MODULAR PERSONAL PROTECTIVE EQUIPMENT SYSTEM FOR FIRST RESPONDERS

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Abstract: *Emergency responders are being asked to react to a growing number of violent events and natural disasters as well as evolving threats, such as mass rioting and targeting of response personnel. The aim of this research was to develop modular PPE systems that protect the emergency responders from injury while acting/ operating effectively in hazardous environments and provide the highest level of protection against a range of possible threats. The modular PPE system, built upon a duty uniform, integrates state-of-the-art protective tehnologies; provides basic protection from most likely threats (for example: fire, extremes weather etc.); enhances daily-wear comfort; provide increased localized protection as needed (for example: knees, forearms); includes next-to-skin layer and outer layer to provide varying levels of protection as needed; the modular layers easily donned and undonned. This modular approach: i) provides several advantages, including preserving comfort and flexibility until the intervention mission requires the use of the next level of protection; ii) it is a guarantee that emergency responders are not in a position of choosing between their safety and the effectiveness of the mission; iii) the use of modular layers could be the most cost-effective option, because only certain layers may become damaged or be in need of decontamination following an incident.*

Key words: *protection, safety and health, duty uniform, mission-specific layers, functional design, modular layers.*

1. INTRODUCTION

Emergency responders, due to the specifics of their work, are exposed to a combination of several different risks and there may be several possible consequences for their safety and health. An assessment of the risks specific to emergency response actions revealed the presence of the following types: physical risks (falling objects, ballistic projectiles / fragments, sharp edges and objects, slippery surfaces, excessive vibrations etc.); environmental risks (high heat, humidity, strong wind, insufficient light, excessive noise etc.); chemical risks (inhalation /absorption on the skin, contact with chemicals in liquid/vapor/powder form, ingestion, injection, chemical explosions etc.); biological hazards (pathogens carried/propagated by blood, tuberculosis or airborne pathogens, biological toxins, biogenic allergens etc.); thermal hazards (radiant and convective heat, flame, hot liquids or gases, hot solids or molten substances etc.); electrical hazards (electric shock, electric arc, static charge generation etc.); radiation risks (ionizing radiation - alpha / beta particles, gamma rays, X-rays, non-ionizing radiation etc.) [1], [2]. The relative risk significantly influences the decisions regarding the compromise that must be made between the level of protection, functionality and comfort provided to the emergency responder.

The aim of the project is to provide emergency responders with a modular PPE system built upon a duty uniform that provides limited protection and physiological benefits (for example, moisture wicking) in combination with a series of modular, mission - specific layers, to provide specialized protection.

This modular approach: i) provides several advantages, including preserving comfort and flexibility until the intervention mission requires the use of the next level of protection; ii) it is a guarantee that emergency responders are not in a position of choosing between their safety and the effectiveness of the mission; iii) the use of modular layers could be the most cost-effective option, because only certain layers may become damaged or be in need of decontamination following an incident.

2. EXPERIMENTAL

2.1 Materials

Considering: i) the specifics of the intervention missions: the confrontation with a multitude of known and unknown threats; ii) the capabilities necessary for the health and safety of the emergency responder: ensuring increased protection against threats without wearing specialized equipment and without compromising comfort and maneuverability; iii) the performance requirements imposed by the specific European standards, a solution for the realization of an PPE system intended for use in emergency intervention actions, is a multilayer structure: a) the inner layer, in contact with the skin/Underwear PPE – which covers the sensorial and thermophysiological comfort functions, ensures thermal protection; b) intermediate layer (base): Duty uniform - with the function of barrier against the risk factors with the highest probability of occurrence in case of an intervention action (thermal risks: convection heat, flame; external risks: splashes with liquids; mechanical hazards: cutting, abrasion etc.); c) outer layer: modular protective layers - Specialized PPE for intervention missions in case of: fires, dangerous materials, weapons of mass destruction, firearms, extreme weather conditions etc.

The methodology used for the design and achievement of the modular PPE system for emergency response actions is based on a multidisciplinary approach to the development and management of "complex systems" [3], [4]. Starting from the needs analysis, the key needs of the PPE system were identified, which were the basis for establishing the key performance parameters and the high performance parameters. The established performance parameters were translated into design requirements, based on which the raw materials, the realization technologies, the conception (design) of the PPE system were identified [5].

Starting from the key needs identified: *User Comfort; Certification of protection properties in accordance with the legislation in the field of PPE; Durability for Daily Wear; Usability/Functionality; Aesthetics;Multi-service Applicability; User acceptability; Reasonable cost* and taking into account the performance requirements imposed on the materials, it was decided to use them for manufacturing: *inner layer* (in contact with the skin) - underwear PPE - for a knitted fabric made of yarn 93/5/2% meta-aramid fibres/ para-aramid fibres/antistatic fibers; *intermediate layer (base*) - Duty uniform - for a woven fabric made of yarn 29/59/10/2% aramid fibres/ FR viscose fibres/polyamide fibres/antistatic fibers; *outer layer* - specialized PPE for firefighters - for a combination of materials: a) fabric 78/20/2% para-aramid fibres/ meta-aramid fibres/antistatic fibers (with fire protection role) + b) 3-D spunlace non-woven made of para-aramidic / meta-aramidic fibers + ePTFE / PU-bicomponent membrane (acting as a thermal-moisture barrier) + c) non-woven made of FR viscose fibres/ aramid fibers + viscose FR / aramid / polyamide fiber fabric (with the role of thermal liner); *outer layer* - specialized PPE for intervention missions in extreme weather conditions - for a multilayer textile support laminated in 3 layers: 100% PES fabric + PTFE film + 100% PES knit

2.2 Prototype design

Based on the protection requirements and the minimum required performance parameters specified, the following experimental program was established for the realization of the prototypes of intervention PPE systems in the modular structure.

***Table 1**: Experimental program*

Prototype variant of PPE intervention system	Prototype component of PPE intervention system	Constructive variant
Prototype PPE system for intervention in emergency situations Variant V1	*Modular layer 1:* Underwear PPE - inner layer (in contact with the skin)	Suit consisting of a blouse with long/short sleeves and long /short pants
	Modular Layer 2: Duty Uniform -base layer	Suit consisting of blouse and pants
Prototype PPE system for intervention in emergency situations Variant V2	*Modular layer 1:* Underwear PPE - inner layer (in contact with the skin)	Suit consisting of a blouse with long sleeves and long pants
	Modular Layer 2: Duty Uniform - base layer (intermediate)	Suit consisting of blouse and pants
	Modular layer 3: Specialized PPE for firefighters (outer layer)	Outer suit: Jacket and pants Detachable underwear: Jacket + pants
Prototype PPE system for intervention in emergency situations Variant V3	*Modular layer 1*: Underwear PPE - inner layer (in contact with the skin)	Suit consisting of a blouse with long sleeves and long pants
	Modular Layer 2: Duty Uniform - base layer (intermediate)	Suit consisting of blouse and pants
	Modular layer 3: Specialized PPE for interventions in extreme weather conditions (outer layer)	Jacket with detachable hood and lining

The physical realization of the prototypes of PPE systems for intervention in emergency situations was preceded by the virtual realization of these integrated systems, using solutions for digital design of patterns, modeling and 3D simulation of products on a parameterized mannequin, corresponding to size 50 I, using the OptiTex software suite [6].

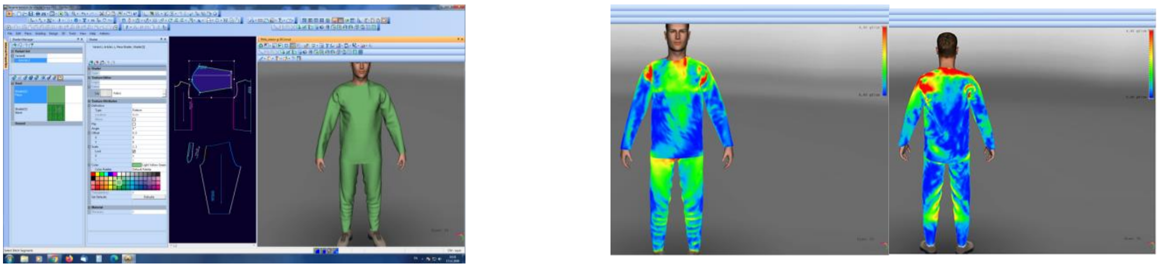


***Fig. 1**: Inner layer simulation - underwear PPE: Suit consisting of long-sleeved blouse and long pants*

Fig. 2: *Inner layer simulation – Underwear PPE: Suit consisting of a short-sleeved blouse and shorts*

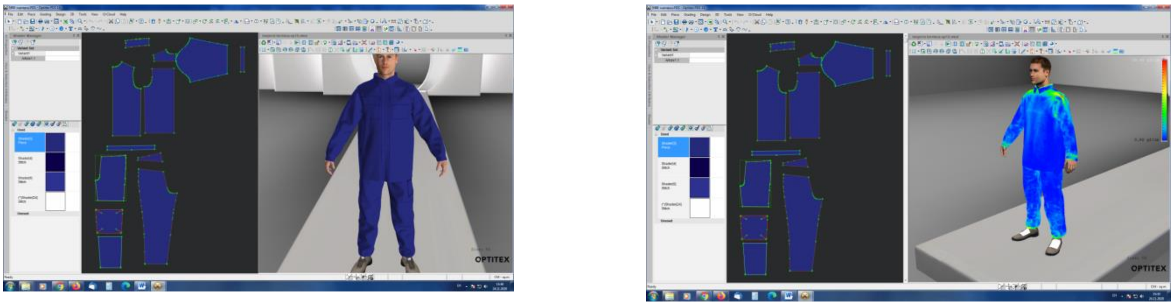


Fig3: *Simulation of the PPE system for intervention in emergency situations that integrates the inner layer (in contact with the skin) - Underwear PPE and the intermediate layer (base) – Duty uniform*

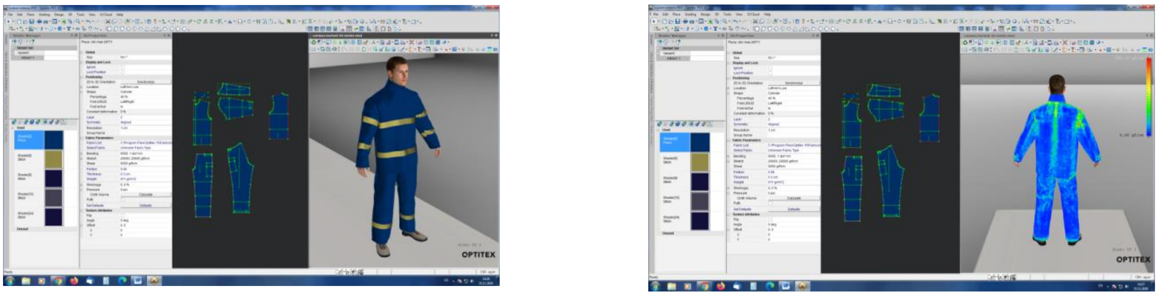


Fig.4: *Simulation of PPE system for intervention in emergency situations that integrates the inner layer (in contact with the skin) - Underwear PPE, intermediate layer (base) – Duty uniform and specialized PPE for firefighters*

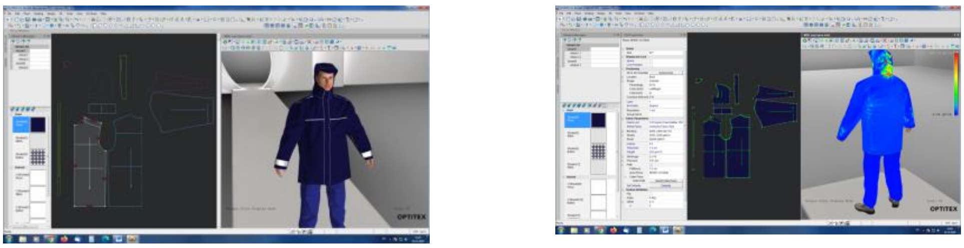


Fig. 5: *Simulation of PPE system for intervention in emergency situations that integrates the inner layer (in contact with the skin) - Underwear PPE, intermediate layer (base) – Duty uniform and specialized PPE for interventions in extreme weather conditions*

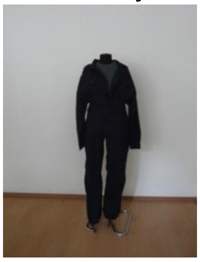
Based on the results of the evaluation of the adaptation of the modular layers/integrated systems of modular layers of the intervention PPE on the parameterized virtual manikin (Fig.1, 2, 3, 4, 5), 3 variants of PPE intervention system prototypes were made (Fig. 6, 7, 8), respectively:

Modular layer 1

Underwear PPE

Modular layer 1

Underwear PPE

Modular layer 2

Duty Uniform

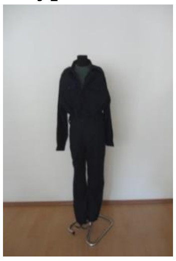
Prototype Variant V1

PPE intervention system prototype

Fig. 6*: Prototype PPE system for intervention in emergency situations Variant V1*

Modular layer 1

Underwear PPE

Modular layer 2

Duty Uniform

Modular layer 3

PPE for firefighters

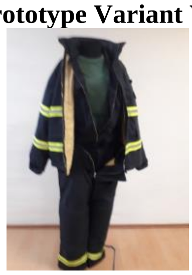
Prototype Variant V2

PPE intervention system prototype

Fig. 7*: Prototype PPE system for intervention in emergency situations Variant V2*

Modular layer 1

Underwear PPE

Modular layer 2

Duty Uniform

Modular layer 3

PPE for interventions in extreme weather conditions

Prototype Variant V3

PPE intervention system prototype

Fig. 8: *Prototype PPE system for intervention in emergency situations Variant V3*

3. RESULTS AND DISCUSSIONS

In order to evaluate the performances of the prototypes of PPE intervention systems in the modular structure, the specific laboratory tests performed for the verification of the protection parameters were performed, in accordance with the requirements of the applicable standards, respectively: SR EN ISO 11612:2015- *Protective clothing. Clothing to protect against heat and flame. Minimum performance requirements*; SR EN 469: 2020 - *Protective clothing for firefighters.*

Performance requirements for protective clothing for firefighting activities; SR EN 342: 2018- *Protective clothing. Ensembles and garments for protection against cold*; SR EN 343:2019 - *Protective clothing. Protection against rain*; SR EN ISO 13688: 2013- *Protective clothing - General requirements.*
The performance evaluation highlighted the fact that:

-The PPE intervention system Variant V1 has characteristics according to the specifications of the following standards:

a) SR EN ISO 11612: 2015: point 6.3 (resistance to limited flame spread) - the mean value of afterflame time and afterglow time:0 s, code letter A1 (for knitted fabric of the underwear PPE, respectively for the fabric of the duty uniform); point 6.4 (dimensional change) within the limits imposed, less than ± 3%, in both directions, longitudinally and transversely (for knitted fabric of the underwear PPE) respectively, warp and weft (for the fabric of the duty uniform); point 6.5.1 (tensile strength) above the minimum value imposed, 300 N in warp and weft (for fabric of the duty uniform); point 6.5.2 (tear strength) above the minimum value imposed, 15 N in warp and weft (for fabric of the duty uniform); point 6.5.3 (burst strength) above the minimum required value, 200 kPa (for knitted fabric of the underwear PPE); point 6.9.2 (pH value) within the required limits, greater than 3.5 and less than 9.5 (for knitted fabric of the underwear PPE, respectively for the fabric of the duty uniform);

b) SR EN ISO 13688: 2013: point 4.2 (innocuousness - content of carcinogenic amines) within the imposed limits, undetectable; point 4.3 (design); section 4.4 (comfort).
-The **PPE intervention system Variant V2** has characteristics according to the specifications of the following standards:

a) SR EN ISO 11612: 2015: point 6.3 (resistance to limited flame spread) - the mean value of afterflame time and afterglow time:0 s, code letter A1 (for knitted fabric of the underwear PPE, respectively for the fabric of the duty uniform); point 6.4 (dimensional change) within the limits imposed, less than ± 3%, in both directions, longitudinally and transversely (for knitted fabric of the underwear PPE) respectively, warp and weft (for the fabric of the duty uniform); point 6.5.1 (tensile strength) above the minimum value imposed, 300 N in warp and weft (for fabric, of the duty uniform); point 6.5.2 (tear strength) above the minimum value imposed, 15 N in warp and weft (for fabric of the duty uniform); point 6.5.3 (burst strength) above the minimum required value, 200 kPa (for knitted fabric of the underwear PPE); point 6.9.2 (pH value) within the required limits, greater than 3.5 and less than 9.5 (for knitted fabric of the underwear PPE, respectively for the fabric of the duty uniform);

b) SR EN 469: 2020: point 6.1 (resistance to limited flame spread) - the mean value of afterflame time and afterglow time:0 s, code letter A1 (for specialized PPE for firefighters); point 6.5 (thermal resistance) - dimensional changes after exposure 5 minutes at 180°C, below 5% (for materials made of specialized PPE for firefighters); point 6.6 (tensile strength) above the minimum value imposed for the outer material of the PPE for firefighters, 450 N in warp and weft; point 6.7 (tear strength) above the minimum value imposed for the outer material of the PPE for fighters, 25 N in warp and weft; point 6.8 (surface wetting), above the minimum value imposed for the outer material of the PPE for firefighters, 4 (ISO degree scale); point 6.9 (dimensional change when washing) below the required minimum values, ± 3% (for all materials in the component of the PPE for firefighters); point 6.10 (resistance to penetration of liquid chemicals), rejection rate over 80% for each of the

liquid chemicals mentioned in the standard (for the set of materials in the component of the PPE specialized for firefighters); point 6.11 (resistance to water penetration) over 20 kPa, level 2 performance (for the multilayer assembly with a barrier of moisture of the PPE specialized for firefighters); point 6.12 (water vapor resistance), below 30 m^2Pa/W, performance level 2 (for the set of materials in the component of the PPE specialized for firefighters);
c) SR EN ISO 13688: 2013: point 4.2 (innocuousness - content of carcinogenic amines) within the imposed limits, undetectable; point 4.3 (design); section 4.4 (comfort); point 5 (aging).

-The **PPE intervention system Variant V3** has characteristics according to the specifications of the following standards:

a) SR EN 343:2019: point 4.2 (resistance to water penetration) above the minimum required value, 13000 Pa (for multilayer textile support, material of the specialized PPE - Jacket); point 4.3 (water vapor resistance) below the maximum value imposed, 55 m^2Pa/W (for multilayer textile support, material of the specialized PPE - Jacket); point 4.4 (tensile strength) above the required value, 450 N in warp and weft (for multilayer textile support, material of the specialized PPE- Jacket); point 4.5 (tear strength) above the imposed value, 25 N in warp and weft (for multilayer textile support, material of the specialized PPE - jacket); point 4.6 (dimensional changes) below the required minimum values, ± 3% in both directions of the material of the specialized PPE- Jacket;

b) SR EN 342:2018: point 4.2 (thermal resistance) above the required minimum value, 0.31 m^2K/W (for multilayer textile support, material of specialized PPE-Jacket); point 4.3 (air permeability, AP) within the limit values imposed for performance class 3 (AP <5 mm/s) (for multilayer textile support, material of the specialized PPE- Jacket); point 4.4 (resistance to water penetration) above the minimum value imposed, 13000 Pa (for multilayer textile support, material of the specialized PPE - Jacket); point 4.5 (water vapor resistance) below the maximum value imposed, 55 m^2Pa/W (for multilayer textile support, material of the specialized PPE- Jacket); point. 4.6 (tear strength) above the minimum value imposed, 25 N in warp and weft (for multilayer textile support, material of the specialized PPE - Jacket);

c) SR EN ISO 11612: 2015: point 6.3 (resistance to limited flame spread) - the mean value of afterflame time and afterglow time: 0 s, code letter A1 (for knited fabric of the underwear PPE, respectively for the fabric of the duty uniform); point 6.4 (dimensional change) within the limits imposed, less than ± 3%, in both directions, longitudinally and transversely (for knitted fabric of the underwear PPE) respectively, warp and weft (for the fabric of the duty uniform); point 6.5.1 (tensile strength) above the minimum value imposed, 300 N in warp and weft (for fabric of the duty uniform); point 6.5.2 (tear strength) above the minimum value imposed, 15 N in warp and weft (for fabric of the duty uniform); pt. 6.5.3 (burst strength) above the minimum required value, 200 kPa (for knitted fabric of the underwear PPE); 6.9.2 (pH value) within the required limits, greater than 3.5 and less than 9.5 (for knitted fabric of the underwear PPE, respectively for the fabric, of the duty uniform);
d) SR EN ISO 13688: 2013: point 4.2 (innocuousness - content of carcinogenic amines) within the imposed limits, undetectable; point 4.3 (design); section 4.4 (comfort).

5. CONCLUSIONS

The aim of this research was to develop modular PPE systems that protect the emergency responders from injury while acting/ operating effectively in hazardous environments and provide the highest level of protection against a range of possible threats.

To meet this objective the modular PPE system: integrates state-of-the-art protective tehnologies including flame resistance, water repellency; provides basic protection from most likely threats (for example: fire, extremes weather etc.); enhances daily-wear comfort; provide increased localized protection as needed (for example: knees, forearms); includes next-to-skin layer and outer layer to provide varying levels of protection as needed; the modular layers easily donned and undonned.

The test and evaluation process consisted of objective and subjective testing. The objective laboratory testing quantitavely determined if a fabric could meet the minimum performance requirements. The testing objective consist of material testing and sistem level testing. However, laboratory data cannot accuaratelly assess the operational suitability and effectiveness of a PPE system when used under operational conditions. Critical attributes, such as comfort, appearance, durability, freedom and range of motion, coult not be fully evaluated under laboratory conditions. That is why this research will continue with the Wear Trial of the PPE system under operational conditions. This subjective evaluation will be essential to differentiating the performance of the modular layers integrated into the PPE system prototypes

ACKNOWLEDGEMENTS

This work was carried out through the Nucleu Programme, with the support of MCID, project no. 4N/08.02.2019, PN 19 17 02 01, project title: “Advanced multifunctional logistics, communications and protection systems to improve the safety, operability and efficiency of emergency workers – SiMaLogPro”.

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