ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

ANALYZING AND MODELLING OF COMFORT AND PROTECTION PROPERTIES OF FIRE FIGHTERS PROTECTIVE CLOTHINGS

M.Sc. THESIS

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Department of Textile Engineering

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Tolera A. Negawo, a **M.Sc.** student of ITU **Institute of / Graduate School of Science Engineering and Technology** student ID **503121812**, successfully defended the **thesis** entitled "**ANALYZING AND MODELLING OF COMFORT AND PROTECTION PROPERTIES OF FIRE FIGHTERS PROTECTIVE CLOTHING'S**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my spouse and family

FOREWORD

While fighting fire, fire fighters are exposed to both the high working temperatures which can cause burning and also to the stress from internal body temperature increament. In order to ensure the workers thermal comfort, the heat exchange of human body and the surrounding through the fire fighters clothing should be studied. In this thesis the thermal comfort properties of different fabric layers (outer layer, moisture barrier and thermal barrier) that can be layered and used to make fire fighters protective clothing are tested for their comfort and fire protection properties. The moisture transporting properties like water vapour permeability, airpermeability, and also heat loss and gain properties of fabric layers is measured by using Alambeta and Permetest measuring instruments. Thermal resistance, thermal absorptivity, water vapor resistance, thermal diffusion and air permeability are considered in calculating thermal comfort index. Additionaly thermal camera is used to measure temperature difference while wear trials were done at varying working environment temperature. The fabric selection for fire fighters clothing can be suggested based on the overall measurement results.

May 2015 Tolera Aderie NEGAWO

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Additional thanks go to Funda BÜYÜKMAZARI for her assistance in doing experimental works by Alambeta device at Technical University of Liberec, Czech Republic and to KIVANÇ GROUP Company Safety Division staffs for providing test materials, fabrics, readymade garments and laboratory burning tests done there. Again I want to thank my friend Vagiz Gareev, who is also student of Istanbul Technical University for his good wish to help me in wear trials done by wearing fire fighters protective clothings. And of course finally to my family and beloved spouse for their daily backing me while studying my education.

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ABBREVIATIONS

TCI **:**Thermal Comfort Index

RTCI **:**Relative Thermal Comfort Index

NFPA **:** National Fire Protection Association

TPP **:**Thermal Protective Performance

NIOSH **:**National Institute for Occupational Safety and Health

RPP **:**Radiant Protective Performance

THL **:**Total Heat Loss

KES **:**Kawabata Evaluation System

PPC **:**Personal Protective Clothing

FFPC **:**Fire Fighters Protective Clothing

ASHRAE **:**American Society of Heating, Refrigerating and Air Conditioning Engineers

WVTR **:**Water Vapor Transfer Rate

WVP **:**Water Vapor Permeability

HTI **:**Convective Heat Transfer Index

RHTI **:**Radiant Heat Transfer Index

ASTM **:**American Society for Testing and Materials

ISO **:**International Standards Organization

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SUMMARY

Protection together with comfort is very important subject for the performance of protective equipment. Firefighting is very dangerous work and today firefighters wear personal protective equipment to protect themselves during their highly dangerous work. Also they have to perform their jobs under very restrict time intervals so their motion and working performances are highly dependent on clothing comfort. The balance of thermal protection from fire and metabolic heat stress generated by the human body due to metabolic activities is very important during fire situations. The structure of the garments must allow evaporation of perspiration, ventilation and also thermal protection from fire.

In this study, first of all the technical literatures were reviewed concerning the studies related to thermal comfort properties, fire protection performance of fire fighters clothings, factors contributing to improvement of thermo-physiological comfort, wear trials comfort analysis and also the reviews including researchers recomendations. The thesis aimed to focus on studying both comfort and protection performance of fire fighters protective clothings by using objective measurements applied generally and specifically in screening the most comfortable/ protective fabric layers used to produce fire fighters protective clothing.

The objective measurement equipments such as Alambeta device and Permetest were found to be appropriate and useful instruments to measure comfort parameters, and also both being fast and non-destructive. Beside these there are others test apparatus used such as air-permeability tester, thermal camera, burning tests equipment sets, all described well in materials and methods sections of this thesis work. The analysis of results is supported by basic knowledges of various aspects of comfort, thermal comfort, clothing comfort properties, mechanisms of heat and moisture transfer through the coveralls all which provided in chapter two of the thesis. Additionally,

understanding about fire protection, fire fighters thermal environments, and appropriate test apparatus based on standards were used.

Water vapour resistance, thermal resistance, thermal conductivity, thermal absorption, thermal diffusion, air permeability were measured and analysed. The relative thermal comfort index of multi-layered fabrics was calculated to see their comfort levels. This thermal comfort index was used to compared against the burning test results to attain an objective of screening and listing the layers of fabrics. The results and discussions section of the thesis represents all steps and values based on the analysis of the several test results. Additionaly the wear trials have been conducted to compare the objective measurements conformity with the analysis done by measuring human worn fire fighters protective clothings. The Testo 885 thermal imaging camera was used to measure. Statistical analysis showed that the conformity of fabric evaluation using RTCI with those carried out by wear trials measurements by using thermal camera.

The thesis addressed several potential problems with the current methods for screening each single layered fabrics used in assembly according to their demand to comfort and protection level based on objective measurements. In analysis of properties such as water vapour permeability, thermal resistance, thermal absorptivity, thermal diffusion and protection performances total of sixty four layered fabrics used. All of the multilayered firefighters protective clothings are not air permeable because of the thermal barriers which hinder air transmission. From several tests done for all samples its possible to conclude that, the thermal resistance measured by Alambeta device results greater than that measured by Permetest device for the same sample.

The relative thermal comfort index calculated for fabric layers evaluate and provide well screened status weather a particular type of fabrics when made garments and investigated wear trially would definitely ensure thermal comfort. The more burning tests resistance time in seconds to convective and radiant heat source, the more protective the assemblies and its used to rank the performances of samples. In order to meet the best expectations to this conclusion, it is necessary to precisely specify the conditions of using the garments, not only concerning microclimate parameters but also personal features of the user and the type and intensity of physical activity.

İTFAİYECI KORUYUCU KIYAFETLERININ KONFOR VE KORUMA ÖZELLİKLERİNİN ANALİZİ VE MODELLEME

ÖZET

İtfaiyeci kıyafetlerinin konfor özellikleri koruyuculuk özellikleriile birlikte önemli bir performans göstergesidir. Yangın söndürme oldukça tehlikeli bir iş olup, günümüzde itfaiyeciler çok tehlikeli çalışma koşullarında bulunduklarından kendilerini koruyabilmek için kişisel koruyucu kıyafetler giymektedirler. Ayrıca itfaiyeciler işlerini çok kısıtlı birsüre de gerçekleştirmek zorunda olduklarından hareket kabiliyetleri veçalışma performansları yüksek oran da giysi konforuna bağlıdır. Koruyucu giysinin yangın ortamında gereken termal korumayı sağlaması ve aynı zamanda vücut tarafından gerçekleştirilen metabolic aktiviteler sonucu üretilen ısıyı dengelemesi yangın koşullarında çok önemlidir. Koruyucu giysi yapısıterin buharlaşmasını, havalanmayı ve aynı zamanda yangından korunmayı sağlamalıdır.

Bu çalışmada ilk aşama olarak termal konfor özellikleri, itfaiyeci kıyafetlerinin yangın koruması, termo-fizyolojik konfor özelliklerinin geliştirilmesine katkı sağlayan faktörler, giysi denemeleri analizleri ve araştırmacı yorumları ile ilgili çalışmalar hakkında literatür araştırması yapılmıştır. Bu tezde, itfaiyeci giysisi üretiminde kullanılan kumaş katmanlarının belirlenmesinde genel ve özel olarak uygulanan objektif ölçüm metodlarını kullanarak, koruyucu itfaiyeci giysisi için konfor ve koruyuculuk özelliklerinin çalışılması üzerine odaklanılmıştır.

Alambeta ve Permetest gibi kumaşların konfor özelliklerinin incelenmesinde kullanılan objektif ölçüm cihazları hızlı ölçüm kabiliyeti ve giysiye zarar vermeden ölçüm yapması bakımından çalışmada kullanılması uygun görülmüştür. Hava geçirgenliği, termal kamera, yanma testi cihazları gibi çalışmada kullanılan diğer konfor ve yanmaya dayanıklılık ölçüm cihazları tezin malzeme ve metot kısmında

detaylı bir şekilde açıklanmıştır. Sonuçların analizi, tezin ikinci bölümünde detaylı bir şekilde verilen konfor, termal konfor, giysi konforu özellikleri, giysi katmanlarından ısı ve nem transfer mekanizmaları gibi temel bilgilerle desteklenmiştir. Ayrıca, yangından korunma, itfaiyeci termal ortamları ve standartlara göre uygun test cihazları detaylı bir şekilde incelenerek çalışmada kullanılmıştır.

Su buharı direnci, termal direnç, termal iletkenlik, termal absorplama, termal difüzyon, hava geçirgenliği ölçülmüş ve analiz edilmiştir. Çok katmanlı kumaşların konfor seviyelerini belirlemek için rölatif termal konfor indeksi hesaplanmıştır. Bu termal konfor indeksi yanma test sonuçları ile karşılaştırılarak kumaş katmanlarının objectif olarak değerlendirilmesi ve sıralanması sağlanmıştır. Sonuçlar ve tartışma bölümünde uygulanan tüm test yöntemi sonuçları ve değerlendirilmesi sunulmuştur. Bu çalışmalara ek olarak giysi denemeleri gerçekleştirilerek objektif test yöntemleri kullanılarak elde edilen konfor deneyi sonuçlarının gerçek giysi giyimi esnasında oluşan durumla uygunluğu karşılaştırılmıştır.Testo 885 termal kamera ölçümler esnasında kullanılmıştır. İstatistiksel analizler rölatif termal konfor indeksi kullanılarak elde edilen kumaş değerlendirmesinin termal kamera kullanılarak gerçekleştirilen giyim denemeleri ile uyumlu olduğunu göstermiştir. Son olarak, gelecek çalışmalar için sonuçlar ve tavsiyeler verilmiştir.

Genellikle bu tez geçerli yöntemlerle birçok potansiyel sorunları ele adı ve nesnel ölçümlere dayalı konfor ve koruma seviyesine kendi isteğine göre montajında kullanılan her katmanlı kumaş tarama yapilabıldi. Su buharı geçirgenliği, ısıl direnç, termal ekstensiyonu termal difüzyon ve kumaş koruma performansları kullanılan 64 katmanlı toplamı olarak özelliklerinin analize yapıldı. Çok katmanlı itfaiyeciler tüm koruyucu giysiler için hava iletimini engelleyen termal engellerin nedeniyle hava geçirgen değildir. Bu sonuca en iyi beklentilerini karşılamak amacıyla, giysiler kullanan tek mikroklima parametrelerini aynı zamanda kullanıcı ve fiziksel aktivite türü ve yoğunluğu kişisel özellikleri ile ilgili koşullarını belirlemek gereklidir.

1. INTRODUCTION

Optimal comfort will enable the wearer to work efficiently over long periods of time and help to protect the body from dangerous local cooling or from imminent overheating. During their regular work operations, firefighters are exposed to conditions involving intense thermal exposures that have the potential to cause serious injury or death unless proper protective clothing is utilized. The abilities of a firefighter to mitigate a fire hazard successfully are limited because the length of time such conditions can safely be endured is dependent on the performance of the protective clothing. However, the special clothing ensembles firefighters wear should provide not only thermal protective performance but also thermal- and moisture-related comfort**[93].**

There exist a number of factors contributing to the effectiveness of a firefighter protective clothing garment. These factors range from operational features such as the weight, comfort, mobility, and cost of the garment, to fundamental protective features such as reduced ignition propensity, resistance to heat and moisture transport, and dissemination of stored thermal energy. By improving the understanding of the thermal properties of fire fighting clothing, as well as the physiology of the user, improvements can be made in comfort of these materials**[3].**

Historically, protective clothing was designed based upon subjective comments, and not on the physiology of the user or basic physical principles. This practice began to change in the 1940's, when the armed services initiated programs to investigate protective clothing, due to the climatic extremes encountered by servicemen. This initial military work led to the standardized tests, such as the Thermal Protective Performance Test**[4].**

The National Fire Protection Association (NFPA) first released an industry wide standard on fire fighting clothing 1975, designated NFPA 1971 Protective Clothing for Structural Fire Fighting. This document has been revised every three to five years, per the normal NPFA Standard developmental process. Despite advancements in the development of synthetic fibers and materials that provide better insulation, fire ground burn injuries remain a significant issue (according to data collected by NFPA, Fire Fighting Injuries, 1997) **[80].**

The thermal performance of fire fighters' protective clothing is primarily based on the thermophysical properties of the materials that are used to construct the clothing and the insulating air space that is provided by the garment as a result of its design. is possible to improve the thermal protection provided by a garment simply by increasing the thickness of its protective layers; however, such an improvement increases the cost and weight of the garment and reduces its mobility, rendering succesful firefighter operations more difficult.

A complete evaluation of comfort phenomenon requires a substantial multidisciplinary approach, like objective analysis, in which quantitative measures characterizing comfort can be determined (tactile and thermal parameters). Another is subjective analysis, in which psychological evaluation is made by surveys, ratings and scales and also correspondence analysis, in which the subjective and objective analysis are combined to develop quantitative measures.The overall measured values of comfort properties shall be evaluated in one system and then used to screen the comfort level of firefighters protective clothings.

Numerous studies of textile thermal protective properties as well as theoretical considerations have allowed to develop a generalised formula for a comprehensive index representing the capability of textiles to ensure thermal comfort (ThermalComfort Index)**[90]** . TCI can be used to assess textiles for specialist protective clothing, which have normative requirements for the range of values of an indicator influencing thermal protection. Small-scale laboratory tests are a practical alternative to expensive, time-consuming wear trials; however, they do not take into account factors related to garment fit and design. With the development of high resolution infrared cameras, thermography is gaining increased attention of the researcher not merely as a non contact tool to measure surface temperature of the objects, but also as a tool in fine physical experiments to analyze thermo-physical phenomena**[92].**

1.1 Objectives of Thesis

The general objectives of this thesis are to study the comfort and protection of selected Firefighters protective clothing's and this is done based on the objective measurement results and scientific analysis methods. Thermo-physiological comfort properties of protective clothing's have been studied both at fabric level and garment level.

At fabric level, the properties such as thermal resistance, thermal conductivity, water vapor resistance, thermal diffusion, thermal absorption, air permeability were evaluated and analyzed. Beside this, the protection ability of fire fighters protective clothing to burning flame, radiant heat and other hazards were measured according to the standards and these results were used to rank the selected fabrics to study at garment level. At garment level, the wear trials were implemented for selected firefighters clothing's that were recommended to be sewn from good protective and comfort lists, medium in protection and comfort and bad both in protective and comfort properties.

Specifically, fabrics selected; from stock of Kivanç Group Safety Division, Istanbul Turkey, well-known Protective clothing Manufacturing Company; were measured for their thermo physiological properties such as thermal resistance, thermal conductivity, thermal diffusion and thermal absorption; by using Alambeta Instrument. The experiments were conducted at Istanbul Technical University, Turkey by using Fast Permetest to measure water vapor resistance and thermal resistance, and also Air permeability tester to measure air permeability.

Similarly, the fabric burning tests were done at Kivanç Group Company to measure selected fabrics assemblies when exposed to a source of radiant heat as per EN ISO 6942 standards and also determination of heat transmission on exposure to flame as per EN ISO 9151 or EN 367. Finally, the overall thermal comfort index and protection abilities were analyzed to pick readymade garments for wear trials analysis by using thermal camera. Thus to undergo all the above objectives the road map model was prepared and given by Figure 1.1 on next page showing the main work flows followed.

ROAD MAP MODEL FOR STUDY

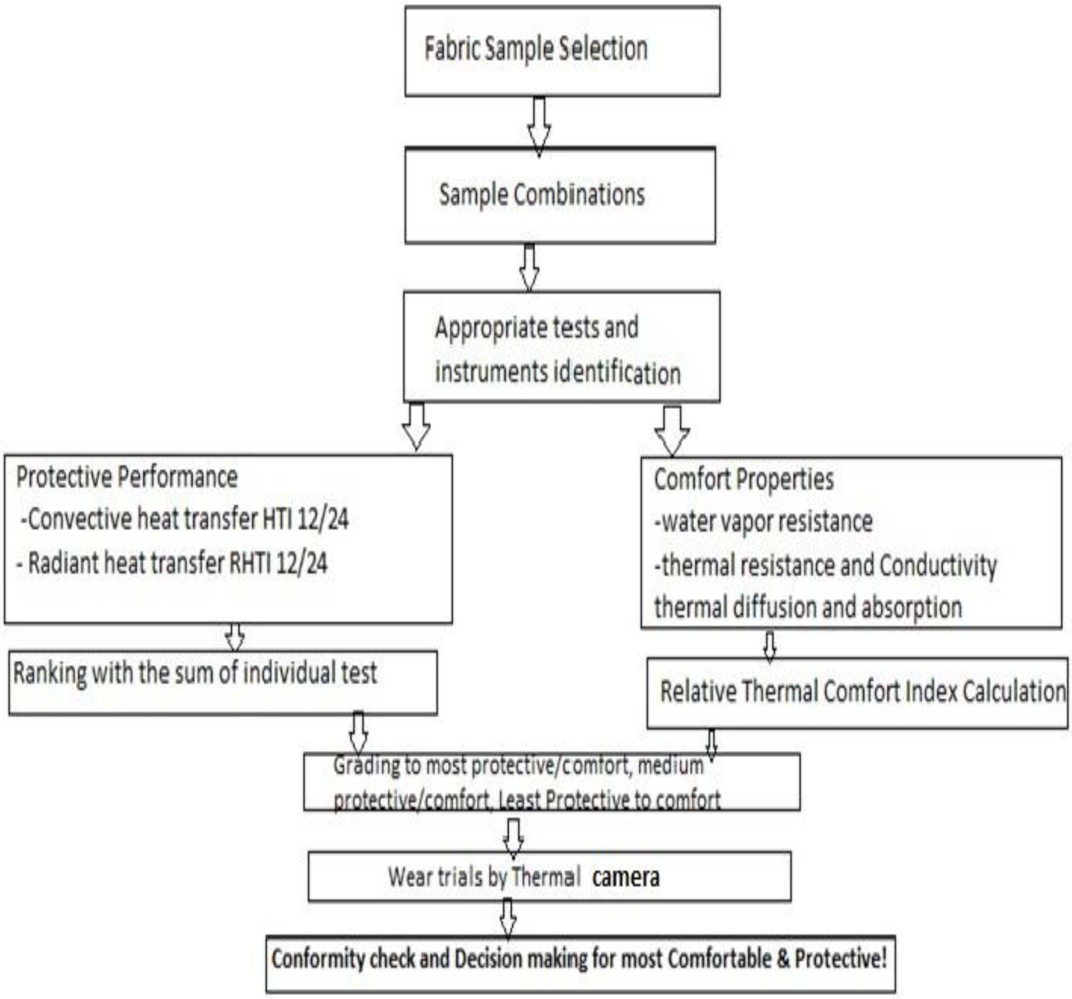

Figure 1.1: Roadmap model for study.

1.2 Literature Reviews

Gi-Soo Chung, Dae Hoon Lee, (2005) studied comfort of protective clothing for fire fighters and suggested that the system of of clothing designs and material layers must be chosen carefully to balance protection and comfort. It is because of that, when performing a task in a fire the heat and perspiration generated from the body become trapped inside the protective clothing. This heat and moisture result in heat stress and physical fatigue of the firefighter, which hinder their work **[1].**

Similarly, Yunyi Wang et al, 2012 concluded that the special clothing ensembles firefighters wear should provide not only thermal protective performance but also thermal- and moisture-related comfort. The comfort property of protective clothing has great influence on work efficiency**[2].**

Mah, T. & Song, G. W., (2010) outlined that firefighting clothing's heat and moisture transfer capacity was affected by many factors, such as material properties, the style, fit, size and drape of garments **[3].** According to the study results of Antonio M.Raimundo and Antonio R.Figueiredo, (2008) it was possible to enhance firefighter safety by the augmentation of clothing insulation and vapour permeability efficiency and by diminishing the emissivity of its external surface. However, the results clearly showed that, besides the improvement of clothing properties, the safety of firefighters was essentially related with a good control of the exposure times to these high intensity radiation fluxes**[9]**.

Historically, fire fighters did not have the same level of protective clothing used today. Because of this most fires were fought from the outside of burning buildings, and structures were rarely entered. Early in the history of fire fighting, a fire fighter's outer clothing was more for warmth and dryness than for protection from fire.

In the early 19th century, the early use of long trench coats, made of leather or canvas and later made of rubber, was the fore runner of modern turnout jackets. Early coats had felt or wool liners to provide warmth in the winter. These liners later developed in basic thermal protection liners found in today's modern coats. Earlier rubber coats were much longer than today's modern turnout jackets, reaching down to a fire fighter's mid thigh and were worn with long rubber boots called "three-quarter boots" which came above the fire fighter's knees. This interface of boot and coat left a large gap of protection against fire. This system has since been replaced by the modern combination of a jacket, pants with suspenders, and shorter rubber or leather boots, although some departments still wear the traditional old style of gear**[4].**

The National Fire fighters Protection Association has set a fundamental requirement that protective clothing for fire fighters has a minimum thermal protective performance TPP value of 35, which means the clothes, can protect a person engulfed in a fire for 17.5 seconds

According to Holcombe, 1983, The professional firefighter in an urban environment faces hazards which include contact with falling objects, contact with projecting objects which can puncture both garments and skin, exposure to heat, flames and hot objects, water, corrosive liquids, toxic gases and combustion products, and even molten metals and live electrical wiring. Apart from the risk of direct physical injury, he was also faced with the more subtle danger of heat stress and heart strain due to strenuous work in hot environments, or simply excessive exposure to heat which overloads his metabolic system**[5].**

Raheel, M. (Ed.), 1994, Bajaj, Sengupta,1990, Jeffries, Berichte,1989 studied and identified some occupations in which the hazards from heat and flame were such an integral part of the job that the worker needed to wear protective clothing more or less continuously and Table1.1 illustrates their studies**[6-7].**

Working conditions for fire fighters can be described according to the environment temperature and the incident radiant heat flux. Rossi, (2003), made some measurements for their study in buildings for fire fighting training and he has shown that fire fighters were typically exposed to radiant heat fluxes of between 5 and 10 kWm^{-2} during this kind of exercise. The heat load can nevertheless be much higher.

Table 1.1: Hazardous occupations requiring protection against flame and heat**[6-7].**

Industry	Flame	Thermal Contact	Radiant Heat
Foundry (Steel and glass manufacturing, metal casting, forging)	*	**	**
Engineering (Welding, cutting, boiler work)	*	**	*
Oil, gas, and chemicals	*	-	-
Aviation and space	*	-	-
Military	**	*	*
Firefighters	**	*	*

** Major hazard; * Subsidiary hazard; - Minor/no hazard, In one case, 42 kWm^{-2} was measured. The temperatures were reached between 100 and 190°C at 1 m above ground, going up to 278°C in one case**[8].**

Human trials have been performed with 17 fire fighters. After exercises (about 15 min) in a heated room, the mean core temperature of the fire fighters rose by 0.6°C with a surrounding temperature of 31°C and 1.0°C with 38°C. The sweat production varied from 0.7 to 2.1 l/hr; 16% to 45% of sweat remained in the clothing layers. During the exercises in the training buildings, a mean of 48°C has been measured between fire fighters' clothing and workwear. These conditions lead to an increase of the relative humidity in all the jackets up to 100%**[8].**

Significant thermal degradation to the turnout materials are not always observed in sub-flashover incidents. Visually observable thermal degradation to moisture barrier and thermal liner components can occur with no visual degradation to the outer shell of the turnout. Heat degradation and melting are most often observed in reflective trim components attached to the outer shell**[10].**

According to the report presented to National Institute for Occupational Safety and Health **(**NIOSH) in 2008 and supported by Figure 1.2 showing the location and frequency of burn injuries, observed in the limited survey of sub-flashover burn incidents, may be associated with stored thermal energy. These data indicate that most of the reported burns occur on the shoulders and arms. Some of the burns occur in areas where the turnout is compressed, such as the shoulder area by the weight of the SCBA, or in the elbow and/or knee areas where clothing compression occurs as a result of bending of the arms and/or legs. A number of the burns occur in areas where reflective trim or reinforcements are attached to the outer shell of the turnout. A few of the burns occurred around the knees in cases where the firefighter was in a crouched position. Some burns even appeared to occur where patches or logos are attached to garments worn underneath the turnout suit**[10].**

Radiant protective performance, air permeability, vapor evaporation, and the thermal resistance of clothing are fundamentally related to the chemical and physical structures of fabrics.According to G. Sun et al, 2000, the results of selected fabrics made from aramid, modacrylic, polyimide, and fire resistant cotton fibers, though not exclusive, indicate that radiant protective performance and transport properties were affected by the material, structure, thickness, and weight. The higher the thickness or the heavier the weight, the better the radiant protection. Radiant protective performance was not affected significantly by color in the varieties they tested. The thermal resistance of the tested fabrics varies in a relatively small range, but is associated with fabric thickness. Thick fabrics possessed high thermal resistance, but the structural impacts on RPP Radiant Protective Performance and transport properties of fabrics were different**[11].**

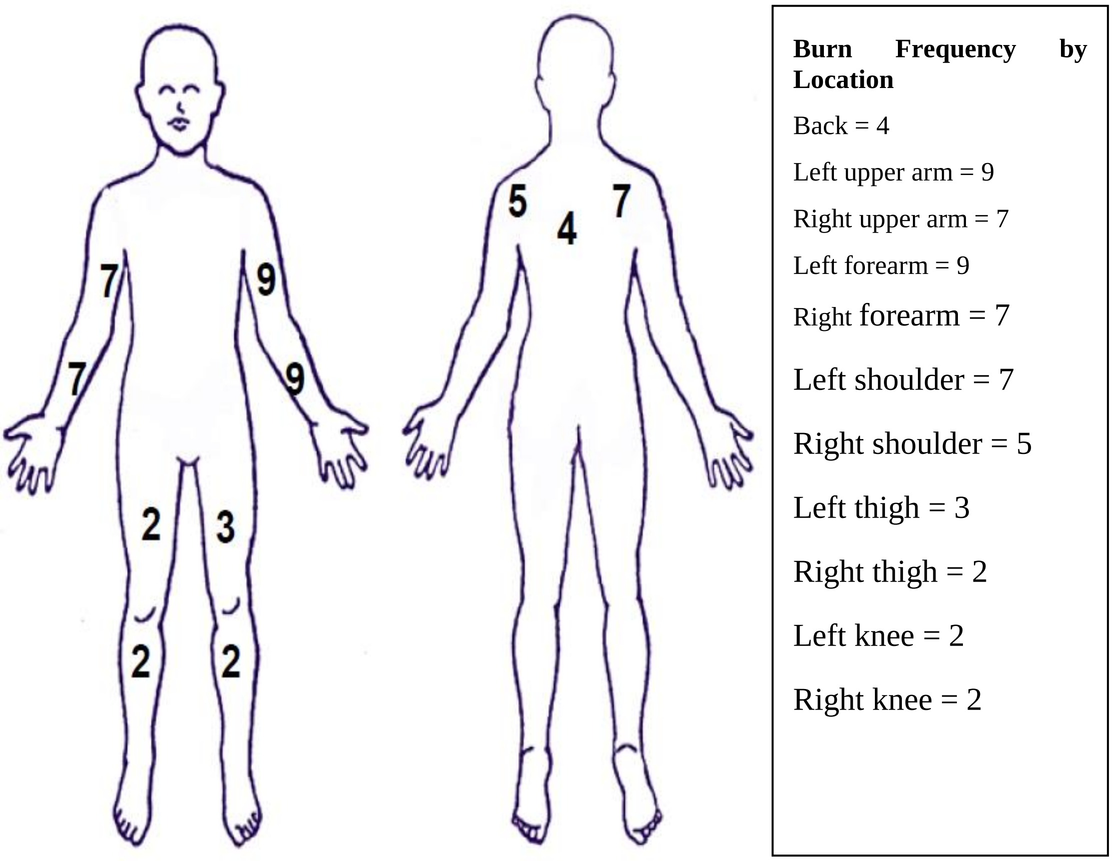

Figure 1.2: Distribution of burn injuries observed in twenty-four incidents assumed to be subflashover thermal exposures[10].

The Jun Li et al, (2007) research work was done to evaluate effects of material component and design feature on heat transfer in firefighter turnout clothing. By using a sweating manikin heat and moisture transfer performance of firefighter turnout clothing including outer shell, moisture barrier and thermal liner was evaluated considering clothing material, design (style), size (fitness) and accessory (design detail in clothing) and clothing design were concluded as six explainable factors. Their effects on heat loss of firefighter protective clothing were differentiated by the indices thermal insulation (It), moisture permeability index (I_m), CI_t and CI_m **[12].**

CI_t and CI_m, the changing rates of It and Im, respectively, under two different dressing ways, with openings sealed or not, were proposed as new indices in the study. CI_t quantified the effects of clothing design features (design, size, accessory) on heat transfer through firefighter turnout clothing, while Ci_m was dependent greatly on the material moisture permeability**[12].**

J. Randal Lawson' and Robert L. Vettori, 2002 suggested that Fire fighters protective clothing thermal performance must be evaluated while dry, when wet, in full loft and when fully compressed. Additionally, it was apparent that thermocouple pad temperature measurement devices can create significant errors when attempting to measure heat transfer in protective clothing systems, and a greater understanding of thermal performance may be gained by using materials thermal properties to model the behavior of protective clothing systems. These new measurement techniques and approaches to predicting thermal performance provided opportunities for improving fire fighters' protective clothing. In addition, their application to the design of protective clothing and training in the fire service had the potential for reducing the number of serious burn injuries experienced by fire fighters**[13].**

According to J. Randall Lawson et al, 2005 the thermal performance of fire fighters' protective clothing was primarily based on the thermophysical properties of thematerials that were used to construct the clothing and the insulating air space that was provided by the garment as a result of its design. The experimental data show that the thermal conductivity generally increases as exposure temperature increases. As a comparison, the following are thermal conductivity values reported for some materials similar to those measured in their study**[14]:**

- Cotton, 0.0589 W/mK
- Wool felt, 0.0519 W/mK
- Silk, 0.0364W/mK
- *Protective clothing shell fabric,* 0.0470 W/mK
- Hard rubber, 0.1506 W/mK
- Soft rubber, 0.012 W/mK
- Glass wool insulation, 0.038 W/mK

Lubos Hes , 2009 defined thermal comfort for lying or resting human body as thermal equilibrium, no muscular shivering nor vasodilatation, no principal sweating (relatively dry skin), skin temperature between 32 and 34^{O}C, no heat storage or loses[**15].**

Wakatsuki et al, (2013) investigated if the synthetic underwear plays a significant role in moisture and metabolic heat transfer within the fire fighter clothing by total heat loss measurement. The heat loss of synthetic underwear is larger than other underwear including natural fibrous textile. The total heat loss of each fire fighter protective clothing is more than or equal to 300 W/m2. And the latent heat losses are more than or equal to 200 W/m2. Both of the values are over the performance requirement by the guideline of fire fighter's personal protective equipment notified from the Fire and Disaster Management Agency. When underwear and fire fighter protective clothing were made lamination, it became that heat loss decreases significantly. It came out that the fire fighter protective clothing was the main factor which control heat loss. They concluded that the fire fighter's multi-layer fabric controls the heat and moisture transfer within fire fighter clothing and no positive contribution by any types of underwear**[16].**

Thermal insulation is normally provided by a layer of non-woven material. But the real insulation is created by trapped air between the fibers. GORE-TEX® and Airlock® is a new combination of waterproof barrier and thermal protection. Wolfgang Nocker and Johann Seibert, (2005) have studied on these new combination by comparing with leather insulation and concluded as follows. In the fire-fighting suits with the new combination of thermal protection and liquid barrier, very favourable thermophysiological conditions prevailed. Such suits can be expected to produce less heat stress in the wearer. Fire-fighting suits with Airlock® fulfil EN 469 and had been successful in thermo-man-tests. With the new concept, the bulkiness of insulation could be reduced while maintaining the same level of heat protection. Due to minimal moisture absorption and high moisture vapour transfer the risk of injuries by scalding should be reduced. High flexibility and reduced weight of such suits increases the wear comfort**[17].**

1.2.1 Heat and moisture transfer related studies

Yunyi Wanga, et al (2013), studies concluded that the thermal and moisture comfort of firefighters' ensembles when combined with the polyester inner clothing was worse than the other types of inner clothing. It was suggested that firefighters wear cotton or linen inner clothing when extinguishing fires. Specifically, firefighters' ensembles combined with linen inner clothing could provide better thermal and clingy sensation when working in high temperature environments**[18].**

Evaporative resistance is a moisture transfer resistance, as the transferred heat is bound to moisture that evaporates at the skin surface and passes to the environment. Evaporative resistance of clothing may be directly measured with subjects. It can also be determined on the basis of thermal insulation and the permeability index (im) for the fabric or for the ensemble.

Table 1.2: Thermal properties of selected protective ensembles compiled from various sources[19].

Clothing	I_{cl}, clo	I_{Tot}, clo	i_m, n.d.	R_{et}, kPa m^2/W (10^{-3})
Nude	0	0.7	0.50	13
Cotton shirt and trousers, underwear, socks, shoes	0.65	1.25	0.42	28
Coverall, T-shirt, underwear, socks, shoes	0.84	1.41	0.42	31
Cotton shirt and pants (flame resistant), underwear, T-shirt, belt, socks, shoes	1.00	1.51	0.32	44
Aluminized apron, cotton shirt and trousers, underwear, socks, shoes	0.77	1.33	0.38	32
Aluminized coat hip-length, cotton shirt and trousers, underwear, socks, shoes	1.36	1.89	0.33	53
Aluminized overjacket and overtrousers, coverall, long underwear, socks, shoes	1.48	2.0 (1.1*)	0.15	70*
Chemical protective suit (Goretex), coverall, long undershirt and underpant, socks, shoes	1.4	1.9 (1.3*)	0.33	37*
Chemical protective suit (imperm), coverall, long undershirt and underpant, socks, shoes	1.4	1.9 (1.1*)	0.06	180*
Firefighter's turnout coverall, trousers, shirt, underwear, gloves and socks		2.42	0.36	62

Values are obtained with measurements on manikins. Values marked with * denote data obtained with measurements on subjects during work in a climatic chamber. Table modified from Holmér[4, 24].

The permeability index is measured on a "sweating, hot plate" or with a sweating, thermal manikin and expresses the fraction of evaporation that takes place with the sample compared with evaporation through the air layer only. The fire fighters turnout ensembles evaporative resistance have studied and compared with selected garments by I Holmer, (2006) and showed as table below. Values are obtained with measurements on manikins**[19].**

During fire fighting, firefighters can sweat profusely causing moisture to accumulate in their turnout garments. This accumulated moisture can affect the ability of the turnout clothing materials to protect against prolonged exposure to heat in a structural fire within a room that has not reached flashover condition. The research by Barker et al, (2006) was conducted to study the effects of moisture on the thermal protective performance of firefighter turnout materials in this type of radiant heat environment**[20].**

A basic heat transfer model was constructed to estimate the effect of added moisture on turnout systems. A turnout system consisting of an outer shell, moisture barrier and thermal liner is illustrated in Figure 1.3. The heat flux boundary condition and the heat flux measuring device are also shown in Figure 1.3. the addition of moisture negatively impacts the predicted burn protection to the greatest degree when the moisture was added at a comparatively low level of approximately 15% of turnout composite weight. As the moisture level increased beyond this critical level, predicted second-degree burn times increase to approach values measured for dry composites**[21].**

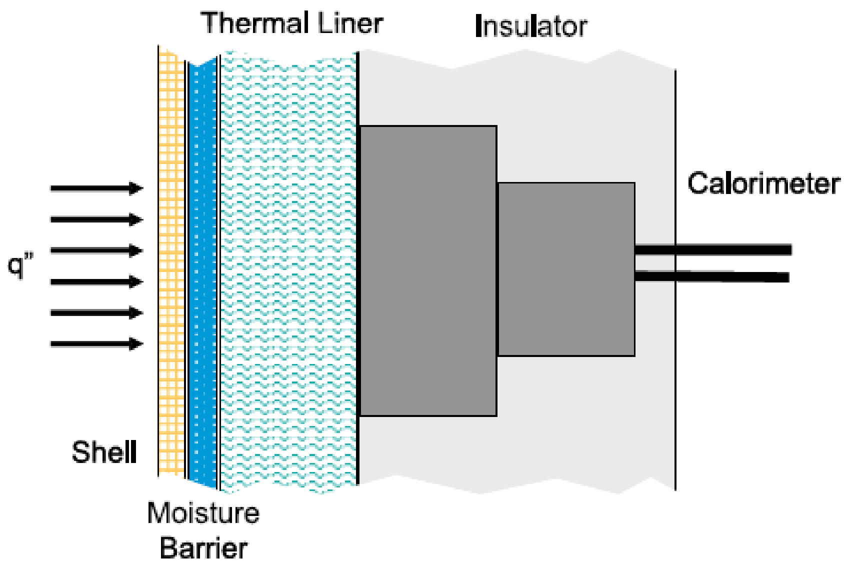

Figure 1.3: Measuring heat transfer in turnout systems[21].

Jiazhen He et al, (2014) study showed the heat and moisture transport performance of the multilayer protective clothing under seven different ambient conditions. As ambient temperature increased, microclimate temperature was observed to be higher and the microclimate vapor pressure rose with the increase of ambient vapor pressure. It also revealed that the overall moisture accumulation distribution in multilayer clothing could be influenced by the ambient condition. microclimate, the nearest environment surrounding the human body. It was closely associated with the ambient conditions, and also that it changed with the periods of time, indicating that the wearer was exposed to a changeable microclimate instead of the constant ambient conditions. The results of this study challenged designers and producers of firefighters' clothing to put more effort into improving the properties of the materials or the designs of the protective clothing in order to adapt to the ambient conditions**[22].**

The research of moisture effects on the protective properties of PC is of great importance to avoid and minimize skin burn and heat stress. The amount and location of moisture influences the transfer ability of water vapor through the clothing layers. The protective performance of fabrics made for PC is significantly influenced by the internal or external moisture as conducted byKeiser et al, (2008)**[40].** Internal moisture can originate from perspiration produced by firefighters who often sweat profusely during fire fighting. External moisture sources normally comprise the dousing water from a hose spray and water produced from dew or rains.

The effects of the moisture on the protective properties of PC is either increase or decrease the heat protection of PC which depends on the amount and location of the moisture. Barker et al.(2006) **[41]** studied the influences of absorbed moisture on the protective performance of the PC. Experimental measurement indicated that the moisture severely decreases protective performance at a low moisture level. Fukazawa et al.(2004)**[42]** measured water vapor transfer through PC and distribution of the condensation using a sweating manikin. It was found that an intensive condensation occurs in the ensembles for a high sweat rate, especially in parts of the trunk, thigh and leg. Similarly Ming Fu, Wenguo Weng, Xuefeng Han,(2013) have tested two kinds of PC with different vapor permeability in order to study the design influence on protective properties. The measurement has demonstrated that the level of gas permeability of PC was so vital to the protective performance in that sweating contributes to the cooling effect for high-level permeability and had the negative effects on the protective performance for low-level permeability**[43].**

1.2.2 Sweat absorption in firefighter turnouts

Physiological studies on the effects of turnout breathability on firefighter heat stress and comfort show that the highest percentage of moisture accumulates in absorbent clothing or layers in closest contact with sweat-wetted skin. An absorbent t-shirt material absorbs moisture levels that approach saturation (> 90%). In comparison, turnout garments, worn over a t-shirt and station uniform, absorb moisture in amounts that are significantly below saturation levels (1,5 - 15%). Within individual fabric layers of the turnout composite, moisture was absorbed primarily by the thermal liner component. Moisture absorption, and distribution within the turnout, were determined by the moisture absorption capacity of the thermal liner, by the breathability of the moisture barrier, and by the sweat output in wear. More moisture was absorbed by turnout liners that incorporate thicker thermal liners, principally because thicker thermal liners have greater capacity to contain moisture than thinner liner components**[44,45].**

When thermal liners do not directly contact liquid sweat, and the level of moisture in inner clothing layers is less than saturation level, moisture accumulates by condensation of evaporated moisture vapor. Moisture build up by processes involving the wicking of liquid sweat can be expected in cases where the thermal liner is in intimate contact with sweat wet skin**[46]**

1.2.3 Moisture transport mechanisms in turnouts

Moisture is transferred in turnout materials by two basic mechanisms: by wicking of liquid moisture into clothing materials through direct contact with sweat wetted skin, or by condensation of moisture vapor from evaporated sweat. Between the sweat wetted surface and the thermal liner of the turnout composites. Tests showed that absorbent clothing inner layers reduce the amount of liquid moisture absorption into the liner system. However, moisture pick up continued to exceed saturation levels in Aralite® liner systems. These findings suggested that moisture was transported by wicking mechanisms that occur as the intervening absorbent inner layers exceed their saturation capacity**[46].**

A typical fire-fighting ensemble (including SCBA) weighs ~ 26 Kg. The protective clothing of fire fighters has an insulation value of ~ 0.47 m^2KW^{-1} (clo rating of 2.44) **[48].** The overall function is to provide the firefighter with adequate protection from heat, flames, and other hazardous environments. However, this protection is often achieved at the expense on body heat balance. The limited vapour permeability across the protective clothing's layers and the added metabolic heat production resulting from the increased weight impact on the thermoregulatory system by reducing the ability to dissipate generated heat. The end result is continued heat storage in the body**[47].**

Total heat loss (THL) test measures the thermal and evaporative resistance of the clothing and combines these measures to yield a single number, the THL, to indicate the capability of the sample to dissipate heat. Testing adhered to NFPA (2006) guidelines using a sweating hot plate test apparatus and different base layers, under fire fighters clothing or turn outs (TO), THL values were recorded as shown in figure 1.4.

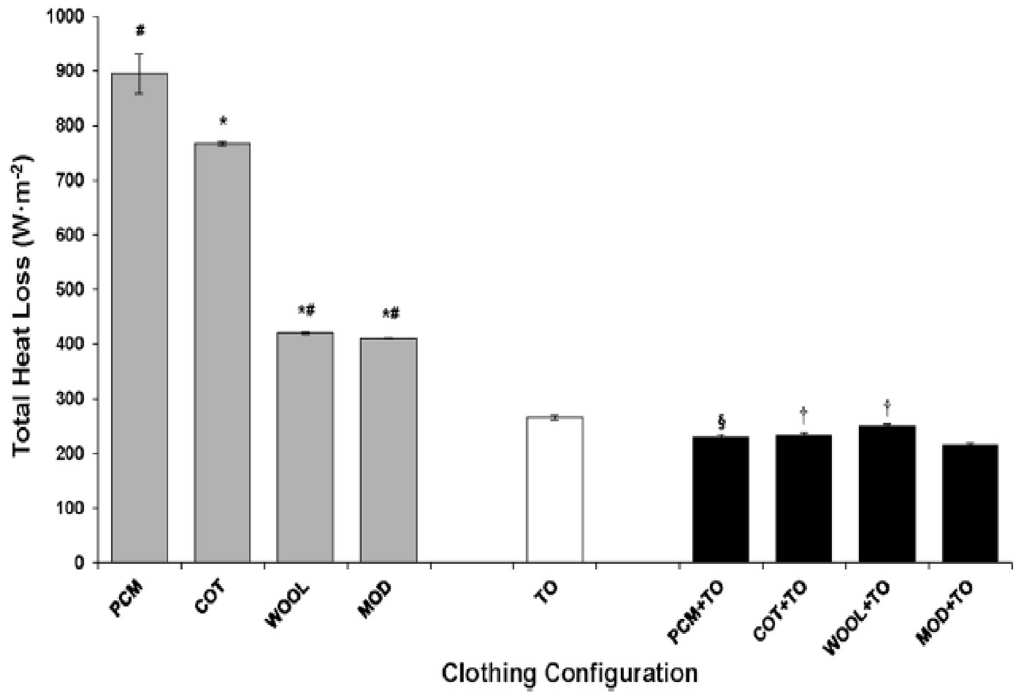

Figure 1.4: Total heat loss for different materials and ensembles.TO, turnout gear; PCM, phase change material; COT, cotton; MOD, modacrylic[49].

Interestingly, the differences in THL among the base layers do not correspond to the differences in THL among the ensembles. Fewer differences existed among the combined ensembles and when THL values were ordered from high to low, the base layers are not in the same sequence for the individual layers and the ensembles of base layer and turnout gear. A marked difference exists for PCM, whose highest THL was 213% greater than WOOL but when combined with Turnout (TO) was 92% that of WOOL + Turn out (TO)**[49].**

Sensorial comfort, usually described as "fabric hand or feel", and defined as the sensation of how the fabric feels when it is worn next to the skin. This feeling deals with properties of the fabric such as prickling, itching, stiffness or smoothness. Wet feeling and wet clinging can be a major source of sensorial discomfort in situations of profuse sweating like in firefighters' working environment. For the objective evaluation of this aspect of comfort Kawabata Evaluation System (KES) was used for the present study**[68].**

The presence of moisture on fabric-skin contact has been found to be positively correlated with the frictional force and thus with the perception of roughness. Moisture at the skin surface can alter the intensity of the perceived fabric roughness: as the moisture content increases, the friction and displacement of the skin increases as well activating more touch receptors. Therefore, a fabric that is perceived to be comfortable under low humidity conditions may be perceived to be uncomfortable under high humidity or sweating conditions**[50].**

Nazia et al, (2011) have investigated the surface properties of different knitted fabrics suitable for skin layers of firefighters' protective clothing. For that purpose 100% wool, 100% cotton, 100% polyester and different wool blends were studied in virgin state and then in wet state. From the results it was cleared that wool fibre and wool fibre blends can be considered to perform better in terms of sensorial comfort in single jersey constructions. Wool is an elastic and resilient fibre due to having inherent fibre crimp and its micro-structure with scales compared to bamboo, cotton or polyester. It seemed to provide better sensorial comfort due to its resiliency when used next to skin in single jersey structure. Finally they have concluded that fibre content and fabric structure were the most critical parameters to influence the fabric surface properties relevant to sensorial comfort**[51].**

The performance of protective clothing has a significant influence on the level of protection provided. During their lifetime, materials used in protective clothing age under the action of various environmental and operation aggressors (temperature, light, moisture etc.). These factors constitute a severe limitation to the use of protective materials. Banu Ozgen and Gulsah Pamuk have studied thermal aging of Nomex and Kevlar made fabrics. Accordingly, woven fabrics produced from various combinations of Kevlar and Nomex yarns were exposed to 220°C and 300°C for duration ranging from 24 hours to 30 days to investigate the effects of thermal aging. Mass loss and tensile strength values of fabrics were measured before and after exposure and results were statistically analysed**[52].**

The study revealed that the structure and properties of specimens changed in a similar manner after each thermal exposure, but the magnitude of changes varied with both temperature and cumulative duration of exposure. The changes in the specimens observed at higher temperatures and shorter durations were similar to the changes observed at lower temperatures and longer duration. As temperature increased, the percentage of mass loss was also increased. It was also concluded that material type had an effect on mass loss results**[52].**

According to the test results, highest mass loss values were achieved for 100% Kevlar fabrics for both temperatures. Percentage of mass loss was decreased when amount of Nomex yarns used in fabric production was increased. The effect of thermal exposure on tensile strength was dependent on the fabric type, temperature and exposure duration. Highest strength loss was also measured for 100% Kevlar fabrics for both temperatures. The percentage of strength loss for 100% Kevlar was about 95%, while this value was calculated as 4% for 100% Nomex fabrics**[52].**

While fighting fire, fire fighters are not only exposed to one thermal hazard but two: burns and heat stress [**71].**The external heat and the working load did not affect the core temperature in the same way: heat from the environment had first to get through the clothing and the skin before it may influence the core temperature. The work load provoked heat flux in the contrary direction: first the core temperature increased before the excessive heat was transmitted to the skin. When the outside temperature is higher than the skin temperature, the body can only get rid of excessive heat by evaporation of sweat on the skin. The evaporative cooling should furthermore compensated for the heat storage due to the external heat.

The resistance of protective clothing materials to the loss of body heat is dependent upon the thickness of the material, and the influence of fibre type is small enough to be neglected**[72].** The resistance of protective clothing materials to penetration by radiant heat of an intensity which might be found under fireground conditions was dependent upon the thickness of the material, and was not influenced significantly by the type of fibre involved so long as the fibre itself was not substantially degraded. Such degradation only occurs after exposures well in excess of that required to cause burn injury to human skin. The resistance of protective clothing materials to penetration by convective heat of an intensity which might be found in flashover or backdraught conditions is largely dependent upon fabric thickness.

Clothing provides a barrier to heat and vapor transfer between the skin and the environment. The barrier is composed of the clothing materials and the air they enclose**[73].** When multiple layers of clothing are worn, the air layers between the material layers add to the insulative properties of the ensemble. These layers as well as the air layer between the innermost layer of PPC and the skin have their own microclimate.

Research suggests that adding an additional layer of clothing with an accompanying air layer causes an increase in thermal stress due to a decrease in evaporative cooling efficiency and increases in thermal insulation and water vapor resistance**[74].**

The thermal performance of fire fighters' protective clothing was primarily based on the thermophysical properties of the materials that were used to construct the clothing and the insulating air space that is provided by the garment as a result of its design**[75].** Thermal conductivity (k) of a material relates to the rate of heat transfer through the material**[76].** Heat flow by this mechanism was based on the transfer of energy through motion between adjacent molecules. Therefore, insulating materials were typically lower density, lower thermal conductivity materials that have fewer numbers of molecular interfaces per unit volume.

Synthetic textile such as polyester and poly-urethane has been used for underwear in terms of moisture released and function in underwear. However, the synthetic underwear has high risk for skin burns due to melting and shrinking by heat. The data indicated that the fire fighter's multi-layer fabric controls the heat and moisture transfer within fire fighter clothing and no positive contribution by any types of underwear**[77].**

2. CLOTHING COMFORT AND FIRE PROTECTION

2.1 Clothing Comfort

2.1.1 Definition of comfort

Comfort is difficult to explain since it is a complex and interdependent combination of physical, psychological and sensorial perceptions and highly depends of subjective evaluation of the individuals. Lower thermal resistance results in discomfort for the wearer because excessive heat may be dissipated rapidly by vapourisation of the body water. A garment that permits free access of liquid (water) can become uncomfortable in wet weather, when the reverse movement of exterior water towards the skin is experienced **[36].**

Comfort is a fundamental and universal need of a human being. However it is very complex and is very difficult to define. According to Fourt and Hollies (1970) comfort involves thermal and non thermal components and is related to wear situations such as working, non critical and critical conditions. The physiological responses of the human body to a given combination of clothing and environmental conditions are predictable when the system reaches steady state. According to Slater (1985), comfort is a pleasant state of physiological, psychological, neuro-physiological and physical harmony between a human being and the environment **[33].**

He identified the importance of environment to comfort and defined the following three types.

1. Physiological comfort is related to the human body's ability to maintain life.

2. Psychological comfort to the mind's ability to keep it functioning satisfactorily without external help, and

3. Physical comfort to the effect of the external environment on the body.

Although it is difficult to describe comfort positively, discomfort can be easily described in such terms as prickle, itch, hot and cold. According to Hatch (1993), comfort is 'freedom from pain and from discomfort as a neutral state'. The discomfort arises from too hot, too cold, and odorous or stale atmosphere. Comfort conditions are those that do not cause unpleasant sensation of temperature, drafts (unwanted local cooling), humidity or other aspects of the environment. In ideally conditioned space, people should be an aware of noise, heat or air motion. Comfort depends on subjective perceptions of visual, thermal and tactile sensations, psychological processes, body- apparel interaction and external environmental effects**[50].**

2.1.2 Various aspects of clothing comfort

Comfort is related to subjective perception of various sensations. It may be psychological or physiological. Three aspects of clothing comfort are:

1. Thermal comfort is attainment of a comfortable thermal and wetness state; it involves transport of heat and moisture through fabric.

2. Sensorial comfort is the sensation of how the garment fabric feels when it is touched by hands and worn next to the skin. These sensations are often expressed as feelings of softness, smoothness, dampness, clinginess, prickliness, and the like **[68].** Sensorial comfort can also be related to the thermo-physiological comfort, as a fabric wetted through with sweat will change its properties and may, for instance, cling to the skin**[69].** The tactile quality of fabrics is a key parameter in successful marketing strategies for conventional textiles. However, since FFPC firefighters protective clothing is seldom worn next to the skin, the tactile sensations of the materials used in their construction are considered less important than other properties, particularly those that influence their level of protection.

Clothing that sticks to skin when it is wet with sweat is perceived as dragging and restrictive when people move. Textiles to be worn next to the skin should therefore designed in such a way that they do not stick to the surface of the skin and that they can wick large quantities of sweat away to layers that are not in contact with the skin. To meet these requirements the most important thing is the construction of the underlying textile from which a garment is made. Whether the textile is made of natural fibres such as cotton or from synthetic fibres is in fact of secondary importance - what is more important is the construction of the textile, i.e. the yarn structure and the method of weaving or knitting it. Many of the materials used for occupational and protective clothing are mixed fibres, which combine the positive characteristics of both types of fibre**[50].**

3. Body movement comfort- ability of textile to allow freedom of movement, reduced burden, and body shaping, as required.

2.1.3 Thermal comfort

Thermal comfort is very subjective issue. It is that state when an individual prefers neither warmer nor cooler condition and that condition are comfortable when largest percentage people in any particular grouping are comfortable. It can be defined as "the absence of any unpleasant sensations of being too cool or too warm, or of having too much perspiration on the skin". The thermal comfort of clothing is associated with the thermal balance of the human body and its thermal responses to the dynamic interactions with the clothing and environment systems. Man, being a homeotherm, strives to keep his body core at a constant temperature, ie, 37°C and a rise or fall of ±5°C can be fata. In the cold conditions the blood supply to the extremities is reduced and shivering occurs. In hot days or during high activity level, blood comes to the skin surface to reduce the body temperature**[37].**

According to generally accepted definition given by American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), thermal comfort is "the condition of mind that expresses satisfaction with the thermal environment" **[53].** Nonetheless, the concept of thermal comfort is not solely in a subjective domain since it depends to a certain extent on physiological processes in the body. It is in direct relation with a heat balance of the human body, i.e. the processes that lead to heat production and heat loss. The heat balance depends on a number of factors that could be classified into environmental, physiological and clothing factors. Therefore, the role of protective clothing in high-risk profession as fire fighting is of crucial significance for the thermal comfort of a wearer and its performance.

Definition of thermal comfort for lying or resting human body**:** thermal equilibrium, no muscular shivering nor vasodilatation, no principal sweating (relatively dry skin), skin temperature between 32 and 34^{O}C, no heat storage or loses. Changes of stored (accumulated) heat**[32].**

$$\Delta QAC = cspec \,.\, (0.35\ \Delta tS + 0.65\ tN) \qquad \textbf{(2.1)}$$

Where: cspec = 3300 J/kg. K

Clothing has a vital part to play in maintaining this heat balance as it modifies the heat loss from the skin surface under the same time has the secondary effect of altering the moisture loss from the skin. The heat balance also varies with climatic conditions. It should be the main property of textiles to conserve the heat that body divers away, and dissipate heat from body surrounding when body generates it. Because of above two different actions, it is impossible to design a single clothing system, which acts comfortable to body for all the seasons and reasons. A clothing system, which is suitable for one climate may not be suitable for another climate. Good thermal insulation properties are required for clothing and textiles used specially in cold climates. In warm climate, or when the wearer performs hard work, it is important that the clothing transmits the moisture secreted by the body. So it is necessary to understand the mechanism of thermal comfort.

2.1.3.1 Mechanism of thermal comfort

a. Heat Balance

The human body tries to maintain a constant core temperature of about *37°C.* The actual value varies slightly from person to person but the temperature of any one person is maintained within narrow limits. In most climates, body temperature is above that of the external environment so that there has to be an internal source of heat in order to maintain the temperature difference**[38].**

The required heat comes from the body's metabolism that is necessary burning of calories to provide power to the muscles and other internal functions. However, the body must be kept in thermal balance. The metabolic heat generated together with the heat received from external sources must be matched by the loss from the body of an equivalent amount of heat. If the heat gain and the heat loss are not in balance then the body temperature will either rise or fall. The heat balance is mathematically expressed as below.

$$Q = M \pm R + C\infty v \pm C\infty d - E \qquad \textbf{(2.2)}$$

Where, Q = Heat gain or loss

C∞v = Convective gain or loss

C∞d = Conductive gain or loss

E = Evaporative loss

M = Metabolism

R = Radiant gain or loss

b. Heat loss

There are five mechanisms like conduction, convection, radiation, evaporation and respiration that allow the body to lose heat to the environment in order to maintain its thermal balance. Thermal conductivity measures of how rapidly heat flows through a material that is exposed to a difference in temperatures. Convection gently removes the warmed air from your skin and replaces it with cooler air. Heat can also exchange by radiation. In radiation skin emits electromagnetic waves toward human body surroundings and they emit electromagnetic waves toward skin.The heat loss by evaporation is made up of two, the insensible heat loss by skin diffusion, and the heat loss by regulatory sweating. The way the heat loss is divided between the mechanisms depends on the external environment**[38].**

Clothing has a large part to play in the maintenance of heat balance as it modifies the heat loss from the skin surface and at the same time has the secondary effect of altering the moisture loss from the skin surface. However, no one clothing system is suitable for all occasions a clothing system that is suitable for one climate is usually completely unsuitable for another. The main fabric properties that are of importance for maintaining thermal comfort are Insulation, moisture vapour permeability and waterproofing.

c. Insulation

Anair temperature of 28 – 29^{o}C would be required for a person to be able to sit in comfort without wearing any clothes. At air temperatures lower than this, therefore, the body will lose heat without the added insulation given by clothing. It losses by convection can be prevented, the air itself offers a very high resistance to heat conduction having a value of thermal resistance which is only slightly less than that of a vacuum.

2.1.3.2 Thermo-physiological clothing comfort

The thermo-physiological comfort required by the various users of protective clothing, work, sports and leisure wear is an important parameter of clothing fabrics and designs. Water vapour resistance and thermal resistance are essential elements to assess comfort. The standardised test method - described in ISO 11092, EN 31092 - a.k.a. “skin model”, simulates the heat and moisture transfer of the human skin **[32].**

Thermo-physiological Clothing Comfort - Evaluation:

1. Measurement of thermal resistance and of warm-cool feeling of fabrics, both in dry and wet state, by means of the ALAMBETA computer-controlled device
2. Evaluation of warm-cool feeling in simulated conditions of medium and intensive sweating
3. Measurement of water vapour resistance (in dry and wet state) and heat of absorption of fabrics, by means of the fast PERMETEST instrument
4. A new principle of evaluation of thermal comfort of clothing based on thermal mannequins, small thermal-comfort instruments and data storage in PC

Thermal mannequin simulate a human body as a thermal machine divided into up to 17 independently heated segments, which keeps (by means the PC control) their surface (skin) temperature t_S at the average level of 33^OC, and which enables exact measurement of an electric power P [W] required for this relatively truly simulation of heat distribution in the human body. From these values, the PC calculates the levels of individual superficial heat fluxes qi of the mentioned segments. First, heat fluxes qin for the naked mannequin should be measured and used for the calculation of the exterior resistances R_{EN} of the naked body:

$$R_{EN}, i = (t_{Si} - t_E) / q_{N, i} \quad \textbf{(2.3)}$$

In the next step, the mannequin is dressed and total thermal resistances R_{TOT},,i will be determined by similar procedure:

$$R_{TOT} = (t_{Si} - t_E) / q_{TOT, i} \quad \textbf{(2.4)}$$

The differences between the both above given measurement present the demanded individual clothing resistance levels R_{TOT}, i

$$R_{CL}, i = R_{TOT}, i - R_{EN}, i \quad \textbf{(2.5)}$$

Factors affecting comfort

Clothing is an integral part of human life as an extension of human skin. It is important to realize that clothing is not just a passive cover over the body, but that it interacts with the body and the environment constantly. It is isolative to discuss the comfort of clothing without putting it into the context of human and environmental parameters. Human comfort in a human-clothing-environment system therefore is determined by factors from three aspects: person attributes, clothing attributes and environmental attributes, as listed in Table 2.1 **[70]**

Table 2.1: Factors affecting comfort[70].

Person Attributes	Fabric/ Clothing Attributes	Environment Attributes
Sex Age Race Weight Height Physical Condition Activity Covered Surface Area	Thickness Weight Mechanical Properties Surface Properties Heat Transfer Properties VapourTransfer Properties Moisture-Management Properties Air Permeability Covered Surface Area Design Fit	Air Temperature Radiant Temperature Wind Velocity Ambient-Vapour Pressure

(Branson & Sweeney, 1991)

2.1.4 Clothing comfort properties

2.1.4.3 Air permeability

The woven and knitted textile fabrics are made of interlaced yarns. Between the yarns as well as between the fibers the existing free space contributes in the formation of air-flow paths when a differential air-pressure will be applied. The air permeability of the textile fabrics is essential for the prediction of the fabric comfort, the performance during drying procedure etc. The rate of airflow through a textile fabric under differential pressure applications between its two surfaces is believed to be important in determining many of the physical and mechanical properties of it. Critical fabric characteristics such as transportation of the moisture from body to environment, thermal insulation properties, the rate of liquid removal during drying of fabrics, effluent movement through filtration devices, etc. depend on the permeability of textiles. Fabric thickness and the applied pressure drop are among dominant factors that affect permeability**[31].**

2.1.4.4 Air permeability and its effect on moisture transport

The water-vapor permeability of clothing materials is noted to be a critical property of textiles which contribute to comfort under hot and cold weather conditions. When fabrics made from yarns of a particular count and twist are considered on moisture transfer rate finer the fibers used for preparing the fabric, lower will be the moisture transport through the fabric. This may be due to reduced air space in these fabrics made from finer fibers . It was observed from experimental results that fabrics made from finer yarns were able to displace a greater amount of moisture in a given time. Finer yarns will produce a fabric with lower cover factor, thereby increasing the total air space within the fabric.

Fabrics which allow easy flow of air through them will also be permeable to moisture. Similarly, water vapor transfer takes place through air spaces in the fabric. The movement of air, water vapor and heat dependson the air space within the fabric and hence wouldobviously depend to some extent on the fabricstructure guided by the total air space and itsdistribution **[59].**

2.1.4.5 Thermal transfer properties

Thermal conductivity

Thermal conductivity is an intensive property of a material that indicates its ability to conduct heat.Thermal conductivity increases depending on the single jersey, 1×1 rib and interlock structures of the cotton and polyester fabric samples. This situation can be explained by the amount of entrapped air in the fabric structure. The amount of fibre in the unit area increases and the amount of air layer decreases as the weight increases. As is known, thermal conductivity values of fibres are higher than the thermal conductivity of entrapped air **[31].** So heavier fabrics that contain less still air (like interlock) have higher thermal conductivity values.

Thermal resistance

Thermal resistance is a measure of the resistance that a garment provides against heat loss from the body of the wearer to the external environment **[25].** It is influenced by a combination of the thermal resistance provided

- by the clothing,
- by the layer of air between the skin and the clothing, and
- by the layer of air between the inner and outer surfaces of the fabric.

The thermal resistance of a fabric is more or less proportional to the thickness of the fabric. Thermal resistance is measured in m^2K/W, and can be converted to "tog" or "clo". One tog can be defined as a temperature difference of 0.1°C between two surfaces caused by the heat flow of 1 $Watt/m^2$ (1 tog = 0.1 m^2K/W) **[26].**

Thermal resistance is also sometimes measured in clo (a unit of thermal insulation of clothes). One clo represents the amount of clothing required to keep a sitting man of average metabolic rate comfortable in an average indoor atmosphere at 21°C **[25].**

Thermal absorptivity

A 'warm–cool' feeling is the first sensation experienced when a human touches a fabric. This feeling is a result of heat exchange that takes place between the human hand and the fabric because of the temperature difference between the fabric surface and that of the human skin. This is referred to as thermal absorptivity. If the thermal absorptivity of a garment is high it can be expected to give a cooler feeling upon first contact **[27].**

2.1.4.6 Moisture transfer properties

Water vapour permeability

The human body continuously produces insensible perspiration in the form of water vapour. The body's natural mechanism for cooling itself when overheating is through sensible perspiration in the form of liquid sweat. This is caused by strenuous activity or climatic conditions. Both of these have to be managed rapidly by the wearer's clothing in order to maintain the body's thermal regulation **[24].** Evaporation of the liquid sweat requires heat. Body heat is used to evaporate the perspiration, resulting in the dissipation of the surplus heat and the cooling of the body. However, if the water vapour cannot escape to the surrounding atmosphere then the relative humidity inside the clothing increases, causing a wet feeling on the skin, and leading to an uncomfortable sensation.

Also known as “breathability”, water vapour permeability is defined as a fabric’s ability to transport water vapour from the skin surface through the fabric to the external environment. Hatch (1993:33) defines water vapour permeability as "the rate at which water vapour diffuses through a fabric.” This should ocur spontaneously because of the vapour pressure gradient. The water vapour dissipates from the high vapour pressure region (humid body surface) to the lower vapour pressure region (drier external environment). The diffusion of water vapour occurs through fabric interstices and air spaces between the skin and the fabric.

Water vapour resistance

Water vapour permeability is indirectly related to water vapour resistance. The latter property can be described as the amount of resistance against the transport of water vapour through a fabric. Because water is an excellent conductor of heat, the thermal resistance of a garment will be directly influenced by the amount of moisture present in the fabric. Thus, the more water present in a fabric, due to either normal absorption from the air or as a result of the absorption of liquid water (e.g. perspiration), the higher the rate will be at which heat is conducted. The amount of water present in a garment therefore plays a significant role in the degree of comfort that will be felt. Although a fabric with good absorption will initially increase comfort, a wet fabric touching the skin will create an unpleasant sensation.

Relative water vapour permeability

Water vapour permeability is the ability to transmit vapour from the body. If the moisture resistance is too high to transmit heat, by the transport of mass and at the same time the thermal resistance of the textile layers considered by us is high, the stored heat in the body cannot be dissipated and causes an uncomfortable sensation.

2.1.5 Clothing heat transfer coefficients

Heat transfer through clothing is often broken down into dry heat transfer (conduction, convection, and radiation), and evaporative heat transfer (diffusion and convection of evaporated sweat vapor). Typical units to characterize clothing dry heat transfer are thermal resistance Rct (m^2-°C/Watt) and the alternate thermal resistance unit of clo. Typical units for evaporative heat transfer are evaporative resistance Ret (m^2-Pa/Watt), the equivalent parameter i_m/clo, and the related water vapor transfer rate, WVTR (g/m^2-day). These properties may all be dependent to some extent on the measurement methods used--material properties related to air permeability, liquid sweat wicking, etc., may be lumped together into overall measurements made using system tests such as sweating thermal manikins**[57].**

Conventional testing methods for obtaining thermal properties for clothing heat balance include the sweating guarded hot plate, water-filled cup tests, and various permeation cells. All give equivalent values and can be converted if testing conditions are known. I_m (permeability index) is a relative measure of the permeability of the material to the passage of water vapor. The i_m index should vary between 0 (for completely impermeable materials), and 1 (for completely permeable materials). In practice, the value of 1 as an upper limit is not approached until the wind speed over the thermal manikin or sweating guarded hot plate becomes great enough to minimize the contribution of radiative heat transfer.

In heat balance equations, the thermal resistance is divided out of the i_m index to give the variable related to water vapor permeability (i_m /clo, Ret, MVTR, etc.) The effects of wind speed and measurement bias can be subtracted off to give “intrinsic” values for the materials that are closer to true material properties. For clothing system testing (i_m, clo), all values depend on wind speed, fit, and air permeability (commonly included by testing thermal manikins at three different wind speeds) **[57].**

As mentioned previously, total heat transfer is equal to dry heat transfer plus evaporative heat transfer. The importance of the term i_m/clo is illustrated if the equations for dry heat transfer (E_{dry}), and evaporative heat transfer (E_{evap}), are written:

$$E_{dry}(\text{watts/m}^2) = (6.45/\text{clo})(\Delta T) \qquad \textbf{(2.6)}$$

$$E_{evap}(\text{watts/m}^2) = i_m\,(6.45/\text{clo})S(\Delta p) \qquad \textbf{(2.7)}$$

$$\text{Total heat transfer (watts/m}^2\text{)} = (6.45/\text{clo})(\Delta T) + 14.2(i_m/\text{clo})(\Delta p) \quad \textbf{(2.8)}$$

Where: ΔT = temperature difference, °C

S = Lewis Relation (2.2 °C/mmHg)

Δp = vapor pressure difference, mmHg

clo = R_{dry}in clo units

It is important to note that the value for i_m/clo is inversely equivalent to evaporative resistance Ret (m^2-Pa/Watt) as defined in an alternate system of units, and can also be converted directly into water vapor flux values (g/m^2-day) **[58].**

2.2 Fire Protection

2.2.1 Introduction:

In protection against flames and heat radiation, two cases have to be distinguished: first, flames and heat may occur sporadically and unexpectedly, e.g. in accidents or in war; second, they are characteristic of many work places, e.g. in smelting-works or rolling mills, during fire-fighting or rescue operations.

Human skin is very sensitive to heat, pain is felt at 45°C and the skin is completely burn at 72°C. The amount of heat delivered causes an increase of skin temperature. Above 44 °C the cells become damaged by degradation of tissue proteins; the rate and depth of this damage increase with temperature. Burns can be classified into three categories according to depth of damage:

1st degree: Erythema, dilatation of capillaries; a normal reaction, with no damage.

2nd degree: Separation of epidermis, formation of edematous blisters; painful but reversible.

3rd degree: Necrosis of skin and deeper tissues, largely pain full; scar formation Unavoidable **[60].**

Fire protective clothing reduces the rate of heating of human skin so that the wearer gets enough time to react and escape. Normally only 3-10 seconds are available for a person to escape from a place of fire with a heat flux of about 130 – 330kW/m^2[65]. Most of the textile fibres are easy to burn and untreated cotton will either burn with flame or smoke whenever it is in the presence of oxygen and temperature is high enough to initiate combustion (360 – 420 °C).

Protective clothing must be flame resistant and should form a heat barrier. The latter is very important if the wearer needs to stay near flames for a fairly long time. Flame retardant clothing is generally used for occupation uniforms **[65].** It may also be noted that the main cause of death in a fire accident is not direct burning. Therefore, the use of non toxic or low-toxic burning materials is very important for protection. Considering safety, the government regulations says that certain classes of garments and home textiles such as children's sleep wear, carpets, upholstery fabrics and bedding should be made flame retardant or flame resistant [60]. Clothing and textiles are made flame retardant by using inherently flame retardant materials such as Kevlar and Nomex or by applying a flame retardant finish.

2.2.2 The firefighters' environment

The conditions in firefighting are variable. Burning buildings can be fought from an adequate distance. In underground facilities and ships we find smoldering fires with toxic gases and an oxygen deficit. At crash landings of aircraft, fuel often is set afire and heat radiation (up to 8000 $kcal/m^2h$) and darting flames (up to 1000 °C) may occur. The rescue time for a person, however, is limited to about 1 min, so that short-term heat reflective protection with high mobility is needed. At burning fuel tanks, the radiation increases up to 30,000 $kcal/m^2h$, so that the reflective cover has to be supplemented by an insulation layer. At catastrophes, e.g. like the area configarations of World War II, They found similar values of radiation combined with darting flames, toxic air-contamination and falling fragments, so that complete protection against radiation, flames, toxic gases and mechanical injuries was required **[60].**

The situations under which protective clothing will be used was described by Coletta et al. and Abbott et al.about the exposure conditions encountered by firefighters. Similar studies by Makinen H have discussed the conditions by numerical value of radiant heat flux and temperature range of exposures. Accordingly, fire fighters exposure conditions were grouped as follows **[39, 54].**

"*Routine*" conditions, applicable to firefighters who are operating hoses or otherwise fighting fires from a distance, are generally equivalent to being outdoors on a hot summer day, or standing in front of a small open fireplace. No special clothing is necessary. It corresponds to a common intervention for firefighters characterized by low radiant heat flux from 0.42 to 1.26 kW/m2 and air temperatures in the range of 10 to 60°C;

"*Hazardous*" conditions (described as "ordinary" by Abbott) are typical of those that would be encountered outside a burning room or a small burning building. The less severe conditions of the hazardous region are applicable to firefighters ventilating a fire without water support. The more severe conditions of the hazardous region are applicable to firefighters who are first into a burning building. A "turnout uniform" is necessary to provide adequate burn protection and to minimize the thermal stress endured by the firefighter.It represents an intervention in the presence of high radiant heat flux from 1.26 to 8.37 kW/m2 and air temperatures in the range of 60 to 300°C, and firefighters generally have less time to intervene;

"*Emergency*" exposures are not normally encountered by civilian firefighters; such conditions exist around a crashed aircraft when fuel is burning fiercely. They may also be encountered during "flashover" of a building fire. Special equipment is required for these very high levels of heat flux and temperature. It means extreme conditions from 8.37 to 125,6 kW/m2 and air temperatures in the range of 300 to 1 000°C, and firefighters have only several seconds to escape.Proximity suits are used by firefighters working close to the fire, and fire entry suits must be employed together with breathing apparatus for working in the fire. Fire entry would only be necessary in rare cases, for example, to manipulate valves on fuel storage vessels.

2.2.3 Fire fighting thermal environments

The primary thermal exposures that a fire fighter must be concerned with are thermal radiation from flames, smoke, hot gas convection, and conduction from high temperature surfaces **[85].**Each of these heat transfer modes has an impact on the thermal performance of fire fighters' protective clothing, and they all can independently cause burn injuries. However, in actual fire fighting situations these different components of heat transfer will likely be combined in varying fractions depending on the location and position of the fire fighter in relation to the fire's varying thermal environment. The fact that the component fractions of heat transfer vary during an exposure complicates the measurement process and increases the measurement uncertainty.

Another factor that varies during the process of measuring heat transfer through fire fighters' protective clothing systems is the amount of moisture in the system. Moisture is often a significant factor in the creation of fire fighter burn injuries. The moisture in fire fighters' protective clothing originates from human perspiration, hose spray, and weather. Moisture levels can be controlled to some degree when making thermal measurements in laboratory test environments. These laboratory environments initially provide a stable level of control over wetting and moisture conditions at the beginning of a thermal exposure. The protective clothing systems then respond to heating processes and begin to dry. Controlling moisture input to the protective clothing system after heating begins is difficult and accurately replicating wetting processes that take place in the field environment is difficult. However, basic information on wet thermal performance can be gained by studying the drying processes of wet protective clothing systems and applying this knowledge to physics based predictive models.

2.2.4 Fire fighter protective clothings

When firefighters are exposed to a heat stress, their body reacts by activating sweat glands, i.e. through evaporative cooling mechanism. The protective clothing protects the firefighters from environmental heat and moisture but simultaneously prevents their flow in the opposite direction, away from the body to the environment. Consequently, risks of heat stress and steam burn injuries strongly increase. In such hot environments, heat and moisture transfer properties of the protective clothing have prevailing impact on firefighters' performances and their safety. Optimization of these coupled transfer phenomena from the skin through the garment could improve comfort of the wearers and hence their performance. Effective protective clothing should minimize heat stress while providing protection **[55].** For this purpose, the firefighter protective clothing has to fulfill a variety of different demands according to the European standard EN 469 2006: protection against heat from flames and thermal radiation, protection against hot liquids and other chemicals, resistance against abrasion and other mechanical stress, breathability, being not flammable, unshrinkable, easy to wash, light and comfortable **[56].**

People all around the world depend on the bravery and training of firefighters to offer protection against fires. In turn, firefighters depend on firefighter apparel made with DuPont™ Nomex® and Kevlar® fiber to help them meet the demands of a rigorous and challenging job. Together, these innovative fibers help offer fire resistance, strength, durability, and more. Kevlar® is five times stronger than steel on an equal-weight basis, yet fabrics can be lightweight, comfortable, and thermally protective. It helps to enhance the overall durability and strength of lightweight turnout gear outer-shell and-thermal-liner systems. Nomex® fiber is inherently flame resistant, tough and flexible **[34].**

- Nomex® fiber carbonizes and thickens when exposed to the intense heat of today's fires. This increases the protective barrier between the heat source and the user, helping to reduce burn injury and providing valuable time to work or escape.

- When fabric made with Kevlar® fiber is engineered with Nomex® fiber or used with another blend, it can help to further enhance tear strength and abrasion resistance of outer shells protecting the moisture barriers and thermal liners inside.

- Garments made from Nomex® fiber last, on average, two to three times longer than most other standard and protective fabrics, including 100% cotton, polyester/garment blends, and FR cotton.

- Per garment manufacturers, the average wear life of Stationwear made of Nomex® is about five years, and it can be washed and worn at least 125 times, making it an affordable choice.

DuPont™ NOMEX® and DuPont™ KEVLAR® brand fibers are widely used in firefighter clothing systems. These fibers will not melt, drip, or support combustion, providing a stable barrier that helps minimize burn injuries. The flame resistant properties of NOMEX® and KEVLAR® are permanent; they cannot be washed out or removed in any way. Each layer of flame resistant clothing provides a protective barrier from the heat source and traps insulating air. Multiple layers provide more thermal insulation but can also trap metabolic heat, increasing heat stress.

2.2.5 Test methods for fire fighters clothing fabric

There are five main industry test procedures performed on the fabric that conform to certain industry standards that have been developed through the standards organisations involved. In order for a fabric to be accepted to use as a flame resistant material it must pass these tests and therefore conform to the ASTM (American

Society for Testing and Materials) and the NFPA (National Fire Protection Association) standards**[79].**

These five tests are as follows

- Vertical flame test
- Thermal protective performance test
- Instrumented manikin tests for flash fires
- Instrumented Mannequin and panel tests for Electric Arc exposure

2.2.6 Components of fire fighting clothings

According to NFPA1971 and similar standards in other countries, all turnout clothing must have three components: outer shell, a moisture barrier, and a thermal barrier. In between these layers are pockets of air referred to as "dead zones".

These layers of air along with the three protective layers help to further insulate the wearer from the extreme environments of fires. Usually turnout pants are outfitted with reinforced knees and leather cuffs. The materials used for the three layers in turnout trousers and coats may vary but will very often include a Nomex/Kevlar combination of material As an example, the materials used by the Los- Angeles City Fire Department, as found in their 2005 recruit handout are as follows:

- Outer shell: Nomex/Kevlar blend in a "rip stop weave", with water repellent finish.
- Thermal insulated layer: Quilt material.
- Moisture barrier: Breathe-Tex material combined with Nomex/Kevlar blend laminated cloth.

Thermal and moisture barriers are sewn together for removal for cleaning, repair and replacement from outer shell. The main components in most firefighter clothing are kevlar and nomex, two fabrics created by chemical giant DuPont in the 1960s. Many protective clothing companies use a mix of the two fabrics, whereas other focuses more on the flame-resistant Nomex. Nomex is the fabric that gives the protective gear its resistance to heat and flame while kevlar adds flexibility, comfort and allows the fabric to breathe **[79].**

2.2.7 Fire fighting clothing design

Construction and design of the protective clothing for firefighters

The special attention should be given to the construction of certain parts of garment that will protect the user from burning, penetration of moisture or chemicals to underwears and then to skin. Additionally, it is very important to consider how to satisfy the comfort of the garment which to be dressed in multi layered way , while not to inhibit movement in extreme conditions**[61].** Construction and design of the protective jacket and trousers are shown by figure 2.1 and figure 2.2 below respectively.

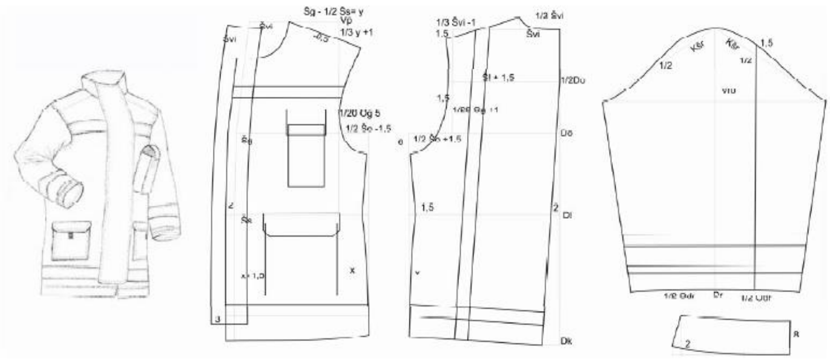

Figure 2.1: Construction and design of the protective jacket[61].

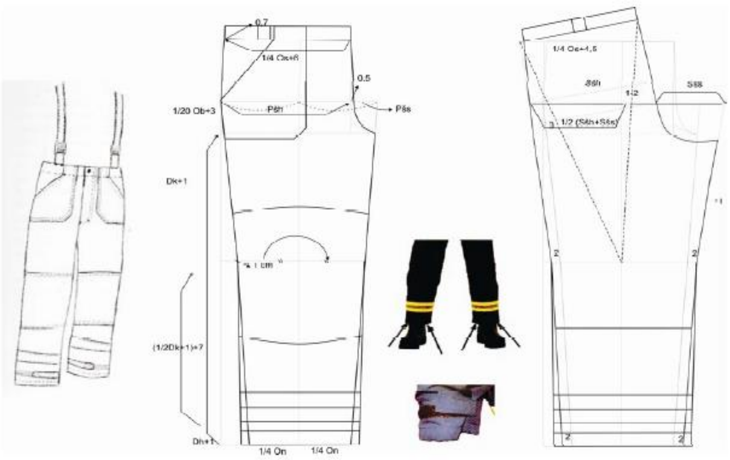

Figure 2.2: Construction and design of the protective trousers [61].

There are several different types of protective clothing used by fire fighters, and consequently several different standards outlining the performance requirements of each type.

Structural fire fighting clothing is typically constructed of a flame resistant outer shell, and an insulating thermal liner consisting of a moisture barrier and a thermal barrier**[85].** The outer shell material resists ignition when being exposed to thermal radiation or direct flame contact. The moisture barrier prevents the passage of moisture between the thermal barrier exposed to the skin and the outer shell, exposed to the fire environment. This barrier will prevent water, as well as chemicals, from passing through the garment to the wearer. The thermal barrier is a thicker, air filled, material that resists heat flow to the skin. In addition to preventing excessive heat from reaching the wearer, the clothing ensemble prevents the flow of heat and moisture from the body, reducing the ability of the body to give off excess heat.

Wildland fire fighting clothing is not designed to provide the same level of protection as that provided by structural fire fighting clothing, due to the differences in the anticipated work environment. Wildland fire fighting clothing is designed to provide protection from radiant environments, the primary thermal hazard encountered**[86].**

2.2.7.7 The wild land fire suit

The wild land fire suit is manufactured either as a double layer suit comprising of an outer shell and Thermal barrier or as a single layer suit.Its features are**:[79]**

- Outer shell fabric is predominantly made from Nomex & Kevlar and has inherent fire resistant properties, ensuring durability and consistent protection
- The outer shell fabric does not melt or drip when exposed to fire or heat but carbonises and closes up for a few seconds thereby preventing flame from injuring the wearer
- The Thermal barrier on the double layer suit takes away or reduces heat stress providing a comfortable and longer working tie for the fire fighter
- The Wildland suit is lightweight and comfortable
- The sizing is off a loose fit to prevent heat build up
- The jacket has no turn ups or cuffs that may catch burning embers
- Reflective trims on the jacket and trousers ensure 360° visibility
- Extra-large underarm gusset ensures uninhabited arm and shoulder movement and prevents the jacket from lifting

2.2.7.8 Protective ensemble for structural firefighting

Standard: NFPA 1971, Standard on Protective Ensemble for Structural Firefighting. NFPA 1971 includes helmets, hoods, coats, pants, coveralls, boots and gloves. Every firefighter's turnout is a composite of outer shell, moisture barrier and thermal liner.

Outershell

The outer shell is designed to take the everyday abuse of firefighting. This outermost layer is designed to protect the inner components from thermal hazards, abrasion, sunlight and other factors involved in fighting fires. The outer shell resists ignition upon being exposed to thermal radiation for a short period of direct flame contact.

Normally only inherently flame-retardant fibres, such as aromatic polyamides (aramids) and polybenzimidazole (PBI) are used for the outer layers of firefighters' turnout suits. On the market there are meta-aramids from different manufacturers, e.g., Nomex (DuPont), Conex (Teijin), Fenilon (Russian) and Apyeil (Unitika). Para-aramid fibres like Kevlar (DuPont), Twaron (Akzo Nobel) and Technora (Teijin) are used in blends with meta-aramids to increase durability, e.g., Nomex III (blend of Nomex and Kevlar (95/5%) and X-fire (blend of Teijin Conex and Technora). Especially in France, a polyamide-imide fibre called Kermel from Rhone-Poulenc is used for firefighters' protective clothing. Polybenzimidazole (PBI) fibre was developed by Celanese. Its advantage is that it absorbs more moisture than does cotton, and has a comfort rating from the wearers equivalent to that of 100% cotton.

The fibres on the market have the following trade names: Nomex®III, Nomex® Antistatic (IIIA), Nomex® Outershell Tough (Delta T), Kermel® HTA, PBI®Gold (Ibena). Typical blends are PBI/aramid, Nomex with flame-retardant viscose and flame-retardant wool, Kermel with viscose. Typical constructions of the outer fabrics are twill or ripstop woven fabrics with a mass of 195±270 g/m2. In addition to the above fibres in the garments for wildland firefighting, some materials with flame-retardant finishes (FR) (e.g. Proban® and Pyrovatex® for cotton) are used. They must retain the FR properties after 50 launderings (ISO 15384:2003)**[64].**

Moisture Barrier

Moisture membranes are an essential element in protective clothing against heat and flame due to their double role in preventing water penetration while allowing water vapor perspiration to exit. Microporous moisture barriers are generally made of expanded polytetrafluroethylene (e-PTFE) laminated on an aramid fabric. The principle under the membrane breathable function is the enormous difference in size between water vapor molecules (~ 0.4 nm in diameter) and water droplets which usually exceed 100 µm in diameter and are thus larger than the membrane pores**[67].**

The moisture barrier in firefighters' clothing is:

i. laminated or coated to the inside of the outer shell fabric,
ii. is a lightweight knitted material or web, and the structure is inserted loosely between the outer fabric and the liner, or
iii. is on the outside of the thermal liner.

The moisture barrier provides protection against water as well as against many common liquids such as common chemicals and bloodborne pathogens. The moisture barrier can be a microporous or hydrophilic membrane or coating **[65].** GORE-TEX®, CROSSTECH® and TETRATEX® are textile laminates incorporating microporous polytetrafluoroethylene. PORELLE®, PROLINE® and VAPRO® are microporous polyurethane laminates with textiles. BREATHE-TEX PLUS®, STEDAIR 2000® are hydrophilic polyurethane laminates or coated fabrics, SYMPATEX® is a hydrophilic polyester laminate. The microporous and hydrophilic coatings are normally polyurethane products. ACTION® is example of a polyurethane coating. Neoprene (NEOGUARD®) and polyvinyl chloride (PVC) are non-breathable moisture barrier products.

Thermal Liner

The thermal liner provides the most thermal insulation by trapping air in either a traditional needle-punched batting or between multiple layers of fabric. The durability of this layer is improved by quilting these materials to a woven facecloth fabric. Because this layer is close the body, its friction and moisture absorption characteristics can impact the comfort and mobility of the entire garment.

The thermal liner is normally made of inherently flame-retardant fabrics or their blends. A similar fibre content of the thermal liner and outer shell fabric make the laundering of the garment easier. Fibres and yarns are not the real thermal insulators of a garment because fibres conduct heat 10±20 times better than still air. The WL Gore company therefore developed a non-textile insulation material, i.e., an air cushion to replace the traditional textile insulation. Airlock® is a combination of a moisture barrier and thermal protection. `Spacers' made of foamed silicone on the GORE-TEX® moisture barrier create the insulating air buffer in the material **[66].**

Figure 2.3: Structural Firefighting protective clothings [66].

2.2.7.9 Thermal performance tests:

Two thermal performance tests in the NFPA1971 standard: a fabric flammability test and the TPP test.

- The fabric flammability test has resulted in the development of protective garments that resist flaming ignition.
- The thermal protective Performance (TPP) test measures how well a fabric protects theFirefighter against second-degree burns in a flash fire. The higher the TPP value, the more thermal protection the fabric provides relative to other fabrics. A minimum TPP rating of 35 required according to the NFPA standard.

At this level of protection a fire fighter would have approximately 17.5 seconds to escape from a flashover exposure before sustaining second degree burns. A popular misconception is that if 35 is good, a rating of 40, 50, or even 60 must be better. It is important to remember, however, that the only way to increase your TPP rating is to add more insulation, usually by specifying heavier material components. Generally speaking, added insulation will mean increased weight of the total system, resulting in greater heat stress for the firefighter.

3. TESTS STANDARDS AND TESTS APPARATUS

3.1 Review of Standard Tests

Taking universal application into consideration, some countries have established their own standards for firefighter turnout clothing, which are different with respect to evaluating the heat and moisture transfer property. In NFPA1971 Standard (Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting) of the US, total heat loss (THL) is adopted. Different from THL, other measurements are adopted in EU and Chinese standards (*Table 1 below*).

Although testing the WVTR of a single moisture barrier by the cup method in a steady state is much simpler than to measure the total heat loss or water vapour resistance of a turnout ensemble's multi-layers using a sweating hot plate, the latter ones can be a better way to evaluate the effect of the heat and/or moisture transfer property of firefighter turnout clothing**[62,63].**

Note that:

- ❖ Total heat loss (THL) is the amount of conductive (dry) and evaporative (wet) heat loss. The total heat loss testing apparatus is sweating hot plate as per US and EU standards.
- ❖ Water vapour resistance (WVR) is the amount of resistance against the transport of water vapour through a fabric.
- ❖ The water vapour transmission rate (WVTR) , the tesing apparatus for water vapour transmission rate is called WVTR cup as per China standards and it was calculated by the following formula:

$$\mathrm{WVTR} = \frac{4 \text{ x } \Delta \mathrm{m}}{\mathrm{S \text{ x } t}} \quad \textbf{(3.1)}$$

Where:

WVTR – weight of water vapor permeability, g/ (m^2 · 24h);

Δm – difference in weight of experimental assemble before test and after test, g;

S – area of the sample, m^2;

t – test time, h.

Table 3.1: Requirement for the heat and moisture transfer property of firefighter turnout clothing in different standards[63].

Category	Standard title	Edition	Testing objects	Indices	Requirement	Testing apparatus
US	NFPA1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting	2000	Multi-layered fabric assemblies	Total Heat Loss (THL)	≥130 w/m^2	Sweating hot plate
		2007			≥205 w/m^2	
	ASTMF 1868			THL	≥130W/m^2	
EU	EN469 Protective clothing for firefighters – Performance requirements for protective clothing for firefighting	2005	Multi-layered fabrics assemblies	Water Vapour Resistance	30 m^{2}Pa/W	Sweating hot plate
	EN 31092		Layer combination, testing from inside out	Water Vapour Resistance	Level 2 ≥30m^{2}Pa/W	
China	GA10Standard onFirefighting ProtectiveClothing	2002	Moisturebarriers	water vapourtransmission rate(WVTR)	≥5000 g/(m^2 · 24 h	WVTR cup
	ISO 11092		Layer combination testing, from inside out	Water Vapour Resistance	Level 1 ≥30m^{2}Pa/W	
	FTMS (Federal test method standard) 191A, 5504		outer shell and collar lining	Water absorptionresistance	≤30%	

Fire fighting protective clothing standards as per EN 469

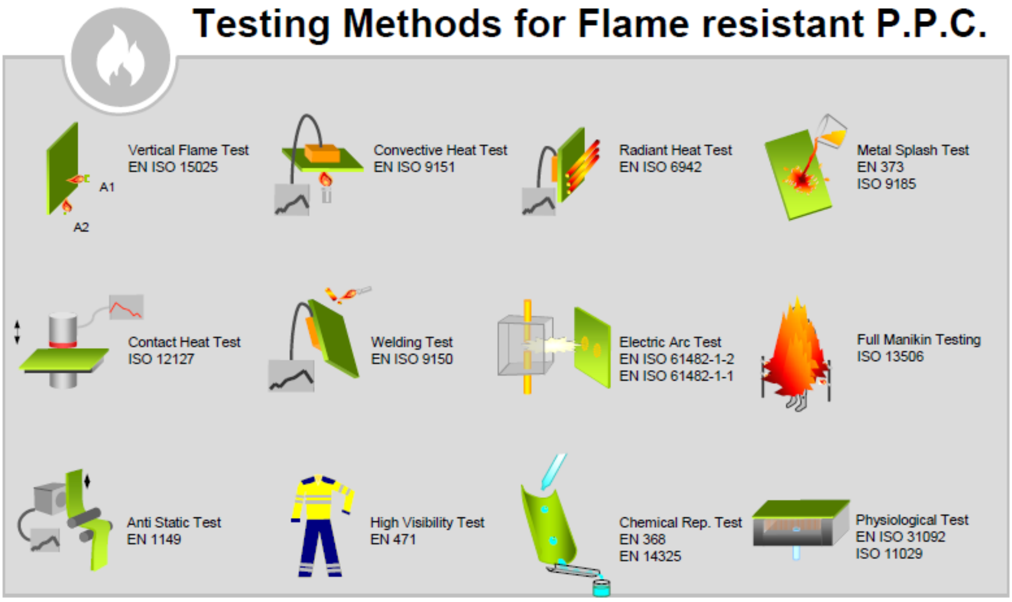

Figure 3.1: Testing methods for flame resistant personal protecting clothing [83].

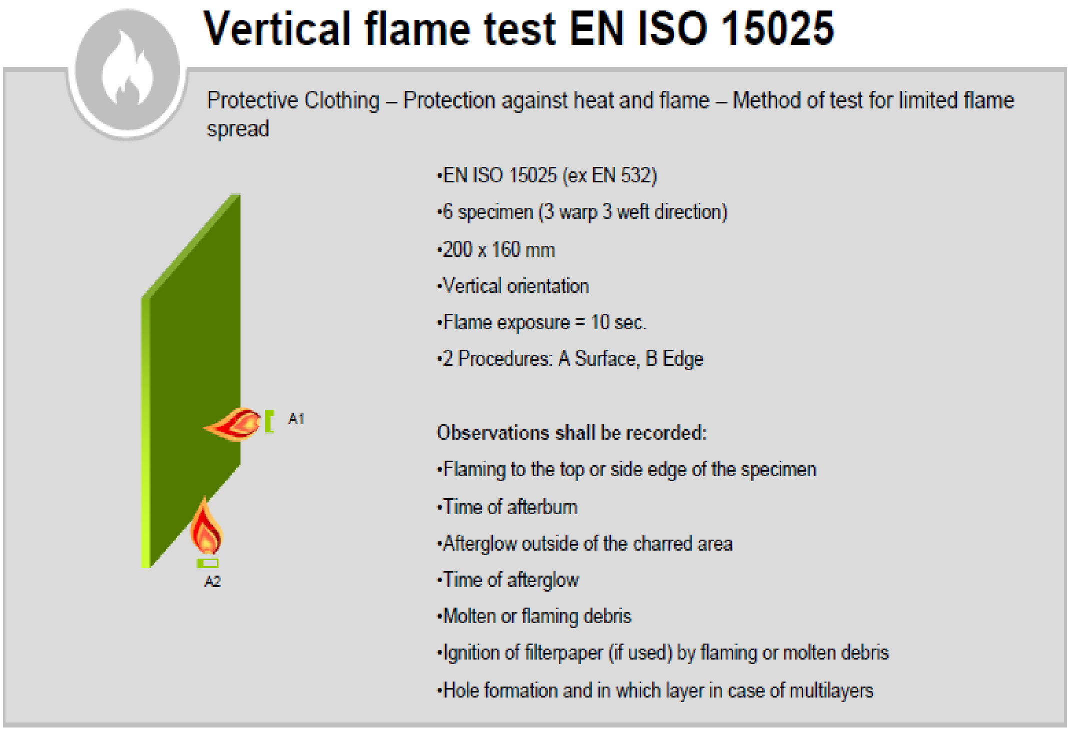

Figure 3.2: Vertical flame test exemplary according to EN ISO 15025 [83].

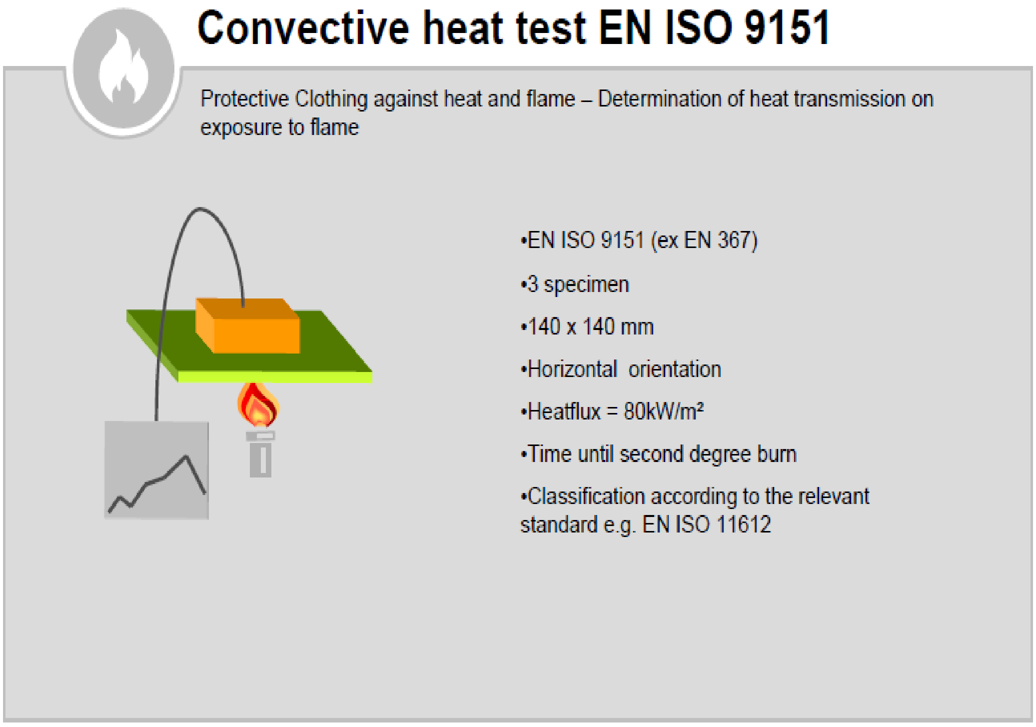

Figure 3.3: Convective heat test according to EN ISO 9151 [83].

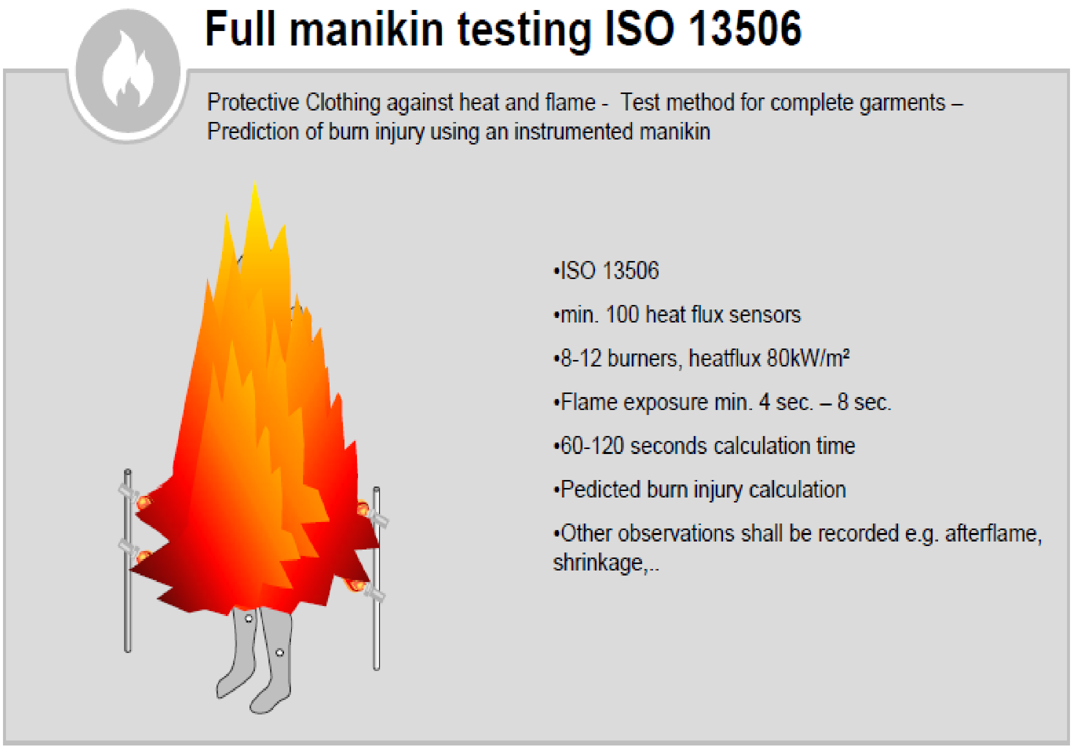

Figure 3.4: Full manikin testing exemplary according to ISO 1350 [83].

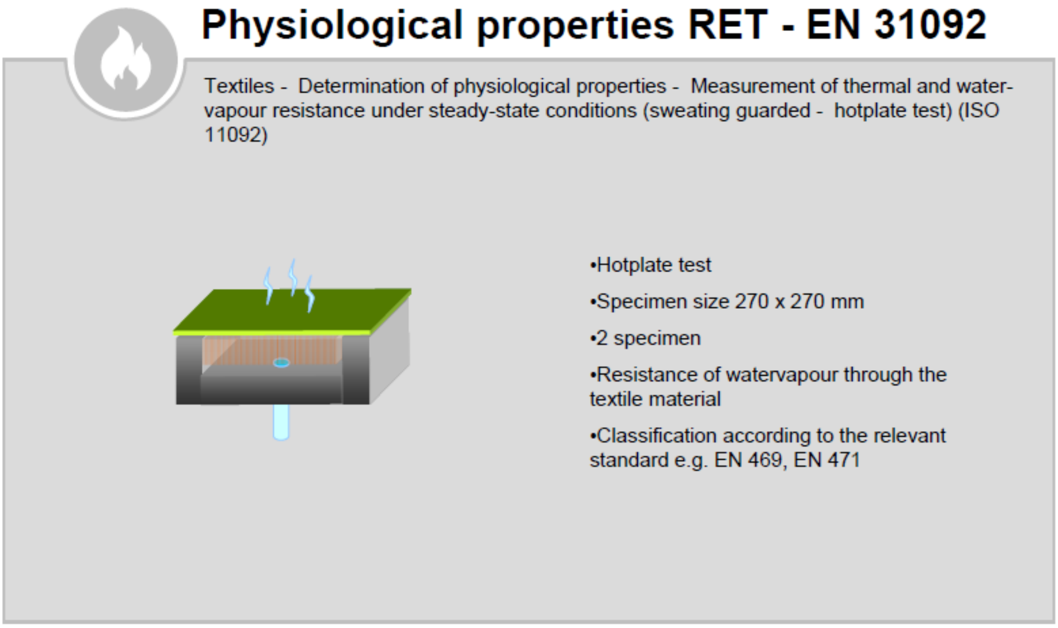

Figure 3.5: Physiological properties exemplary according to EN 31092 [83].

Two representatives of the standardized test methods, one in the field of protection and one related to comfort, shall be described shortly[**87]. The protective property of clothing materials against radiant heat can be measured according to IS0 6942 *I* EN 366. The test device consists of a radiation source able to produce a heat flux density up to 80 kW/m2 and a calorimeter which allows the measurement of the heat flux. The results of this test are the transmission factor and two threshold times. The threshold times correspond approximately to the time spaces until pain sensation and second degree burn respectively occur.

The comfort properties of clothing materials, Le. thermal and water vapour resistance, can be assessed with a sweating guarded hot plate according to IS0 11092 / EN 3 1092. The thermal resistance of the material is determined by measuring the heating power of the plate which is needed to keep a given temperature difference between the plate and the air. For the measurement of the water vapour resistance the porous plate is fed with destilled water which evaporates at the surface and simulates the sweating. The heating power of the plate is only used for the evaporation of the water – the measurement is done under isothermal conditions - and is therefore a measure for the water vapour permeability of the material under test[23].

These two test methods are qualified as standardized material tests because they provide reasonably repeatable and reproducible results. On the other hand they have several drawbacks compared with real life conditions:

1. The geometrical conditions do not correspond at all to reality. Normally the different layers of the clothing are not lying flat on each other; there are air gaps between them which constitute additional thermal and water vapour resistances.

2. When measuring the protection against radiative heat the humidity in the materials play an important role on the heat transmission **[23].**

3**.** Another very important effect, the so called pumping effect, cannot be assessed by the skin model. It is the transport of air containing heat and humidity through the openings of the clothing, caused by the movement of the wearer.

4.A simultaneous assessment of protective and comfort properties, which is necessary because they are dependent of each other,is not possible.

According to ASTM 1518 Standard, a guarded hot plate is used for measurement of thermal transport properties. And in order to obtain a rapid technique to measure the thermal properties of fabrics simulating the condition of sweating, different kinds of thermal manikins were developed. According to ASTM F1291 and ISO 7730, thermal insulation measured by thermal manikins can be used to predict thermal comfort of overall clothing systems. **[84]**

a. Fabric thermal insulation:

Property: Resistance to dry heat transfer (i.e. fabric insulation value)

Methods: ASTM D 1518 "Thermal Resistance of Batting Systems Using a Hot Plate"

ASTM F 1868 “Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate Test”

ISO 11092 "Textiles--Determination of Physiological Properties— Measurement of Thermal and Water-Vapour Resistance"

Instrument: Guarded hot plate in an environmental chamber; custom hoods provide either still air conditions, horizontal air flow, or vertical air flow at different levels

b. Evaporative resistance of fabrics

Property: Resistance to evaporative heat transfer

Methods: ASTM F 1868 “Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate Test”

ISO 11092 "Textiles--Determination of Physiological Properties—

Measurement of Thermal and Water-Vapour Resistance"

Instrument: Sweating hot plate in an environmental chamber; custom hoods provide either horizontal or vertical air flow at different levels

c. NFPA total heat loss test

Property: Total heat loss (from fire fighter fabrics)

Method: ASTM F 1868 “Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate Test”

THL Specification criteria are given in:

- NFPA 1971 "Protective Clothing for Structural Fire Fighting and Proximity Fire Fighting"
- NFPA 1977 “Protective Clothing and Equipment for Wildland Fire Fighting”
- NFPA 1992 “Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies”

Instrument: Sweating hot plate in an environmental chamber; custom hoods provide either horizontal or vertical air flow at different levels

3.2 Tests Apparatus

3.2.1 Perspiring fabric thermal manikin

General features of Perspiring Fabric Thermal Manikin are as follows**[28].**

1. There are two heaters and a water pump that control the temperature of the manikin body 37°C, similar to a real person’s body temperature:
2. Perspiration simulation using a waterproof, but moisture-permeable fabric skin, which holds the water inside the body, but allows moisture to pass through the skin:

3. The skin of the manikin can be interchanged so as to simulate different rates of perspiration:
4. It takes only one step to measure the thermal insulation and moisture-vapour resistance of textiles.

With this manikin, the total thermal insulation Rd of garment can be measured and calculated by using the following equations:

$$Rd = [A * (ts - ta)]/Hd \quad \textbf{(3.2)}$$

$$H = Hd + He \quad \textbf{(3.3)}$$

$$He = E * Q \quad \textbf{(3.4)}$$

Where,
R d is the total thermal insulation value (m^2.°C/W);
A is the total surface area of the manikin (*A* = 1.79 m2);
ts is the mean skin temperature (°C);
ta is the mean temperature of the environment (°C);
H is the total heat which the manikin needs to maintain constant core temperature (W);
He is the evaporative heat loss from the water evaporation (W);
Hd is the dry heat loss(W);
E is the heat of evaporation of water at the skin temperature(0.672W.h/g at 35°C);
Q is the "perspiration" rate or water loss per unit time, which can be measured by measuring the amount of water needed to top up the water level in the projecting tube to the original level(g/h).

3.2.2 Guarded hot plate apparatus

The Guarded Hot Plate Apparatus (see Fig 3.6 below) was composed of a test plate, guard section and bottom plate, each electronically maintained at a constant temperature within the range of human skin temperature (33 to 36°C). The guard section shall be designed to prevent lateral loss of heat from the test plate. Thermal resistance is calculated by measuring the temperature difference between the surface of the heated measurement area of the guarded hot plate and the temperature of the ambient air away from the plate. The temperature difference drives heat transfer through the fabric [9]. The plate's dry heat loss, the temperature difference between the plate's mean temperature and the chamber's air temperature, heating time as well as the CLO of samples can be read directly from the apparatus. The CLO can be calculated using the following equation[28].

$$CLO = \frac{U_{bp} - U_1}{0.155 * U_{bp} * U_1} \quad \textbf{(3.5)}$$

Where: $U1$ is the thermal conductivity with a sample (W/ m^2.°C);

Ubp is the thermal conductivity without a sample (W/ m^2.°C).

Considering the thermal resistance, including the surface air layer resistance, we use the following equation to calculate the total thermal resistance:

$$R_d` = \frac{A` *(t_s` - t_a`)}{H_d`} \quad \textbf{(3.6)}$$

Where: *Rd*`is the total thermal resistance with air layer (m^2.°C/W);

A' is the area of test section (0.09m^2);

t_s`is the surface temperature of the plate (°C);

ta` is the air temperature (°C);

Hd`is the heat loss (W).

Firefighting is hot and strenuous work which Leads to dehydration and heat stress. Thermal resistance (Rct) is expressed in m^2.K/W and quantifies the thermal insulation capacity. Water vapour resistance (Ret) is expressed in m^2.Pa/W and is a measure for breathability. ISO 11092-EN 31092 - measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test)

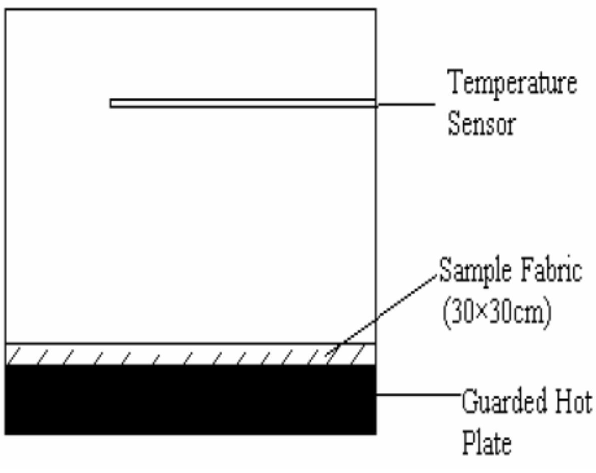

Figure 3.6: Guarded hot plate apparatus[28].

3.2.3 Objective evaluation of fabric comfort properties

Various forms of physical and simulative tests have been developed, and improved over the years, to assess comfort through the measurement of specific properties related to uncomfortable sensations. Success has also been achieved with various tests simulating wearing conditions on different models of thermal and sweating manikins [28].

3.2.4 WALTER^{TM} sweating thermal manikin

According to Fan and Qian (2004), the best simulative test involves the use of thermal manikins, but simulation of human perspiration remains a challenge. They are of the opinion that the Walter^{TM} sweating thermal manikin (US patent 6,543,657) offers great potential in terms of measurement accuracy during tests comprising the simulation of walking and perspiration on fully made-up garments. Measurements are made while the 172-cm breathable fabric manikin is simulating walking at a speed of 0–5 km/h or is in a stationary state.

"Walter" achieves a body temperature distribution similar to that of a human by pumping water at body temperature (37°C) from its centre to its extremities. During testing, the manikin is dressed in a garment made from the test fabric. Sensors measuring temperature and humidity are placed on specific areas on the manikin and connected to a computer, which controls and monitors the rate of heat loss and perspiration. A photograph of the manikin in the test chamber is shown in Figure 1.

The Walter^{TM} apparatus measures thermal resistance (Rt), water vapour resistance (Ret) and absorbency of a garment and calculates the moisture permeability index (Im). Unlike many other manikins, Walter^{TM} measures the two most important parameters, thermal resistance and water vapour resistance, in only one step. The moisture permeability index is an overall indication of the thermo -physiological comfort, which is dimensionless. The moisture permeability index is calculated by the Walter^{TM} software according to the following formula: Im = 60.6 X Rt / Ret

The water absorbency (%) of the textile fabric, in other words, the amount of moisture accumulated in the fabric, is determined by weighing the conditioned garments before dressing the manikin (Wb) and after removing the garments at the end of the procedure (Wa), and calculated as follows:

$$Ma\ (\%) = (Wa - Wb) / Wb \times 100 \quad \textbf{(3.7)}$$

According to Hes (1999 and 2008), a person becomes aware of his clothing within a very short time period after putting it on or experiencing a change in environmental conditions. Therefore, measuring thermal and moisture management properties within a short time frame will give a more realistic measurement of the fabric properties. Several test instruments have been developed specifically for this purpose, e.g. the Alambeta and Permetest instruments.

3.2.5 The Alambeta instrument

This test instrument was developed at the Technical University of Liberec (Czech Republic) for the objective evaluation of the thermal absorptivity of textile fabrics. The instrument is computer controlled, and uses the statistical parameters of measurements for thermal conductivity, thermal resistance and sample thickness to calculate the thermal absorptivity (Ws½/m2K). An auto diagnostic program checks measurement precision to avoid any faulty instrument operation. The main advantage of this instrument is that the entire evaluation process takes less than three minutes to complete. Thermal absorptivity is regarded as an indication of the warmcool feeling that will be experienced upon touch [27,29]. A photograph of the Alambeta instrument is shown in Figure 3.7

Figure 3.7: Photograph of Alambeta test instrument[27].

3.2.6 The Permetest instrument

The Permetest instrument is a semi-automated, portable, computercontrolled instrument, developed by Hes and manufactured by the Sensora Company in Liberec, Czech Republic. It was developed for the fast measurement of water vapour permeability (WVP) and resistance (WVR) as well as thermal resistance (Rt).

The instrument measures the amount of water vapour transmitted through a test sample, and the average WVP and WVR as well as the percentage coefficient of variance (CV) are automatically calculated. The measurements are based on the principle of heat flux sensing. A fabric sample, 80 mm in diameter, is mounted on the machine against a highly sensitive measuring head, containing a highly sensitive heat flow sensor with a thermal inertia similar to that of the human skin. The sensors are able to distinguish very small changes in the amount of water absorbed by the fabric during unsteady state of diffusion and to record, for example, the heat of absorption. This results in high measurement repeatability, with CV often less than 3%. The test is conducted under isothermal conditions; the temperature of the measuring head is maintained at room temperature. When water flows into the measuring head, some heat is lost due to evaporation. The instrument

measures the evaporation of the “uncovered” head as well as that of the head when covered with the test fabric. The full test is completed when the transfer of water from the measuring head to the atmosphere reaches steady-state (usually within two to three minutes).

Figure 3.8: Photograph of Permetest test instrument[29].

The relative WVP (P) is a non-standardised, practical parameter and indicates the water vapour permeability of the tested sample as a percentage relative to that of a free measuring surface (where the WVP = 100%). To calculate P, the ratio of heat loss from the measuring head with fabric (qs) and without fabric ($q0$) are used [27,29].

$$P = 100[qs/q0]\ \% \qquad \mathbf{(3.8)}$$

The water vapour resistance (Ret) is expressed in m2Pa/W and thermal resistance (Rt) in m2K/W as described in ISO standard 11092. A photograph of the Permetest instrument is shown in Figure 3.8 above.

3.2.7 Hydrostatıc head tester

The Hydrostatic Head Tester measures the resistance of a fabric to penetration by water under hydrostatic pressure. This new instrument is applicable to all types of woven, knitted and nonwoven fabrics, including those with water repellent and waterproof finishes and complies with AATCC, ISO and BS testing standards. Specimens are subjected to increasing (dynamic) or static hydrostatic pressure until three points of leakage occur. After a minimum of three specimens ere tested, calculation of the average maximum hydrostatic pressure is reported in mBars or cm H_2O, to rate the fabric. This Hydrostatic Head Tester offers increased capacities in both hydrostatic pressure and fabric thickness, greater efficiency through end-of-test alarms and auto head refills. Pre loaded test standards and downloadable results are included for ease of use [30].

Figure 3.9: Photograph of hydrostatic head tester[30].

3.2.8 Air permeability tester

The Air Permeability Tester offers unmatched ease of use, efficiency and reliability for air permeability tests. It automatically measures the flow of air through a given area of a fabric (set by a selected standard orifice) at a given pressure drop over this test area during the time called out by the accepted standard. Exclusive features include automatic detection of the test head size and an automatic ranging system that eliminates the need for a pretest to discover and then set the instrument range. The 50 cm test arm allows for simple testing on a large sample without having to cut multiple small specimens. The compact size and included casters permit the instrument to be setup quickly and easily whenever testing needs to be done, from the laboratory to the production flor [30].

Figure 3.10: Air permeability tester[30].

4. MATERIALS AND METHODS

4.1 Experimental Materials

All samples utilize common firefighter protective clothing materials combined to form multilayered assemblies. The individual layers of these assemblies are square pieces of material roughly by in size. These layers are unattached and can be inverted and rearranged with respect to one another to construct varying assembly types and configurations . Once finalized, assembly configurations and type remain constant, utilizing the same collection of materials in the same orientation throughout testing to ensure consistent results.

4.1.1 Test fabrics

Sample materials are supplied by KIVANÇ Group Company*****. Various types of fabrics currently used in firefighter turnout clothing were selected as shown in table 4.1, including 4 outer shells coded (A1~A4), 4 moisture barriers coded (B1~B4), 4 thermal barriers coded (C1~C4). Fabric samples were combined to make a multi-layer fabric assembly for firefighter turnout clothing in order to measure their comfort propeties like water vapor resistance, airpermebility, thermal resistance and others. These sample fabrics were supposed to fulfill the requirements of the EN 469:2005 standards.

One of the basic ideas of the EN 469:2005 is that 3 different letters (X-Y-Z) indicate the level of performance (a lower level 1 or a higher level 2). The properties represented by the letters are justified. Xf1 or Xf2 is to mean the performance in the heat test of flame; X1 or X2 is to mean the performance in the heat test of radiation; Y1 or Y2, to mean the performance in the waterproofness tests ; and Z1 or Z2 to mean the resistance against water vapour.EN 469:2005 Level 2 is the higher requirement for structural fire fighting and is used by professional firefighters. Level 2 suits should include a waterproof moisture barrier.

Xf2 = Convective heat HTI24 $\geq$ 13 second and HTI24 – HTI12 $\geq$ 4second

Xr2 = Radiant heat RHTI24 $\geq$ 18second and RHTI24 – RHTI12 $\geq$ 4 second

Y2 = Water resistance $\geq$ 20 KPa

Z2 = Water vapour resistance $\leq$ 30 m2 Pa/W

The characteristics of the specimens are provided in Table 4.1 All the selected layers for firefighters' clothing are commercially available and popularly used in the fire fighters protective clothing

Table 4.1: Sample fabrics characteristics descriptions.

Type	Fabric Code	Fabric Name	Weight
Outer shell	A1	Nomex Outershell Tough	195 g/ m²
	A2	PBI gold	200 g/m²
	A3	PBI Matrix	200 g/m²
	A4	Nomex Outershell Tough Ripstop	195 g/m²
Moisture barrier	B1	PU membrane laminated to nonwoven (50/25/25)	55 g / m2
	B2	PU membrane laminated to nonwoven (50/25/25)	85 g / m2
	B3	PU membrane laminated to knitted fabric	85 g/m2
	B4	PU membrane laminated to knitted fabric	145 g/m2
Thermal barrier:	C1	Two layers of nonwoven(55+55) quilted to Aramid Viscose FR inner lining	110 g/m2
	C2	Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining	110 g/m2
	C3	Nonwoven quilted to Aramid Viscose FR inner lining	55 g / m2
	C4	Nonwoven quilted to Aramid Viscose FR inner lining	85 g / m2

4.1.2 Test apparatus:

Experimental works is done by using the following test apparatus

4.1.2.1 Air permeability tester

The air permeability of the fabrics was measured on a Textest M821A Air Permeability Tester according the Standard: EN ISO 9237,400Pa, Temp. 23.7-24.5^{o}c, l/m^{2}/s, 20cm^{2} sample area and described test conditions. Refer to chapter 3 of the theses above about the equipment.

Figure 4.1: Prowhite air permeability tester.

4.1.2.2 Permetest

The tests were conducted with the PERMETEST apparatus. The instrument uses the same principle as specified in ISO 11092 developed by Hohenstein Institute, whereby a heated porous membrane is used to simulate the sweating skin. The heat required for the water to evaporate from the membrane, with and without a fabric covering, is measured. The fabric sample is placed on a measuring head over a semi-permeable foil and exposed to parallel air flow at a velocity of 1m/s. The measurement is carried out under isothermal conditions 22 °C. The computer connected to the apparatus determines the evaporative resistance Ret and the thermal resistance Rct and RWVP of textile fabrics according the standard ISO 11092.

Figure 4.2: Permetest instrument.

4.1.2.3 Alambeta

The thermal properties were measured with the Alambeta device which is a computer controlled instrument for measuring the basic static and dynamic thermal characteristics of textiles. This method belongs to the so-called ‘plate methods’, the acting principle of which relies on the convection of heat emitted by a hot upper plate in one direction through the sample being examined to the cold bottom plate adjoined to it.

Figure 4.3: Alambeta instrument .

4.1.2.4 Radiant heat tester EN ISO 6942

Evaluation of materials and material assemblies when exposed to a source of radiant heat as per EN ISO 6942 standard requires the followings:3 specimen with 230 x 70 mm , Vertical orientation, Heatflux = 20kW/m², Time until second degree burn

Figure 4.4: Radiant heat transmision tester model.

4.1.2.5 Convective heat transfer tester as per EN 367

Test models for determination of the heat transmission on exposure to flame icludes the following as instrument constructing parts. Gas burner (unless the defense), Copper disc calorimeter, Specimen support frame, Calorimeter plate, Leg support, Measuring instrument, Mould (model)[83].

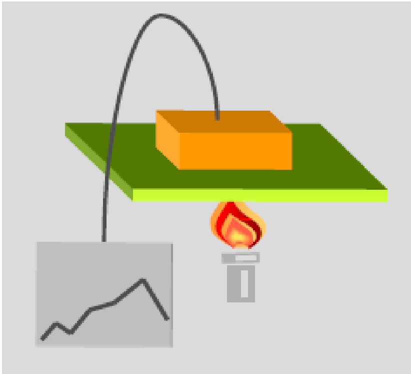

Figure 4.5: Convective heat transfer tester model.

4.1.2.6 Thermal camera

The testo 885 is a handy and robust thermal imager. It enables you to carry out contactless determination and display of the temperature distribution on surfaces. The testo used in this thesis work has the following specifications**[82].**

Testo 885-1: high-quality wide angle lens 30° x 23, detector 320 x 240, NETD < 30 mK at 30°C, 2GB SD card for approx. 2000 to 3000 images, minimum focusing distance 0.1 m, touchscreen, built-in digital imager with power LEDs for illumination, auto-focus, isotherm, min/max/avg on area, panorama image wizard, laser (not available in all countries), rotatable handle, rotatable and pivoting display

Figure 4.6: Testo 885 - Thermal imaging camera.

Flexible camera with rotatable display, Resolution of 160 x 120 pixels (Optional: SuperResolution technology increases res. to 320 x 240 pixels), thermal sensitivity < 80 mK, integrated digital camera. The testo 876 stands out thanks to its large rotatable display. This allows you to keep the display in view when thermographing in any position, securely reaching every corner.

4.2 Methodology

4.2.1 **Air permeability**

The inner layer and the thermal liner were put together with no extra air gap, in order to simulate the real situation**[81].**

How the test works:

A circle of fabric is clamped into the tester and through the use of a vaccum, the air pressire is made different on one side of the fabric. Airflow will occur from the side with higher air pressure, through the fabric, to the side with the lower air pressure. From this rate of air flow, the air permability of the fabric is determined.Air Permeability testing apparatus, Circular test head with a test area of 5.93 square inches (15.07 cm)., Clamping system to secure test specimens, Pressure gage or manometer, Flowmeter, Cutting dies.

Scientific testing requirements:

When using this equipment for scientific purposes, the fabric must be prepared according to ASTM D1776.

Procedure:

Sample preparation

1) When cutting specimens, avoid wrinkles, folds or creases.
2) Avoid getting oil, water, grease, etc. on the specimens when handling.
3) For the purposes of the lab, each student will test one sample. For scientific testing, 10 samples are used.
4) Use the medium cutting die (sized 4.5 inches/114. cm)
5) Use specimens representing a broad distribution across length and width, preferably along the diagonal of the fabric.

Preparation of test apparatus

1) Make all tests in the standard atmosphere for testing textiles.
2) Loosen the clamping system by twisting the top ring counter-clockwise.
3) Position the fabric sample between the top and bottom of the column, ensuring that fabric covers the entire opening. The fabric should be placed right side down.
4) Tighten the clamping system completely.
5) Place coated test specimens with the coated side down (toward the low pressure side) to minimize air edge leakage.

Test procedure

1) Read and record the individual test results in SI units or in inch-pound units rounded to three significant digits.
2) Ensure that the control vales .“A.” and .“C.” on the right are completely closed.
3) Check that the manometer (the glass tube of liquid) indicates zero. Adjust if necessary using the black knob on the top right of the machine to raise and lower the level.
4) Using the foot switch, turn on the vacuum pump
5) Using the black flowtube switch closer to the center on the left side of the machine, select flow tube number 4.
6) Gradually open .“Valve C.” (on the right side) until the required pressure is shown on the manometer tube.
7) If the flowtube float has not moved close .“Valve C..”
8) Select Flowtube number 3.
9) Gradually open .“Valve C.” (on the right side) until the required pressure is shown on the manometer tube.
10) If the flowtube float has not moved close .“Valve C..”
11) Select flowtube number 2.
12) Gradually open .“Valve A.” until the required pressure drop is shown on the manometer.
13) If the float in tube 2 does not rise, close .“Valve A..”
14) Select flowtube number 1.

15) Gradually open .“Valve A.” until the required pressure drop is shown on the manometer.
16) Once a range has been established for a particular type of material, the correct flowtube can be selected without going through the sequence.

4.2.2 Permetest

The measurement by fast permetest is carried out under isothermal conditions 22 °C. The computer connected to the apparatus determines the evaporative resistance Ret and the thermal resistance Rct and RWVP of textile fabrics according the standard ISO 11092. It does not refer to the fabric surface temperature, when there is an air gap between the skin model surface and the tested fabric (Eq. below). These values serve to reflect the thermo-physiological properties of textile fabrics and garments.

1) Join the PT with any modern computer (no VISTA, pls) by means of a RS 232 cable. The FRB cable for small computers (desktops) is also, included, along with a special conversion programme.
2) Swirch on both devices.
3) Install the CD program into the PC. The program must be downloaded on the C harc disciplines, and open the PERMETEST window. The use of the program will explained later.
4) On PT select the air velocities I (1 m/s) or II (1,6 m/s).
5) On the temperature controller OMRON adjust the required teperature gradient (0 deg. C for water vapour resistance measurement and 10 deg. C for thermal resistance measurement). The gradient shows the green scale. Use the buttons on the right hand side.
6) Install a small cup on the output of the free end of plastic tube, which will contain the water excess.
7) Fill the syring with distilled water containing 0,1 % of pure non-aggressive liquid soap used for hand washing with neutral acidity PH = 7), and insert it into the hole on the right hand side of the PT.
8) Wait 5 minutes to get the temperature deviation less then 0,2 ^{o} C (later it will be less then 0,1 ^{o}C), and the membrane on the measuring head surface returns back to the porous surface.
9) Press the zero “short“ on the top (I) to make short circuit on the entrance of the analogue amplifier.

10) Adjust slowly the **zero potentiometer** to zero on the black digital indicator. The adjustment requires patience, but it will keep adjusted for long time.
11) Press the “zero short“ on the bottom to open the entrance of the analogue amplifier.
12) Move the **amplifier potentiometer** to reach the signal level on the black digital indicator approx. 100, practically between 90 and 110.
13) Repeat the procedure according to 7,8,9 and 10 points, to improve the zero adjustment.
14) Adjust the amplification to 100 with better precision (95 to 105).
15) Pull down the measuring head (special knob on the top surface of the instrument enables easy pulling the head down) and insert the measured sample between the head and the botton of the air channel. Then pull back (upwards) the measuring head to the channel. Thus, the sample keeps fixed on the semi-permeable surface of the measuring head. Insert the measured sample between the bottom of the channel and the measuring head. Try not to scratch the surface membrane on the edges.
16) After 2-4 minutes read the relative water vapour permeability on the digital indicator. The observed turbulency is inevitable, but the PC program will avoid the variations of the readings – see the next expanation.

Use similar procedure for the measurement of thermal resistance Rct (with no water in the measuring head – drying the wet head takes more than 2 hours!). Use the foam foil as the reference fabric with the R_{et} value written on the foil.

4.2.3 Alambeta instrument

Principle of Alambeta instrument - tester of thermal properties of fabrics

This apparatus use in this study enables the measurement of the following thermal parameters: thermal conductivity, thermal absorbtivity, thermal resistance, thermal diffusion and sample thickness. The Alambeta simulates the dry human skin and its principle depends in mathematical processing of time course of heat flow passing through the tested fabric due to different temperatures of bottom measuring plate (22°C) and measuring head (32°C) **[78]**.

Procedures

1) When the specimen is inserted, the measuring head drops down, touches the fabrics and the heat flow levels are processed in the computer and thermo-physical properties of the measured specimen are evaluated.
2) After insertion of the sample the head moves down, and the heat ($q1 = f(\tau)$) flows from the heated plate to the sample, accumulating in it during the non-stationery state, and from the sample to the lower plate $q2 = f(\tau)$
3) The measurement lasts for several minutes only.
4) By measuring the electric power at the known area of the plates), the temperature difference between the upper and bottom fabric surface, and the fabric’s thickness.
5) The sample thickness is measured by an optoelectronic incremental sensor connected to a screw. The measuring head pressure is set and adjusted. The heat flow density is detected using thermocouples that measure the temperature gradient across a very thin plastic foil.
6) Device calculates the real thermal resistance (from the above-mentioned quantities) for all fabric configurations.
7) In contrast, the other thermal parameters such as thermal conductivity, thermal absorption and the thermal diffusion are calculated on the basis of the properties measured using algorithms appropriate for unstratified (homogeneous) materials.
8) The measurements were made for the left side (the left side of the fabric sticks to the upper plate) and the right side (the right side of the fabric sticks to the upper plate) of each sample.
9) For each side 20 measurements were made, and then the average values of the measured parameters were calculated.
10) The following thermal parameters were assessed: thermal conductivity, thermal diffusion, thermal absorption, thermal resistance, stationary heat flow density, the ratio of the maximum and stationary heat flow density as well as the fabric thickness.

In multilayer textile structures we can consider the results calculated on the basis of the measured parameters as equivalent values, i.e. equivalent conductivity, absorption and diffusion, for comparisons valid only for similar measuring conditions and comparable layer configuration. In this context the values of λ, a, and b should be considered.

4.2.4 Radiant heat tester EN ISO 6942

This test method is the Protective Clothing – Protection against heat and fire – Method of test. Evaluation of materials and material assemblies when exposed to a source of radiant heat as per EN ISO 6942 standard requires the followings:

1) 3 specimen
2) 230 x 70 mm
3) Vertical orientation
4) Heatflux = 20kW/m²
5) Time until second degree burn
6) Classification according to the relevant standard such as EN ISO 11612

4.2.5 Convective heat tester EN 367/ISO 9151

Protective Clothing against heat and flame – Determination of heat transmission on exposure to flame as EN ISO 9151 (ex EN 367) needs the following.

1) 3 specimen
2) 140 x 140 mm
3) Horizontal orientation
4) Heatflux = 80kW/m²
5) Time until second degree burn
6) Classification according to the relevant standard e.g. EN ISO 11612

Test principle:

A horizontally oriented test specimen is partially restrained from moving and subjected to an incident heat flux of 80 kW/m^2. From the flame of a gas burner placed beneath. The heat passing through the specimen is measured by means of a small copper calorimeter on top and in contact with the specimen. The time (s) for the temperature to rise 24 +/- 0.2 °C is recorded. The mean result of three specimens is calculated as the heat transfer index.

Expression of results:

- The time (s) for the temperature to rise 24 +/- 0.2°C is recorded. The mean result of three specimens iscalculated as the heat transfer index (HTI24)
- The time (s) for the temperature to rise 12 +/- 0,2)°C is recorded if requested (HTI12)

Terms definitions:

- *Incident heat flux density*: amount of energy incident per unit time on the exposed face of the specimen,expressed in kilowatts per square meter (kW/m2)
- *Heat transfer index (flame):* whole number calculated from the mean time in seconds to achieve a temperaturerise of 24+/-0,2°C when testing by this method using a copper disc of mass 18+/-0,05 g and a startingtemperature of 25+/-5°C
- *Calorimeter:* instrument to measure the heat energy absorbed by it; a calorimeter has a well defined heatcapacity, i.e. the amount of energy can be calculated from the temperature rise in the calorimeter.

4.2.6 Thermal camera testo 885 principle

Product components:

The testo 885 thermal camera have the following components. The digital imager lens which used for taking visual images and and also two power -LEDs for illuminating the image. Infrared imager lens for taking thermograms and release lens for releasing the lens lock. Thread (1/4" - 20 UNC) is used for attaching a tripod (bottom of imager) and Laser for marking the measurement object. Focusing ring is used for adjusting the focus manuallyand rotatable handle with adjustable hand strap and fastening loop for the lens cover. Two fixing eyelets for carrying/shoulder strap and also display that can be flipped out 90° and rotated 270.

1. Digital imager lens and power -LEDs
2. Infrared imager lens
3. [Release lens]
4. Thread (1/4" - 20 UNC)
5. Laser
6. Focusing ring
7. Rotatable handle
8. Battery compartment
9. Operating buttons (back and top of imager):
10. Two fixing eyelets.
11. Interface terminals:
12. Display

Figure 4.7: Thermal camera testo 885 product components.

Table 4.2: Infrared image output by Testo 885 thermal camera [82].

Feature	**Values**
Detector type	FPA 320 x 240 pixels, a.Si
Thermal sensitivity (NETD)	< 30 mK at 30°C (86°F)
Field of vision/min. focusing distance	30° x 23°/0.1 m (0.33 ft) Telephoto lens (optional): 11° x 9°/0.5 m (1.64 ft)
Geometric resolution (IFOV)	1.7 mrad (standard lens) 0.6 mrad (telephoto lens)
Super-resolution (pixels/IFOV) -optional	640 x 480 pixels / 1.06 mrad (standard lens) 0.38 mrad (telephoto lens)
Image refresh rate	33 Hz within EU, 9 Hz outside of EU
Focus	Automatic/manual
Spectral range	8 - 14 μm
Visual image output	
Feature	Values
Image size	3.1 megapixels
Min. focusing distanc	0.5 m (1.64 ft.)

5. RESULTS AND DISCUSSIONS

5.1 Air Permeability:

The test results are reported in Tables 5.1, 5.2, 5.3and also supported for comparison by the figure 5.1 below as an average of at least five independentreplications.Air permeability test results for single layers of fire fighters clothings constructing fabrics: (outer shell, moisture barriers and thermal linings) and also multilayered fabrics is done as per the following standard and conditions.

Standard: EN ISO 9237,400Pa, Temp. 23.7- 24.5^{o}c, l/m^2/s, 20cm^2 sample area.

Outer shell Air permeability test results which was done according to Standard:EN ISO 9237 by applying 400Pa pressure to 20cm^2 sample area at air Temp. 23.7- 24.5^{o}c is given in l/m^2/s unit,

Table 5.1: Outer shell fabrics Air permeability test results.

Fabric code	Measure 1 (l/m^2/s)	Measure 2 (l/m^2/s)	Measure 3 (l/m^2/s)	Measure 4 (l/m^2/s)	Measure 5 (l/m^2/s)	Average (l/m^2/s)
A1	590	561	564	565	533	562.6
A2	834	842	829	843	829	835.4
A3	470	483	464	490	493	480
A4	562	534	515	572	574	551.4

Moisture barriers Air permeability test results which was done according to

Table 5.2: Moisture barrier fabrics Air permeability test results.

Fabric code	Measure 1 (l/m^2/s)	Measure 2 (l/m^2/s)	Measure 3 (l/m^2/s)	Measure 4 (l/m^2/s)	Measure 5 (l/m^2/s)	Average (l/m^2/s)
B1	0	0	0	0	0	0
B2	1	0	1	0	0	0.4
B3	0	0	0	0	1	0.2
B4	2	1	0	0	2	1

Standard:EN ISO 9237 by applying 400Pa pressure to $20cm^2$ sample area at air Temp. 23.7- 24.5^{o}c is given in $l/m^2/s$ unit

Thermal linings air permeability test results which was done according to Standard:EN ISO 9237 by applying 400Pa pressure to $20cm^2$ sample area at air Temp. 23.7- 24.5^{o}c is given in $l/m^2/s$ unit.

Table 5.3: Thermal lining fabrics Air permeability test results.

Fabric code	Measure 1 ($l/m^2/s$)	Measure 2 ($l/m^2/s$)	Measure 3 ($l/m^2/s$)	Measure 4 ($l/m^2/s$)	Measure 5 ($l/m^2/s$)	Average ($l/m^2/s$)
C1	450	465	425	410	407	431
C2	383	447	438	423	429	424
C3	321	417	473	398	487	419.2
C4	910	820	898	939	989	911.2

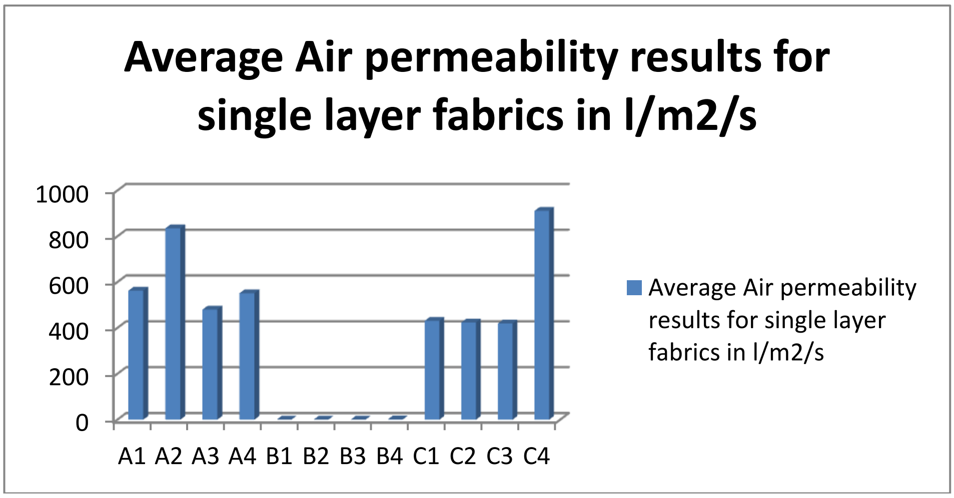

Figure 5.1: Average air permeability test results for single layer fabrics.

The test results for the layered sample fabrics show that the fire fighters clothing under study is not air permeable since all 64 combinations test measurements value are zero. This is understandable that moisture barriers which air permeability results are almost zero causes the fire fighters assembly layers not to permit airs.

These results lead us to exclude the air permeability properties while comparing the comfort properties of the samples understudy.

5.2 Water Vapor Permeability

The mentioned PERMETEST instrument enables the determination of relative WVP [%] and evaporation resistance Ret [m^2Pa/W] of single and layered fabrics within 3-5 minutes as the results are shown below. Measuring head of this small Skin Model is covered by a resistant semi permeable foil, which avoids the liquid water transport from the measuring system into the sample. Cooling heat flow caused by water evaporation from the thin porous layer is quickly recorded by a special computer evaluated sensing system. In terms of heat transfer this instrument presents the model of real human skin.

Table 5.4: Relative water vapor permeability and Water vapor resistance of single layer fabrics.

Fabric codes ⇓	Relative water vapor permeability (%)				Water vapor resistance R_{et} (m^2PaW^{-1})			
	Test 1	Test 2	Test 3	Average	Test 1	Test 2	Test 3	Average
A1	62.39	62.13	63.75	62.75	4.92	4.6	4.42	4,65
A2	60.27	62.26	60.66	61.06	5.14	4.29	4.9	4,78
A3	62.15	61.39	61.06	61.53	3.72	3.79	3.84	3,78
A4	62.87	61.63	61.74	62.08	3.56	3.71	3.72	3,66
B1	46.69	43.68	48.1	46.16	7	7.6	6.62	7.07
B2	37.55	38.75	36.41	37.57	10.12	9.56	10.73	10.14
B3	57.73	57.85	55.75	57.11	4.47	4.5	4.74	4.57
B4	39.95	35.04	37.44	37.48	9.79	11.79	10.77	10.78
C1	50.95	51.1	49.71	50.59	6.26	6.14	6.56	6.32
C2	48.31	47.08	47.72	47.70	7.02	7.22	7.1	7.11
C3	50.95	48.13	46.62	48.57	6.26	7.07	7.36	6.90
C4	51.1	51.34	52.93	51.79	6.14	6.22	5.78	6.05

For layered fabric samples only average test results of relative water vapor permeability and water vapor resistance are given here, the full test data is attached at appendix number A table A.2

The relative water vapor permeability and water vapor resistance of the layered fabrics is analyzed separately for their outer shell A1, A2, A3 and A4.

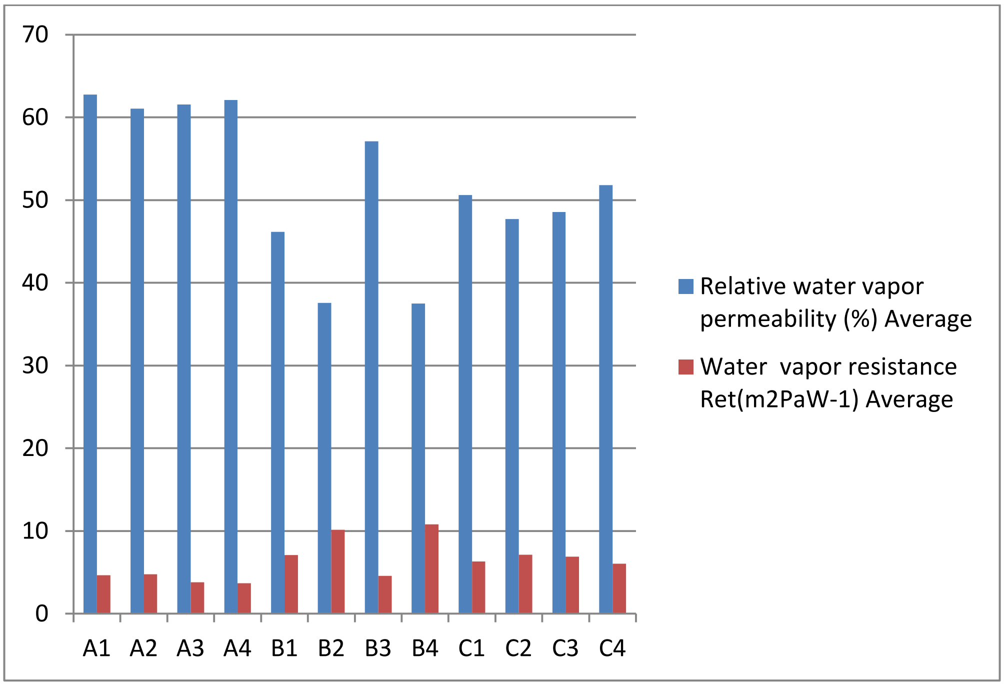

Figure 5.2: Histogram of relative water vapor permeability and water vapor resistance of single layer fabrics.

When comparing the water vapor resistance of moisture barriers B1-B4;

- ➢ As the mass of PU membrane laminated to nonwoven (50/25/25) increases the Ret increases and also the same is true for PU membrane laminated to knitted fabric.
- ➢ Keeping the same weight of two moisture barriers; PU membrane laminated to nonwoven (50/25/25) showed more water vapor resistance than that laminated to knitted fabric.

When comparing the water vapor resistance of thermal barriers C1-C4;

- ➢ As the sample mass per unit area of Nonwoven quilted to Aramid Viscose FR inner lining increases, the water vapor resistance Ret decreases and in turn comfort increases.
- ➢ Keeping the same weight of two thermal barriers; C2 (Two layers of nonwoven (55+55) quilted to Nomex Comfort inner lining) has more Ret than C1 (Two layers of nonwoven (55+55) quilted to Aramid Viscose FR inner lining)

Table 5.5: Relative water vapor permeability and Water vapor resistance of multi-layered fabrics for outer shell A1 Nomex Outershell Tough common.

No.	Layered Fabric Code	Relative water vapour permeability %	Water Vapour resistance $R_{et}(m^2PaW^{-1})$
1	A1B1C1	20.13	21.94
2	A1B1C2	19.01	21.16
3	A1B1C3	18.08	22.48
4	A1B1C4	17.34	23.14
5	A1B2C1	18.39	26.91
6	A1B2C2	17.72	22.38
7	A1B2C3	17.25	24.55
8	A1B2C4	16.83	25.69
9	A1B3C1	22.18	21.37
10	A1B3C2	20.69	19.94
11	A1B3C3	19.61	21.59
12	A1B3C4	21.49	19.16
13	A1B4C1	17.57	29.14
14	A1B4C2	17.28	22.67
15	A1B4C3	14.76	28.25
16	A1B4C4	15.94	25.57

From the layered fabrics in which an outer shell A1 or Nomex Outershell Tough with 195 g/ m^2 weight has been used;

→ The combination of moisture barrier B4 or PU membrane laminated to knitted fabric with 145 g/m2 and thermal barrier C1 or Two layers of nonwoven(55+55) quilted to Aramid Viscose FR inner lining with 110 g/m2 found to be the highest water vapor resistant layers which can be concluded because of the highest mass per unit area from their respective groups.

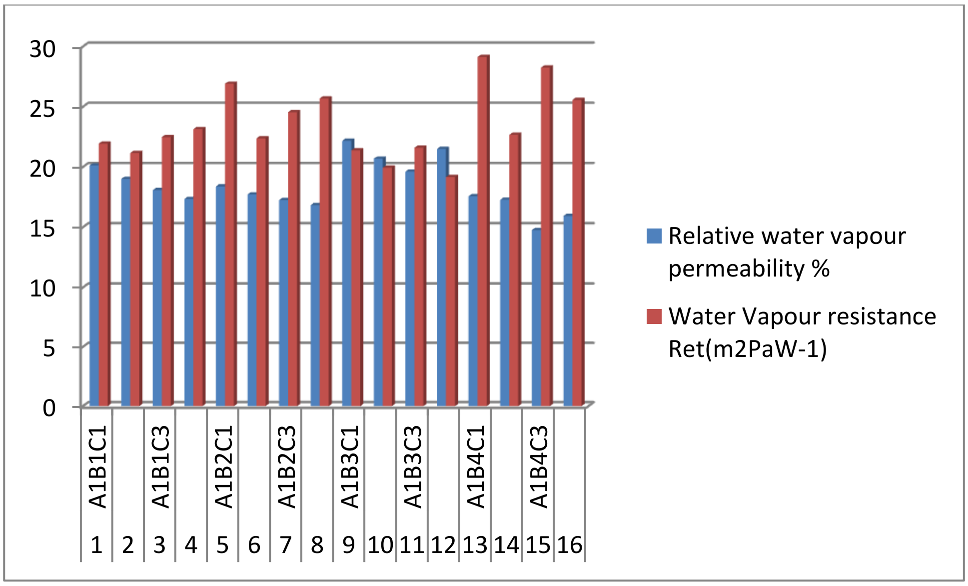

Figure 5.3: Histogram of multilayered fabrics water vapor resistance when outer shell A1 is common.

→ The combination of moisture barrier B3 or PU membrane laminated to knitted fabric and thermal barrier C4 or Nonwoven quilted to Aramid Viscose FR inner lining both with 85 g/ m² mass per unit area found to be the most comfortable by allowing water vapor transmission through the layer. This can be because of lamination of moisture barrier to knitted fabric.

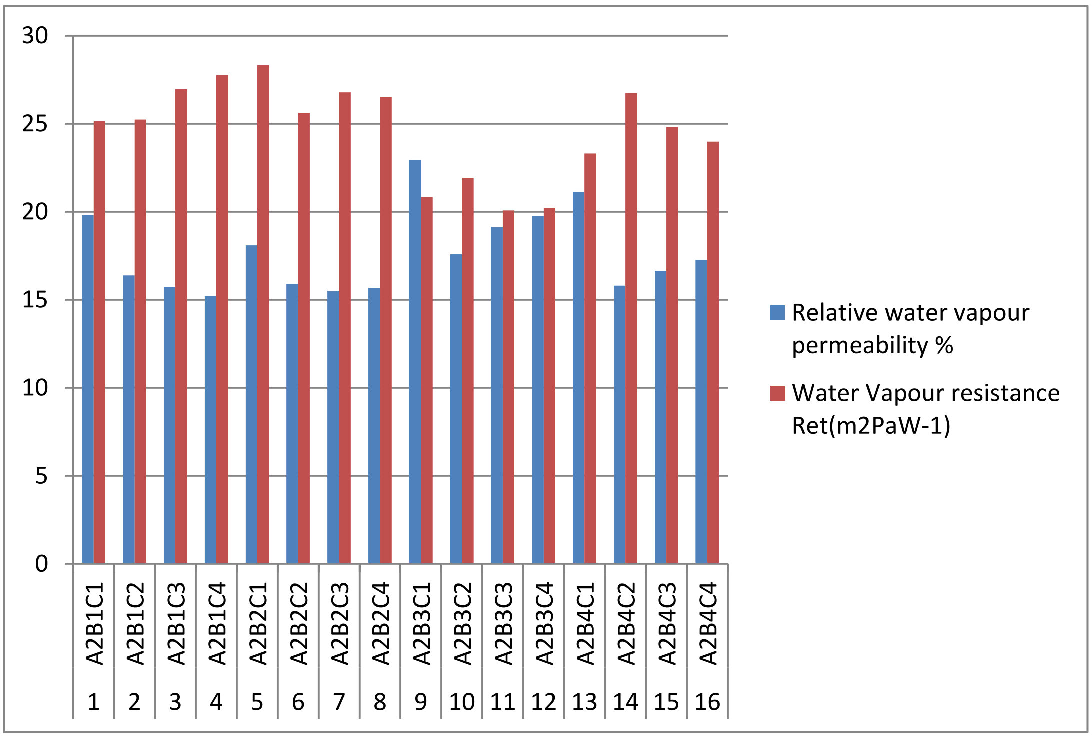

Figure 5.4: Histogram of multilayered fabrics water vapor resistance when outer shell A2 is common.

Table 5.6: Relative water vapor permeability and Water vapor resistance of multi-layered fabrics for outer shell A2 PBI gold 200 g/m² as common.

No.	Layered Fabric Code	Relative water vapour permeability %	Water Vapour resistance $R_{et}(m^2PaW^{-1})$
1	A2B1C1	19.80	25.13
2	A2B1C2	16.38	25.23
3	A2B1C3	15.73	26.95
4	A2B1C4	15.20	27.76
5	A2B2C1	18.08	28.32
6	A2B2C2	15.88	25.62
7	A2B2C3	15.51	26.78
8	A2B2C4	15.67	26.52
9	A2B3C1	22.92	20.84
10	A2B3C2	17.58	21.92
11	A2B3C3	19.15	20.07
12	A2B3C4	19.74	20.22
13	A2B4C1	21.10	23.31
14	A2B4C2	15.80	26.73
15	A2B4C3	16.63	24.81
16	A2B4C4	17.26	23.98

From the layered fabrics in which an outer shell A2 or PBI gold 200 g/m² weight has been used;

→ The combination of moisture barrier B2 or PU membrane laminated to nonwoven (50/25/25) with 85 g/m2 and thermal barrier C1 or Two layers of nonwoven(55+55) quilted to Aramid Viscose FR inner lining with 110 g/m2 found to be the highest water vapor resistant layers which can be because of the highest mass per unit area from their nonwoven fabric and also form the group.

→ The combination of moisture barrier B3 or PU membrane laminated to knitted fabric and thermal barrier C4 or Nonwoven quilted to Aramid Viscose

FR inner lining both with 85 g/ m² mass per unit area found to be the most comfortable by allowing water vapor transmission through the layer. This can be because of lamination of moisture barrier to knitted fabric.This agrees with outershell A1 illustrated above.

Table 5.7: Relative water vapor permeability and Water vapor resistance of multi layered fabrics for common outer shell A3 PBI Matrix.

No.	Layered Fabric Code	Relative water vapour permeability %	Water Vapour resistance $R_{et}(m^2PaW^{-1})$
1	A3B1C1	19.94	25.62
2	A3B1C2	17.14	24.03
3	A3B1C3	16.10	25.48
4	A3B1C4	16.82	24.57
5	A3B2C1	17.88	28.61
6	A3B2C2	14.93	27.79
7	A3B2C3	15.64	26.17
8	A3B2C4	15.91	24.82
9	A3B3C1	21.14	23.77
10	A3B3C2	17.81	21.93
11	A3B3C3	19.57	19.89
12	A3B3C4	17.52	22.91
13	A3B4C1	20.06	25.51
14	A3B4C2	13.32	31.69
15	A3B4C3	14.73	28.48
16	A3B4C4	13.47	29.64

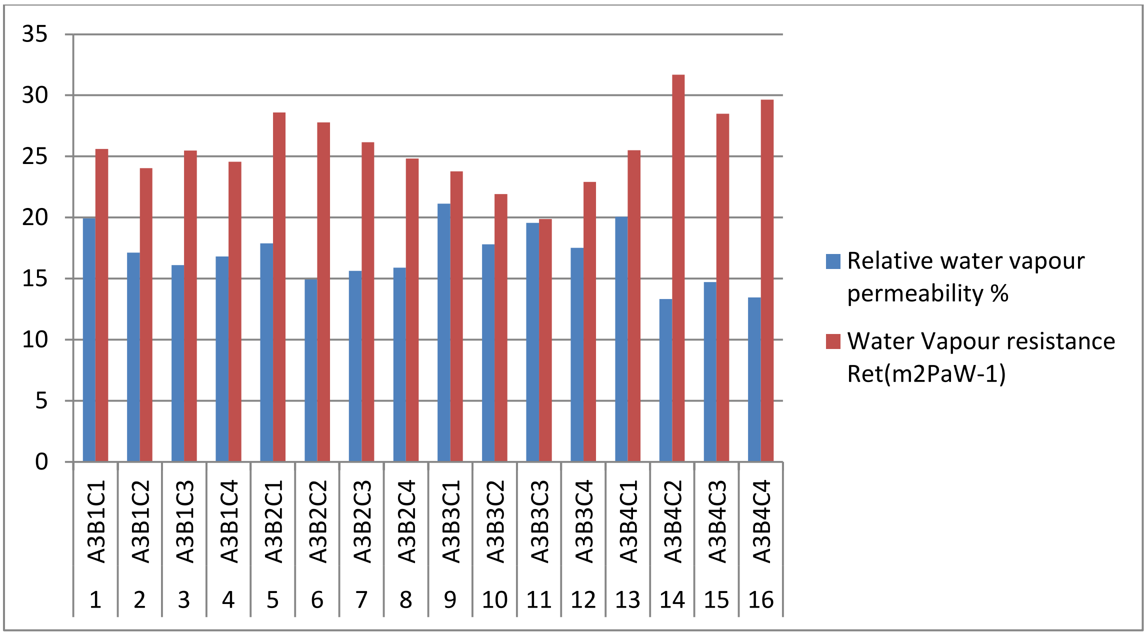

Figure 5.5: Histogram of multilayered fabrics water vapor resistance when outer shell A3 is common.

From the layered fabrics in which an outer shell A3 or PBI Matrix with 200 g/m² weight has been used;

→ The combination of moisture barrier B4 or PU membrane laminated to knitted fabric with 145 g/m2 and thermal barrier C2 or Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining with 110 g/m2 found to be the highest water vapor resistant layer which can be because of the highest mass per unit area from their groups and also Nomex comfort inner lining. The value is above the standard limit which showed it is the least comfortable assembly.

→ The combination of moisture barrier B3 or PU membrane laminated to knitted fabric with 85 g/ m² and thermal barrier C3 or Nonwoven quilted to Aramid Viscose FR inner lining with 55 g/ m² mass per unit area found to be the most comfortable by allowing water vapor transmission through the layer. This can be because of lamination of moisture barrier to knitted fabric and also low mass per unit area.

From the layered fabrics in which an outer shell A4 or Nomex Tough Ripstop with 195 g/m² weight has been used;

→ The combination of moisture barrier B3 or PU membrane laminated to knitted fabric and thermal barrier C4 or Nonwoven quilted to Aramid Viscose FR inner lining both with 85 g/ m² mass per unit area found to be the most comfortable by allowing water vapor transmission through the layer. This can be because of lamination of moisture barrier to knitted fabric.This agrees with outershell A1, A3 illustrated below.

→ The combination of moisture barrier B4 or PU membrane laminated to knitted fabric with 145 g/m2 and thermal barrier C2 or Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining with 110 g/m2 found to be second highest water vapor resistant layer which can be because of the highest mass per unit area from their groups and also Nomex comfort inner lining.

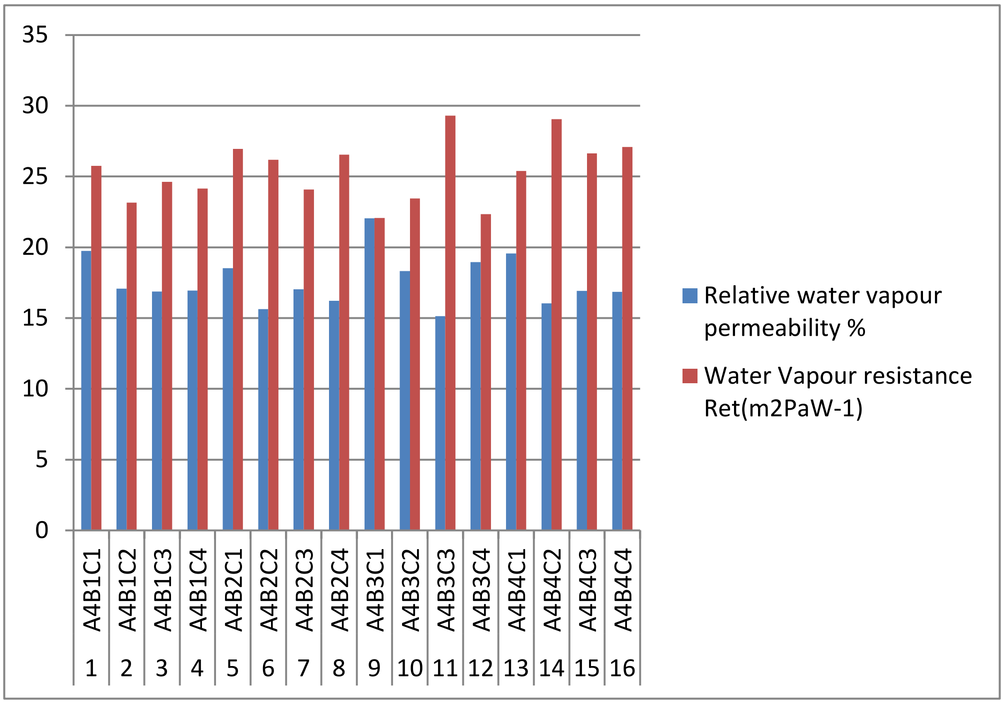

Figure 5.6: Histogram of multilayered fabrics water vapor resistance when outer shell A4 is common.

Table 5.8: Relative water vapor permeability and Water vapor resistance of multi-layered fabrics for outer shell A4 Nomex Tough Ripstop 195 g/m² as common.

No.	Layered Fabric Code	Relative water vapour permeability %	Water Vapour resistance $R_{et}(m^2PaW^{-1})$
1	A4B1C1	19.75	25.74
2	A4B1C2	17.07	23.15
3	A4B1C3	16.87	24.62
4	A4B1C4	16.95	24.15
5	A4B2C1	18.52	26.95
6	A4B2C2	15.64	26.19
7	A4B2C3	17.03	24.07

8	A4B2C4	16.21	26.54
9	A4B3C1	22.04	22.06
10	A4B3C2	18.33	23.44
11	A4B3C3	15.14	29.29
12	A4B3C4	18.94	22.34
13	A4B4C1	19.56	25.40
14	A4B4C2	16.03	29.04
15	A4B4C3	16.92	26.63
16	A4B4C4	16.84	27.08

Relative water vapour permeability of the textile sample p_{wv} can be determined from the relation

$$p_{wv}[\%] = 100 u_s / u_o \qquad (5.1)$$

Here, u_o means the instrument reading without a sample (heat loses of the free wet surface), and u_s presents the heat loses of the wet measuring head (skin model) with a sample.

Water vapour resistance R_{et} [m^2Pa/W], when expressed in terms of the according to the ISO 11092 Standard (Textiles - Physiological effects - Measurement of the thermal and water-vapour resistance), then the following relationship is applied (and used :

$$R_{et} = (p_{wsat} - p_{wo})(1/u_s - 1/u_o) = C\,(100 - \varphi)(1/u_s - 1/u_o) \qquad (5.2)$$

The values of water vapour partial pressures $p_{w\ sat}$ and p_{wo} in Pascals in this equation represent the water vapour saturate partial pressure valid for the temperature of the air in the measuring laboratory t_o (22-25 ^{o}C), and the partial water vapour pressure in the laboratory air. The relative humidity φ should be kept between 45-60 %. The constant **C** will be determined by the calibration procedure. Special hydrophobic polypropylene reference fabric for this purpose is delivered with the instrument.

The instrument provides all kinds of measurements similar to the ISO Standard 11092, and the results are evaluated by identical procedure as required in this standard. The correlation coefficient of measurements related to the ISO Standard SKIN MODEL exceeds 0.9. The results are treated statistically, displayed and recorded for next use [88].

Based on the standard EN 469:2005 Level 2 which is the higher requirement for structural fire fighting and is used by professional firefighters we have to comapare the results obtained by permetest instrument. The standard suggests the acceptable value of water vapor resistance Z2 as follows.

- ✓ Z2 = Water vapour resistance $\leq$ 30 m2 Pa/W,
- ✓ Level 2 suits should include a waterproof moisture barrier.

Thus all of combination of layered fabrics fulfill the requirement except one. That is **A3B4C2 ;** The combination of outer shell A3 or PBI Matrix with 200 g/m², moisture barrier B4 or PU membrane laminated to knitted fabric with 145 g/m2 and thermal barrier C2 or Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining with 110 g/m2 having 13,32% of RWVP and 31,69m^2 Pa/W water vapour resistance value.

5.3 Thermal Resistance Properties

Thermal resistance and conductivity of the sample fabrics under study are measured by using Alambeta and Permetest instruments. Alambeta modern device is designed to measure the following thermal parameters: thermal conductivity (λ), thermal absorptivity (b), thermal diffusion (a), thermal resistance (R) and sample thickness (h). The device basically simulates the dry human skin and its principle is based on the mathematical processing of time course of heat flow passing through the tested fabric due to temperature difference of the bottom measuring plate at 22 °C and the measuring head at 32 °C. The measurement takes only a few minutes, which ensures reliable measurements for the fabrics.

Similar to measurements done by Permetest 12 types of different single layer fabrics each four from outer shell, thermal barrier and moisture barriers and also 64 multi-layered combinations which are commonly used for production of fire fighters protective clothings were measured.

Table 5.9: Single layer fabrics average thermal parameters results by Alambeta.

Single layer Fabric codes	Tests	Thermal conductivity **λ** ($Wm^{-1}K^{-1}$)	Thermal diffusion **a** (m^2s^{-1})	Thermal absorptivity **b** ($Wm^{-2}s^{1/2}K^{-1}$)	Thermal resistance **R** ($mK.m^2/W$)
A1	Average	54.73	0.076	198.33	8.33
A2	Average	57.73	0.086	197.33	8.033
A3	Average	61.97	0.074	228	7.4
A4	Average	47.73	0.085	164.33	10.7
B1	Average	32.63	0.114	97.23	17.13
B2	Average	35.07	0.128	98.1	22.03
B3	Average	32.73	0.089	110	7.8
B4	Average	43.57	0.070	165.33	10.3
C1	Average	36.83	0.53	51.07	76
C2	Average	36.5	0.245	73.67	55.57
C3	Average	36.2	0.288	67.87	54.93
C4	Average	38.13	0.207	84.5	49.03

The thermal absorptivity of single fabrics to mean a 'warm–cool' feeling that first sensation experienced when a human touches a fabric. This feeling is a result of heat exchange that takes place between the human hand and the fabric because of the temperature difference between the fabric surface and that of the human skin. If the thermal absorptivity of a garment is high it can be expected to give a cooler feeling upon first contact.

Thermal resistance of single layer fabrics ;which is a measure of the resistance that a garment/fabric provides against heat loss from the body of the wearer to the external environment; showed by histogram above can be related to their thermal absorptivity which is inversely proportional to each other.That is the more the fabric can resist to thermal transmission, the less value of their thermal absorptivity.

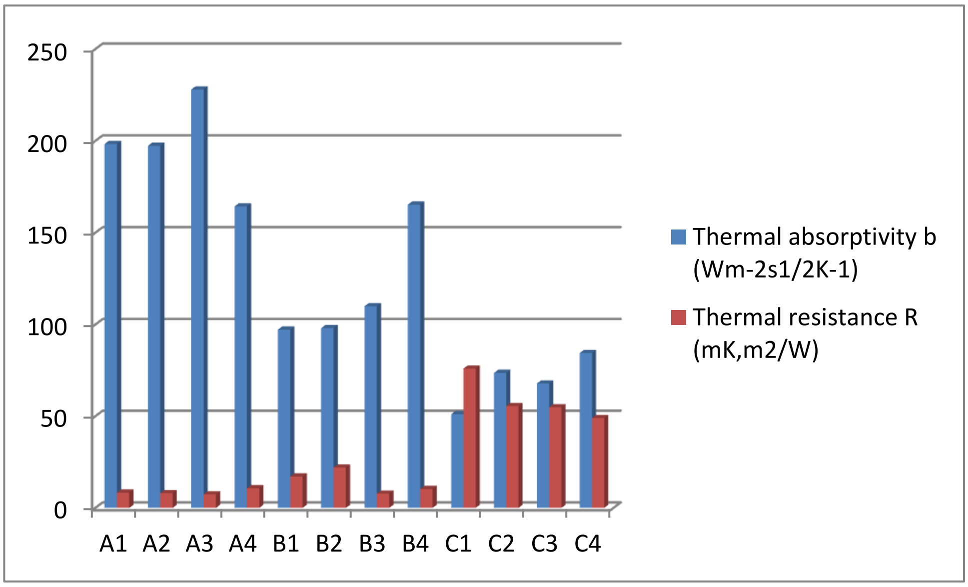

Figure 5.7: Histogram of single layer fabrics thermal absorptivity and thermal resistance.

- Thus from the outershell group fabric coded A3 or PBI Matrix with 200g/m^2 mass per unit area, from moisture barrier B4 or PU membrane laminated to knitted fabric with 145 g/m^2 mass per unit area and from thermal barrier C4 or Nonwoven quilted to Aramid Viscose FR inner lining with 85 g /m^2 mass per unit area were found to be the highest results. Hence because of cooler feelings they provide they could be considered as the most comfortable specifically for fire fighters in warm environment.

The thermal diffusion of single layer fabrics were measured by Alambeta device and the histogram below shows it.

Thermal diffusion is an ability related to the heat flow through the air in the fabric structure. The thermal barrier's measured value indicates that they have high thermal diffusion because of their bulky structure quilted with inner lining. Thermal barrier coded C1 or Two layers of nonwoven(55+55) quilted to Aramid Viscose FR inner lining with 110 g/m^2 had high value because of two layers used in quilting and also Aramid viscose.

Thermal parameters test results for layered fabrics was analyzed for each outershell fabrics separately.

In the analysis there was two thermal resistance values measured by both Alambeta and Permetest.

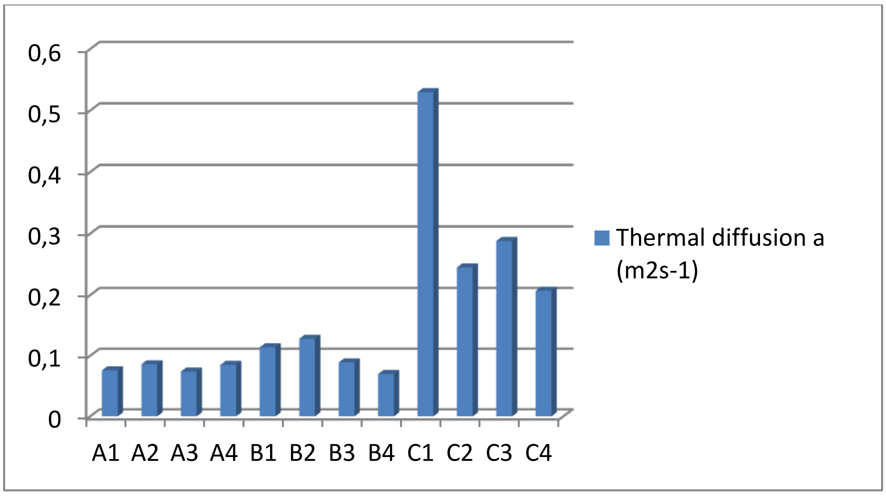

Figure 5.8: Histogram of single layer fabrics thermal diffusion.

Before ignoring one of the two, first I had to see their relationship based on the following null hyphothesis Ho.

- Ho- There is no relationship between measured values of thermal resistance properties of Fire fighters protective clothing's materials by using Alambeta and Permetest instruments.

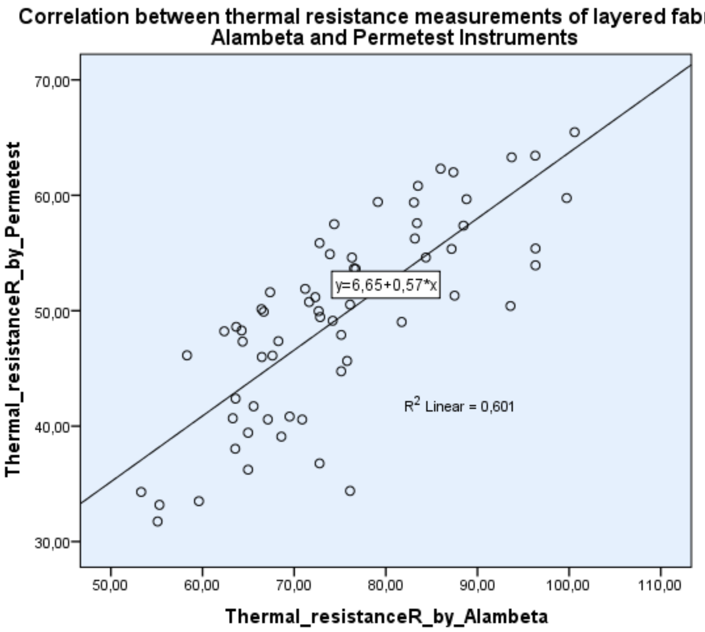

Figure 5.9: Correlations between thermal resistance measurements of layered fabrics by Alambeta and Permetest.

Table 5.10: Comparison of Thermal resistance measurements of layered fabrics by Alambeta and Permetest.

Correlations

		Thermal_resistanceR_by_Alambeta	Thermal_resistanceR_by_Permetest
Thermal_resistanceR_by_Alambeta	Pearson Correlation	1	.776**
	Sig. (2-tailed)		.000
	N	64	64
Thermal_resistanceR_by_Permetest	Pearson Correlation	.776**	1
	Sig. (2-tailed)	.000	
	N	64	64

**. Correlation is significant at the 0.01 level (2-tailed).

From this correlation results the relationship between measured values of thermal resistance of layered fabrics by Alamabeta and Permetest have the correlation coeficient of 0.776 which is greater than 0.65. Therefore there is statistical relationship between two measured values and the null hyphothesis above was rejected.

Additionally; in order to proceed the discussions it was better to understand wich instruments results is best suit to our fabrics understudy. Alambeta measures the heat flow through garments which has direct contact with human skin based on its dry skin model between upper and bottom plates. Permetest measures the heat flow from high to low thermal regions and it is not better for underwear when compared with Alambeta. Hence, Firefighters protective clothing has no direct contacts with wearers skin the Permetest was chosen to be considered in thermal resistance results discussions.

For layered fabric samples only average test results of thermal parameters measured by Alambeta device and also thermal resistance results by Permetest are given here, the full test data is attached at Appendix B. Table B.2

From the histogram below the thermal absorptivity of thermal barrier coded C4 or Nonwoven quilted to Aramid Viscose FR inner lining with 85 g /m^2 mass per unit area results in the highest value of thermal absorptivity of layered combination coded

Table 5.11: Multi - layer fabrics thermal parameters results by Alambeta and Permetest for common outershell coded A1 Nomex Outer shell Tough.

No.	Multi-layered Fabric codes	Thermal Parameters by Alambeta				By Permetest
		Thermal conductivity **λ** $(Wm^{-1}K^{-1})$	Thermal diffusion **a** (m^2s^{-1})	Thermal absorption **b** $(Wm^{-2}s^{1/2}K^{-1})$	Thermal resistance **R** $(mK.m^2/W)$	Thermal resistance R_{ct} $(mK.m^2/W)$
1	A1B1C1	39.90	0.27	77.57	96.30	63.43
2	A1B1C2	39.87	0.39	64.20	80.20	51.99
3	A1B1C3	40.63	0.38	66.77	75.13	47.90
4	A1B1C4	41.30	0.32	73.23	72.77	36.77
5	A1B2C1	40.47	0.31	73.33	100.60	65.47
6	A1B2C2	39.93	0.61	52.70	83.17	56.25
7	A1B2C3	39.47	0.40	62.67	81.73	49.02
8	A1B2C4	41.10	0.26	80.50	67.13	40.58
9	A1B3C1	40.77	0.26	79.87	87.50	51.31
10	A1B3C2	39.47	0.38	64.33	75.13	44.75
11	A1B3C3	39.63	0.34	68.77	65.57	41.72
12	A1B3C4	42.13	0.24	85.47	55.30	33.18
13	A1B4C1	41.87	0.24	85.50	88.80	59.66
14	A1B4C2	40.93	0.37	68.57	76.70	53.63
15	A1B4C3	40.70	0.26	79.83	63.67	48.60
16	A1B4C4	43.10	0.23	89.27	59.60	33.50

A1B4C4. In all combinations it is understandable that the higher thermal absorptivity the lower thermal resistance as observed for the single layers also. Thermal absorptivity ‘warm cool feelings’ of moisture barriers which is sandwiched between outershell and thermal barrier cannot have significant effect in combinations measured values. The thermal resistance of layered combinations in which C4 or Nonwoven quilted to Aramid Viscose FR inner lining with 85 g /m^2 mass per unit area used shows the least results which could be because of not being two layers of non woven.

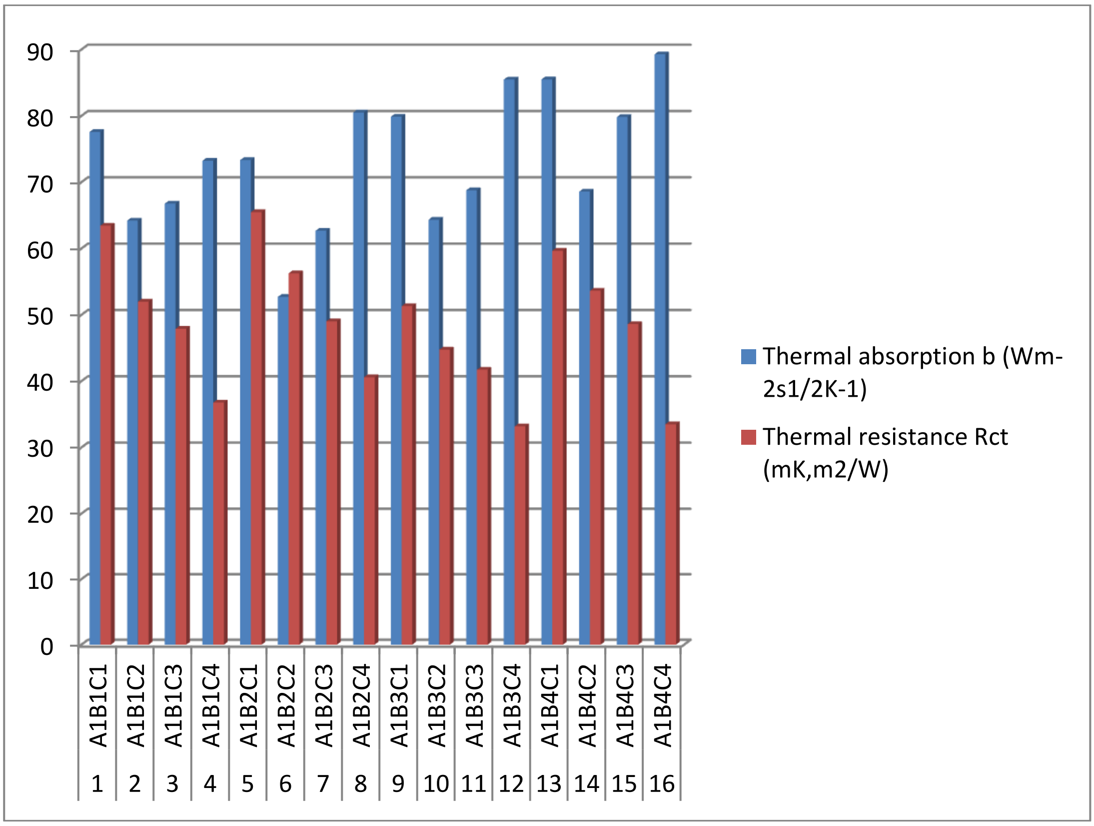

Figure 5.10: Histogram of thermal absorptivity and thermal resistance values of layers with common outer shell A1 or Nomex Outershell Tough with 195 g/ m²

Thermal diffusion (a) values of layered fabrics with common outershell A1 or Nomex Outershell Tough with 195 g/ m² mass per unit area is compared and showed by histogram below.

From the histogram, the thermal diffusion values in which thermal barrier C2 or Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining with 110 g/m^2 used shows the highest values in all combinations even if moisture barriers changed. This could be because of Nomex comfort inner ling used to be quilted.

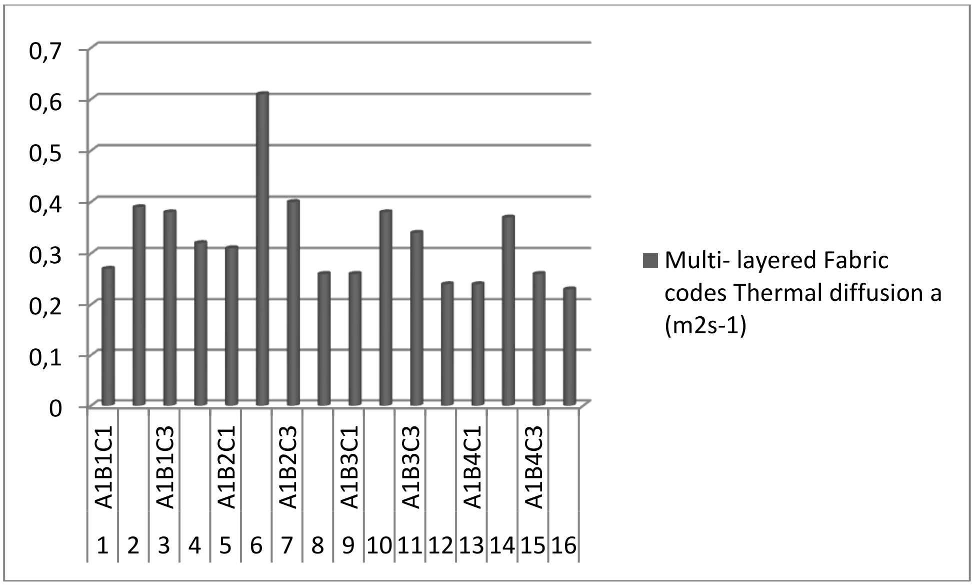

Figure 5.11: Histogram of thermal diffusion values of layered fabrics with common outershell A1 or Nomex Outershell Tough with 195 g/ m²

Table 5.12: Multi- layer fabrics thermal parameters results by Alambeta and Permetest for common outershell code A2 or PBI gold with 200 g/m^2.

No.	Multi-layered Fabric codes	Thermal Parameters by Alambeta				By Permetest
		Thermal conductivity **λ** ($Wm^{-1}K^{-1}$)	Thermal diffusion **a** **(m^2s^{-1})**	Thermal absorption **b** **($Wm^{-2}s^{1/2}K^{-1}$)**	Thermal resistance **R** ($mK.m^2/W$)	Thermal resistance **R_{ct}** ($mK.m^2/W$)
1	A2B1C1	42.27	0.19	98.10	88.47	57.37
2	A2B1C2	40.33	0.33	70.97	74.20	49.13
3	A2B1C3	40.03	0.26	78.43	67.63	46.11
4	A2B1C4	41.60	0.23	76.67	76.10	34.39
5	A2B2C1	41.87	0.22	91.33	93.73	63.29
6	A2B2C2	40.57	0.29	76.67	76.10	50.53
7	A2B2C3	40.70	0.28	77.23	72.67	49.96
8	A2B2C4	42.10	0.42	73.50	64.97	39.43

9	A2B3C1	41.90	0.19	96.63	83.07	59.38
10	A2B3C2	41.17	0.29	77.10	64.27	48.28
11	A2B3C3	40.90	0.26	82.23	68.27	47.36
12	A2B3C4	42.57	0.21	92.70	53.30	34.30
13	A2B4C1	42.40	0.18	100.87	83.50	60.81
14	A2B4C2	41.40	0.36	69.20	74.37	57.50
15	A2B4C3	42.40	0.31	76.33	62.37	48.22
16	A2B4C4	43.93	0.30	82.17	64.97	36.23

From the histogram below the thermal absorptivity values in which thermal barrier coded C1 or Two layers of nonwoven(55+55) quilted to Aramid Viscose FR inner lining with 110 g /m^2 mass per unit area used shows the highest values in all combinations even if moisture barriers changed. This could be because of being two layers nonwoven rather than single layers. Thermal absorptivity 'warm cool feelings' of moisture barriers which is sandwiched between outershell and thermal barrier cannot have significant effect in combinations measured values. The thermal resistance of layered combinations in which C4 or Nonwoven quilted to Aramid Viscose FR inner lining with 85 g /m^2 mass per unit area used shows the least results which could be because of not being two layers of non woven. This holds the same for the outshell A1 used as common above.

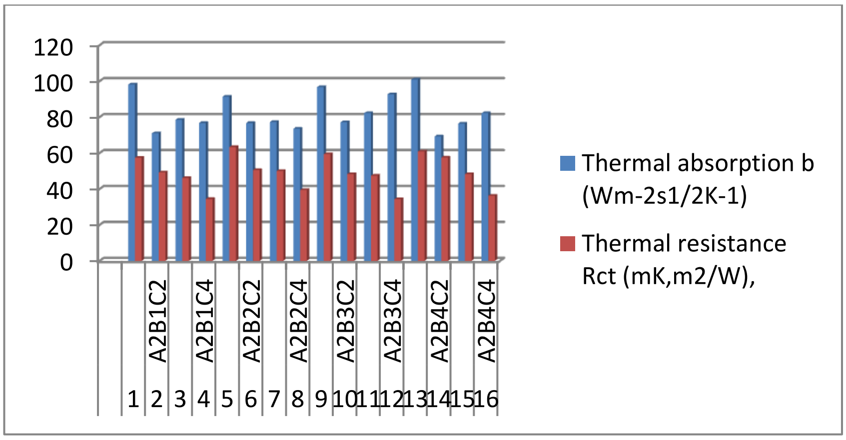

Figure 5.12: Histogram of thermal absorptivity and thermal resistance values of layers with common outer shell A2 or PBI gold with 200 g/ m².

Thermal diffusion (a) values of layered fabrics with common outershell A2 or PBI gold with 200 g/ m² mass per unit area is compared and showed by histogram below. From the histogram the thermal diffusion of thermal barrier coded C4 or Nonwoven quilted to Aramid Viscose FR inner lining with 85 g /m^2 mass per unit area results in the highest value of thermal absorptivity of layered combination coded A2B2C4. Here the effects of higher mass per unit area with higher air density of sample results in this value when compared to C3 or Nonwoven quilted to Aramid Viscose FR inner lining with 55 g /m^2 mass per unit area.

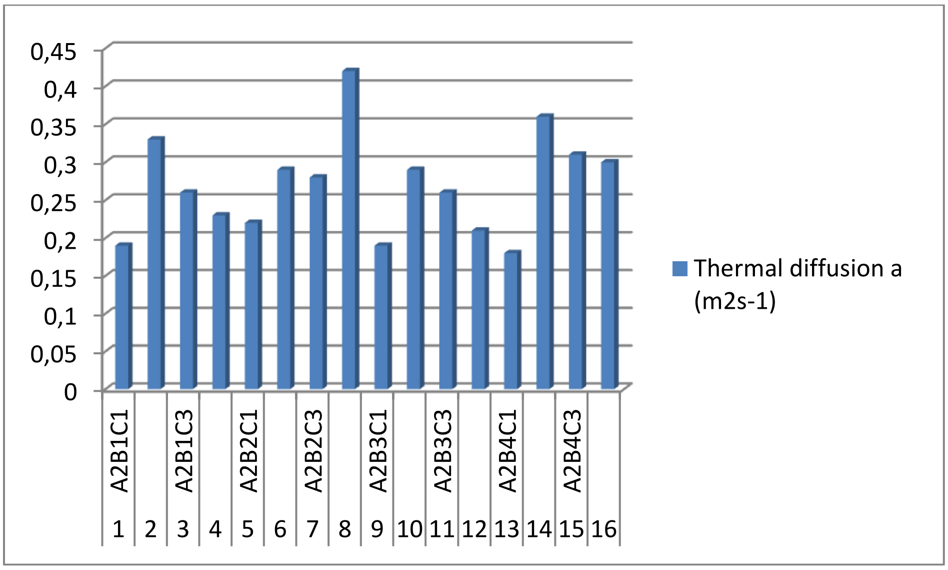

Figure 5.13: Histogram of thermal diffusion values of layered fabrics with common outershell A2 or PBI gold with 200 g/ m².

Table 5.13: Multi- layer fabrics thermal parameters results by Alambeta and Permetest for common outershell A3(PBI Matrix with 200 g/ m²).

No.	Multi-layered Fabric codes	Thermal Parameters by Alambeta				By Permetest
		Thermal conductivity **λ** ($Wm^{-1}K^{-1}$)	Thermal diffusion **a** (m^2s^{-1})	Thermal absorption **b** ($Wm^{-2}s^{1/2}K^{-1}$)	Thermal resistance **R** ($mK.m^2/W$)	Thermal resistance R_{ct} ($mK.m^2/W$)
1	A3B1C1	40.77	0.23	86.07	93.60	50.41
2	A3B1C2	40.87	0.29	76.40	73.90	54.90

3	A3B1C3	41.33	0.31	74.17	72.83	49.45
4	A3B1C4	42.53	0.27	81.70	68.60	39.09
5	A3B2C1	42.33	0.22	91.30	96.33	53.93
6	A3B2C2	40.27	0.40	65.87	79.13	59.42
7	A3B2C3	40.33	0.33	70.80	72.30	51.17
8	A3B2C4	42.17	0.51	64.10	70.87	40.57
9	A3B3C1	42.33	0.22	91.30	96.33	55.39
10	A3B3C2	41.40	0.41	65.10	67.37	51.60
11	A3B3C3	41.53	0.38	67.50	63.60	42.39
12	A3B3C4	43.27	0.31	78.57	55.10	31.74
13	A3B4C1	41.33	0.22	89.43	84.37	54.61
14	A3B4C2	43.13	0.39	50.10	66.43	50.14
15	A3B4C3	42.50	0.33	75.03	64.37	47.33
16	A3B4C4	44.73	0.25	79.87	58.30	46.13

From the histogram below the thermal absorptivity values in which thermal barrier coded C1 or Two layers of nonwoven(55+55) quilted to Aramid Viscose FR inner lining with 110 g /m^2 mass per unit area used shows the highest values in all combinations even if moisture barriers changed. This could be because of being two layers nonwoven rather than single layers. Further more this thermal barrier was quilted to Aramid viscose FR inner lining not Nomex comfort FR inner lining. This results agreed with the case of outershell PBI gold with 200 g/ m^2. Thermal absorptivity ‘warm cool feelings’ of moisture barriers which is sandwiched between outershell and thermal barrier cannot have significant effect in combinations measured values. The thermal resistance of layered combinations in which C4 or Nonwoven quilted to Aramid Viscose FR inner lining with 85 g /m^2 mass per unit area used shows the least results which could be because of not being two layers of non woven. This holds the same for the outshells A1 and A2 used as common above.

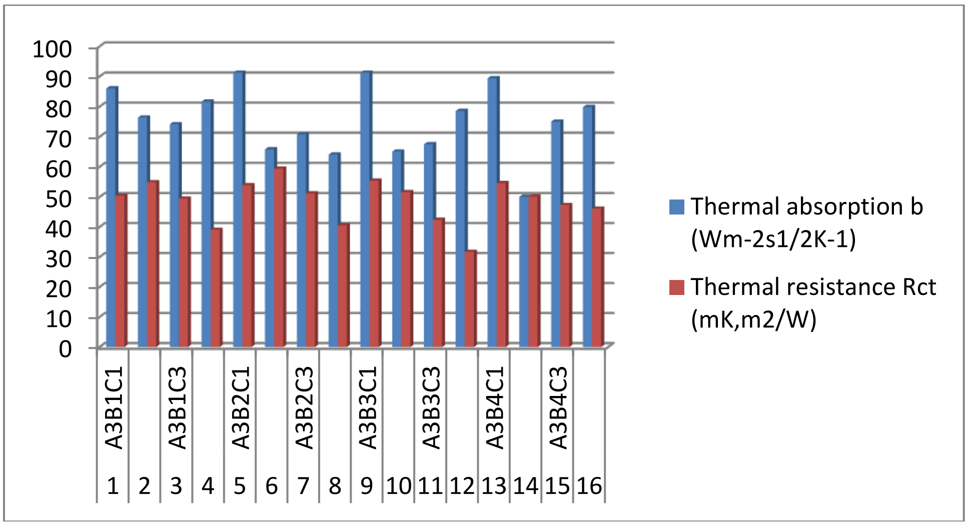

Figure 5.14: Histogram of thermal absorptivity and thermal resistance values of layers with common outer shell A3 or PBI Matrix with 200 g/ m².

Thermal diffusion (a) values of layered fabrics with common outershell A3 or PBI Matrix with 200 g/ m² mass per unit area compared and showed by histogram below. From the histogram the thermal diffusion of thermal barrier coded C4 or Nonwoven quilted to Aramid Viscose FR inner lining with 85 g /m^2 mass per unit area results in the highest value of thermal absorptivity of layered combination coded A3B2C4. Here the effects of higher mass per unit area with higher air density of sample results in this value when compared to C3 or Nonwoven quilted to Aramid Viscose FR inner lining with 55 g /m^2 mass per unit area. This agreed with the values of outershell A2 or PBI gold with 200 g/m² above.

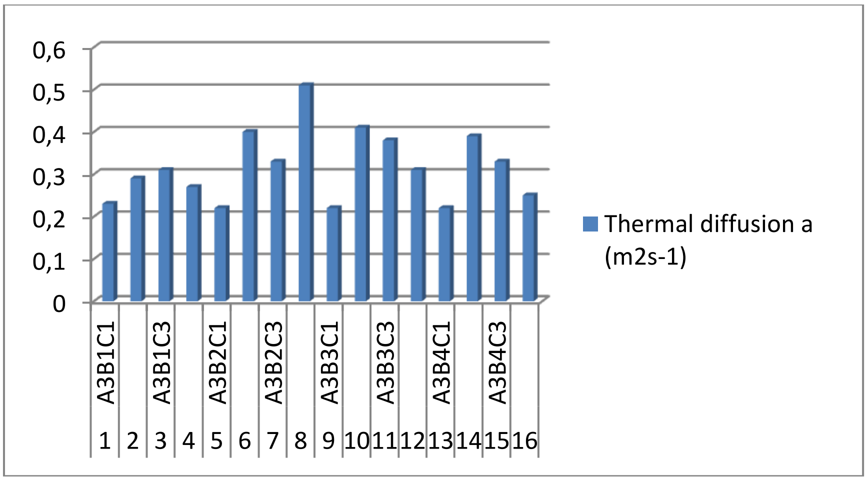

Figure 5.15: Histogram of thermal diffusion values of layered fabrics with common outershell A3 or PBI Matrix with 200 g/ m².

Table 5.14: Multi- layer fabrics thermal parameters results by Alambeta Permetest for common outershell code A4 or Nomex Outer shellTough Ripstop

No.	Multi-layered Fabric codes	Thermal Parameters by Alambeta				By Permetest
		Thermal conductivity **λ** $(Wm^{-1}K^{-1})$	Thermal diffusion **a** (m^2s^{-1})	Thermal absorption **b** $(Wm^{-2}s^{1/2}K^{-1})$	Thermal resistance **R** $(mK.m^2/W)$	Thermal resistance $\mathbf{R_{ct}}$ $(mK.m^2/W)$
1	A4B1C1	41.83	0.22	90.53	87.37	62.00
2	A4B1C2	40.13	0.34	69.20	76.30	54.60
3	A4B1C3	40.37	0.41	65.57	71.20	51.89
4	A4B1C4	41.50	0.26	82.13	69.50	40.83
5	A4B2C1	41.13	0.20	92.20	99.73	59.76
6	A4B2C2	40.10	0.28	75.57	83.40	57.58
7	A4B2C3	40.97	0.29	76.60	76.53	53.66
8	A4B2C4	41.73	0.27	71.27	75.77	45.65
9	A4B3C1	40.73	0.19	93.97	87.17	55.35
10	A4B3C2	41.00	0.32	74.13	71.63	50.76
11	A4B3C3	40.93	0.31	73.53	66.47	45.99
12	A4B3C4	42.33	0.24	87.60	63.57	38.04
13	A4B4C1	42.13	0.18	101.13	85.97	62.30
14	A4B4C2	41.43	0.30	77.03	72.77	55.86
15	A4B4C3	41.80	0.38	69.93	66.67	49.91
16	A4B4C4	43.50	0.25	87.13	63.30	40.68

From the histogram below the thermal absorptivity values in which thermal barrier coded C1 or Two layers of nonwoven(55+55) quilted to Aramid Viscose FR inner lining with 110 g $/m^2$ mass per unit area used shows the highest values in all combinations even if moisture barriers changed. This could be because of being two layers nonwoven rather than single layers. Further more this thermal barrier was quilted to Aramid viscose FR inner lining not Nomex comfort FR inner lining. This results agreed with the case of outershell PBI gold with 200 g/ m² and PBI Matrix with 200 g/ m². Thermal absorptivity 'warm cool feelings' of moisture barriers which is sandwiched between outershell and thermal barrier cannot have significant effect in combinations measured values. The thermal resistance of layered combinations in which C4 or Nonwoven quilted to Aramid Viscose FR inner lining with 85 g /m^2 mass per unit area used shows the least results which could be because of not being two layers of non woven. This holds the same for the outshells A1, A2 and A3 used as common above.

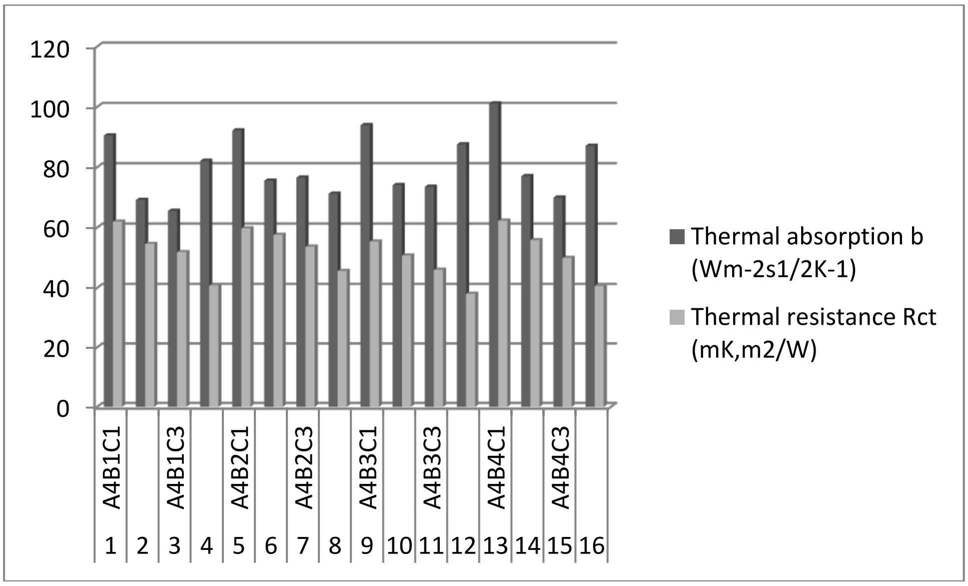

Figure 5.16: Histogram of thermal absorptivity and thermal resistance values of layers with common outer shell A4 or Nomex Outershell Tough Ripstop with 195 g/ m².

Thermal diffusion (a) values of layered fabrics with common outershell A4 or Nomex Outershell Tough Ripstop with 195 g/ m² mass per unit area compared and showed by histogram below. From the histogram the thermal diffusion of thermal barrier coded C3 or Nonwoven quilted to Aramid Viscose FR inner lining with 55 g /m^2 mass per unit area results in the highest value of thermal absorptivity of layered combination coded A4B1C3. Here the effects of moisture barrier might be considered for not agreeing with the previous outershell results.

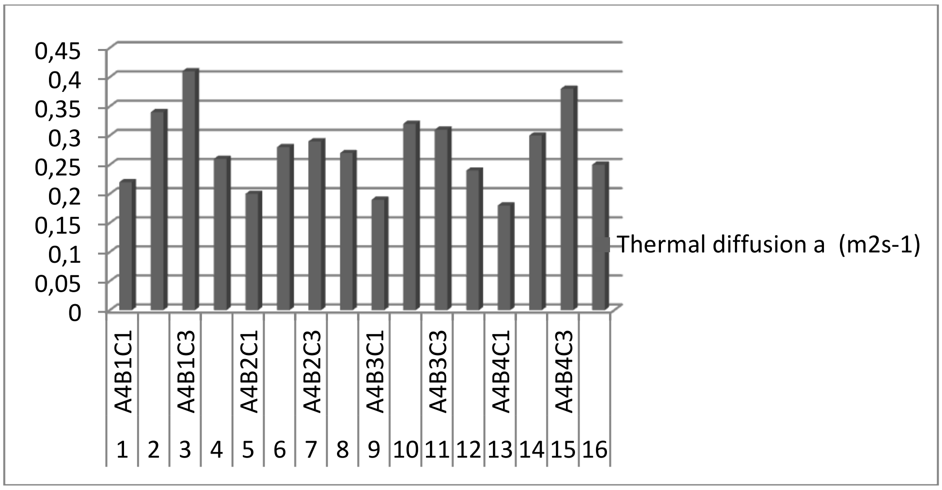

Figure 5.17: Histogram of thermal diffusion values of layered fabrics with common outershell A4 or Nomex Outershell Tough Ripstop with 195 g/ m².

5.4 Protection Performance Test Results and Discussions

The burning tests have done only for layered fabrics because of the single layers alone cannot fulfill the standards minimum protection requirements. Knowing this and testing for single layers have no importance rather than consuming the sample fabrics. The layered fabrics are tested for two tests. The first one is convective heat transfer test which is done according to EN 367 standard. This test measures the time in seconds that indicates the convective heat transfer index at 12 and 24 seconds. It is abbreviated as EN367 HTI 12 AND EN367 HTI 24, and their difference is also calculated as shown in table 5.x. The second test is layered fabrics protection test to radiant heat flux which is done according to EN6942 and the index measures times in seconds at 12 and 24 seconds. It is abbreviated as RHTI 12 and RHTI 24. Thus the more time(s) resists to burn, the more protective the layer.

Before discussing on the results of burning tests it is better to correlate the results and see their relationship for tests separately. Comparison of EN367 HTI 12 and EN367 HTI 24 convective heat transfer index at 12 second and 24 second relations by correlation was observed.

Based on the null hyphothesis which says; there is significant difference between measured values of burning tests according to EN367 HTI 12 and EN367 HTI 24, convective heat transfer index at 12 second and 24 second, and also; There is significant difference between measured values according to EN6942 RHTI 12 and EN6942 RHTI 24, radiant heat transfer index at 12 second and 24 seconds.

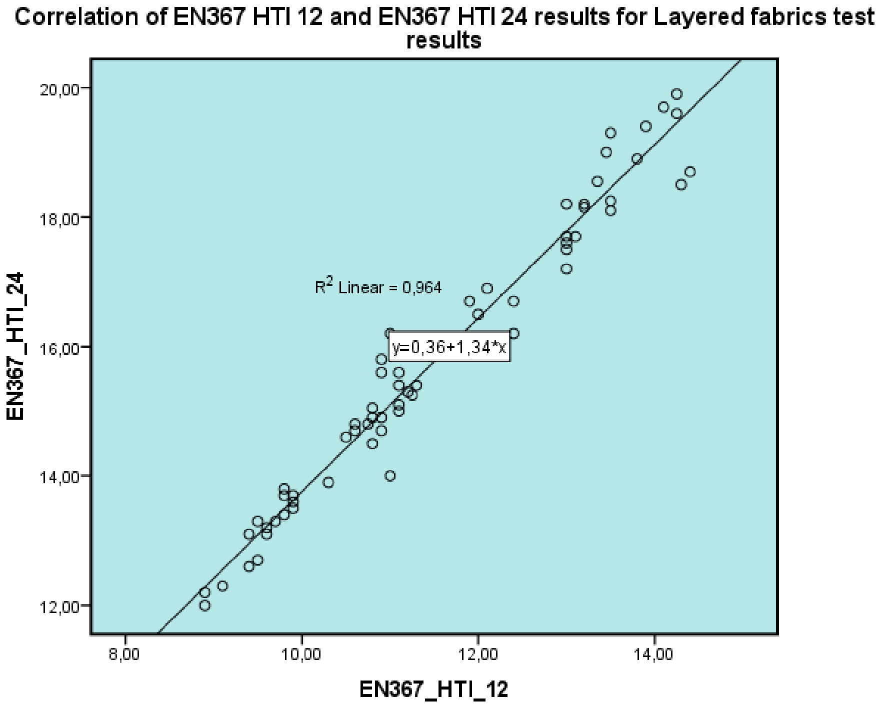

Figure 5.18: Correlation EN367 HTI 12 and EN367 HTI 24 convective heat transfer index at 12 second and 24 second.

Table 5.15: Comparison of EN367 HTI 12 and EN367 HTI 24 convective heat transfer ındex at 12 second and 24 second.

Correlations

		EN367_HTI_12	EN367_HTI_24
EN367_HTI_12	Pearson Correlation	1	,982**
	Sig. (2-tailed)		,000
	N	64	64
EN367_HTI_24	Pearson Correlation	,982**	1
	Sig. (2-tailed)	,000	
	N	64	64

**. Correlation is significant at the 0.01 level (2-tailed).

It shows that there is very significat relationship between the two results of cenvective heat transfer index at 12 and 24 seconds with correlation coeffiecient of 0.982 which is greater than 0.65 and thus we can consider EN367 HTI 24 as their comparison parameter in place of two results compared to each other.

Similarly, the comparison of EN6942 RHTI 12 and EN6942 RHTI 24 radiant heat transfer ındex at 12 second and 24 second relations by correlation

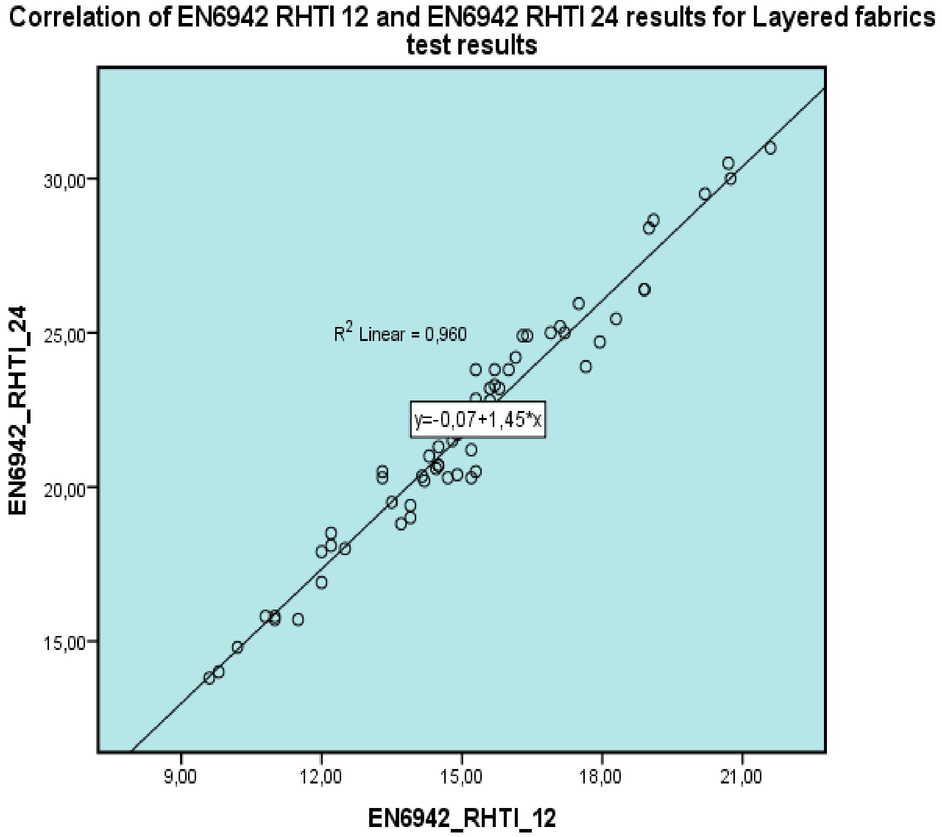

Figure 5.19: Correlation of EN6942 RHTI 12 and EN6942 RHTI 24 radiant heat transfer index at 12 second and 24 second.

It shows that there is very significat relationship with 0.980 correlation coefficients between the two results (EN6942 RHTI 12 and EN6942 RHTI 24 radiant heat transfer index at 12 second and 24 second) and thus we can consider EN6942 RHTI 24 as their comparison parameter in place of two results compared to each other

Table 5.16: Comparison of EN6942 RHTI 12 and EN6942 RHTI 24 radiant heat transfer index at 12 second and 24 second.

Correlations

		EN6942_RHTI_12	EN6942_RHTI_24
EN6942_RHTI_12	Pearson Correlation	1	.980**
	Sig. (2-tailed)		.000
	N	64	64
EN6942_RHTI_24	Pearson Correlation	.980**	1
	Sig. (2-tailed)	,000	
	N	64	64

**. Correlation is significant at the 0.01 level (2-tailed).

Table 5.17: Burning test results for layered fabrics HTI and RHTI with common moisture barrier B1(PU membrane laminated to non woven (50/25/25))

No.	Multi-layered fabrics code	**EN 367 HTI12**	**EN 367 HTI24**	**EN 367 HTI24-HTI12**	**EN 6942 RHTI 12**	**EN 6942 RHTI24**	**EN 6942 RHTI 24-RHTI 12**
1	B1C1A1	13.5	18.25	4.75	17.65	23.9	6.25
2	B1C1 A2	12.1	16.9	4.8	20.75	30	9.25
3	B1C1 A3	10.8	14.9	4.1	21.6	31	9.4
4	B1C1 A4	13.2	18.15	4.95	16.4	22.2	5.8
5	B1C2 A1	13	17.5	4.5	15.2	20.3	5.1
6	B1C2 A2	11.9	16.7	4.8	20.2	29.5	9.3
7	B1C2 A3	10.6	14.7	4.1	20.7	30.5	9.8
8	B1C2 A4	13.1	17.7	4.6	15.3	20.5	5.2

9	B1C3 A1	10.8	14.5	3.7	13.9	19	5.1
10	B1C3 A2	9.9	13.6	3.7	14.8	21.5	6.7
11	B1C3 A3	10.3	13.9	3.6	14.5	20.7	6.2
12	B1C3 A4	9.4	13.1	3.7	11	15.8	4.8
13	B1C4 A1	11.1	15.1	4	14.7	20.3	5.6
14	B1C4 A2	10.9	14.9	4	15.7	23.3	7.6
15	B1C4 A3	11.2	15.3	4.1	15.6	23.2	7.6
16	B1C4 A4	10.6	14.8	4.2	12.2	18.1	5.9

From the histogram below for common moisture barrier B1 or PU membrane laminated to nonwoven (50/25/25) with 55g/m^2, the outershell coded A3 or PBI Matrix with 200 g/m² mass per unit area resulted in the highest protection to radiant heat transfer from each groups, even if thermal barriers changed. However, burning results for convective heat transfer protection is the lowest for PBI Matrix with 200g/m^2 from the groups.

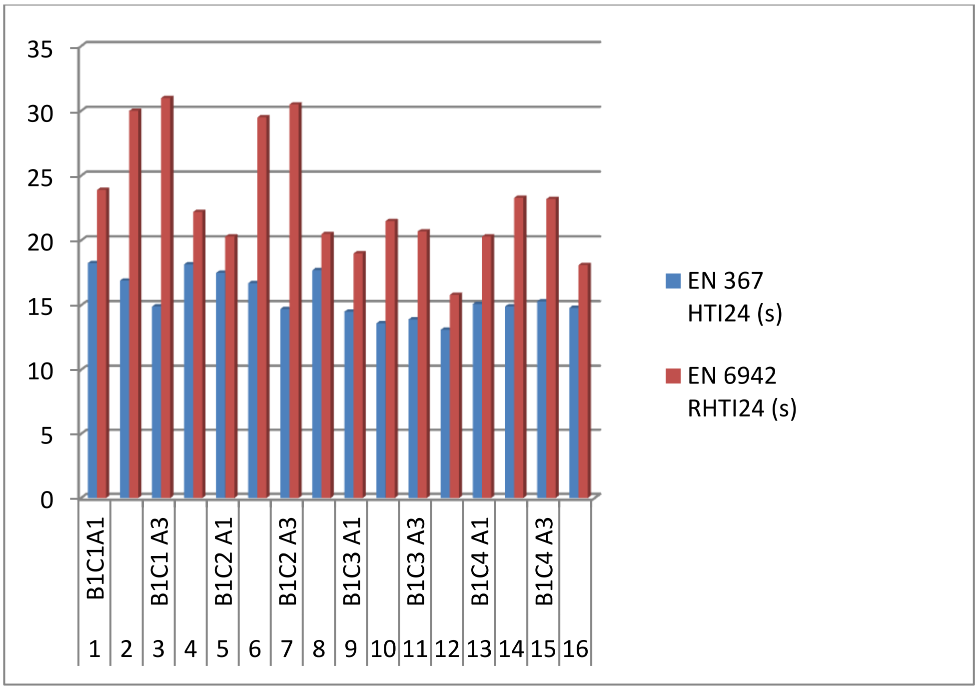

Figure 5.20: Histogram of layered fabrics EN367 HTI 24 and EN6942 RHTI 24 results with common moisture barrier B1 or PU membrane laminated to nonwoven (50/25/25) with 55g/m^2.

Table 5.18: Burning test results for layered fabrics HTIRHTI, common moisture barrier B2 or PU membrane laminated to non woven (50/25/25).

No.	Multi-layered fabrics code	**EN 367 HTI12**	**EN 367 HTI24**	**EN 367 HTI24-HTI12**	**EN 6942 RHTI 12**	**EN 6942 RHTI24**	**EN 6942 RHTI 24-RHTI 12**
1	B2C1 A1	13.8	18.9	5.1	17.95	24.7	6.75
2	B2C1 A2	14.25	19.9	5.65	19.1	28.65	9.55
3	B2C1 A3	14.1	19.7	5.6	19	28.4	9.4
4	B2C1 A4	14.25	19.6	5.35	18.3	25.45	7.15
5	B2C2 A1	14.3	18.5	4.2	15.7	22.4	6.7
6	B2C2 A2	13.9	19.4	5.5	18.9	26.4	7.5
7	B2C2 A3	13.5	19.3	5.8	18.9	26.4	7.3
8	B2C2 A4	14.4	18.7	4.3	15.5	22.2	6.7
9	B2C3 A1	13	17.2	4.2	15.2	21.2	5.9
10	B2C3 A2	12.4	16.2	3.8	15.6	22.8	7.2
11	B2C3 A3	11.1	15	3.9	15.4	22.6	7.2
12	B2C3 A4	12.1	16	3.9	14.3	21	6.7
13	B2C4 A1	12.4	16.7	4.3	14.2	20.2	6
14	B2C4 A2	13	17.6	4.6	16.4	24.9	8.5
15	B2C4 A3	12	16.5	4.5	16.3	24.9	8.6
16	B2C4 A4	13	17.7	4.7	15.8	23.2	7.4

From the histogram below for common moisture barrier B2 or PU membrane laminated to nonwoven (50/25/25) with 85 g/m^2, the outershell coded A3 or PBI Matrix with 200 g/m² mass per unit area and outer shell coded A2 or PBI gold with 200 g/m² are first and second respectively with slight differences in protection to radiant heat transfer from each groups, even if thermal barriers changed. Protection to convective heat transfer is also proportional to radiant heat transfer unlike in moisture barrier PU membrane laminated to nonwoven (50/25/25) with 55g/m^2.

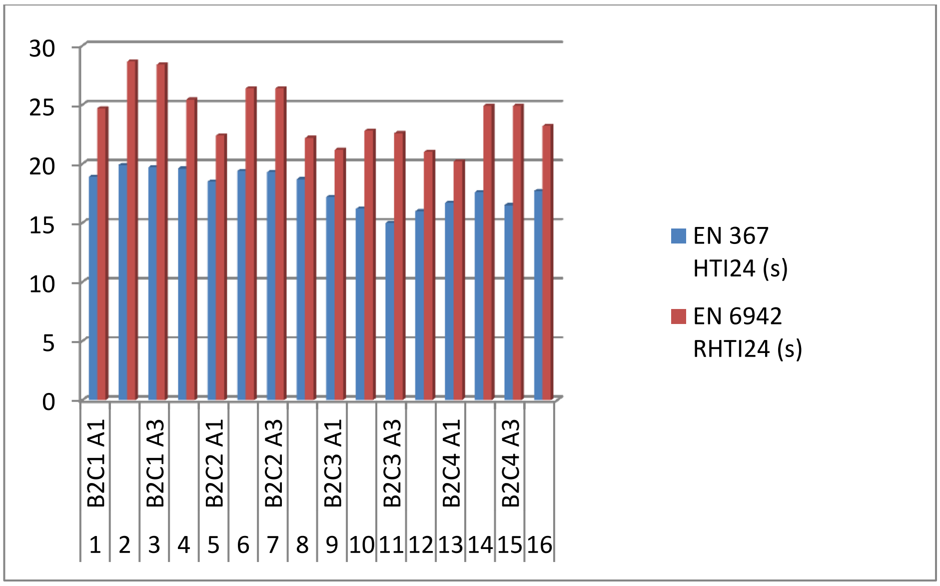

Figure 5.21: Histogram of layered fabrics EN367 HTI 24 and EN6942 RHTI 24 results with common moisture barrier B2 or PU membrane laminated to nonwoven (50/25/25) with 85 g/m^2.

Table 5.19: Burning test results for layered fabrics HTI and RHTI with common moisture barrier B3 or PU membrane laminated to knitted fabric.

No.	Multi-layered fabrics code	**EN 367 HTI12**	**EN 367 HTI24**	**EN 367 HTI24-HTI12**	**EN 6942 RHTI 12**	**EN 6942 RHTI24**	**EN 6942 RHTI 24-RHTI 12**
1	B3C1 A1	10.75	14.8	4.05	14.15	20.35	6.2
2	B3C1 A2	11.4	16.05	4.65	16.15	24.2	8.05
3	B3C1 A3	11	16.2	5.2	16	23.8	7.8
4	B3C1 A4	10.8	15.05	4.25	14.45	20.6	6.15
5	B3C2 A1	9.8	13.7	3.9	13.9	19.4	5.5
6	B3C2 A2	10.9	15.8	4.9	15.7	23.8	8.1
7	B3C2 A3	10.9	15.6	4.7	15.3	23.8	8.5
8	B3C2 A4	9.8	13.8	4	13.5	19.5	6

9	B3C3 A1	9.4	12.6	3.2	9.6	13.8	4.2
10	B3C3 A2	9.1	12.3	3.2	12.2	18.5	6.3
11	B3C3 A3	8.9	12.2	3.3	12	17.9	5.9
12	B3C3 A4	8.9	12	3.1	9.8	14	4.2
13	B3C4 A1	9.6	13.1	3.5	10.2	14.8	4.6
14	B3C4 A2	9.8	13.4	3.6	13.3	20.5	7.2
15	B3C4 A3	9.5	13.3	3.8	13.3	20.3	7
16	B3C4 A4	9.6	13.2	3.6	10.8	15.8	5

From the histogram below for common moisture barrier B3 or PU membrane laminated to knitted fabric with 85 g/m^2, the outershell coded A3 or PBI Matrix with 200 g/m² mass per unit area and outer shell coded A2 or PBI gold with 200 g/m² are first and second respectively with slight differences in protection to radiant heat transfer from each groups, even if thermal barriers changed. Protection to convective heat transfer is also proportional to radiant heat transfer.

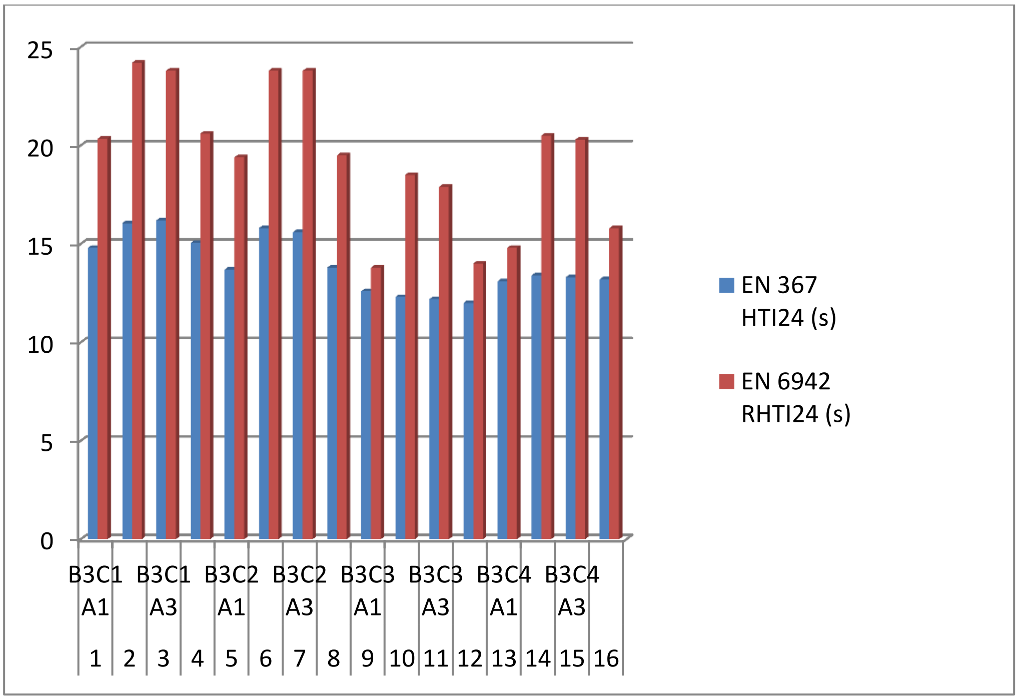

Figure 5.22: Histogram of layered fabrics EN367 HTI 24 and EN6942 RHTI 24 results with common moisture barrier B3or PU membrane laminated to knitted fabric with 85 g/m^2.

Table 5.20: Burning test results for layered fabrics HTI and RHTI with common moisture barrier B4 or PU membrane laminated to knitted fabric.

No.	Multi-layered fabrics code	**EN 367 HTI12**	**EN 367 HTI24**	**EN 367 HTI24-HTI12**	**EN 6942 RHTI 12**	**EN 6942 RHTI24**	**EN 6942 RHTI 24-RHTI 12**
1	B4C1 A1	11.25	15.25	4	15.05	22.1	7.05
2	B4C1 A2	13.35	18.55	5.2	17.5	25.95	8.45
3	B4C1 A3	13	18.2	5.2	17.2	25	7.8
4	B4C1 A4	13.45	19	5.55	15.3	22.85	7.55
5	B4C2 A1	10.9	14.7	3.8	14.9	21.7	6.8
6	B4C2 A2	13.2	18.2	5	17.1	25.2	8.1
7	B4C2 A3	13.5	18.1	4.6	16.9	25	8.1
8	B4C2 A4	10.5	14.6	4.1	14.9	20.4	5.5
9	B4C3 A1	9.5	12.7	3.2	11.5	15.7	4.2
10	B4C3 A2	10	14	4	16	23.8	7.8
11	B4C3 A3	9.9	13.5	3.6	13.7	18.8	5.1
12	B4C3 A4	9.9	13.7	3.8	11	15.7	4.7
13	B4C4 A1	9.7	13.3	3.6	12	16.9	4.9
14	B4C4 A2	11.1	15.6	4.5	14.5	21.3	6.8
15	B4C4 A3	11.3	15.4	4.1	14.5	20.7	6.2
16	B4C4 A4	11.1	15.4	4.3	12.5	18	5.5

From the histogram below for common moisture barrier B4 or PU membrane laminated to knitted fabric with 145 g/m^2, the outershell coded A2 or PBI gold with 200 g/m² mass per unit area and outer shell coded A3 or PBI Matrix with 200 g/m² are first and second respectively with slight differences in protection to radiant heat transfer from each groups, even if thermal barriers changed. Protection to convective heat transfer is also proportional to radiant heat transfer.

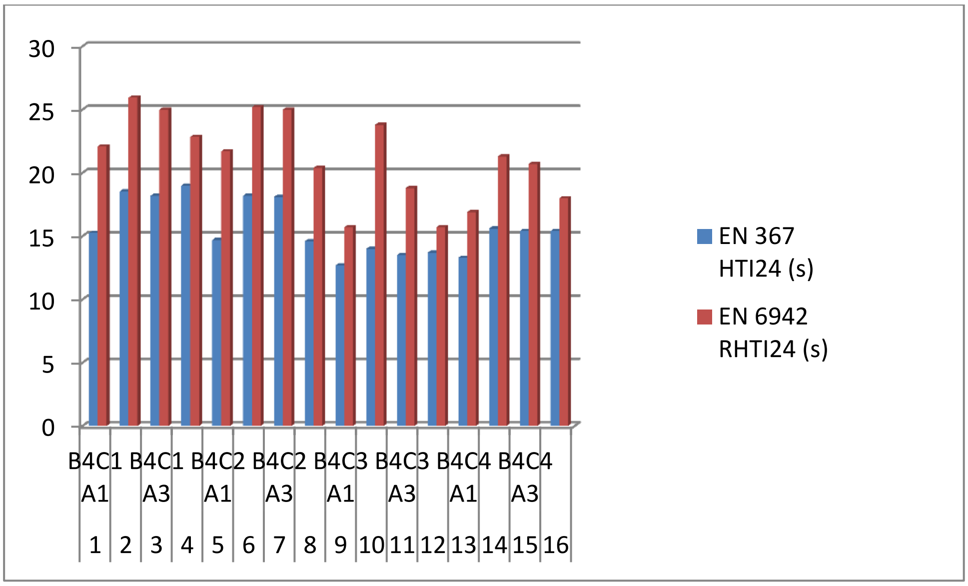

Figure 5.23: Histogram of layered fabrics EN367 HTI 24 and EN6942 RHTI 24 results with common moisture barrier B4 or PU membrane laminated to knitted fabric with 145 g/m^2.

Generally concluding from all histograms of protection performance, the higher mass per unit area of outershell, the higher the protection to radiant heat transfer and also protection to convective heat transfer. Moreover,considering the results of outershell materials PBI are better in burning protection performance when compared to Nomex Outershell fabrics.

5.5 Thermal Comfort Index as Comparison Term

The overall measured values of comfort properties shall be evaluated in one system and then used to screen the comfort level of firefighters protective clothings. Accordingly the thermal comfort index calculation is suitable to rank all 64 samples understudy. Numerous studies of textile thermal protective properties as well as theoretical considerations have allowed to develop a generalised formula for a comprehensive index representing the capability of textiles to ensure thermal comfort (*Thermal Comfort Index*). The formula is as follows**[90]**

$$TCI = \sum_{i=1}^{n}\left(a_{xi} * \frac{Xi - Ximin}{Xi}\right) + \sum_{j=1}^{m}\left(a_{zj} * \frac{Zjmax - Zj}{Zjmax}\right) \quad \textbf{(5.3)}$$

Where:

TCI – Thermal Comfort Index,

xi – the value of *ith* parameter,which results in an improvement of thermal comfort

when increased, where *i* = 1, 2, …, *n*,

x imin – minimum value of *ith* parameter needed to ensure thermal comfort,

zj – the value of *jth* parameter, which results in a deterioration in thermal comfort when

increased, where *j* = 1, 2, …, *m*,

z jmax – maximum value of *jth* parameter, which is acceptable from the point of view of

thermal comfort,

ax,i, *a z,j* – parameters calculated on the basis of the importance degree of particular

properties used for calculations.

The value of *TCI* ranges between 0 and 1. The higher the value of the index, the higher the capability of a fabric to ensure thermal comfort. A certain limitation of *TCI* lies in the fact that the current level of knowledge does not allow to determine *minima and maxima*, i.e. critical points at which values of particular parameters of fabrics for everyday clothing are acceptable for providing thermal comfort. The basic difficulty in determining these values lies in the impossibility to define conditions in which clothing would be worn, the changeability of these conditions during the wearing of the clothing which result from all the manner of wearing, thermal environmental conditions, individual features and the type of physical activity of the wearer **[89].** *TCI* can be used to assess textiles for specialist protective clothing, which have normative requirements for the range of values of an indicator influencing thermal protection. Also the index is useful if a receiver has particular requirements for textiles used in his/ her order. In this case requirements can be taken as critical values, i.e. minimum and maximum values in the formula for *TCI*.

5.5.1 Relative thermal comfort index

Matusiak M., Sikorski K.(2011), In a comparative analysis of fabrics evaluated with *TCI* above formula, it is advisable to use a maximum value of the *zj* property obtained for the group of fabrics under evaluation instead of the maximum *zmax* value acceptable for providing thermal comfort. Similarly, instead of using the minimum value *xmin* necessary to ensure thermal comfort, the lowest value of the *xi* property obtained for the group of fabrics under evaluation and comparison can be used**[90].**

An index calculated on the basis of minimum and maximum values of particular parameters obtained as a result of testing a group of fabrics should be considered as a relative measure of the quality of fabrics from the point of view of their ability to ensure thermal comfort, since it allows a comparative evaluation of fabrics and assessment of the level of fabric quality with regard to the quality of other fabrics evaluated by means of the same procedure. All things considered, an index calculated on the basis of minimum and maximum values of parameters obtained by measuring a group of fabrics that are under collective evaluation is referred to as Relative Thermal Comfort Index (*RTCI*), the formula of which is as follows:

$$RTCI = \sum_{i=1}^{n}\left(a_{xi} * \frac{Xi - XiminIG}{Xi}\right) + \sum_{j=1}^{m}\left(a_{zj} * \frac{Zjmax - Zj}{ZjmaxIG}\right) \quad \textbf{(5.4)}$$

Where:

RTCI – Relative Thermal Comfort Index,

Xi – the value of *ith* parameter, which results in an improvement of thermal comfort when increased, where *i* = 1, 2, …, *n*,

ximinIG – minimum (intragroup - *IG*) value of *ith* parameter obtained as a result of measuring a group of textiles under collective evaluation,

zj – the value of *jth* parameter, which results in a deterioration of thermal comfort when increased, where *j* = 1, 2, …, *m*,

zjmaxIG – maximum (intragroup - *IG*) value of *jth* parameter obtained as a result of measurements made on a group of textiles under collective evaluation,

$$ax = Pi/[\sum_{i=1}^{n}(\mathrm{pi}) + \sum_{j=1}^{m}(\mathrm{pj})] \quad \textbf{(5.5)}$$

$$aj = Pj/[\sum_{i=1}^{n}(\mathrm{pi}) + \sum_{j=1}^{m}(\mathrm{pj})] \quad \textbf{(5.6)}$$

Where:

pi – significance of *ith* property (1 ÷ 5),

pj – significance of *jth* property (1 ÷ 5).

The properties of fabrics which influence their capability to ensure thermal comfort as well as significance degrees corresponding to these properties have been selected on the basis of experience, an analysis of the heat exchange processes which take place in various climatic conditions, and the results of numerous prior studies concerning human body protection against hot and thermal discomfort **[91].**

Water vapour permeability is assumed to be a key parameter since it is body's natural mechanism for cooling itself when overheating is through sensible perspiration in the form of liquid sweat. This is caused by strenuous activity or climatic conditions. Sweating is troublesome in this case. If the water vapour cannot escape to the surrounding atmosphere then the relative humidity inside the clothing increases, causing a wet feeling on the skin, and leading to an uncomfortable sensation. Consequently,water vapour resistance is scored 5, i.e. the highest degree of significance. Thermal resistance is also one of important parameter since body protection against excessive heat gain is an absolute condition for maintaining thermal comfort in a hot microclimate and has been scored 4.

Table 5.21: Degree of importance of the properties used for RTCI calculation.

	Property	Units	P	a
1	Water-vapour resistance	m^2.Pa/W	5	0.357
2	Thermal resistance	mK.m^2/W	4	0.286
3	Thermal absorptivity	$Wm^{-2}s^{1/2}K^{-1}$	3	0.214
4	Thermal diffusion	m^2s^{-1}	2	0.143
	Σpi		14	

Thermal absorptivity is the characteristic of how textile feels when touched, i.e. warm or cold. A warm or cold sensation when skin touches clothes is important parameter for comfort because it influences the subjective feeling of thermal comfort. This feeling is a result of heat exchange that takes place between the human hand and the fabric because of the temperature difference between the fabric surface and that of the human skin. Consequently, thermal absorptivity has been regarded as an important property, hence it is scored 3 (out of 5). Thermal diffusion is an ability related to the heat flow through the air in the fabric structure. The thermal diffusion of the textile materials is the transient thermal characteristic of textiles.hence it should also considered while discusing thermal comfort index and scaled as 2 out of 5. Then Relative comfort index has been calculated acccording to below formula.

RTCI=0,214*(1-0,18/a)+0,143*(1-52,7/b)+0,357*(1-Ret/31,69)+0,286*(1-Rct/65,47)

Relative thermal comfort index calculated values ranges between zero and one and the more values close to 1 the more it is comfortable. Accordingly, from 64 total samples, layered fabrics coded A1B3C4, A3B3C4 and A3B3C3 ranked 1 up to 3 respectively as the most comfortable layered and samples A2B2C1, A4B4C1, A4B2C1 are screened from the least in comfort levels respectively

Table 5.22: The calculated RTI of the layered fabrics.

No.	Code	a	b	R_{et}	R_{ct}	RTCI
1	A1B1C1	0.27	77.57	21.94	63.43	0.317333
2	A1B1C2	0.39	64.20	21.16	51.99	0.317333
3	A1B1C3	0.38	66.77	22.48	47.90	0.322858
4	A1B1C4	0.32	73.23	23.14	36.77	0.355625
5	A1B2C1	0.31	73.33	26.91	65.47	0.1849
6	A1B2C2	0.61	52.70	22.38	56.25	0.295643
7	A1B2C3	0.40	62.67	24.55	49.02	0.292592
8	A1B2C4	0.26	80.50	25.69	40.58	0.293612
9	A1B3C1	0.26	79.87	21.37	51.31	0.293883
10	A1B3C2	0.38	64.33	19.94	44.75	0.360731
11	A1B3C3	0.34	68.77	21.59	41.72	0.350435
12	A1B3C4	0.24	85.47	19.16	33.18	0.393405
13	A1B4C1	0.24	85.50	29.14	59.66	0.162887
14	A1B4C2	0.37	68.57	22.67	53.63	0.294915
15	A1B4C3	0.26	79.83	28.25	48.60	0.22799

16	A1B4C4	0.23	89.27	25.57	33.50	0.316784
17	A2B1C1	0.19	98.10	25.13	57.37	0.183856
18	A2B1C2	0.33	70.97	25.23	49.13	0.276575
19	A2B1C3	0.26	78.43	26.95	46.11	0.251542
20	A2B1C4	0.23	76.67	27.76	34.39	0.271025
21	A2B2C1	0.22	91.33	28.32	63.29	0.146581
22	A2B2C2	0.29	76.67	25.62	50.53	0.2574
23	A2B2C3	0.28	77.23	26.78	49.96	0.244733
24	A2B2C4	0.42	73.50	26.52	39.43	0.335054
25	A2B3C1	0.19	96.63	20.84	59.38	0.226545
26	A2B3C2	0.29	77.10	21.92	48.28	0.309741
27	A2B3C3	0.26	82.23	20.07	47.36	0.324329
28	A2B3C4	0.21	92.70	20.22	34.30	0.359384
29	A2B4C1	0.18	100.87	23.31	60.81	0.178131
30	A2B4C2	0.36	69.20	26.73	57.50	0.231676
31	A2B4C3	0.31	76.33	24.81	48.22	0.286084
32	A2B4C4	0.30	82.17	23.98	36.23	0.350427
33	A3B1C1	0.23	86.07	25.62	50.41	0.232862
34	A3B1C2	0.29	76.40	24.03	54.90	0.25644
35	A3B1C3	0.31	74.17	25.48	49.45	0.271353
36	A3B1C4	0.27	81.70	24.57	39.09	0.318401
37	A3B2C1	0.22	91.30	28.61	53.93	0.182622
38	A3B2C2	0.40	65.87	27.79	59.42	0.217343
39	A3B2C3	0.33	70.80	26.17	51.17	0.257735
40	A3B2C4	0.51	64.10	24.82	40.57	0.34962
41	A3B3C1	0.22	91.30	23.77	55.39	0.230731

42	A3B3C2	0.41	65.10	21.93	51.60	0.317341
43	A3B3C3	0.38	67.50	19.89	42.39	0.377496
44	A3B3C4	0.31	78.57	22.91	31.74	0.381469
45	A3B4C1	0.22	89.43	25.51	54.61	0.210873
46	A3B4C2	0.39	50.10	31.69	50.14	0.174316
47	A3B4C3	0.33	75.03	28.48	47.33	0.254155
48	A3B4C4	0.25	79.87	29.64	46.13	0.216958
49	A4B1C1	0.22	90.53	25.74	62.00	0.1842
50	A4B1C2	0.34	69.20	23.15	54.60	0.278849
51	A4B1C3	0.41	65.57	24.62	51.89	0.286402
52	A4B1C4	0.26	82.13	24.15	40.83	0.310591
53	A4B2C1	0.20	92.20	26.95	59.76	0.162559
54	A4B2C2	0.28	75.57	26.19	57.58	0.217608
55	A4B2C3	0.29	76.60	24.07	53.66	0.263831
56	A4B2C4	0.27	71.27	26.54	45.65	0.253713
57	A4B3C1	0.19	93.97	22.06	55.35	0.22494
58	A4B3C2	0.32	74.13	23.44	50.76	0.291029
59	A4B3C3	0.31	73.53	29.29	45.99	0.24421
60	A4B3C4	0.24	87.60	22.34	38.04	0.332677
61	A4B4C1	0.18	101.13	25.40	62.30	0.150734
62	A4B4C2	0.30	77.03	29.04	55.86	0.203299
63	A4B4C3	0.38	69.93	26.63	49.91	0.273238
64	A4B4C4	0.25	87.13	27.08	40.68	0.276283

Relative thermal comfort index calculated values ranges between zero and one and the more values close to 1 the more it is comfortable. Thus, all 64 samples are ranked for their comfort properties as shown by table below

Table 5.23: Ranks of 64 sample layered fabrics based on calculated RTCI values.

Code	RTCI	Ranks	Code	RTCI	Ranks	Code	RTCI	Ranks
A1B3C4	0.39340	1	A1B2C4	0.293612	23	A3B2C2	0.217343	45
A3B3C4	0.38146	2	A1B2C3	0.292592	24	A3B4C4	0.216958	46
A3B3C3	0.37749	3	A4B3C2	0.291029	25	A3B4C1	0.210873	47
A1B3C2	0.36073	4	A4B1C3	0.286402	26	A4B4C2	0.203299	48
A2B3C4	0.35938	5	A2B4C3	0.286084	27	A2B1C1	0.183856	49
A1B1C4	0.35562	6	A4B1C2	0.278849	28	A3B2C1	0.182622	50
A1B3C3	0.35043	7	A2B1C2	0.276575	29	A2B4C1	0.178131	51
A2B4C4	0.35042	8	A4B4C4	0.276283	30	A3B4C2	0.174316	52
A2B2C4	0.33505	9	A4B4C3	0.273238	31	A1B4C1	0.162887	53
A4B3C4	0.33267	10	A3B1C3	0.271353	32	A4B2C1	0.162559	54
A2B3C3	0.32432	11	A2B1C4	0.271025	33	A4B4C1	0.150734	55
A1B1C3	0.32285	12	A4B2C3	0.263831	34	A2B2C1	0.146581	56
A3B1C4	0.31840	13	A3B2C3	0.257735	35	A3B2C4	0.34962	57
A3B3C2	0.31734	14	A3B4C3	0.254155	36	A3B1C2	0.25644	58
A1B1C1	0.31733	15	A4B2C4	0.253713	37	A4B3C3	0.24421	59
A1B1C2	0.31733	16	A2B1C3	0.251542	38	A1B4C3	0.22799	60
A1B4C4	0.31678	17	A2B2C3	0.244733	39	A4B3C1	0.22494	61
A4B1C4	0.31059	18	A3B1C1	0.232862	40	A2B2C2	0.2574	62
A2B3C2	0.30974	19	A2B4C2	0.231676	41	A1B2C1	0.1849	63
A1B2C2	0.29564	20	A3B3C1	0.230731	42	A4B1C1	0.1842	64
A1B4C2	0.29491	21	A2B3C1	0.226545	43			
A1B3C1	0.29388	22	A4B2C2	0.217608	44			

5.6 Screening Firefighters Clothings for Wear Trials

Screening for Most Protective to least protective

Step 1: comparison of EN367 HTI 12 and EN367 HTI 24 convective heat transfer index at 12 second and 24 second relations by correlation has been done and considering EN367 HTI 24 as their ranking parameter in place of two results.

Step 2: comparison of EN6942 RHTI 12 and EN6942 RHTI 24 radiant heat transfer index at 12 second and 24 second relations by correlation has been done and considering EN6942 RHTI 24 as their ranking parameter in place of two results

Step 3: ranking as per EN367 HTI 24 and EN6942 RHTI 24 and adding their corresponding ranks to re rank from most protective to least one

Table 5.24: Ranking of samples as per EN367 HTI 24 and EN6942 RHTI 24 from most protective to least one.

Ranks	Multi-layered fabrics code	**EN367 HTI24 (s)**	**EN6942 RHTI24 (s)**	Ranks By EN367 HTI24	Ranks by EN6942 RHTI 24	Sum of two ranks
1	A2B2C1	19.9	30	1	3	4
2	A1B2C1	18.9	26.4	7	7	14
3	A1B1C1	18.25	28.65	11	5	16
4	A1B1C2	17.5	28.4	19	6	25
5	A3B2C4	16.5	31	24	1	25
6	A2B4C1	18.55	23.8	9	19	28
7	A2B2C3	16.2	29.5	25	4	29
8	A2B2C4	17.6	24.9	18	14	32
9	A3B2C2	19.3	22.6	5	27	32
10	A1B2C2	18.5	22.85	10	25	35
11	A1B2C3	17.2	24.7	20	16	36
12	A2B1C2	16.7	24.9	22	14	36
13	A3B2C1	19.7	20.6	2	40	42

14	A1B1C4	15.1	26.4	36	7	43
15	A2B1C1	16.9	23.2	21	23	44
16	A1B4C1	15.25	25	35	12	47
17	A2B4C2	18.2	21.3	12	35	47
18	A2B3C2	15.8	23.8	29	19	48
19	A4B2C2	18.7	20.5	8	41	49
20	A1B3C1	14.8	25.95	41	9	50
21	A1B2C4	16.7	22.2	22	29	51
22	A2B2C2	19.4	20.2	4	48	52
23	A2B3C1	16.05	22.8	27	26	53
24	A3B4C1	18.2	20.4	12	43	55
25	A4B2C1	19.6	18.8	3	52	55
26	A1B1C3	14.5	25.45	46	10	56
27	A3B3C4	13.3	30.5	55	2	57
28	A3B2C3	15	23.3	38	22	60
29	A4B2C4	17.7	20.3	16	45	61
30	A4B1C1	18.15	19.5	14	49	63
31	A2B4C3	14	23.8	47	19	66
32	A3B1C2	14.7	23.2	43	23	66
33	A3B4C2	18.1	19	15	51	66
34	A4B1C2	17.7	19.4	16	50	66
35	A2B4C4	15.6	20.7	30	38	68
36	A1B3C4	13.1	25.2	58	11	69
37	A3B3C1	16.2	20.35	25	44	69
38	A3B4C4	15.4	20.7	32	38	70
39	A4B4C1	19	13.8	6	64	70

40	A1B4C2	14.7	22.2	43	29	72
41	A1B4C3	12.7	25	60	12	72
42	A2B1C4	14.9	21.2	39	36	75
43	A4B1C4	14.8	21.5	41	34	75
44	A1B3C2	13.7	22.4	50	28	78
45	A1B3C3	12.6	23.9	61	18	79
46	A2B3C3	12.3	24.2	62	17	79
47	A3B1C3	13.9	22.1	48	31	79
48	A3B1C4	15.3	20.3	34	45	79
49	A3B3C2	15.6	18.1	30	54	84
50	A3B4C3	13.5	**22**	53	32	85
51	A4B2C3	16	16.9	28	57	85
52	A2B3C4	13.4	21	54	37	91
53	A3B1C1	14.9	18	39	55	94
54	A4B3C1	15.05	15.8	37	58	95
55	A4B4C4	15.4	14	32	63	95
56	A1B4C4	13.3	20.5	55	41	96
57	A3B3C3	12.2	21.7	63	33	96
58	A2B1C3	13.6	20.3	52	45	97
59	A4B4C2	14.6	18.5	45	53	98
60	A4B4C3	13.7	17.9	50	56	106
61	A4B3C2	13.8	14.8	49	62	111
62	A4B3C4	13.2	15.7	57	60	117
63	A4B1C3	13.1	15.7	58	60	118
64	A4B3C3	12	15.8	64	58	122

After multilayered fabrics were grouped to most protective to least protective and also the most comfortable to the least comfortable that done by relative thermal comfort index calculations, the following fabrics used to construct firefighters protective clothings at KIVANÇ Group Safety Division were listed.

Table 5.25: Grading to High, Medium and Low both in protective& Comfortable combinations.

Code	Category	Outershell	Moisture Barrier	Thermal Barrier
A3B2C4	High protective and good comfortable	PBI Matrix 200 g/m²	PU membrane laminated to nonwoven (50/25/25) 85g/m^2	Nonwoven quilted to Aramid Viscose FR inner lining 85g/m^2
A2B2C4		PBI gold 200 g/m²	PU membrane laminated to nonwoven (50/25/25) 85g/m^2	Nonwoven quilted to Aramid Viscose FR inner lining 85g/m^2
A1B2C2		Nomex Outershell Tough 195 g/m²	PU membrane laminated to nonwoven (50/25/25) 85g/m^2	Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining 110 g/m²
A3B2C3	Medıum protective and medium comfortable	PBI Matrix 200 g/m²	PU membrane laminated to nonwoven (50/25/25) 85g/m^2	Nonwoven quilted to Aramid Viscose FR inner lining 55g/m^2
A4B2C4		Nomex Outershell Tough Ripstop 195 g/m²	PU membrane laminated to nonwoven (50/25/25) 85g/m^2	Nonwoven quilted to Aramid Viscose FR inner lining 85g/m^2
A3B1C2		PBI Matrix 200 g/m²	PU membrane laminated to nonwoven (50/25/25) 55g/m^2	Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining 110 g/m²

A4B1C2		Nomex Outershell Tough Ripstop 195 g/m²	PU membrane laminated to nonwoven (50/25/25) 55g/m^2	Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining 110 g/m²
A2B1C4		PBI gold 200 g/m²	PU membrane laminated to nonwoven (50/25/25) 55g/m^2	Nonwoven quilted to Aramid Viscose FR inner lining 85g/m^2
A1B4C2		Nomex Outershell Tough 195 g/m²	PU membrane laminated to knitted fabric 145g/m^2	Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining 110 g/m²
A3B2C3		PBI Matrix 200 g/m²	PU membrane laminated to nonwoven (50/25/25) 85g/m^2	Nonwoven quilted to Aramid Viscose FR inner lining 55g/m^2
A4B2C4		Nomex Outershell Tough Ripstop 195 g/m²	PU membrane laminated to knitted fabric 145g/m^2	Nonwoven quilted to Aramid Viscose FR inner lining 85g/m^2
A3B1C2		PBI Matrix 200 g/m²	PU membrane laminated to nonwoven (50/25/25) 55g/m^2	Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining 110 g/m²
A4B4C2	Low protection and low comfort	Nomex Outershell Tough Ripstop 195 g/m²	PU membrane laminated to knitted fabric 145g/m^2	Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining 110 g/m²
		Nomex Outershell	PU membrane	Two layers of

A4B3C1		Tough Ripstop 195 g/m²	laminated to knitted fabric 85g/m^2	nonwoven(55+55) quilted to Aramid Viscose FR inner lining 110 g/m²
A3B1C1		PBI Matrix 200 g/m²	PU membrane laminated to nonwoven (50/25/25) 55g/m^2	Two layers of nonwoven(55+55) quilted to Aramid Viscose FR inner lining 110 g/m²

Selected Garments

Three types of fire fighters protective clothings made at KIVANÇ GROUP Safety Division worn over and used in this study as shown in figure 5.24 in wear investigination sub topic below

Table 5.26: Descriptions of selected fire fighters protective clothings components.

Garment name	Codes	Outer shell	Moisture barrier	Thermal barrier	Remarks
Prostar	A2B2C4	PBIgold 200 g/m^2	PU membrane laminated to nonwoven (50/25/25) 85g/m^2	Nonwoven quilted to Aramid Viscose FR inner lining 85 g/m^2	High protective and good comfort
Firestar	A4B1C2	Nomex Outershell Tough Ripstop 195 g/m²	PU membrane laminated to nonwoven (50/25/25) 55g/m^2	Two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining 110g/m^2	Medium protective and medium comfort
Oldprostar	A1B4C3	Nomex Outershell Tough 195 g/ m²	PU membrane laminated to knitted fabric 145g/m^2	Nonwoven quilted to Aramid Viscose FR inner lining 55g/m^2	Low protective and low comfort

The garment system included a long-sleeved 100% cotton, knit shirt and pants.The descriptions of the design and structure of the of the fire fighters clothing Prostar, Old prostar and Firestar are given in table below. Prior to testing and between trials, garments were stored under environmental conditions of 21 ± 3°C and 50- 60% relative humidity for at least 24 hours.

5.7 Wear Trial Investigation Of Thermo-Physiological Comfort

Laboratory testing of textile fabrics properties; using Permetest, Alambeta, Airpermeability, hydrostatic tester, and others; have been widely used to evaluate clothing comfort. Bench-scale testing of thickness, mass per unit area, air permeability, thermal resistance, and evaporative resistance, thermal diffusion, thermal absorptions have been used successfully to evaluate the thermal comfort of fabrics. Small-scale laboratory tests are a practical alternative to expensive, time-consuming wear trials; however, they do not take into account factors related to garment fit and design. With the development of high resolution infrared cameras, thermography is gaining increased attention of the researcher not merely as a non contact tool to measure surface temperature of the objects, but also as a tool in fine physical experiments to analyze thermo-physical phenomena **[92].**

Understanding the relationships between fabric/garment properties and the associated thermo-physiological comfort of fire fighters protective clothing on the wearer is still limited. The purpose of part of this thesis is to determine the comfort level of three different Fire fighters Protective Clothings during moderate treadmill exercise in controlled environmental conditions.

Methods

The experiment was carried out in an ambient temperature of 22±2 °C and ~55% RH , and it involved wearing protective clothings. Each fire fighters protective clothings was worn for about 15 minutes by one person. During intervals between the trials, the person who tested the clothings take off and relax for 45 minutes so as to regain thermal comfort and obtain identical initial conditions for an other wearing. Due to the long duration of the tests, it was impossible to carry out the experiment outdoors because of the inability to maintain identical microclimate conditions for 3 hours, i.e.

the duration of the experiment. Therefore, it was necessary to limit the study to testing in a conditioned fitness room.

Prostar Old prostar Firestar

Figure 5.24: Selected fire fighters protective clothings worn by human.

For the purpose of the study, it was assumed that the feeling of thermal comfort of a user wearing a fire fighters protective clothings made of the fabrics under investigation could be estimated and ordered on the basis of two measurable indicators:

1. The temperature of air under the clothing (between the clothing and skin of the user)
2. The temperature of the outer fire fighters clothings surface.

The temperature measured in both places corresponds to the thermal feeling of a clothing wearer. The temperature of air under the clothing corresponds to the feeling of thermal comfort in a positive manner since the air under the clothing is in direct contact with the skin of the wearer.

A testo 885 Thermal imager camera was used to measure the temperature of the outer surface of the fire fighters protective clothings. Measurements were taken at the beginning and at the end of the exercises which is done by running 3-5 minutes at 8km/hr followed by running 6-8 min at 10 km/hr speed. The temperature was measured with Detector type of FPA 320 x 240 pixels, a.Si Thermal sensitivity

(NETD) < 30 mK at 30°C (86°F) Field of vision/min. focusing distance 30° x 23°/0.1 m (0.33 ft) Telephoto lens (optional): 11° x 9°/0.5 m (1.64 ft) Geometric resolution (IFOV) 1.7 mrad (standard lens) 0.6 mrad (telephoto lens). Temperature ranges (can be changed) -20 to 100°C (-4 to 212°F) 0 to 350°C (32 to 662°F) Accuracy ±2°C (±3.6°F) or ±2% of meas. val. (higher value applies).

In order to measure the air temperature under clothings the thin wire connected to head of small thermometer was placed in a manner preventing it from touching the body and clothes. The air temperature under the clothing was recorded at the start of the exercise and at the finish and at the time of taking measurements, the ambient temperature was recorded, which oscillated around 22 °C, ranging between 21.8 °C and 22.8 °C.

In order to eliminate the influence of ambient air temperature fluctuations on the results of the analysis, the difference between the temperature of air under the clothing and the ambient air temperature was taken as a measure characterising fabrics from the point of view of the wearer's thermal comfort.

An exemplary thermal image taken at the initial phase of wearing fire fighters protective clothings and also after the exercise, its for illustration of front and back images. The region at which the temperature of the outer surface was recorded is marked on the Figure. The temperature of the outer surface of the clothings was calculated as an integral mean of temperatures on the area of the region seleceted surface as shown by the graphs below. The exemplary images are given below for both before and after exercise with mean integral of temperature.

Before exercise

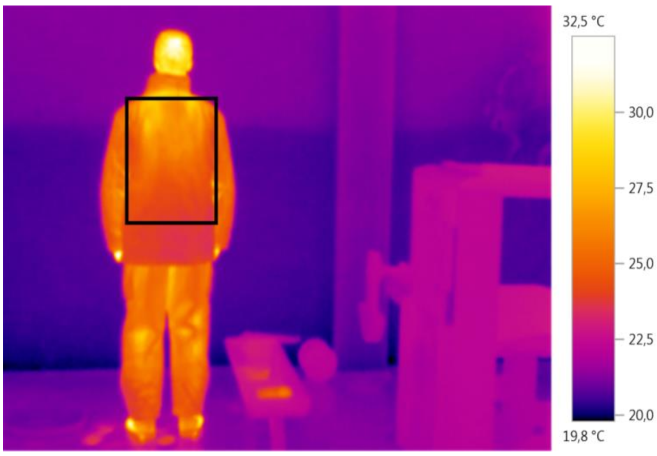

Figure 5.25: Exemplary therma camera image taken before exercise.

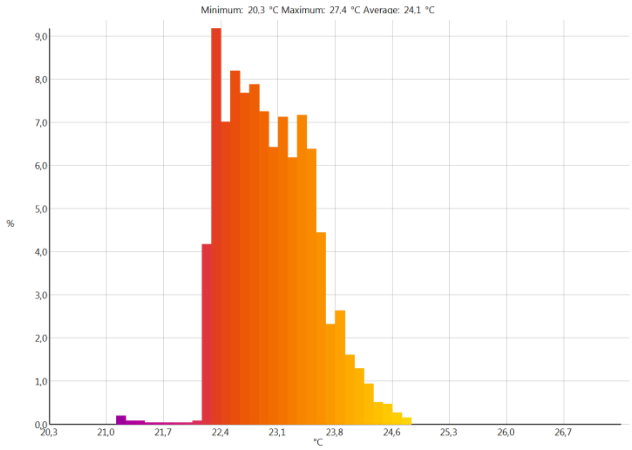

Figure 5.26: Exemplary Mean integral of temperature caculated before exercise.

After exercise

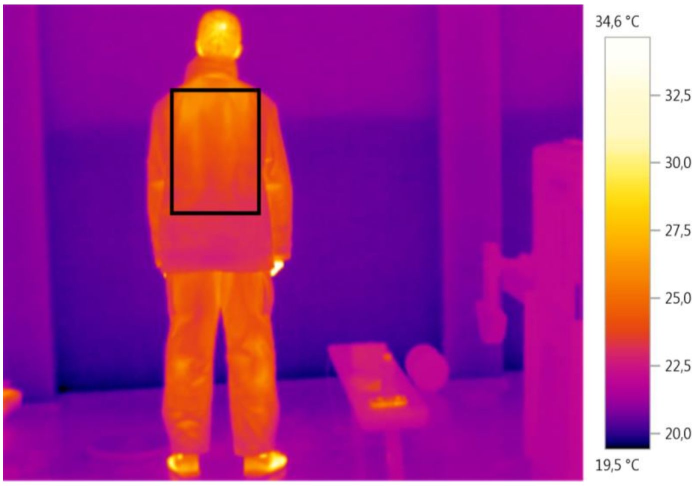

Figure 5.27: Exemplary thermal camera image taken after exercise.

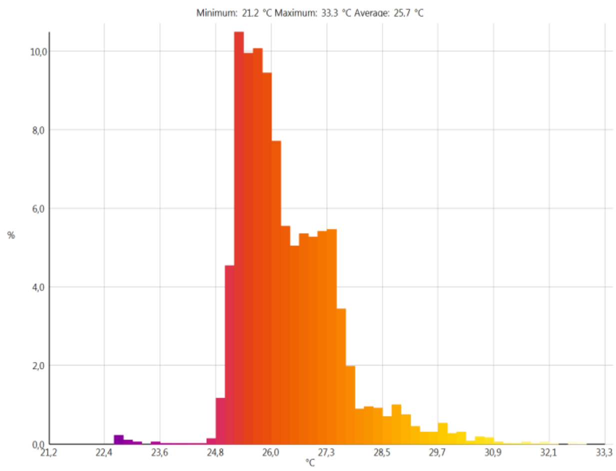

Figure 5.28: Exemplary Mean integral of temperature caculated after exercise.

The wear trials experimental results are given in table below.

Table 5.27: Measured surface temperature of fire fighters clothings before and after exercise.

Garment type	Surface temperature Before Exercise in °C				Surface temperature After exercise in °C			Change in Temp. °C	
		Min	Max.	Average	Min.	Max.	Average		Av
Prostar A2B2C4	Front	23.1	30.3	25.1	23.4	32.8	25.7	0.6	0.7
	Back	20.3	27.4	24.1	23.4	27.8	24.9	0.8	
Firestar A4B1C2	Front	22.8	28.0	24.0	23.6	28.4	25.1	1.1	1.0
	Back	22.3	26.3	24.3	21.4	28.6	25.3	1.0	
Oldprostar A1B4C3	Front	23.3	28.0	24.3	21.2	33.3	25.7	1.4	1.2
	Back	22.8	25.6	23.9	21.2	28.6	24.9	1.0	

Table 5.28: Measured temperature of air under fire fighters clothings and ambient temperature before and after exercise.

Garment type	Ambient temp. During exercise °C	The temperature of air under the clothing before exercise	The temperature of air under the clothing after exercise	Change in Temp. Of air under clothing and ambient temp.
Prostar A2B2C4	22.6 54%RH	26.8	33.2	10.6
Firestar A4B1C2	22.8 54%RH	26.9	32.6	9.8
Oldprostar A1B4C3	22.2 55% RH	26.7	31.8	9.6

The difference between the temperature of air under the clothing and that of air in a cold room reflects the ability of the heat barrier by clothing, to protect the air layer adherent to the skin under the clothes against a drop in temperature. Similarly, in hot working environments; in which an air layer adherent to the skin under fire fighters clothing has lower temperature than ambient temperature; the heat barrier by clothing should protect an air layer temperature from increament so as to stay comfortable. Hence, this principle should be checked for conformity for fire fighters protective clothings used in wear trials based on results given above in table form.

For fire fighters protective clothings under investigation, Relative Thermal Comfort Index values were calculated based on the laboratory test results of the parameters such as water vapor resistance, thermal resistance, thermal diffusion and thermal absorption. The formula used to calculate was explained earlier in this chapter. The RTCI values calculated are presented in Table below.

Table 5.29: Calculated RTCI values, Change in Temp. Of air under clothing and ambient temperature and also Δ in Surface temperature in ^{o}C for garments under wear trial study.

Garment type	Codes	RTCI	ΔTemp. Of air under clothing and ambient temp.	Δ in Surface temperature in ^{o}C
Prostar	A2B2C4	0.335054	10.6	0.7
Firestar	A4B1C2	0.278849	9.8	1.0
Oldprostar	A1B4C3	0.22799	9.6	1.2

Correlation between RTCI values and Change in Temp. Of air under clothing and ambient temperature was done and the relationship is showed by figure 5.29 below. The relationship between thermal comfort index and heat barrier results by firefighters protective clothings agree with the screening steps done to rank as the most protective and the most comfortable (Prostar in this case) to the least protective and least comfortable (Oldprostar).

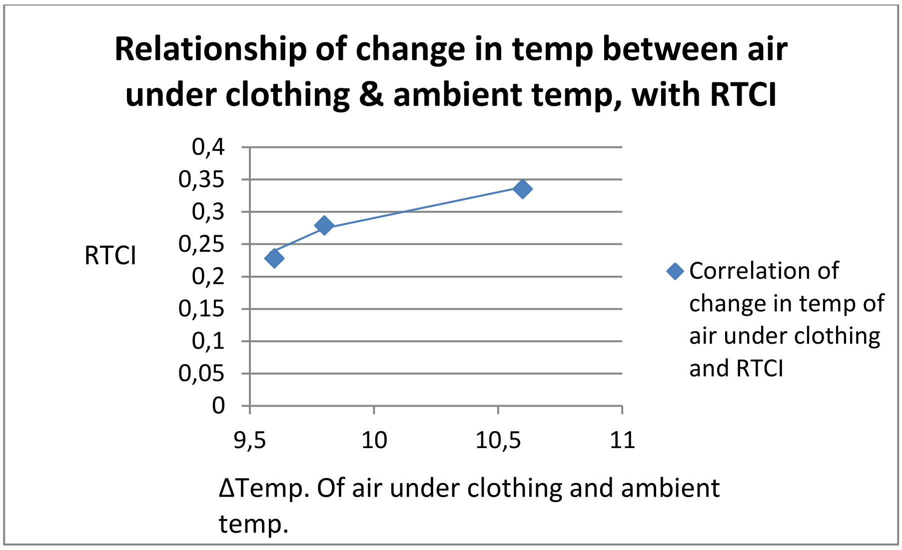

Figure 5.29: Relationship between the values of RTCI and change in temperature of air under clothing and ambient temp.

Relationship between the values of RTCI and Change in surface temperature of fire fighters protective clothings after exercise is shown by correlation figure 5.30 below. The figure indicates that the most comfortable garments with the highest values of calculated RTCI values such as Prostar have no significant effects in changing outer surface temperature of the clothings due to their high heat barrier properties which to mean they are also the most protective based on wear trial analysis.

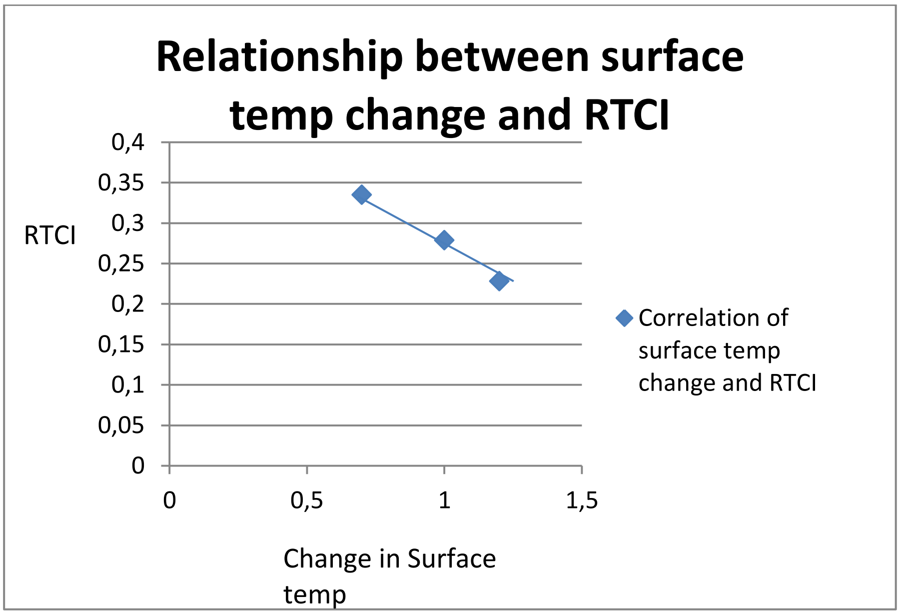

Figure 5.30: Relationship between the values of RTCI and change in surface temperature of fire fighters protective clothings.

Generally, analayzing the objective measurement datas used to rank the comfort properties and protection properties of fire fighters protective clothings can be further supported by wear trial investigations in order to model the screening systems of garments used for fire fighters as tried to be checked for conformity.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In this thesis, an experimental analysis is presented examining the comfort properties and protective performance of a collection of multi layered fabrics used to made firefighters protective clothings. Several series of tests are conducted, each assessing the thermo-physiological comfort parameters and also assembly protective performance of coveralls. Thus, this thesis addressed several potential problems with the current methods for screening each single layered fabrics used in assembly according to their demand to comfort and protection level based on objective measurements.

In analysis of properties such as water vapour permeability, thermal resistance, thermal absorptivity, thermal diffusion and protection performances total of sixty four layered fabrics used. By combinations of Outer shells (A1 or Nomex Outershell Tough with 195 g/ m², A2 or PBI gold with 200 g/m² , A3 or PBI Matrix with 200 g/m², A4 or Nomex Outershell Tough Ripstop with 195 g/m²), Moisture barriers (B1 or PU membrane laminated to nonwoven (50/25/25) with 55 g / m2, B2 or PU membrane laminated to nonwoven (50/25/25) with 85 g / m2, B3 or PU membrane laminated to knitted fabric with 85 g/m2 and B4 or PU membrane laminated to knitted fabric with 145 g/m2) and Thermal barriers (C1 or two layers of nonwoven(55+55) quilted to Aramid Viscose FR inner lining with 110 g/m2, C2 or two layers of nonwoven(55+55) quilted to Nomex Comfort inner lining with 110 g/m2, C3 Nonwoven quilted to Aramid Viscose FR inner lining with 55 g / m2 and C4 or Nonwoven quilted to Aramid Viscose FR inner lining with 85 g / m2); have been done in order to compare and screen the best combinations in specified comfort and protection properties.

According to test results done by using Permetest instrument the fire fighters protective multilayered from Nomex® Outershell Tough 195 g/ m² + moisture barrier laminated to knitted fabric PU Membrane85 g/m2 + thermal barrier of Nonwoven Aramid Viscose FR valve has been quilted inner lining 85 g / m2) is found to be the best in water vapour permeability and so as to improve the comfort level in turn. To the opposite A3B4C2 coded assembly of PBI® Matrix 200 g/m²+ moisture barrier PU Membrane laminated to knitted fabric 145 g/m2 + thermal barrier of Nonwoven Nomex Comfort which has been quilted inner lining until 2 times (55 + 55) is identified as the only assembly which cannot fulfill the standard of EN 469:2005 Level 2 requirement which says Water vapour resistance < 30 m2 Pa/W. Thus this layered fabrics with above 31m2Pa/W water vapor resistance is concluded as the least in its comfort assesement by this parameter and others are listed in results and discusions sections of the thesis. Additionaly its measured and concluded that all of the multilayered firefighters protective clothings are not air permeable because of the thermal barriers which hinder air transmission.

The thermal parameters such as thermal conductivity (λ), thermal absorptivity (b),thermal resistance (R) and sample thickness (h) have been measured by Alambeta modern device which basically simulates the dry human skin . From several tests done for all samples its possible to conclude that, the thermal resistance measured by Alambeta device results greater than that measured by Permetest device for the same sample. This limits the Alambeta device to measure fabrics such as underwear which have direct contacts with human skin. From their real applications fire fighters protective clothings are worn as outer cover next to underwears and it is decided to take the results by Permetest in calculations of overall properties Thermal Comfort Index TCI. The calculated relative thermal index values of all 64 samples were compared to rank the comfort level of the assemblies. Thus the fabric layers of code A1B3C4 which mean of outer shell: Nomex® Outershell Tough 195 g/ m², Moisture barrier: PU Membrane laminated to knitted fabric 85 g/m2, Thermal barrier of Nonwoven Aramid Viscose FR valve which has been quilted inner lining 85 g / m2 is screened as the most comfortable combinations among the samples.

The burning tests done for the fabric layers as per standards of EN367 HTI 12/24and EN6942 RHTI 12/24 measure the protective performance of fire fighters clothings and the correlation analysis showed that both convective heat transfer index and radiant heat transfer index at 12 and 24 seconds are very significantly proportional to each other. The more burning tests resistance time in seconds to convective and radiant heat source, the more protective the assemblies and its used to rank the performances of samples. From relative thermal comfort index and burning tests rank, the priority lists for three classes have done. The High protective and good comfortable are A3B2C4, A2B2C4, and A1B2C2 Medıum protective and medium comfortable are A3B2C3, A4B2C4 , A3B1C2, A4B1C2, A2B1C4 and A1B4C2

Low protection and low comfort A4B4C2, A4B3C1 and A3B1C1. From these lists the available ready made firefighters protective clothings taken from KIVANÇ KIMYA PLC have investigated for wear trials by using testo 885Thermal imager camera.

The relative thermal comfort index calculated for fabric layers evaluate and provide well screened status weather a particular type of fabrics when made garments and investigated wear trially would definitely ensure thermal comfort . In order to meet the best expectations to this conclusion, it is necessary to precisely specify the conditions of using the garments, not only concerning microclimate parameters but also personal features of the user and the type and intensity of physical activity. However, it is not possible to define the above-mentioned conditions accurately for the mass production of everyday clothing.

6.2 Recommendations of Future Researches

The scope of this thesis work in examining fire fighters protective clothings comfort properties;via thermo-physiological parameters and simultaneously the study assemblies protection performance is found very important and there is still researches shall be done to further understand comfort improving parameters. Further studies and investigations of other comfort parameters while improving their protection can be measured either objectively or subjectively to optimize this importance. For instance, studying influences of common hazards while fighting fires on workers performance can be studied by simulation of real working situations. The material especially fabrics selection process before sewing them to coveralls can be done after measuring other necessary tests other than those done by Permetest and Alambeta. In order to have fire fighters with air permeable properties, the thermal barriers used currently can be studied to replace with demanded characteristics. The use of thermal camera can be supported by subjective assesement of professional fire fighters in order to increase the accuracy of conclusions about comfort and protection.

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APPENDICES

Appendix A. Permetest test results

Appendix B. Alambeta test results

Appendix C. Air permeability test results

Appendix D. Burning tests results

Appendix A. Permetest test results

Table A.1 Single layer fabrics permetest test results.

Single layered Fabric codes	Relative wvp (%)	WVP (m^2PaW^{-1})	Thermal resistance ($mK.m^2/W$)
A1	62.39	4.92	8.60
	62.13	4.60	9.27
	63.75	4.42	7.53
A2	60.27	5.14	11.30
	62.26	4.29	9.22
	60.66	4.90	9.42
A3	62.15	3.72	9.99
	61.39	3.79	9.23
	61.06	3.84	10.37
A4	62.87	3.56	12.52
	61.63	3.71	12.37
	61.74	3.72	16.25
B1	46.69	7.00	10.69
	43.68	7.60	10.62
	48.10	6.62	10.18
B2	37.55	10.12	11.16
	38.75	9.56	12.19
	36.41	10.73	12.94
B3	57.73	4.47	0.86
	57.85	4.50	2.02
	55.75	4.74	1.36
B4	39.95	9.79	0.40
	35.04	11.79	0.35

	37.44	10.77	0.39
C1	50.95	6.26	40.8
	51.1	6.14	38.20
	49.71	6.56	41.72
C2	48.31	7.02	52.11
	47.08	7.22	54.03
	47.72	7.10	46.36
C3	50.95	6.26	37.86
	48.13	7.07	34.37
	46.62	7.36	40.23
C4	51.10	6.14	22.61
	51.34	6.22	19.83
	52.93	5.78	26.85

Table A.2 Layered fabrics permetest test results.

No.	Combination code	RelativeThermal permeability in %	Thermal permeability (m^2PaW^{-1})	Thermal resistance ($mK.m^2/W$)
1	A1B1C1	22.07	18.94	61.21
		18.07	24.84	68.90
		20.24	22.04	60.19
2	A1B1C2	17.58	23.01	52.99
		19.76	20.28	53.83
		19.68	20.19	48.98
3	A1B1C3	18.20	21.99	48.35
		16.92	24.50	45.92
		19.12	20.96	49.44
4	A1B1C4	15.65	26.24	34.23

		18.19	21.79	38.89
		18.19	21.40	37.19
5	A1B2C1	18.56	26.23	65.87
		17.26	29.06	65.29
		19.34	25.44	65.24
6	A1B2C2	18.15	22.62	57.56
		18.55	20.44	56.91
		16.46	24.08	54.27
7	A1B2C3	16.88	25.03	48.20
		17.32	24.51	46.17
		17.56	24.11	52.68
8	A1B2C4	15.12	28.99	40.71
		17.04	24.92	42.81
		18.33	23.16	38.22
9	A1B3C1	21.51	22.27	48.17
		21.27	22.15	55.43
		23.76	19.70	50.33
10	A1B3C2	20.38	20.91	44.37
		21.07	19.29	42.55
		20.63	19.62	47.34
11	A1B3C3	20.14	20.66	42.51
		18.35	23.35	41.60
		20.34	20.75	41.06
12	A1B3C4	22.68	17.50	31.66
		22.93	17.44	30.66
		18.85	22.53	37.23
13	A1B4C1	19.05	26.75	62.83

		17.16	29.76	54.14
		16.50	30.92	62.00
14	A1B4C2	16.13	24.66	53.97
		18.47	20.87	50.91
		17.25	22.47	56.02
15	A1B4C3	15.03	27.77	51.74
		14.67	28.37	48.41
		14.58	28.62	45.65
16	A1B4C4	14.42	29.21	32.83
		17.46	22.69	34.50
		15.94	24.81	33.18
17	A2B1C1	18.43	27.28	54.13
		20.06	24.77	60.82
		20.92	23.34	57.15
18	A2B1C2	16.82	24.28	51.49
		15.45	26.99	44.45
		16.87	24.42	51.44
19	A2B1C3	17.22	23.96	49.95
		15.00	28.82	45.34
		14.98	28.06	43.03
20	A2B1C4	16.82	24.57	34.56
		13.77	30.39	31.35
		15.02	28.32	37.26
21	A2B2C1	17.52	29.89	63.42
		17.25	30.23	69.68
		19.48	24.85	56.77
22	A2B2C2	15.76	26.48	54.08

		15.99	25.32	49.02
		15.88	25.05	48.48
23	A2B2C3	14.75	28.51	47.74
		15.66	26.38	47.80
		16.13	25.46	54.33
24	A2B2C4	16.46	24.98	36.93
		15.19	27.19	42.28
		15.36	27.39	39.07
25	A2B3C1	23.46	20.19	55.21
		21.82	21.92	61.78
		23.49	20.40	61.16
26	A2B3C2	17.46	22.22	51.71
		18.40	20.64	45.84
		16.87	22.90	47.28
27	A2B3C3	19.69	19.78	48.72
		17.95	21.38	49.17
		19.82	19.05	44.18
28	A2B3C4	18.75	21.22	37.87
		19.31	20.65	32.64
		21.16	18.79	32.39
29	A2B4C1	20.15	24.64	61.55
		21.10	23.21	55.24
		22.06	22.09	65.65
30	A2B4C2	14.52	29.93	57.25
		16.02	26.47	56.61
		16.86	23.79	58.65
31	A2B4C3	15.27	26.83	47.16

		16.92	24.40	48.08
		17.71	23.20	49.41
32	A2B4C4	15.91	26.79	39.08
		17.71	23.13	34.40
		18.16	22.03	35.21
33	A3B1C1	21.39	23.90	49.94
		18.44	28.19	50.15
		19.98	24.78	51.15
34	A3B1C2	17.26	24.36	52.69
		16.53	24.58	54.27
		17.62	23.15	57.75
35	A3B1C3	14.80	27.54	49.82
		17.07	23.65	52.08
		16.42	25.25	46.44
36	A3B1C4	17.34	24.51	37.20
		16.76	23.93	37.26
		16.37	25.27	42.82
37	A3B2C1	16.68	30.11	57.80
		19.34	25.81	50.90
		17.61	29.90	53.10
38	A3B2C2	15.83	26.15	60.17
		13.81	29.83	61.05
		15.16	27.40	57.03
39	A3B2C3	16.58	23.68	50.28
		14.94	27.76	52.60
		15.41	27.08	50.63
40	A3B2C4	16.67	23.45	41.42

		14.57	26.89	37.25
		16.49	24.13	43.05
41	A3B3C1	20.26	25.75	54.90
		22.19	22.17	54.49
		20.98	23.39	56.79
42	A3B3C2	17.46	23.34	56.55
		18.40	20.67	51.15
		17.58	21.77	47.09
43	A3B3C3	19.10	20.33	40.27
		19.92	19.36	43.18
		19.69	19.97	43.73
44	A3B3C4	16.93	23.43	34.55
		18.67	20.92	30.68
		16.97	24.38	29.98
45	A3B4C1	18.80	27.34	53.75
		21.66	23.03	50.12
		19.72	26.17	59.96
46	A3B4C2	14.87	28.64	46.42
		12.65	33.24	53.74
		12.45	33.20	50.26
47	A3B4C3	14.14	29.15	49.64
		14.97	28.08	46.90
		15.07	28.21	45.46
48	A3B4C4	13.11	30.58	48.02
		12.90	30.97	45.50
		14.39	27.37	44.87
49	A4B1C1	18.32	27.30	57.17

		21.33	23.27	61.79
		19.59	26.66	67.04
50	A4B1C2	17.44	21.25	54.69
		16.53	24.55	53.10
		17.24	23.64	56.02
51	A4B1C3	16.74	24.51	51.27
		17.05	24.42	52.03
		16.83	24.93	52.36
52	A4B1C4	19.05	21.22	39.85
		16.08	24.94	39.93
		15.71	26.30	42.70
53	A4B2C1	17.89	27.77	65.18
		18.12	27.55	57.30
		19.56	25.54	56.80
54	A4B2C2	15.81	27.11	56.61
		16.12	24.89	55.07
		15.00	26.56	61.07
55	A4B2C3	16.56	25.01	54.69
		16.76	24.79	52.42
		17.76	22.41	53.87
56	A4B2C4	14.50	30.42	47.61
		16.65	25.31	45.28
		17.48	23.89	44.06
57	A4B3C1	20.43	24.28	51.90
		22.91	21.18	52.83
		22.78	20.73	61.31
58	A4B3C2	17.11	25.96	49.01

		19.26	22.06	51.46
		18.61	22.30	51.81
59	A4B3C3	16.31	26.50	50.62
		14.59	30.54	43.60
		14.52	30.84	43.74
60	A4B3C4	18.82	22.91	36.00
		19.37	21.36	37.68
		18.62	22.75	40.44
61	A4B4C1	17.88	28.51	60.68
		21.04	23.80	61.56
		19.77	23.90	64.67
62	A4B4C2	16.88	27.51	53.73
		15.75	29.38	58.84
		15.46	30.23	55.02
63	A4B4C3	17.48	25.58	48.86
		16.56	27.00	48.01
		16.71	27.30	52.86
64	A4B4C4	16.76	27.53	38.94
		15.00	30.45	38.74
		18.75	23.25	44.36

Appendix B. Alambeta test results

Table B.1 Single layers Alambeta device test results.

Single layer Fabric codes	Thermal Parameters by Alambeta				
	Tests	Thermal conductivity **λ** ($Wm^{-1}K^{-1}$)	Thermal diffusion **a** **(**m^2s^{-1}**)**	Thermal absorptivity **b** **(**$Wm^{-2}s^{1/2}K^{-1}$**)**	Thermal resistance **R** ($mK.m^2/W$)
A1	Test 1	55.3	0.074	204	8.4
	Test 2	55.4	0.08	194	8.1
	Test 3	53.5	0.073	197	8.5
	Average	54.73	0.076	198.33	8.33
A2	Test 1	58.3	0.094	191	8.2
	Test 2	59.1	0.087	200	7.9
	Test 3	55.8	0.077	201	8
	Average	57.73	0.086	197.33	8.033
A3	Test 1	61.5	0.071	231	7.3
	Test 2	62.3	0.078	223	7.5
	Test 3	62.1	0.073	230	7.4
	Average	61.97	0.074	228	7.4
A4	Test 1	50	0.102	157	10.6
	Test 2	49.9	0.085	171	10.3
	Test 3	43.3	0.069	165	11.2
	Average	47.73	0.085	164.33	10.7
B1	Test 1	32.3	0.117	95.8	17.3
	Test 2	32.7	0.112	97.5	16.9
	Test 3	32.9	0.112	98.4	17.2
	Average	32.63	0.114	97.23	17.13
B2	Test 1	35.6	0.117	104	21.6

	Test 2	35.3	0.129	98.2	22.1
	Test 3	34.3	0.139	92.1	22.4
	Average	35.07	0.128	98.1	22.03
B3	Test 1	32.3	0.094	106	7.9
	Test 2	33.1	0.094	106	7.7
	Test 3	32.8	0.078	118	7.8
	Average	32.73	0.089	110	7.8
B4	Test 1	43.6	0.069	166	10.2
	Test 2	44.2	0.068	169	10.4
	Test 3	42.9	0.071	161	10.3
	Average	43.57	0.070	165.33	10.3
C1	Test 1	36.6	0.613	46.8	75.3
	Test 2	37.6	0.523	51.8	71.6
	Test 3	36.3	0.44	54.6	81.1
	Average	36.83	0.53	51.07	76
C2	Test 1	36.7	0.239	75.1	54.2
	Test 2	36.6	0.227	76.1	53
	Test 3	36.2	0.269	69.8	59.5
	Average	36.5	0.245	73.67	55.57
C3	Test 1	36.5	0.243	74	56.6
	Test 2	36	0.302	65.5	54.1
	Test 3	36.1	0.317	64.1	54.1
	Average	36.2	0.288	67.87	54.93
C4	Test 1	38.6	0.182	90.5	49.8
	Test 2	37.7	0.247	75.9	51.4
	Test 3	38.1	0.192	87.1	45.9
	Average	38.13	0.207	84.5	49.03

Table B.2 Layered fabrics Alambeta device test results.

Combination fabric layers code	Thermal conductivity λ (Wm-1K-1)	Thermal diffusion a (m2s-1)	Thermal absorptivity b (Wm-2s1/2K-1)	Thermal resistance R (mK.m2/W)
A1B1C1	40.5	0.255	80.2	95.1
	40.1	0.288	74.7	97.7
	39.1	0.252	77.8	96.1
A1B1C2	39.8	0.36	66.3	82.7
	40	0.399	63.3	79.8
	39.8	0.399	63	78.1
A1B1C3	41.3	0.296	75.9	72.4
	40.4	0.424	62	77
	40.2	0.416	62.4	76
A1B1C4	41.5	0.28	78.5	74
	41.2	0.339	70.8	70.9
	41.2	0.343	70.4	73.4
A1B2C1	40.5	0.372	66.4	102
	40.7	0.237	83.6	101
	40.2	0.329	70	98.8
A1B2C2	40	0.84	43.7	89.2
	40	0.444	60	78.6
	39.8	0.535	54.4	81.7
A1B2C3	39.6	0.352	66.7	81.7
	39.3	0.447	58.8	81.3
	39.5	0.399	62.5	82.2
A1B2C4	41.6	0.239	85.1	65.9
	41.1	0.241	83.7	65.7

	40.6	0.311	72.7	69.8
A1B3C1	40.9	0.231	85.1	87.3
	40.6	0.265	78.8	86.2
	40.8	0.291	75.7	89
A1B3C2	39.7	0.399	62.8	79.5
	39.4	0.387	63.4	72.8
	39.3	0.347	66.8	73.1
A1B3C3	40.1	0.287	75	65
	39.7	0.393	63.3	65.7
	39.1	0.329	68	66
A1B3C4	42.2	0.236	86.8	54.2
	42.6	0.223	90.1	51.4
	41.6	0.274	79.5	60.3
A1B4C1	41.8	0.23	87.2	89.9
	42.7	0.226	89.7	87.7
	41.1	0.266	79.6	88.8
A1B4C2	40.7	0.276	77.4	74.9
	41.1	0.427	62.8	78
	41	0.392	65.5	77.2
A1B4C3	40.9	0.223	86.6	62.5
	40.8	0.279	77.1	63.7
	40.4	0.284	75.8	64.8
A1B4C4	43	0.214	92.8	59.7
	43	0.263	83.9	62.3
	43.3	0.226	91.1	56.8
A2B1C1	42.9	0.157	108	86
	42.2	0.203	93.6	90.6

	41.7	0.202	92.7	88.8
A2B1C2	40.5	0.289	75.3	75.2
	40.9	0.327	71.5	72.6
	39.6	0.36	66.1	74.8
A2B1C3	40.2	0.248	80.7	65.9
	39.6	0.288	73.7	69.7
	40.3	0.248	80.9	67.3
A2B1C4	41.8	0.226	85.6	73.2
	41.4	0.247	70.7	74.9
	41.6	0.216	73.7	80.2
A2B2C1	42.7	0.178	101	94.1
	41.6	0.183	97.3	92
	41.3	0.298	75.7	95.1
A2B2C2	40.7	0.226	85.6	73.2
	40.7	0.331	70.7	74.9
	40.3	0.299	73.7	80.2
A2B2C3	41.3	0.24	84.2	74.2
	40	0.323	70.3	73
	40.8	0.276	77.2	70.8
A2B2C4	42.1	0.218	90.2	63.7
	42.2	0.259	82.9	66.5
	42	0.787	47.4	64.7
A2B3C1	42	0.161	105	82
	42.2	0.189	97.1	84.6
	41.5	0.224	87.8	82.6
A2B3C2	41.1	0.305	74.5	66.5
	41.5	0.281	78.3	61.5

	40.9	0.272	78.5	64.8
A2B3C3	41.7	0.226	87.8	58.7
	40.7	0.328	71.1	58.3
	40.3	0.211	87.8	87.8
A2B3C4	43	0.198	96.7	54.3
	41.4	0.235	85.3	56.6
	43.3	0.203	96.1	49
A2B4C1	43	0.144	114	81.5
	42.7	0.168	104	84.4
	41.5	0.216	84.6	84.6
A2B4C2	41.8	0.327	73.1	72.6
	40.7	0.377	66.3	77.7
	41.7	0.375	68.2	72.8
A2B4C3	42.9	0.29	79.2	56.2
	41.8	0.302	76	65.9
	42.5	0.332	73.8	65
A2B4C4	43.4	0.398	68.8	69.9
	43.4	0.247	87.3	65.6
	45	0.248	90.4	59.4
A3B1C1	41.5	0.192	93.6	90.1
	41	0.222	87	91.6
	39.8	0.263	77.6	99.1
A3B1C2	41.1	0.271	78.9	74.9
	40.9	0.289	76.1	70.6
	40.6	0.3	74.2	76.2
A3B1C3	41.4	0.304	75.1	72
	40.7	0.326	71.2	74.3

	41.9	0.302	76.2	72.2
A3B1C4	42.5	0.28	80.3	75.4
	42.5	0.281	80.2	68.2
	42.6	0.254	84.6	62.2
A3B2C1	41.7	0.215	89.9	97.7
	43	0.186	99.8	97.7
	42.3	0.252	84.2	93.6
A3B2C2	39.7	0.589	51.8	80.8
	40.3	0.297	74	78.8
	40.8	0.323	71.8	77.8
A3B2C3	40.9	0.382	66.2	69.7
	40	0.313	71.6	74.6
	40.1	0.289	74.6	72.6
A3B2C4	42.7	0.864	46	69.5
	42.2	0.308	76	73.4
	41.6	0.35	70.3	69.7
A3B3C1	41.9	0.188	96.7	82.6
	40.7	0.241	82.9	87.5
	41.4	0.217	88.7	83
A3B3C2	40.5	0.362	67.4	70.6
	42.2	0.397	67	66.3
	41.5	0.464	60.9	65.2
A3B3C3	41.2	0.374	67.4	65.3
	41.6	0.367	68.7	62.2
	41.8	0.396	66.4	63.3
A3B3C4	43.9	0.333	76.1	53.9
	42.8	0.322	75.4	58.5

	43.1	0.263	84.2	52.9
A3B4C1	41.5	0.156	105	86
	42.5	0.221	90.4	87.5
	41.5	0.296	76.2	88.6
A3B4C2	43.4	0.38	72.9	63.7
	43.1	0.366	71.2	69.2
	42.9	0.419	66.2	66.4
A3B4C3	42.4	0.275	80.8	63.9
	42.6	0.304	77.3	65.4
	42.5	0.402	67	63.8
A3B4C4	45.3	0.241	92.3	58.6
	43.9	0.245	60.3	57.9
	45	0.268	87	58.4
A4B1C1	41.6	0.196	94.1	93.2
	40.9	0.219	87.4	93.4
	41	0.259	80.6	89.2
A4B1C2	40.4	0.348	68.5	77
	40.1	0.287	75	74.9
	39.9	0.388	64.1	77
A4B1C3	40.8	0.269	78.6	70.5
	39.9	0.566	53.1	74.1
	40.4	0.386	65	69
A4B1C4	42.3	0.2	94.5	68.8
	40.7	0.294	74.9	70.5
	41.5	0.291	77	69.2
A4B2C1	41.4	0.168	101	100
	41.1	0.215	88.8	97.2

	40.9	0.222	86.8	102
A4B2C2	40.3	0.256	79.7	88.1
	40	0.308	72.1	82.2
	40	0.285	74.9	79.9
A4B2C3	41.1	0.238	84.3	76.4
	40.9	0.29	76	77.8
	40.9	0.346	69.5	75.4
A4B2C4	42.7	0.218	91.4	76.6
	40.9	0.33	71.3	76.8
	41.6	0.265	51.1	73.9
A4B3C1	40.8	0.186	94.6	88.3
	40.2	0.172	96.8	84.6
	41.2	0.207	90.5	88.6
A4B3C2	40.8	0.226	85.8	72.3
	41.2	0.375	67.3	71.9
	41	0.35	69.3	70.7
A4B3C3	40.7	0.261	79.7	68.6
	40.9	0.316	72.9	65.3
	41.2	0.367	68	65.5
A4B3C4	42.3	0.211	92.1	68.4
	41.9	0.22	89.2	58.9
	42.8	0.276	81.5	63.4
A4B4C1	41.7	0.137	113	85.6
	42	0.183	98.2	84.6
	42.7	0.214	92.2	87.7
A4B4C2	40.8	0.207	89.7	78.1
	41.9	0.345	71.3	69.9

	41.6	0.353	70.1	70.3
A4B4C3	42	0.536	57.3	67.3
	41.9	0.355	69.9	67.2
	41.5	0.253	82.6	65.5
A4B4C4	42.3	0.249	84.9	66.8
	44.6	0.245	90	59
	43.6	0.254	86.5	64.1

Appendix C. Air permeability test results

Table C.1 Single layers air permeability test results.

Fabric code	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Average
A1	590	561	564	565	533	562.6
A2	834	842	829	843	829	835.4
A3	470	483	464	490	493	480
A4	562	534	515	572	574	551.4
B1	0	0	0	0	0	0
B2	1	0	1	0	0	0.4
B3	0	0	0	0	1	0.2
B4	2	1	0	0	2	1
C1	450	465	425	410	407	431
C2	383	447	438	423	429	424
C3	321	417	473	398	487	419.2
C4	910	820	898	939	989	911.2

Appendix D. Burning tests results

Table D.1 Layered fabrics burning test results.

No.	Multi-layered fabrics code	**EN 367 HTI12**	**EN 367 HTI24**	**EN 367 HTI24-HTI12**	**EN 6942 RHTI 12**	**EN 6942 RHTI24**	**EN 6942 RHTI 24-RHTI 12**
1	A1B1C1	13.5	18.25	4.75	17.65	23.9	6.25
2	A1B1C2	13	17.5	4.5	15.2	20.3	5.1
3	A1B1C3	10.8	14.5	3.7	13.9	19	5.1
4	A1B1C4	11.1	15.1	4	14.7	20.3	5.6
5	A1B2C1	13.8	18.9	5.1	17.95	24.7	6.75
6	A1B2C2	14.3	18.5	4.2	15.7	22.4	6.7
7	A1B2C3	13	17.2	4.2	15.2	21.2	5.9
8	A1B2C4	12.4	16.7	4.3	14.2	20.2	6
9	A1B3C1	10.75	14.8	4.05	14.15	20.35	6.2
10	A1B3C2	9.8	13.7	3.9	13.9	19.4	5.5
11	A1B3C3	9.4	12.6	3.2	9.6	13.8	4.2
12	A1B3C4	9.6	13.1	3.5	10.2	14.8	4.6
13	A1B4C1	11.25	15.25	4	15.05	22.1	7.05
14	A1B4C2	10.9	14.7	3.8	14.9	21.7	6.8
15	A1B4C3	9.5	12.7	3.2	11.5	15.7	4.2
16	A1B4C4	9.7	13.3	3.6	12	16.9	4.9
17	A2B1C1	12.1	16.9	4.8	20.75	30	9.25
18	A2B1C2	11.9	16.7	4.8	20.2	29.5	9.3
19	A2B1C3	9.9	13.6	3.7	14.8	21.5	6.7
20	A2B1C4	10.9	14.9	4	15.7	23.3	7.6
21	A2B2C1	14.25	19.9	5.65	19.1	28.65	9.55
22	A2B2C2	13.9	19.4	5.5	18.9	26.4	7.5
23	A2B2C3	12.4	16.2	3.8	15.6	22.8	7.2

24	A2B2C4	13	17.6	4.6	16.4	24.9	8.5
25	A2B3C1	11.4	16.05	4.65	16.15	24.2	8.05
26	A2B3C2	10.9	15.8	4.9	15.7	23.8	8.1
27	A2B3C3	9.1	12.3	3.2	12.2	18.5	6.3
28	A2B3C4	9.8	13.4	3.6	13.3	20.5	7.2
29	A2B4C1	13.35	18.55	5.2	17.5	25.95	8.45
30	A2B4C2	13.2	18.2	5	17.1	25.2	8.1
31	A2B4C3	14	18	4	17	23	6
32	A2B4C4	11.1	15.6	4.5	14.5	21.3	6.8
33	A3B1C1	10.8	14.9	4.1	21.6	31	9.4
34	A3B1C2	10.6	14.7	4.1	20.7	30.5	9.8
35	A3B1C3	10.3	13.9	3.6	14.5	20.7	6.2
36	A3B1C4	11.2	15.3	4.1	15.6	23.2	7.6
37	A3B2C1	14.1	19.7	5.6	19	28.4	9.4
38	A3B2C2	13.5	19.3	5.8	18.9	26.4	7.3
39	A3B2C3	11.1	15	3.9	15.4	22.6	7.2
40	A3B2C4	12	16.5	4.5	16.3	24.9	8.6
41	A3B3C1	11	16.2	5.2	16	23.8	7.8
42	A3B3C2	10.9	15.6	4.7	15.3	23.8	8.5
43	A3B3C3	8.9	12.2	3.3	12	17.9	5.9
44	A3B3C4	9.5	13.3	3.8	13.3	20.3	7
45	A3B4C1	13	18.2	5.2	17.2	25	7.8
46	A3B4C2	13.5	18.1	4.6	16.9	25	8.1
47	A3B4C3	9.9	13.5	3.6	13.7	18.8	5.1
48	A3B4C4	11.3	15.4	4.1	14.5	20.7	6.2
49	A4B1C1	13.2	18.15	4.95	16.4	22.2	5.8
50	A4B1C2	13.1	17.7	4.6	15.3	20.5	5.2

51	A4B1C3	9.4	13.1	3.7	11	15.8	4.8
52	A4B1C4	10.6	14.8	4.2	12.2	18.1	5.9
53	A4B2C1	14.25	19.6	5.35	18.3	25.45	7.15
54	A4B2C2	14.4	18.7	4.3	15.5	22.2	6.7
55	A4B2C3	12.1	16	3.9	14.3	21	6.7
56	A4B2C4	13	17.7	4.7	15.8	23.2	7.4
57	A4B3C1	10.8	15.05	4.25	14.45	20.6	6.15
58	A4B3C2	9.8	13.8	4	13.5	19.5	6
59	A4B3C3	8.9	12	3.1	9.8	14	4.2
60	A4B3C4	9.6	13.2	3.6	10.8	15.8	5
61	A4B4C1	13.45	19	5.55	15.3	22.85	7.55
62	A4B4C2	10.5	14.6	4.1	14.9	20.4	5.5
63	A4B4C3	9.9	13.7	3.8	11	15.7	4.7
64	A4B4C4	11.1	15.4	4.3	12.5	18	5.5

CURRICULUM VITAE

Curriculum Vitae

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Type of Organization	Government University
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Amharic	

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European level (*)	Listening	Reading	Spoken interaction	
English	C1 Proficient user	Proficient user	C1 Proficient user	C2Proficient user
Turkish	C1 Proficient user	Proficient user	C1 Proficient user	C1Proficient user

I certify that to the best of my knowledge and belief, these data correctly describe me, my qualifications, and my experience.

Tolera Aderie Negawo