take into account a series of factors characteristic for in-use conditions, which affect the permeation process through protective gloves. The permeation can follow earlier than signs of material degradation can be observed. In such a case a worker is being exposed to a contact with aggressive chemicals which is under control.

It is necessary to design a system of chemicals permeation signalization in order to determine a safe time of using protective gloves against aggressive chemicals in real use conditions. For signalization of the end-of-service-life for this type of gloves the colorimetric indicators are used. They are in a form of indicating pigments which change their colors in contact with permeating chemicals and in a form of microcapsules which, in particular conditions, release a pigment closed inside a shell after dissolving it in permeating chemical. The indicators can be incorporated into a textile layer and put under the barrier which is a protective glove. At the time of using gloves at the workstations permeating chemical passes through the barrier into the area between a glove and a skin and causes forming a color sign on the textile layer which can be easily identified by a user. A color change of a textile is a signal of end–of- service- life for a glove which should be a reason of removing it from using.

1. OCCUPATIONAL SKIN EXPOSURE TO CHEMICALS

According to world statistics [1, 2], the occupational skin exposure to chemicals is a common phenomenon, leading to a number of occupational diseases. The causes of work-related dermatoses are different, but it is evaluated [1] that about 90-95% of them is contact dermatitis, which is characterized by erythema, inflammation, itching or scaling in result of contact with chemicals.
Skin absorption, in working conditions, takes place most often on the surface of the hands. It was evaluated, that the surface of the both hands, including wrists (the surface, which is protected during wearing the gloves) is 0.26 m$^2$ [3], which makes about 13% of the surface of the entire body. However, during the work, hands are usually exposed most frequently to direct contact with chemicals, as well as to mechanical injuries leading to skin damage, what causes faster absorption of the compounds to the organism. Therefore they should be particularly protected during the work in spite of relatively small surface of possible exposition. When other technical and organizational means or risk reduction are not enough, protective gloves should be provided to exposed workers.

2. PERFORMANCE OF GLOVES PROTECTING AGAINST CHEMICALS

Effectiveness of gloves protecting against chemicals is being evaluated on the basis of standard laboratory tests according to the requirements, unified in the European Union. However, real level of protection, presented by the material of gloves, depends on a number of factors, which, due to their variability and dependence on the conditions of work, are not taken under consideration at laboratory evaluation. They can considerably influence the effectiveness of protective barrier. There are, among others: ambient temperature, microclimate between the glove and the skin of the user’s hand, mechanical loads (e.g. repeated bending of the glove), repeated contact with one or several substances of different concentrations, storage and cleaning conditions and so on. One of the most significant differences between the practice and laboratory tests is the temperature, at which the permeation process is analyzed. The standard imposes conducting of tests at temperature (23±1)°C, while the temperature inside gloves is considerably higher – about 35°C. Tests confirmed, that the breakthrough time of defined chemical substances through the protective material at temperature 35°C is even threefold lower from the breakthrough time in standard conditions, and the permeation rate of the substance through the gloves is in turn considerably higher [4, 5].

So the user does not dispose with suitable information regarding resistance of the material after several days’ or several weeks’ use of gloves, their cleaning and storage, during which secondary contamination often occurs. He is not provided with information concerning period of safe use of gloves. According to the questionnaire inquiry, performed in Poland by the Central Institute for Labour Protection CIOP-PIB, in many cases gloves are withdrawn from use after several weeks, or even several months of use and usually at the time, when they bear distinct wear traces like breaks, discolouration, stiffening or becoming brittle [5]. However, in the reality, the exposure to the contact with harmful chemical substances can appear considerably earlier than the first symptoms of material degradation are visible. From the operator’s safety point of view it seems to be necessary to elaborate a form of indicator, which in qualitative way and independently on work conditions would indicate the moment, when the glove stops to be a protection and, in order to avoid uncontrolled skin exposure, it should be withdrawn from the use and replaced by new one.

3. SIGNALIZATION OF PERMEATION OF CHEMICALS THROUGH PROTECTIVE GLOVES

3.1. ASSUMPTIONS
The research on indication of chemical substances permeation through protective gloves materials began a few years ago in United States [6, 7]. The subject of signalization of gloves’ end of service life has been also undertaken lately in CIOP-PIB. The following aspects were taken into consideration during elaboration of such signalization system:

- The principle of indicator’s operation comprises in change of its colour in result of contact with permeating chemicals. The color change should be distinct so that identification of the end of service life of glove is clear. It should also be stable in time so that the breakthrough could be identified even after several hours, in case a worker takes off the gloves relatively rarely during the working day.
- The indicator should be reliable independently on the ambient temperature, microclimate around the worker’s hands, kind of executed activities or grade of worker’s exposure to the action of chemical agent,
- The indicator should be efficient in conditions of permeation of a challenge chemical through the material of protective gloves on the level of 1 µg/cm²*min, specified by the standard EN 374-3:2003 [8]. This is a value at which the breakthrough time is determined which corresponds to glove’s level of performance. After exceeding it the glove stops being a barrier against chemical agent.

According to the questionnaire mentioned above [5], over 50% of exposed workers are in frequent contact with different kinds of chemicals, not only with one agent. Chemicals, which are used most often at the workplaces in chemical industry, are: acids, bases and organic solvents [5]. That is why the signalization system should fulfil its tasks simultaneously in contact with several different groups of chemicals.

The signalization system may have a form of thin inner glove, made of textile material (polyamide and cotton) which is worn under the protective glove against chemicals.

### 3.2. SIGNALIZATION OF ACIDS AND BASES PERMEATION

To modify a textile material towards indicative properties it is possible to apply on it an appropriate indicating pigment with one of three following methods:

- dyeing of textile,
- impregnation of textile with resin finish insoluble in water,
- dyeing of yarn.

The color change, which appears on textile surface, is a signal of presence of harmful substance on the other side of the protective glove, indicating necessity of withdrawal it from use.

During the research project realized in CIOP-PIB, over 30 options of modified textile materials were elaborated. The differences among options were as follows:

- a kind of indicating pigment,
- a kind of dyeing method,
- a kind of textile material,
- a composition of the finish used during impregnation.

Preliminary test results showed that it is possible to choose a few options with indicating properties in relation to acids and bases simultaneously (Figure 1).
Figure 1. Examples of selected pigments to be used as indicators of acids and bases: 1 – polyamid textile with pigment (CAS No: 76-60-8) applied with dyeing method, 2 – cotton textile with pigment (CAS No:2303-01-7) applied with impregnation with resin finish; A – before exposition to chemical, B – after contact with CH₃COOH, C – after contact with H₂SO₄, D – after contact with HCl, E – after contact with NaOH

The best option chosen was a pigment CAS No: 76-60-8 applied with dyeing method on a polyamid textile. It indicates precisely the presence of inorganic and organic acids and bases. It is not rinsed out from textile during use and the color change is stable in time.

3.3. SIGNALIZATION OF ORGANIC SOLVENTS PERMEATION

In a case of detection of organic solvents it is possible to use a pigment closed in a polymeric layer. The layer may have a form of thin foil or microcapsules with an organic solvent sensitive shell. In contact with solvents the shell or foil dissolves, releasing the pigment, which in turn colours inner glove, used as indicator of the permeation. Sensitivity of the layer can be regulated by the sizes and thickness of wall of the shell or thickness and pigment concentration in a case of a foil.

10 options of thin PVC foil have been prepared during the research to search the best one possible to use as a solvents indicator. The differences among options were as follows (see examples in a Figure 2):

− a kind of pigment used – water soluble (Food Red 11) and solvent soluble (Solvent red 117),
− thickness of foil: 15 – 75 µm,
− concentration of pigment in matrix: 3 – 20 % weight,
− concentration of polymer in the solvent (cyclohexanon): 2 – 10%.

Figure 2. PCV foil with different concentrations of pigment: A, B – heterogenous system (PCV in cyclohexanon + Food Red 11 in water), C, D – homogenous system (PCV in cyclohexanon + Solvent Red 117 in oil)
The best foil was a 30 µm foil made as a homogenous system, using the pigment Solvent Red 117 dissolved in oil. The main advantages of the foil are: flexibility, durability and sensitivity. It can be also easy applied on a textile by pressure welding.

### 3.4. PERFORMANCE OF SIGNALIZATION SYSTEM

The textile with applied indicating pigment or PCV foil was subjected to different chemicals to assess the sensitivity of signalization system. The specimens consisting of two layers: polymeric glove material and “indicating” textile were placed in a standard permeation cell, according to EN 374-3:2003 [8], and exposed to following chemicals:

- 96% sulfuric acid and 1N sodium hydroxide – for textiles with indicating pigments,
- acetone, toluene, ethyl acetate, cyclohexane, benzene – for textiles with polymeric foil.

During the test one half of the specimen was covered by parafilm – the one at the side of textile. In such a case it was possible to record the chemical’s permeation rate in a collective medium and simultaneously, to separate the indicator from the medium in order to expose it to a concentrated chemical. Permeation tests were being conducted till the moment, when permeation rate of chemical reached the required level of 1µg/cm² min.

The results obtained were satisfactory for both chosen options of signalisation system. The textile with indicating pigment changed its colour at the level of 1µg/cm² min and the PVC foil dissolved and released the pigment which coloured a textile layer (Figure 3).

![Figure 3. Efect of signalization system: color change in contact with base (A) and acid (B), dissolving of foil in contact with acetone (C) and toluene (D)](image)

### 4. DISCUSSION

Proposed solution seems to meet the needs resulting from conditions of work with chemical substances. Independently on conditions in which the glove will be used, the indicator will be designed in such a way to give a clear signal to the worker, that the glove is not a protection anymore and it should be withdrawn from use immediately. If not, an uncontrolled exposition of workers to harmful substances will take place.

In order that the indicator could fulfill its role, it is necessary to create consciousness of the employees and employers in a field of hazards connected with using chemical substances. A worker should be aware of imperfection of the protection provided by the gloves, instead of being sure about his safety during use of personal protective equipment. Furthermore, not less important problem is to design the indicator in such a way, that it will not make difficult execution of professional activities, already handicapped by the use of protective gloves.
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ABSTRACT

Finnish legislation states that pedestrians should, as a general rule, always use appropriate reflectors when travelling in the dark, including on well-lit, urban roads. Visibility accessories are covered by the PPE directive 89/686/EEC. Test methods and requirements are provided in the EN 13356:2001 "Visibility accessories for non-professional use". The purpose of this study was to examine photometric properties of pedestrian reflectors presently available on the Finnish market. The market control surveillance study was organized by the Finnish Consumer Agency. Altogether, 20 products were purchased from the Finnish market during the spring and autumn of 2005. Twelve products were of type 1 (free hanging accessory) and eight of type 2 (removable accessory).

In accordance to the EN 13356, the Finnish Institute of Occupational Health (FIOH) performed photometric and area measurements to the pedestrian reflectors in their original condition and to those meeting the [SPECIFY what requirements] requirements after exposure to water immersion. CIL-values for type 2 reflectors were measured around a cylinder with a 100 mm diameter.

Most of the tested visibility accessories complied with the EN 13356 photometric requirements both in their original condition and after water immersion. With four products, of which three were CE-marked, serious deficiencies were detected. Minor deficiencies were found in two other products.

1. INTRODUCTION

In the Nordic countries, the daylight hours are very short during the autumn and winter. In Finland between the years of 2000 and 2004, half of the fatal pedestrian accidents occurred in the dark (1). The Finnish traffic accident investigative court [USE THEIR OFFICIAL TITLE IF THEY HAVE ONE] has estimated that half of the accidents could have been prevented if visibility accessories had been used (1).

Finnish legislation determines that, as a general rule, pedestrians should use appropriate visibility accessories always in the dark, including when travelling on well-lit, urban roads. Visibility accessories are covered by the PPE directive 89/686/EEC. Test methods and requirements are provided in the EN 13356:2001 "Visibility accessories for non-professional use" (2). Products
conforming to this standard serve their purpose when their movement and retro-reflection attract observers' attention.

2. AREA AND PHOTOMETRIC REQUIREMENTS OF VISIBILITY ACCESSORIES

For accessories designed for non-professional use to be worn, attached or carried by people, EN 13356 specifies optical performance requirements. This standard classifies visibility accessories into three types: Type 1 - free hanging accessories, Type 2- removable accessories, such as a slap wrap, and Type 3 - mounted accessories. This standard does not apply to garments.

Visibility accessories shall meet both area and retro-reflection requirements. s Type 1 accessories shall be between 15 cm² and 50 cm² per side. Type 2 and Type 3 accessories are defined as exceeding the area of 15 cm². Photometric requirements for Type 1 accessories are designated by the minimum coefficient of luminous intensity R [mcd/lx] (CIL) at three observation angles α and three entrance angles β. Photometric requirements for Type 2 and Type 3 accessories are differentiated by the minimum coefficient of retro-reflection R’ [cd/lx m²] at three observation angles α and two entrance angles β. The minimum area for Type 2 and Type 3 accessories must meet the minimum CIL value R = 400 mcd/lx in all directions around the person at α = 0,33°, β = + 5°. The requirements shall be met in both the accessory’s original condition and after specific pretreatments are performed, contingent upon whether an accessory is rigid or flexible.

This study’s purpose was to ascertain the compliance of pedestrian reflectors on the Finnish market with the photometric requirements as specified by EN 13356. The market control surveillance study itself was conducted by the Finnish Consumer Agency.

3. MATERIALS AND METHODS

The Finnish Consumer Agency purchased 20 visibility accessories from the Finnish market during the spring and autumn of 2005: 12 Type 1 products (free hanging accessory) and eight Type 2 products (removable accessory). Ten products were CE-marked, seven of which were claimed to be EN 13356 compliant.

FIOH performed photometric measurements according to the EN 13356, as specified for those products meeting the requirements after having been immersed in water. CIL-values for Type 2 reflectors were measured around a cylinder with a 100 mm diameter to simulate the position of a reflector as it is worn by an user. Retro-reflective areas were also measured.

4. RESULTS

All tested accessories conformed to area requirements. Their compliance with the photometric requirements of EN 13356 is summarized in Table 1 for Type 1 accessories and in Table 2 for Type 2 accessories.

The majority of Type 1 visibility accessories met the EN 13356 photometric requirements. One CE-marked accessory failed, although it made no specific claims to comply with the aforementioned standard. More deficiencies were discovered in Type 2 accessories, as three products failed. Two
were CE-marked; one of which also claimed to be EN 13356 compliant. Photometric properties of the "worst" product only roughly met 10% of the required values.

Table 1. Compliance with photometric requirements of EN 13356 for Type 1 - free hanging accessories

<table>
<thead>
<tr>
<th>Sample no</th>
<th>CE-marking yes/no</th>
<th>Marked with EN 13356 yes/no</th>
<th>Photometric requirements (R) as received pass/fail</th>
<th>Photometric requirements (R) after water immersion pass/fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>yes</td>
<td>yes</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>2</td>
<td>no</td>
<td>no</td>
<td>pass</td>
<td>other side passed/other side failed</td>
</tr>
<tr>
<td>3</td>
<td>no</td>
<td>no</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>4</td>
<td>no</td>
<td>no</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>7</td>
<td>no</td>
<td>no</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>8</td>
<td>no</td>
<td>no</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>9</td>
<td>yes</td>
<td>yes</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>10</td>
<td>yes</td>
<td>yes</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>12</td>
<td>no</td>
<td>no</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>14</td>
<td>yes</td>
<td>yes</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>15</td>
<td>yes</td>
<td>no</td>
<td>fail</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>yes</td>
<td>yes</td>
<td>pass</td>
<td>pass</td>
</tr>
</tbody>
</table>

Table 2. Compliance with photometric requirements of EN 13356 for Type 2 - removable accessories

<table>
<thead>
<tr>
<th>Sample no</th>
<th>CE-marking yes/no</th>
<th>Marked with EN 13356 yes/no</th>
<th>Photometric requirements (R') as received pass/fail</th>
<th>Photometric requirements (R') after water immersion pass/fail</th>
<th>CIL-value as received pass/fail</th>
<th>CIL-value after water immersion pass/fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>no</td>
<td>no</td>
<td>fail</td>
<td>-</td>
<td>fail</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>no</td>
<td>no</td>
<td>pass</td>
<td>pass</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>11</td>
<td>yes</td>
<td>yes</td>
<td>pass</td>
<td>pass</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>13</td>
<td>yes</td>
<td>no</td>
<td>fail</td>
<td>-</td>
<td>fail</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>no</td>
<td>no</td>
<td>pass</td>
<td>pass</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>17</td>
<td>yes</td>
<td>yes</td>
<td>pass</td>
<td>pass</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>19</td>
<td>yes</td>
<td>no</td>
<td>pass</td>
<td>-</td>
<td>fail</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>no</td>
<td>no</td>
<td>pass</td>
<td>pass</td>
<td>pass</td>
<td>pass</td>
</tr>
</tbody>
</table>

5. DISCUSSION AND CONCLUSIONS

The market control surveillance study results indicated that most visibility accessories bought on the Finnish market comply with the EN 13356 photometric requirements. However, some CE-marked
products and even some products marked with the market standard number, were discovered to fall far short of the requirements. Therefore, a CE-mark alone does not necessarily guarantee compliance with the standard requirements, however, CE-marked products that also display the standard number generally do meet all specifications.

Visibility accessories are usually either manufactured by small companies or imported and sold through other channels more so than other personal protective devices. These companies are generally not very familiar with the responsibilities of the PPE directive or the requirements set to visibility accessories. As a result of this market control surveillance study, the Finnish Consumer Agency and the Finnish traffic safety organisation "Liikenneturva" will inform the Finnish manufacturers and importers of the visibility accessory requirements, as well as testing and CE Type-examination procedures.

The EN 13356 is a difficult standard to apply and interpret. The testing is extremely expensive in relation to the actual value of the final product. There are cases in which the manufacturers and/or importers are unable to afford or unwilling to carry out the testing and the CE type examination procedure. To reduce the costs of testing, EN 13356 shall be revised and simplified. It shall be evaluated whether all pretreatments are truly necessary for visibility accessories and their applicability to enhancing safety when used. New types of visibility accessories on the market (e.g. stickers) do not belong to any of the three types defined by EN 13356.

Visibility accessories are often produced in different shapes and sizes, while using the same basic retro-reflective material. Therefore, as per EN 13356 each final product and product shape should be tested. The standard should be revised to also test retro-reflective materials according to the standards of visibility warning garments. EN 471 and EN 1150 could then be utilized, harmonizing all test methods. The retro-reflective area could be calculated to meet the required CIL-value of visibility accessories once the minimum coefficient of basic material’s retro-reflection is determined.

One of the failed Type 2 accessories claimed to comply with the EN 13356. This may result from variance in testing methods of the CIL-value between testing laboratories. According to the EN 13356, a CIL-value should be tested in the position for which it was designed to be worn by the user. In previous Scandinavian standards, this was accomplished by testing around a cylinder with a 100 mm diameter. This method was also used for the purposes of this study. If the test is conducted on a flat accessory, the CIL-value is too high, given that the effect of curving on photometric properties is absent on a flat accessory.

ACKNOWLEDGEMENTS

The author wishes to thank the Finnish Consumer Agency for their kind access to the test results of the market control surveillance study.

REFERENCES

ASSESSING THE FOGGING RESISTANCE
OF COMPLETE EYE PROTECTORS

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Nick.Vaughan@hsl.gov.uk

ABSTRACT

Eye injuries caused by mechanical, chemical or radiation hazards are almost always preventable by properly selected and used eye protection. Research into industrial eye injuries has highlighted that the main reason protective eyewear is not used when it should be is that it tends to fog up, making it impossible to see clearly. Existing standards for assessing the fogging resistance of eye protectors are only applied to the oculars in isolation. Good performance in this test may bear no relationship to the way in which the complete protector behaves in real use.

In collaboration with others, HSL has developed an objective means of assessing the fogging of complete goggles and spectacles, for consideration as a standard test method. This should allow meaningful classification of product for resistance to fogging in use.

The method uses a live television camera image of a specified target to assess the clarity of view through the eye protector, generating a simple voltage/time record to describe fogging resistance. This record can be used to quantify performance against pre-determined requirements. Reproducibility and repeatability of the method has been quantified. The test method will also discriminate between permanent and less durable fogging resistance performance.

Different means of achieving fogging resistance of eye protectors (hydrophilic/hydrophobic coatings; ventilation) yield distinct patterns of performance during this test, and will be illustrated.
INTERLABORATORY COMPARATIVE TESTS, ANALYSIS OF TEST RESULTS AND ASSESSMENT OF THE COLOUR FASTNESS TO PERSPIRATION

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270 Piotrowska Str., 90-361 Łódź, POLAND

ABSTRACT

In the paper the problems related to interlaboratory comparative tests of the colour fastness to perspiration of the materials designed for protective clothing were discussed. There was described process and methodology of tests and the presentation of the comparison of the tests results was made. The objective paper will be presented in the form of poster.

1. THE GOAL AND SCOPE

The IKTT „TRICOTEXTIL” has been an organizer of the inter-laboratory comparative tests from ten years. During last ten years, the range of these tests included the methodology of determination of the qualitative and usable parameters and parameters determining the safety of the products.

The resulting effects from the existing comparative tests have been used by research laboratories as one of the elements of the controlling of the quality of the tests and the results permitted on:
- searching and detecting unexpected errors
- in case of detecting of errors - taking up of repair actions,
- checking, if the quality of results is adequate to the purpose of carried out measurements,
- classifying the own laboratory and comparing to other laboratories, what is giving the satisfaction to personnel in case of the positive result.

The product certifying bodies using in the conformity assessment process the results of the laboratory tests carried out by the laboratory independent of deliverer have a certitude that the results are reliable and comparable. It is peculiarly important in the case when the test results are the base of the conformity assessment of the examined parameters to the documentation used as a ground for certification or official documents or in case of mutual acceptance.

In consequence of granted notification on the directives concerning the personal protective equipment, medical devices and toys the IKTT „TRICOTEXTIL” is entitled for participation in the conformity assessment process of the mentioned above products as a third party and issuance of suitable documents in whole of the European Union. The conformity assessment embraces also the activities related to laboratory tests and conformity certification of the products.

The conformity assessment process requires the permanent implementation to the normalisation of the new European and international standards concerning methodology of examinations for that the research laboratories also have to verify methods.
The IKKT „TRICOTEXTIL” organizing the inter-laboratory comparative tests had regard to interest in safety and human hygiene in the field of requirements which should fulfil the materials designed for protective clothing and which shouldn’t have wrong influence for the user.

One of the parameters informing about harmlessness of the applied material used in protective clothing is a colour fastness to perspiration. Under its definition it is understood the resistance of the colour of the textile product to treatment of the different agents during the production and exploitation processes. Moreover, the colour fastness characterizes the durability of the bonded colouring substance. One of the factors with which the product has a contact and which can cause the change of colour of the textile product is among other thing the sweat.

The results of laboratory tests in the range of colour fastness to perspiration are utilized in the process of conformity of protective clothing. The notified body has to have certainty that the examination is executed actually and results are reflecting the real value of the determined parameter.

2. METHOD OF REALIZATION

The comparative tests of the colour fastness to perspiration were performed with the use of normalized methodology of examinations according to the PN-EN ISO 105-E04:1999 Textiles - Tests for colour fastness - Part E04: Colour fastness to perspiration

A confidentiality of the tests results had been guarantied to all laboratories participating in the tests. The laboratories taking part in tests and tests samples were coded by identification numbers.

Before testing a special instruction on the method of inter-laboratory comparative tests performance was elaborated. It was assumed that participants of the tests would make the determination according to selected method and without any consultation with other laboratories in the range of achieved test results. The test samples (woven fabrics) were selected from production lots. For testing the selection of pieces was not random and chosen pieces were without any defects.

A degree of homogeneity of examined feature for the material given for testing was evaluated on the base of preliminary tests.

In this way prepared testing material in the form of samples marked by the codes A and B was given to the laboratories to carry out the comparative tests. The main goal of these tests was verification of the comparability of evaluation made by each laboratory for identical samples of textile materials and accompanying fabrics, checking on repeatability of results and the indication of dissimilarities in estimation among the laboratories.

For every delivered sample, every laboratory participating in the test executed with the use of identical methodology of examinations, three series of tests.

2.1. DETERMINATION OF THE COLOUR FASTNESS TO PERSPIRATION

The comparative tests in the range of determination of the colour fastness to perspiration according with assumed methodology were carried out for the woven fabrics dyed in black and blue colour destined on protective clothing.

The tests were performed in following way: the tested sample of fabric marked by the code A and B together with the accompanying fabric was subjected to action of the alkaline, and then of sour solution of the sodium chloride and the phosphate double sodium accepted as a natural sweat equivalent. The value of the change of the colour of the sample and accompanying white fabric was given in the degrees of fastness.
The estimation of colour fastness was made on the basis of change of colour of proper sample and separately for control samples named accompanying fabrics. In the test were applied one component accompanying fabrics.

A size of the contrast of two colour surfaces was the basis of a visual estimation - of the original sample and the sample after working of the factor of the sweat.

This contrast was visually compared with contrasts of every five pairs of the neutral colour of fields, which is giving on the model grey scale who are marked with digits giving the degree of colour fastness. The value 5 means the biggest fastness - complete lack of the contrast, but the value 1 is the lowest fastness - maximum dissimilarities. The contrast of the grey scale corresponding to the tested sample assigned the degree of colour fastness. If this contrast was located between two degrees of the scale, colour fastness to perspiration were marked with the average degree. Also, a change of colour of accompanying fabrics, which were in direct contact with tested samples, was evaluated. A grey scale was applied at this estimation.

During carrying the estimation of fastness out they were paying special attention for conditions of the observation and lighting systems. Samples undergoing the comparison were being arranged in the chamber of the daylight in the same surface side by side, being careful so that the direction of the weave is alike in both samples. Scale model were put by samples. The surface neighbouring on samples was slightly darker than the darkest surface of the grey scale and estimated samples were lighted up with daylight, falling under the angle 45°.

2.2. REPORT FROM TESTS

The results of these tests give the opinion to laboratories for the subject of competence and experience in making estimations by their personnel.

For received test results, which are showed on the charts 1, 2, 3 and 4, there were made a statistical analysis for every test sample elaborated with the usage of the computer program on the basis of the standard PN-ISO 2602:1994 "Statistical interpretations of tests results. Estimation of the average value.

Confidence interval .".

The following indicators were calculated:

− average value $x \bar{s}$,
− standard deviation $S$,
− coefficient of variation $V(\%)$,
− confidence interval of the average value,
− limits of the interval of confidence of the average value (lower and top),
− random error of the average value $q(\%)$,
− value of the random error of the average value,
− uncertainty of the measurement,
− limits of the interval of confidence of the standard deviation (lower and top),
− limits of the interval of confidence of the coefficient of variation (\%)
− The indicators of precision were calculated additionally and whom a measure is:
  − repeatability, expressing the value below which with determined probability is lying an absolute value of the difference between single results determination received in the same methods (the same performer, the same laboratory, executing in the small interval of time),
  − reproducibility, determining value below which with the determined probability is lying absolute value of single results determination , received this same method, on the identical test material in various conditions (different performers, various laboratories, execution in the different time),
and limits of the acceptance determining the lower and top limit in which received values are included in all laboratories in, were calculated.

The results of the subjected analysis were placed in tables: 1, 2, 3, and 4.
Sample A

Description
1 Colour change
2 Whiteness soil I accompanying fabric
3 Whiteness soil II accompanying fabric
Red colour means average value
Roman numbers mean number of laboratory
Pict. 1 Colour fastness to alkaline perspiration

Sample A

Description
1 Colour change
2 Whiteness soil I accompanying fabric
3 Whiteness soil II accompanying fabric
Red colour means average value
Roman numbers mean number of laboratory
Pict. 2 Colour fastness to sour perspiration
Sample B

Description

1 Colour change
2 Whiteness soil I accompanying fabric
3 Whiteness soil II accompanying fabric

Red colour means average value
Roman numbers mean number of laboratory

Pict. 3 Colour fastness to alkaline perspiration

Sample B

Description

1 Colour change
2 Whiteness soil I accompanying fabric
3 Whiteness soil II accompanying fabric

Red colour means average value
Roman numbers mean number of laboratory

Pict. 4 Colour fastness to sour perspiration
<table>
<thead>
<tr>
<th>Index</th>
<th>Degree of colour change</th>
<th>Degree of whiteness soil of cotton accompanying fabric</th>
<th>Degree of whiteness soil of wool accompanying fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average value $\bar{x}_p$</td>
<td>4.250</td>
<td>2.667</td>
<td>3.75</td>
</tr>
<tr>
<td>Standard deviation $S$</td>
<td>0.274</td>
<td>0.258</td>
<td>0.274</td>
</tr>
<tr>
<td>Coefficient of variation $V$ (%)</td>
<td>6.444</td>
<td>9.682</td>
<td>7.303</td>
</tr>
<tr>
<td>Limits of the interval of confidence of the average value (lower and top)</td>
<td>3.963 – 4.537</td>
<td>2.396 – 2.938</td>
<td>3.463 – 4.037</td>
</tr>
<tr>
<td>Limits of the interval of confidence of the standard deviation (lower and top)</td>
<td>0.161 – 0.551</td>
<td>0.152 - 0.519</td>
<td>0.161 – 0.551</td>
</tr>
<tr>
<td>Limits of the interval of confidence of coefficient of variation (%)</td>
<td>3.791 – 12.955</td>
<td>5.696 – 19.466</td>
<td>4.296 – 14.682</td>
</tr>
<tr>
<td>Limits of repeatability $r$</td>
<td>1.066</td>
<td>0.923</td>
<td>0.923</td>
</tr>
<tr>
<td>Limits of reproducibility $R$</td>
<td>2.047</td>
<td>1.184</td>
<td>1.465</td>
</tr>
<tr>
<td>Precision quotient $PQ$</td>
<td>1.921</td>
<td>1.283</td>
<td>1.587</td>
</tr>
<tr>
<td>Limits of acceptation of the average value</td>
<td>2.792 – 5.375</td>
<td>2.077 – 3.313</td>
<td>2.911 – 4.646</td>
</tr>
</tbody>
</table>

Table 2: Result of statistic analysis of sample A after colour fastness to sour perspiration tests

<table>
<thead>
<tr>
<th>Index</th>
<th>Degree of colour change</th>
<th>Degree of whiteness soil of cotton accompanying fabric</th>
<th>Degree of whiteness soil of wool accompanying fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average value $\bar{x}_p$</td>
<td>4.333</td>
<td>2.667</td>
<td>3.583</td>
</tr>
<tr>
<td>Standard deviation $S$</td>
<td>0.238</td>
<td>0.258</td>
<td>0.204</td>
</tr>
<tr>
<td>Coefficient of variation $V$ (%)</td>
<td>5.958</td>
<td>9.682</td>
<td>5.979</td>
</tr>
<tr>
<td>Limits of the interval of confidence of the average value (lower and top)</td>
<td>4.062 – 4.604</td>
<td>2.396 – 2.938</td>
<td>3.369 – 3.798</td>
</tr>
<tr>
<td>Limits of the interval of confidence of the standard deviation (lower and top)</td>
<td>0.152 – 0.519</td>
<td>0.152 - 0.519</td>
<td>0.120 – 0.410</td>
</tr>
<tr>
<td>Limits of the interval of confidence of coefficient of variation (%)</td>
<td>3.505 – 11.979</td>
<td>5.696 – 19.466</td>
<td>3.351 – 11.453</td>
</tr>
<tr>
<td>Limits of repeatability $r$</td>
<td>1.191</td>
<td>1.191</td>
<td>1.066</td>
</tr>
<tr>
<td>Limits of reproducibility $R$</td>
<td>1.214</td>
<td>1.172</td>
<td>1.595</td>
</tr>
<tr>
<td>Precision quotient $PQ$</td>
<td>1.019</td>
<td>0.984</td>
<td>1.497</td>
</tr>
</tbody>
</table>

Table 3: Result of statistic analysis of sample B after colour fastness to alkaline perspiration tests

<table>
<thead>
<tr>
<th>Index</th>
<th>Degree of colour change</th>
<th>Degree of whiteness soil of cotton accompanying fabric</th>
<th>Degree of whiteness soil of wool accompanying fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average value $\bar{x}_p$</td>
<td>4.415</td>
<td>1.833</td>
<td>4.167</td>
</tr>
<tr>
<td>Standard deviation $S$</td>
<td>0.290</td>
<td>0.408</td>
<td>0.258</td>
</tr>
<tr>
<td>Coefficient of variation $V$ (%)</td>
<td>6.568</td>
<td>22.268</td>
<td>6.197</td>
</tr>
<tr>
<td>Limits of the interval of confidence of the average value (lower and top)</td>
<td>4.125 – 4.707</td>
<td>1.405 – 2.262</td>
<td>3.896 – 4.438</td>
</tr>
<tr>
<td>Limits of the interval of confidence of the standard deviation (lower and top)</td>
<td>0.160 – 0.550</td>
<td>0.240 – 0.821</td>
<td>0.152 – 0.519</td>
</tr>
<tr>
<td>Limits of the interval of confidence of coefficient of variation (%)</td>
<td>3.791 – 12.955</td>
<td>13.088 – 44.770</td>
<td>3.645 – 12.459</td>
</tr>
<tr>
<td>Limits of repeatability $r$</td>
<td>1.191</td>
<td>0.753</td>
<td>1.305</td>
</tr>
<tr>
<td>Limits of reproducibility $R$</td>
<td>1.214</td>
<td>1.829</td>
<td>1.190</td>
</tr>
<tr>
<td>Precision quotient $PQ$</td>
<td>1.019</td>
<td>2.428</td>
<td>0.912</td>
</tr>
<tr>
<td>Limits of acceptation of the average value</td>
<td>3.962 – 4.868</td>
<td>0.625 – 3.042</td>
<td>3.960 – 4.486</td>
</tr>
</tbody>
</table>
Table 4 Result of statistic analysis of sample B after colour fastness to sour perspiration tests

<table>
<thead>
<tr>
<th>Index</th>
<th>Degree of colour change</th>
<th>Degree of whiteness soil of cotton accompanying fabric</th>
<th>Degree of whiteness soil of wool accompanying fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average value $\bar{x}_n$</td>
<td>4,333</td>
<td>1,667</td>
<td>4,167</td>
</tr>
<tr>
<td>Standard deviation $S$</td>
<td>0,258</td>
<td>0,408</td>
<td>0,258</td>
</tr>
<tr>
<td>Coefficient of variation $V$ (%)</td>
<td>5,958</td>
<td>24,495</td>
<td>6,197</td>
</tr>
<tr>
<td>Limits of the interval of confidence of the average value (lower and top)</td>
<td>4,062 – 4,604</td>
<td>1,238 – 2,095</td>
<td>3,896 – 4,438</td>
</tr>
<tr>
<td>Limits of the interval of confidence of the standard deviation (lower and top)</td>
<td>0,152 – 0,519</td>
<td>0,240 – 0,821</td>
<td>0,152 – 0,519</td>
</tr>
<tr>
<td>Limits of the interval of confidence of coefficient of variation (%)</td>
<td>3,505 – 11,979</td>
<td>14,409 – 49,247</td>
<td>3,645 – 12,459</td>
</tr>
<tr>
<td>Limits of repeatability $r$</td>
<td>1,066</td>
<td>1,066</td>
<td>0,923</td>
</tr>
<tr>
<td>Limits of reproducibility $R$</td>
<td>1,408</td>
<td>1,861</td>
<td>1,184</td>
</tr>
<tr>
<td>Precision quotient $PQ$</td>
<td>1,321</td>
<td>1,747</td>
<td>1,283</td>
</tr>
<tr>
<td>Limits of acceptation of the average value</td>
<td>3,582 – 5,085</td>
<td>0,637 – 2,923</td>
<td>3,577 – 4,813</td>
</tr>
</tbody>
</table>

Sample code A

For tested sample with code A in a range of colour change degree and whiteness soil degree assessment of accompanying fabrics, there were obtained comparable results in every laboratory which have taken part in the test, where the dispersions of results in visual assessment are following:

- from 4th to 5th degree (difference of 1 degree) in case of colour change degree assessment,
- from 2-3 to 3 degree (difference of 0,5 degree) in case of assessment of cotton accompanying fabric whiteness soil degree,
- from 3-4 to 4-5 degree (difference of 1 degree) in case of assessment of wool accompanying fabric whiteness soil degree.

For the results obtained for three series of signatures in particular laboratories, there was calculated a standard deviation which describes average variation of particular property values to average value. The value of deviation is various from 0 to 0,29. Above results present lack of their variation and the value of standard deviation on level of 0 confirm obtaining the identical results by the laboratory.

The identical results in three series of signatures were obtained in a laboratory with the code:

- I – in a range of marking of colour change degree after testing the colour fastness to alkaline perspiration, in range of marking of cotton accompanying fabric whiteness soil degree after testing the colour fastness to alkaline and sour perspiration,
- IV – in a range of marking of colour change degree and cotton accompanying fabric whiteness soil degree after testing the colour fastness to alkaline and sour perspiration,
- V – in a range of marking of cotton and wool accompanying fabric whiteness soil degree after testing the colour fastness to alkaline perspiration and wool accompanying fabric whiteness soil degree after testing the colour fastness to sour perspiration.

The value of coefficient of variation is calculated for all results obtained after testing the colour fastness to alkaline and sour perspiration is below 10 % and testifies the homogeneity of tested property.

The range of limits of the interval of confidence of the average value fluctuate from value of 0,542 to 0,574 and prove the closeness of the results achieved by the laboratories participating in comparisons
between laboratories. In the limits of the interval of confidence of the average value are contained the results of colour change degree assessment and whiteness soil degree of both companying fabrics. The calculated values of precision indicators: reproducibility and repeatability individually for assessment of colour change degree and of whiteness soil degree of companying fabrics are satisfying. On a basis of the tests there wasn’t eliminated any result. Narrow limits of acceptation contain 100% of results.

**Sample code B**

For tested sample with code B in a range of colour change degree and whiteness soil degree assessment of accompanying fabrics, there were obtained comparable results in five laboratories. Only one laboratory (code V) has achieved the result of whiteness soil degree assessment of cotton accompanying fabric on a level differ from others, and this variation is +0,5 degree. The carried out statistic analysis of results has show small difference of separate values from average value inside the laboratory which proves a small dispersion of results of establishing colour change degree and whiteness soil degree assessment of accompanying fabrics.

The coefficient of variation of average values has achieved various levels:
- from a value of 0 % to 5,958 % for results of colour change degree assessment,
- from a value of 22,268 % to 24,495 % for results of assessment of cotton accompanying fabric whiteness soil degree,
- 6,197 % for results of colour change degree assessment.

On a base of presented above mentioned values of coefficient of variation we can observe that only results of assessment of cotton accompanying fabric whiteness soil degree show essential difference which proves tested property homogeneity.

The limits of the interval of the average values are included between:

- for assessment of colour change degree after colour fastness tests:
  - to the alkaline perspiration, lower limit of 4,5 and top limit of 4,5,
  - to the sour perspiration, lower limit of 4,062 and top limit of 4,604,
- for assessment of whiteness soil degree of cotton accompanying fabric:
  - to the alkaline perspiration, lower limit of 1,405, top limit of 2,262,
  - to the sour perspiration, lower limit of 1,238, top limit of 2,095,
- for assessment of whiteness soil degree of wool accompanying fabric:
  - to the alkaline perspiration, lower limit of 3,896, top limit of 4,438,
  - to the sour perspiration, lower limit of 3,896, top limit of 4,439.

The interval of confidence of the average values describes the probability of range of deviation our calculations from the real value. The rower interval of confidence the more precisely calculated. Wider interval of confidence of the average value presents the possibility of big value deviations from a sample than values from the population what means that it is less reliable. The biggest range of the interval of confidence of the average values (0,875) was achieved for the results of assessment of whiteness soil degree of cotton accompanying fabric.

The repeatability and reproducibility which are measures of method precision in a range of assessment of colour change degree and whiteness soil degree of wool accompanying fabric is on satisfying level. In narrow acceptation limits are included the achieved results in all laboratories. In case of assessment of whiteness soil degree of cotton accompanying fabric the precision method indicators are satisfying. In wide acceptation limits are contained all results. The improvement of method precision of the subject parameter could be achieved by increasing the amount of testing samples.
CRITERIA AND ASSESSMENT OF MECHANICAL PROPERTIES OF FABRICS DESTINED FOR THE PROTECTIVE CLOTHING IN THE LIGHT OF HARMONIZED STANDARDS

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ABSTRACT

Modern textiles destined on the protective clothing have to fulfil a wide range of requirements resulting from the fire, heat radiation, mechanical factors, electrostatic charge accumulation, water and chemicals actions. The measurement of fabric mechanical properties is an element of complex assessment of their utility. Analyzing protective clothing requirements they consider mainly a tensile and tear strength, seam strength, bursting, flexing as well as abrasion and puncture resistance. In the paper, there were presented requirements and measurement methods of assessment of mentioned above parameters for textiles destined for the protective clothing of the chosen job groups. Moreover, there were presented results of mechanical property measurements for fabrics destined for the special area of application, for example, a fabric for action against the fire according to the requirements of PN-EN 469.

1. INTRODUCTION

All over the word (also in Poland) there has been recently observed the increase of significance of save utility, especially individual human protective means. It deals with a progress in textile technologies, using new generation of fibers and finishing means, trend of the better protection of the worker at work as well as fulfilling requirements for the utility comfort and attractive clothing appearance. The proper selection of protective clothing for the determined job is possible only then, when there is a full identification of harmful factors, which can create the danger for the human health and life. In the case of protective clothing used during work time, the identification should rely on knowledge of the work conditions, dangers and activities of the worker. Additionally, it should be taken into account that each of these dangers can appear in different conditions, what changes its character and requires a different protection, so a different kind of protective clothing [1]. Only a proper identification of harmful factors at the work enables designing of such a protective clothing, which programmed properties influence the decrease or even elimination of the risk at work.

Law harmonization in the aspect of protecting the human being against the factors dangerous for his life, health and his natural environment is regulated in the European Union by the Directives of New
Approach introduced in 1985. One of the first was the Directive 89/686/EEC concerning the Personal Protective Equipment - PPE. Among the groups of PPE there is also the protective clothing. If the protective clothing is to protect the human being against loosing the health or life, a directive imposes a duty to get certificates for such clothing (designated by CE).

2. MECHANICAL PROPERTIES OF FABRICS DESTINED ON THE PROTECTIVE CLOTHING IN THE LIGHT OF THE STANDARDS HARMONIZED WITH THE DIRECTIVE 89/686/EEC

Modern textiles on protective clothing have to fulfill a very wide range of requirements resulting from such danger sources, like: fire, heat radiation, outer mechanical factors, possibility of accumulation of electrostatic charge, water and chemicals activity, electric current, electromagnetic radiation. The general demands concerning the protective clothing and specification of basic requirements concerning the safety are in the appropriate articles of Directive 89/686/EEC, whereas the criteria and measurements of textiles destined on the protective clothing for specific application are confined in the standards harmonized with the directive. On the basis of standard analysis it was stated that many of them concern a high strength on the mechanical factors, such as: tearing, stretching, bursting, abrasion, punching, a fatigue bending and seam resistance. The assessment of strength properties is described in the II Annex to the Directive 89/686/EEC point 1.3.2 Lightness and design strength. “PPE must be as light as possible without prejudicing design strength and efficiency” [4].

Research carried out in of The Institute of Textile Materials Engineering (IIMW) in Lodz in Poland shows that high mechanical resistance of protective clothing is necessary independently on the other properties dealt with a specific kind of danger, against which the clothing should protect. Below, in Tab. 1 and 2 there are presented measurement methods and criteria of strength property assessment for chosen kinds of protective clothing described in the harmonized standards and concerning the given kind of protective clothing. Additionally, in Tab. 2 there are presented the changes of requirements for protective clothing for firefighters in action, which were in a new edition of harmonized standard EN 469:2005.

2.1. METHODS AND STRENGTH PARAMETERS DESCRIBED IN THE HARMONIZED STANDARDS

Analyzing the presented in Tab. 1 and 2 requirements and criteria of the protective clothing strength property assessment it can be noticed that in each case the requirement concerns the fulfilling of criterion dealt with the tear strength. The most often the minimum tear strength value for the protective clothing is on the level of 25 N, in the case of clothing protected against the liquid chemicals, where the mechanical properties are characterized by classes, for class 1 is above 10 N. It should be pointed out that assessing the protective clothing in the aspect of tear resistance different measurement methods are used. As was shown in [2,3] there is a good correlation between the tear methods (correlation coefficient above 0.9), but it is difficult to compare them directly. Especially, high differences (100%) are seen between results obtained by the single and double tearing. The other aspect is using in the new editions harmonized standards – the standard, which was drawn out, for example, in PN-EN 471:2005 and PN-EN 343:2004. It concerns the standard ISO 4674:1977 for fabrics covered by gummy and polymers, which was cancelled in May 1998. Very important is that the drawn out standard describes
not already applied measurement method determining the maximum tear strength of fabric, so it diminishes so called the “safety coefficient”.

Table 1. Harmonized standards - strength properties - test methods and assessment requirements for chosen groups of protective clothing.

<table>
<thead>
<tr>
<th>Kind of protective clothing</th>
<th>Kind of hazard</th>
<th>Harmonized standard</th>
<th>Tear resistance / Test method / Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-visibility warning for professional use</td>
<td>Mechanical</td>
<td>PN-EN 471-2005; PN-EN 466 and 467 both from 1989/A1:2001; PN-EN 342:2005</td>
<td>ISO 4674:1977; met. A1; Depend on class (5 class) minimum &gt; 10 for 1 class</td>
</tr>
<tr>
<td>Protection against rain</td>
<td>Atmospheric</td>
<td>PN-EN 343:2004</td>
<td>PN-EN ISO 4674-1:2004 met. A; ≥ 25N</td>
</tr>
<tr>
<td>Protection against liquid chemicals</td>
<td>Chemical</td>
<td>PN-EN 342:2005</td>
<td>PN-EN ISO 4674-1:2004 met. A; ≥ 25N</td>
</tr>
<tr>
<td>Protection against cold</td>
<td>Atmospheric</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tensile strength / Test method / Requirement</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Abrasion resistance / Test method / Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN-EN 530:1994</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bursting / Test method / Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN-EN ISO 13938-1:2002; ≥ 800 kN/m² (background)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Seam strength / Test method / Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN-EN ISO 13935-2:2002</td>
</tr>
<tr>
<td>≥ 225N</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Damage by flexing / Test method / Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN-EN ISO 7854:2002</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Puncture resistance / Test method / Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN-EN 863:1999; Depend on class (5 class) minimum &gt; 5N</td>
</tr>
</tbody>
</table>
It is worth to note that this standard, concerning the coated fabrics, is used for the non-coated fabrics, for example, fabrics on the outer layer of firefighters protective clothing. Nevertheless, as was presented in Tab. 2, the newest edition of the harmonized standard EN 469:2005 unifies the measurement methodology on the tear strength as well as breaking force on the basis of appropriate standards for coated and non-coated fabrics. The described in EN 469:2005 methodology for coated and non-coated fabrics on the tear strength is the same (the same sample shape and a way of calculation), what enables the comparison of obtained results. It is worth pointing out that as was shown in [2, 3] using this method we can obtain the lowest result of tear force (high level of the “safety coefficient”). It can be important in the case of using on the protective clothing the cotton fabric, which measured by this method of tearing can not fulfill this criterion. The results of tear strength by the method describes in EN 469:2005 for coated and non-coated fabrics on the outer layer for firefighters protective clothing are presented in Tab. 4. Such big differentiation of methodology is not observed in measurements of other strength properties. In the case of breaking force the measurements of protective clothing are done by so called the “strip test”. The most often the minimum value of breaking force is established on the level of 450 N (warning clothing - min. 400 N).

Table 2. Harmonized standards - strength properties - test methods and assessment requirements for firefighters for firefighting.

<table>
<thead>
<tr>
<th>Kind of protective clothing</th>
<th>For firefighters for firefighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kind of hazard</td>
<td>Mechanical, thermal, atmospheric, chemical</td>
</tr>
<tr>
<td>Harmonized standard</td>
<td>Tear resistance / Test method / Requirement</td>
</tr>
<tr>
<td></td>
<td>Tensile strength / Test method / Requirement</td>
</tr>
<tr>
<td></td>
<td>Seam strength / Test method / Requirement</td>
</tr>
<tr>
<td></td>
<td>PN- EN ISO 13934-1:2002 and after exposed to radiate heat</td>
</tr>
<tr>
<td></td>
<td>PN-EN 366:1993; ≥ 450 N</td>
</tr>
<tr>
<td></td>
<td>ISO 13935-2:1999 ≥ 225 N</td>
</tr>
</tbody>
</table>

Seam strength measurement in the protective clothing is done by the “grab test”. The majority of requirements concerns the level 225 N; whereas for the clothing protecting against the liquid chemicals, minimum value for the first class - above 30 N. It should be noted that the seam strength is a new criterion destined for assessment of outer layer fabrics for firefighters protective clothing. The bigger differentiation of the measurement methodology is observed for the fatigue bending of coated fabrics. The harmonized standards described three bending measurements methods: A, B, C. The choice of measurement method depends on the specific conditions of utility of a given fabric. The similar situation in assessment of protective clothing is observed in the abrasion testing. The differences concern using the different standard abrasion means (wool or sandpaper) and the admitted number of cycles, before the assessment.
Summing up the strength property assessment of fabrics for the protective clothing, especially on the outer layer, is very important. Mechanical defect of this layer, as tearing or abrasion causes that the whole product consisted on a few elements loses its barrier properties. Taking it into account the cost of one set of firefighter protective clothing (about 1 500 PLN) seems to be obvious that fabrics on the outer layer has to be characterize by the appropriate high strength properties.

3. THE CHOSEN ASPECTS OF PROPERTY ASSESSMENT OF THE PROTECTIVE CLOTHING FOR FIREFIGHTERS

The aim of undertaken research by IIMW in Lodz in cooperation with ZPB Andropol SA (in Andrychów in Poland) was elaboration of new textile structures destined for firefighter clothing. It concerns clothing for action as well as for uniforms worn in barracks and by headmasters. Such clothing dependently on the destiny has to fulfil determined by the law and standards requirements resulting from the protection necessity against extreme work conditions or eventual dangers. In the case of protective clothing for firefighters the biggest difficulty at selection of the appropriate kind of protective clothing are different work conditions e.g.; work in the temperatures below 0°C, at night, at high level of humidity, work in the limited space, during the traffic accidents or ruined constructions, also rescue actions during flood as well as difficult situations, in which there is a necessity of going through the fire zone. These facts create the challenge for designers and constructors of protective clothing for this job. On the basis of such an approach, in the result of research the fabrics assortment was elaborated. These fabrics dependably on a destiny have to fulfil requirements for such properties like, flame, heat and chemical resistance, high mechanical strength, electrostatic resistance and physiological comfort. Characteristics of fabric assortments are presented in Tab. 3.

Table 3. Characteristics of new assortments fabric for protective clothing for firefighters.

<table>
<thead>
<tr>
<th>Protective clothing</th>
<th>Fabric A</th>
<th>Fabric B</th>
<th>Fabric C</th>
<th>Fabric D</th>
<th>Fabric E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyamide-imide fibers mixed with conductive fibers. Finish: oil repellent, fluorocarbon compounds</td>
<td>Aramide fibers mixed with conductive fibers. Finish: oil repellent, fluorocarbon compounds</td>
<td>Cotton fibers with conductive fibers in each threads system. Finish: dyeing, flame resistant treatment and oil repellent</td>
<td>Cotton fibers with core spun yarn in each threads system. Finish: dyeing, flame resistant treatment and oil repellent</td>
<td>Polyester fibers; warp - filament; weft - staple. Conductive fibers in each threads system. Finish: dyeing, oil repellent</td>
<td></td>
</tr>
<tr>
<td>Fabric destination</td>
<td>For firefighters</td>
<td>barracks, for commanders, for explosion zone</td>
<td>barracks, for commanders, protected against flame and temperature</td>
<td>for explosion zone before ESD effect</td>
<td></td>
</tr>
</tbody>
</table>

The elaborated fabrics were assessed in the laboratory according to the harmonized standard PN-EN 469, and additional requirements agreed between the fabric manufacturer and client - Main Headquarter of PSP. The set of results of chosen parameters for these fabrics are presented in Tab. 4.
Table 4[5]. Set of chosen parameters for protective clothing.

<table>
<thead>
<tr>
<th>Testing parameter</th>
<th>Method</th>
<th>Unit</th>
<th>Requirement</th>
<th>Fabrics</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass / unit area</td>
<td>PN-ISO 3801:1993</td>
<td>g/m²</td>
<td></td>
<td></td>
<td>213</td>
<td>190</td>
<td>295</td>
<td>292</td>
<td>203</td>
</tr>
<tr>
<td>Breaking force</td>
<td>PN-EN ISO 13934-1:2002</td>
<td>N</td>
<td>≥450</td>
<td></td>
<td>1600</td>
<td>1300</td>
<td>1200</td>
<td>1200</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1000</td>
<td>1000</td>
<td>730</td>
<td>680</td>
<td>1200</td>
</tr>
<tr>
<td>Breaking force</td>
<td>PN-EN ISO 13934-1:2002</td>
<td>N</td>
<td>≥450</td>
<td></td>
<td>1500</td>
<td>1200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>force after</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>970</td>
<td>950</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>exposed to</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>radiate heat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tear resistance</td>
<td>PN-EN ISO 13937-2:2002</td>
<td>N</td>
<td>≥25</td>
<td></td>
<td>83</td>
<td>59</td>
<td>33</td>
<td>34</td>
<td>163</td>
</tr>
<tr>
<td></td>
<td>ISO 4674:1977;A1</td>
<td>m²/N</td>
<td></td>
<td></td>
<td>77</td>
<td>60</td>
<td>33</td>
<td>36</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>123</td>
<td>68</td>
<td>45</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>76</td>
<td>68</td>
<td>52</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Physical comfort</td>
<td>PN-EN 31092:1998</td>
<td>m²Pa/W</td>
<td>≤20</td>
<td></td>
<td>11,1</td>
<td>9,2</td>
<td>3,7</td>
<td>4,0</td>
<td>5,0</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>PN-EN ISO 12947-2:2002</td>
<td>rubs</td>
<td>≤15 000</td>
<td></td>
<td>70</td>
<td>70</td>
<td>20</td>
<td>18</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
</tr>
<tr>
<td>Surface resistance</td>
<td>PN-EN 1149-1:1999</td>
<td>Ω</td>
<td>≤1 x 10⁹</td>
<td></td>
<td></td>
<td></td>
<td>4,5 x</td>
<td>5,2 x</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10³</td>
<td>10³</td>
<td></td>
</tr>
<tr>
<td>Oilrepellency</td>
<td>PN-EN 14419</td>
<td>degree</td>
<td>≥5,5</td>
<td></td>
<td>6</td>
<td>5,5</td>
<td>5,5</td>
<td>6</td>
<td>5,5</td>
</tr>
<tr>
<td>Flame spread</td>
<td>PN-EN 532:1999</td>
<td>s</td>
<td></td>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• Requirements PN-EN – 469; •• Additional requirements

3.1. RESULT OF ANALYSIS

1. **Fabrics A and B** destined on the outer layer of firefighters protective clothing fulfill the requirements of the harmonized standard PN-EN 469. Both fabrics are characterized by the high strength durability at small mass per unit area, the addition of the conductive fibers make them similar to fabrics made of cellulose fiber, what increases their utility comfort. Standard PN-EN 469 does not determine the requirements concerning to antielectrostatic properties for object application. Fibers and their manufacture - ZPB Andropol SA got certificates of agreement with the standard PN-EN 469.

2. **Fabric C** destined for explosion zones and general application due to using reinforced conductive threads is characterized by the high level of the mechanical strength, especially significant for the tear strength without its lowering after the chemical flame resistant treatment. The law level of antielectrostatic properties is constant in the utility period and it is not sensitive for the chemical means.
3. Fabric D - protecting against the temperature and fire as well as general application due to using reinforced threads is characterized by the high level of the mechanical strength, especially significant for the tear strength parameter without its lowering after the flame resistant treatment.

4. Fabric E - antielectrostatic is designed for the clothing protecting against explosion. It has the high mechanical resistance and durable antielectrostatic properties not changing during the long time of utility.

Summing up, the presented above fabrics destined for the protective clothing for firefighters and general destination have good parameters of protection as well as good utility properties. They can broaden the offer of fabrics destined on the protective clothing of a wide range of application as, for example, special uniforms, for police and army, for border guide equipment as well as protective clothing for the industry in places danger for the human being health and life.

4. CONCLUSIONS

1. On the basis of requirement analysis confined in the harmonized standards concerning the chosen groups of the protective clothing it was stated that these cloths independently on its destiny has to be characterized by the high mechanical strength. The parameter, which is used the most often for the assessment of the strength properties in the protective clothing, is the tear resistance. Its low value eliminates fabric from the use.

2. Elaboration in the IIMW in Lodz and implemented for production in the ZPB Andropol SA. fabrics destined on the protective clothing for firefighters for firefighting as well as for clothing worn in barracks and headquarter members have such properties as flame resistance, antielectrostatic properties, high strength and durability as well as a high physiological comfort. The obtained fabric properties qualify them for the application on the protective clothing used for many jobs.

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5. REFERENCES

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APPLICATION OF SYMPATEX REFLEXION
IN PROTECTIVE WEAR ENDUSES

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ABSTRACT

Sympatex Technologies GmbH markets membrane solutions for textile applications, mainly on the basis of polyetherester compact hydrophilic membrane technology. In recent years Sympatex developed a reflective membrane product called Reflexiontm.

Sympatex Reflexiontm is a multicomponent membrane that is based on a first layer of PEE hydrophilic compact film with a nanometer thick second layer of aluminium, sealed with a third layer of PU hydrophilic compact coating. A unique manufacturing process creates sufficient adhesion between PEE and aluminium, and the micrometer thin PU topcoating. Sympatex Reflexiontm becomes a stable membrane system that offers windproofness, waterproofness, breathability and reflection of waves across a large spectrum, reflective values range across thermal and near infrared to visual and ultraviolet with approximately 99.9% reflection. With these values, which are far better than common reflection products that have values of only up to 70%, and with the plus of WWB it brings a combination that has never been possible in one product before.

Sympatex Reflexiontm can be used in a wide range of applications. When laminated with aluminium facing inside Sympatex Reflexiontm allows body heat to be reflected resulting in additional insulation effect. In this combination, it can be used for jackets, shoes, sleeping bags etc. and combines a high insulation value with good breathability, which allows for a superb comfort index value. One can think of military usage (suits, tents, camouflage utilities) allowing almost perfect signature management in IR and RADAR, and heat protection when the reflective layer is used in a textile laminate directed to the outside.

Sympatex Technologies GmbH is very interested to come into contact with anybody that has a need for the newest in WWB technology combined with the fourth dimension: state of the art reflective technology.