8
Smart technology for personal protective equipment and clothing

H. CAO, University of Delaware, USA

Abstract: This chapter reviews personal protective equipment (PPE) and clothing for different occupations and users, e.g., hazardous material (HAZMAT) workers, firefighters, industrial workers, healthcare personnel, and law enforcement and military personnel. The standards, requirements and commercial products for these PPE are discussed. The chapter covers the various types of smart technology that can be incorporated into textiles and clothing for personal protection, and applications and examples of smart PPE, including academic and industrial research and development, and commercial products. Future trends of smart PPE and helpful literature and websites are also included in this chapter.

Keywords: hazardous materials (HAZMAT), firefighter, welder, law enforcement, military, healthcare, active noise reduction, electronic circuits.

8.1 Introduction

According to the U.S. Occupational Health and Safety Administration (OSHA) definition (OSHA, 2006), personal protective equipment (PPE) 'is designed to protect workers from serious workplace injuries or illnesses resulting from contact with chemical, radiological, physical, electrical, mechanical, or other workplace hazards.' First responders, emergency service personnel, military personnel, and workers in specific occupations who may work in environments with chemical, biological, radiological, and nuclear (CBRN) materials, fire, and heat are required to wear specialized PPE. The purpose of wearing PPE, including gloves, foot and eye protection, protective hearing devices (earplugs, muffs), head protection, respirators and full body suits, is to minimize exposure to a variety of hazards (OSHA, 2003).

Based on different types of possible hazards that a person may encounter, PPE products will have different requirements, and are regulated by different government agencies or international nonprofit organizations. In the United States, OSHA, a unit in the Department of Labor, publishes the most comprehensive standards for workplace PPE required in general industry (29 CFR 1910), shipyard employment (29 CFR 1915), marine terminals (29 CFR 1917), longshoring (29 CFR 1918), and construction (29 CFR 1926).

For personnel who may be near the site of hazardous vapors, gases, and particles, U.S. Environmental Protection Agency (EPA) defines four levels of PPE protection, with level A required for the greatest protection and level D required for the minimum level of protection (EPA, n.d.). The EPA levels of protection are widely used by government agencies such as OSHA as well as PPE manufacturers. American National Standards Institute (ANSI), a private non-profit organization, has been developing safety standards since the 1920s. OSHA requires that many categories of PPE meet or be equivalent to standards developed by the ANSI. For instance, OSHA requires that PPE for eye and face protection meets ANSI Z87.1-1989 standard; PPE for head protection meets ANSI Z89.1-1986 standard; and PPE for foot protection meets ANSI Z41.1-1991 standard (OSHA, 2003). The International Safety Equipment Association (ISEA, www.safetyequipment.org) is the trade association for PPE manufacturers. As an accredited member of ANSI, ISEA's product groups draft PPE standards for public review and then for approval as American National Standards.

The National Fire Protection Association (NFPA), an international non-profit organization, publishes Standards for Fire Departments on Occupational Safety and Health Programs (NFPA 1500). The first edition of NFPA 1500 standard was published in 1987, and the revised editions were published in 1992, 1997, 2002 and 2007. Before the introduction of NFPA 1500 standard, fire service organizations relied on the regulations that were developed for general industry, which did not address firefighters' specific needs and concerns (Stull and Stull, 2008).

This chapter discusses various types of PPE and protective clothing, and the applications of smart clothing in PPE. Future trends of smart PPE and helpful literature and websites are also included.

8.2 Types of personal protective equipment and clothing

Based on the threats they may encounter, firefighters, hazardous material (HAZMAT) workers, law enforcement personnel, military personnel, and employees in certain types of occupations such as welders use different types of PPE.

8.2.1 PPE for HAZMAT workers

U.S. EPA's four levels of protection are very useful in selecting PPE for HAZMAT workers who may have chemical and/or biological risks. According to EPA (n.d.), 'Level A protection is required when the greatest potential for exposure to hazards exists, and when the greatest level of skin, respiratory, and eye protection is required. Level B protection is required under circumstances requiring the highest level of respiratory protection, with lesser level of skin protection. At most abandoned outdoor hazardous waste sites, ambient atmospheric vapors or gas levels have not approached sufficiently high concentrations to warrant level A protection, level B protection is often adequate. Level C is required when the concentration and type of airborne substances is known and the criteria for using air purifying respirators are met. Level D protection is the minimum protection required. Level D protection may be sufficient when no contaminants are present or work operations preclude splashes, immersion, or the potential for unexpected inhalation or contact with hazardous levels of chemicals.' Since these four levels are mainly for chemical protection, polyolefin, such as DuPont (Wilmington, Delaware, www.dupont.com) Tyvek®, are commonly used materials for this type of protective clothing.

Both level A and level B protection require the same level of respiratory protection with self-contained breathing apparatus (SCBA) or positive pressure supplied air respirator with escape SCBA. International Safety Instruments (ISI, Lawrenceville, Georgia, www.avon-isi.com) is one of the leading SCBA manufacturers in the U.S. Their SCBA products include Viking Z7, Z3000, Z3100, Vanguard, and Frontier. While levels A and B protection require the same inner and outer chemical-resistant gloves and boots, they have different requirements in protective suits. Level A protection requires a totally encapsulated chemical and vapor protective suit, and level B protection includes face shield, hooded chemical resistant clothing, and coveralls. According to DuPont Personal Protection (n.d.), a leading PPE manufacturer, a level A suit is vapor protective against chemicals with a high vapor pressure, and toxic through skin absorption, or carcinogenic substances. A Level B suit is not gas tight and can be used to protect against chemicals that are not vapors or gases having skin toxicity or which are carcinogenic. DuPont™ TyChem® products include both level A and level B suits.

Branson *et al*. (2005) conducted a series of six focus-group studies with first responders in five cities in the U.S., and found that the level B suit was used much more frequently than the level A suit. Level B HAZMAT suits were used hundreds of times a year in responding to a variety of incidents, while level A suits were typically used less than five times a year. The study also found that heat and humidity build-up were serious problems for both level A and level B suits, and an ambient temperature above 15.6 °C (60 °F) can cause heat exhaustion when wearing either suit (Branson *et al*., 2005). To solve this problem, a team led by Branson developed two liquid cooling vest prototypes, and found that the two prototypes positively affected user's skin temperatures, sweat rate, microclimate temperature, humidity, perceived temperature and perceived humidity (Peksoz *et al*., 2006).

Similar chemical protective suits, gloves and boots can be used for both level B and level C protection. However, SCBA is used for respiratory protection in level B protection, while level C protection requires an air-purifying respirator that uses an air purifying filter, cartridge, or canister to remove air contaminants. Examples of air-purifying respirators include the 6000 series, 7500 series, and 7800 series respirators manufactured by 3M Corp (Maplewood, Minnesota, www.3m.com). No respiratory protection and limited skin protection are provided in level D protection. Level D PPE may include gloves, coveralls, safety glasses, face shield and boots.

8.2.2 PPE for firefighters

Firefighters require the best PPE available because of the nature of their jobs and the environment in which they perform their duties. A firefighter's full protective equipment for structural firefighting consists of personal protective clothing (helmet, protective hood, protective coat and trousers, gloves, safety shoes or boots, eye protection goggles or face shields, hearing protection), personal breathing apparatus SCBA, and personal alert safety system (PASS) (IFSTA, 1992). Good protective clothing and breathing apparatus can reduce and prevent injuries from fire, heat, smoke, oxygen deficiency and toxic atmospheres.

In the U.S., the same group of people may do both fire fighting and HAZMAT material cleaning jobs. Some PPE units such as SCBA may be used for both firefighters and HAZMAT workers. For instance, ISI's top of the line SCBA Viking 7 is National Institute for Occupational Safety and Health (NIOSH), CBRN, and NFPA compliant. The main difference between firefighter PPE and HAZMAT PPE is in the protective suit. Firefighters' main risk comes from fires, and their working environment may be extremely hot. In addition, a large quantity of high pressure water is used by firefighters during their work. Therefore, a firefighter's turnout gear, or bunker gear (coat and trousers), typically has three layers, namely a fire-resistant and water-resistant outer shell to protect against fires, a middle thermal insulation layer to protect against heat, and an inner layer moisture barrier to protect against water. Fire resistance properties are typically required for every layer of the bunker gear. FireDex LLC (Medina, Ohio, www.firedex.com) manufactured customizable gear FX™ that allows customers to choose fabrics for each layer. In FX™ products, fire resistant fibers used in the outer shell include the aramids Nomex® and Kevlar®, polyimide P84®, melamine fiber Basofil®, PBI®, and others. Quilt batting using the above-mentioned flame resistant fibers or a combination of flame resistant fibers and other thermal protection such as Caldura® can be selected as the thermal insulation liner. The moisture barrier could be ePTFE such as Stedair®, Crosstech®, and Gore® RT7100 on fire resistant Nomex®.

8.2.3 PPE for industrial workers

Many industrial sectors such as mining, welding and cutting, and construction require PPE for body protection, eye and face protection, hand protection, hearing protection, and head protection. Workers in different industrial occupations may encounter different types of threats, and thus need different types of PPE for protection. According to OSHA (2003), cooperative efforts of both employers and employees are needed for the greatest possible protection. It is the employers' responsibility to assess workplace hazards; identify, provide, maintain, and replace appropriate PPE for employees; train employees for using and caring for PPE; and periodically review, update and evaluate the effectiveness of the PPE program. It is the employees' responsibility to attend the PPE training session; care for and clean the PPE; and inform a supervisor the need for repair or replacement of the PPE.

ANSI Z89.1 is the PPE standard for head protection. There are two types of head protection: Type I helmet provides protection strictly from blows to the top of the head; and Type II helmet provides protection from blows to both the top and sides of the head. Under Z89.1-1997, three classes of helmets are categorized, based on electrical insulation: Class G (General, equivalent to Class A under Z89.1-1986 standard) for low voltage electrical protection (tested at 2200 volts); Class E (Electrical, equivalent to Class A under Z89.1-1986) for high voltage electrical protection (tested at 20 000 volts); and Class C (Conductive, equivalent to Class C under Z89.1-1986) with no electrical protection. For instance, Bullard (Cynthia, Kentucky, www.bullard.com) produces the Advent protective hat that provides Type II, Class E and G protection. Bullard's Standard Series Model S62 protective hat provides Class C protection.

ANSI Z87.1 is the PPE standard for face and eye protection that includes spectacles (plano and prescription), goggles, face shields, welding helmet, and full facepiece respirators to protect against workplace hazards such as impact, optical radiation, droplet and splash, dust, and fine dust particles (ISEA, n.d. a). ANSI Z41 was the PPE standard for foot protection but was superseded by American Society of Testing and Materials (ASTM) standard F2413 in 2005. ASTM F2413 (Standard Specification for Performance Requirements for Protective (Safety) Toe Cap Footwear) specifies the protective footwear requirements for impact resistance and compression resistance in the toe area, metatarsal protection, electrically conductive properties to reduce hazards from static electricity build-up and possibilities of ignition of explosives and volatile chemicals, electric shock protection, static dissipative (SD) properties, puncture resistance of footwear bottoms, chain saw cut resistance, and dielectric insulation. ANSI/ISEA 105–2011 standard was developed by ISEA's Hand Protection Group for gloves, mittens, partial glove, or other hand protection equipment. The performance and pass/fail criteria against hazards such as cut, puncture and abrasion resistance, chemical permeation and degradation, detection of holes, vibration reduction, and heat and flame resistance are covered in the standard (ISEA, n.d. b). This standard does not address protection for welding, emergency response applications or fire fighter applications (ANSI, n.d.).

According to OSHA (n.d.), noise-related hearing loss has been one of the most prevalent occupational health concerns in the U.S. for more than 25 years. In 2009, the Bureau of Labor Statistics (BLS) reported more than 21 000 hearing loss cases due to high workplace noise level. OSHA sets legal limits on noise exposure in the workplace. These limits are based on a worker's time-weighted average over an eight-hour day. With noise, OSHA's permissible exposure limit (PEL) is 90 dBA for all workers for an eight-hour day. When the noise level is increased by 5 dBA, the amount of time a person can be exposed to a certain noise level to receive the same dose is cut in half (OSHA, n.d.). This means that OSHA allows 4 hours of exposure to 95 dBA sound level, and 2 hours of exposure to 100 dBA sound level. Hearing protection devices include single-use earplugs made of waxed cotton, foam, silicone rubber or fiberglass wool, molded earplugs that must be individually fitted by a professional, and earmuffs (OSHA, 2003).

8.2.4 PPE for healthcare personnel

The greatest threat a healthcare employee may encounter comes from infectious materials. PPE that protects healthcare employees against infectious materials include gloves, gowns, masks, goggles, and respirators. The U.S. Center for Disease Control and Prevention (CDC) provides very helpful guidance for selecting and using PPE for healthcare workers (CDC, n.d.). Fit and comfort are important in healthcare PPE. Healthcare gloves need to fit the hands comfortably and be durable for several hours of use. Common materials for gloves are vinyl, latex, and nitrile. Gowns are usually made from cotton and spun synthetic fibers for comfort purpose. A fluid resistance gown may be used if a fluid penetration threat exists. To ensure protection, the long sleeves of gown, mask, and goggles should fit snuggly at the wrists, over the mouth and nose, and over and around the eyes, respectively. A respirator that filters air before inhaling, or a powered air-purifying respirator if there is an existing higher level of respiratory threat, is used to protect healthcare providers against hazardous and infectious aerosols. Sterile gloves and gowns are necessary in invasive procedures to further protect patients, as well as healthcare providers (CDC, n.d.).

Proper use of PPE is critical for the safety of healthcare providers and patients, and CDC (n.d.) has published detailed guidance for how to don, use and doff PPE to prevent disease transmission. However, it is a challenge for a healthcare provider to always comply with the requirements. Beam *et al*. (2011) studied the PPE usage behavior of ten registered nurses, respiratory therapists, and nursing assistants in a simulated healthcare environment and found that each of the ten participants committed at least one breach of standard airborne and contact isolation precautions. Not conducting a seal check and not tying the gown at both the neck and the waist were among the most common breaches in PPE donning. Not using proper mask removal technique and using poor technique for gown removal were among the most common breaches in PPE doffing. Not donning and doffing PPE in CDC-recommended sequence were also very common, with 7 out 10 not donning, and 9 out of 10 not doffing, in the proper sequence (Beam *et al*., 2011).

8.2.5 PPE for law enforcement and military personnel

Body armor that can protect the wearer against ballistic weapons is the most commonly used PPE for law enforcement and military personnel. For law enforcement armors, National Institute of Justice (NIJ) Standard 0101.04, Ballistic Resistance of Personal Body Armor, specifies seven classes of protection against ballistic threat, depending on bullet composition, shape, caliber, mass, angle of incidence, and impact velocity (NIJ, 2001). They are Type I for .22 caliber Long Rifle Lead Round Nose (LR LRN) bullets and 380 ACP Full Metal Jacketed Round Nose (FMJ RN) bullets; Type IIA for lower velocity 9 mm and 40 S&W ammunition; Type II for high velocity 357 Magnum and higher velocity 9 mm ammunition; Type IIIA for high velocity 9 mm and 44 Magnum ammunition; Type III for rifles; Type IV for armor piercing rifles; and Special Type for a level of protection other than one of the above standard types (NIJ, 2001).

Type I armor provides the minimum protection that any officer should have and Type IIIA armor is suitable for routine wear in many situations. Soft armors, made from many layers of woven or laminated fibers, are capable of providing Types I to IIIA protection. According to NIJ (2004), more than 65 manufacturers worldwide have submitted armor to NIJ to validate their armor's performance in accordance with the NIJ body armor standard. DuPont (Kevlar® fiber), Honeywell (Spectra® fiber), Teijin Twaron (Twaron®), DSM (Dyneema®), and Toyobo (Zylon®) are the predominant ballistic material producers for soft armor (NIJ, 2004). Kevlar® and Twaron® are aramids, Spectra® and Dyneema® are highly oriented polyethylene, and Zylon® is polybenzobisoxazole (PBO) (Phoenix and Porwal, 2003).

Types III and IV armors are used only in tactical situations, when the threat warrants such protection (NIJ, 2001). Soft vests reinforced with metal or ceramic plates are typically used for protecting law enforcement personnel against rifle rounds (Type III and Type IV), and for military personnel. Due to the weight and rigidity of metal and ceramic plates, plate-reinforced hard armor is usually used for torso protection (vest). To protect limbs of combat soldiers against improvised explosive devices (IEDs), Matic *et al.* (2006) developed QuadGard® arm and leg protection armor that have been used by U.S. Marine Corps, Army, Air Force and Navy units. QuadGard®, weighing only 10 pounds, uses lightweight and soft ballistic materials to provide extremity protection against fragments from conventional munitions and IEDs. The testing and evaluation with warfighters showed that it achieved a high level of acceptance for its flexibility and comfort (Matic *et al.*, 2006).

8.3 Applications of smart clothing in personal protective equipment

In materials and structures, 'smart' is defined as sensing and reacting to environmental conditions or stimuli, such as those from mechanical, thermal, chemical, electrical, magnetic or other sources (Tao, 2001). Smart clothing uses clothing as the platform for micro-processors, electronic devices, sensors and communication devices, so it can sense and react to environmental conditions or stimuli, and provide an enhanced environmental and personal awareness. Advances in miniaturization, new sensors, computing science and related technologies have resulted in the emergence of smart clothing (Axisa *et al.*, 2005). Electronic devices can be integrated in any unit of PPE, such as suit, gloves, head and foot protection, and respirator.

8.3.1 Smart PPE for industrial protection

Buchweiller *et al.* (2003) mentioned a few integrations of electronics in PPE during the earlier years. In 1973, Gordon (1975) filed a U.S. Patent (3,873,804) that integrated a liquid crystal display together with an electric circuit into the eye piece of a welding helmet for optical protection. As claimed in this patent, the helmet 'requires nothing from [the welder] except that he puts on the helmet and may then go about his work. He does not have to operate a separate switch or any other piece of equipment. He merely picks up his electrode and this invention (helmet) protects his eyes solely upon approach of his electrode to the workpiece.' This invention was one of the earliest smart technology applications in PPE.

The technology of active noise reduction (ANR), also known as active noise control or noise cancellation, is a technology to reduce unwanted sound by emitting a sound wave with the same amplitude but inverted phase to the noise. Due to its long wavelength, low frequency noise can travel great distances and penetrate passive barriers such as cement walls, which makes it very difficult to attenuate. Pro Tech Technologies Inc. (Wilton, Connecticut, www.noisebuster.net) incorporated ANR technology into a PPE application and developed NoiseBuster® ANR Safety Earmuff. The NoiseBuster® ANR earmuff uses a microphone in the ear cup to capture the noise, electronically create an anti-noise wave that is identical to the noise but opposite in phase, and output the anti-noise wave through a speaker that is also located in the ear cup. The NoiseBuster® ANR earmuff combines passive noise reduction up to 26 dB and electronic active noise reduction up to 20 dB, to provide very effective protection against noise. The NoiseBuster® ANR earmuff is available in three models: over-the-head, behind-the-head, and hard hat cap mount, and can protect employees in many professions such as pipeline workers, assembly line workers, airplane maintenance workers, and coal miners.

8.3.2 Smart PPE for firefighters

The personal alert safety system (PASS) device, about the size of a portable transistor radio worn on the firefighter's SCBA or coat, is mandatory for all firefighters under NFPA 1500 (Standard on Fire Department Occupational Safety and Health Program). PASS uses a motion detector to sense a firefighter's movement or lack of movement and will emit a loud, pulsating shriek if a firefighter collapses or remains motionless for approximately 30 seconds (IFSTA, 1992). It can be considered as one of a few smart PPE devices that are approved and required by an international PPE standard. Caught or trapped has always been one of the leading causes for firefighter on-duty deaths. The most recent NFPA report (Fahy *et al.*, 2011) found that in 2010, eight firefighters died from being caught or trapped, which is the third leading cause for a total of 72 firefighter on-duty deaths. If properly implemented, the PASS device can serve as a platform for the incorporation of additional and more innovative technology to help reduce fatalities and injuries resulting from caught or trapped firefighters (Bryner *et al.*, 2005). Tests performed by the Mesa (Arizona) Fire Department showed that locating even the loud shriek of a PASS device in poor visibility conditions can be more difficult than expected. The reasons include sound reflecting from walls, ceilings, and floors; noise from SCBA operation; and muffled hearing due to protective hoods (IFSTA, 1992).

As indicated previously, firefighters' protective clothing effectively insulates them from the thermal environment around them. Due to the thermal insulation, sometimes it is difficult for the firefighters to appreciate how much heat flux they have been exposed to during fire fighting operations. The thermal environment can range from slightly elevated temperatures, 66 °C, in which firefighters may be able to work for longer periods, up to pre-flashover temperatures, 650 °C, in which firefighters must quickly escape. Currently, thermal sensors are incorporated into many PASS devices to warn firefighters of a range of thermal exposures (Bryner *et al.*, 2005). Viking Life Saving Equipment (Esbjerg, Demark, www.viking-life.com) have developed an NFPA compliant intelligent garment that integrates thermal sensors in the inner and outer layers of a firefighter coat, and the sensors are connected to LED displays on the sleeve and back of the left shoulder. The sensors can monitor heat near the firefighter and outside the coat. The LED displays can alert the firefighter to critical temperatures that cause heat stress and burn. The LED on the lower sleeve indicates elevated temperatures both inside and outside of the coat: flashing slowly when external temperatures reach about 250 °C or the internal temperature reaches about 50 °C, and flashing rapidly when external temperatures reach about 350 °C or the internal temperature reaches about 68 °C. The shoulder LED display of Viking's intelligent clothing is also visible to other firefighters, alerting them to a potentially dangerous thermal environment.

Sudden cardiac death has always been the leading cause for U.S. firefighter on-duty fatalities. In 2010, 35 firefighters died from sudden cardiac death, which accounts for 49% of the total 72 firefighter on-duty deaths (Fahy *et al.*, 2011). From 1995 through 2004, 449 firefighters, or almost half of the total number of fire fighters who died while on duty, fell victim to sudden cardiac deaths (Fahy, 2005). To monitor a firefighter's heart health as well as thermal environment, Peksoz *et al.* (2009) developed smart firefighter clothing prototypes by incorporating a wireless sensor network (WSN) into the firefighter's coat and glove. A WSN is composed of many sensor nodes, also called motes, for sensing and communication. The basic components in a sensor mote include an embedded microprocessor, a memory with limited capacity, a low-power radio for communication and a battery. In the smart firefighter clothing prototypes developed by Peksoz *et al.* (2009), the WSN was based on the Mica sensor motes produced by Crossbow Technology Inc. (San Jose, CA, www.xbow.com). The Mica sensor mote and mote-based pulse oximeter devices, including finger sensor, oximeter board, and connection board, were incorporated into a firefighter glove to monitor a firefighter's heart rate and blood oxygen saturation, and wirelessly send the data to a remote computer (Peksoz *et al.*, 2009). Two sets of stacked Mica sensor mote and environmental sensor board that have the capacity of measuring temperature and relative humidity were placed in sensor receptacles attached to the center back and left side of the chest in the moisture barrier inner lining of the coat, to monitor the microclimate temperature and humidity. A third set of stacked Mica sensor mote and environmental sensor board was placed in an exterior pocket made from one layer of outer shell fabric of the firefighter coat, to monitor ambient conditions (Peksoz *et al.*, 2009).

8.3.3 e-Textiles and smart PPE for military personnel

A lot of smart clothing is based on electronic textiles (e-textiles) (Marculescu *et al*., 2003), in which conductive metal or polymer fibers are embedded in fabrics to serve as electrical circuits. The methods to embed conductive fibers into textile fabrics include weaving (Martin *et al*., 2004; Park and Jayaraman 2001), knitting (Paradiso *et al*., 2005) and embroidering (Post *et al*., 2000). Plain weave, the most elementary and simple textile structure, provides a tight mesh of individually addressable insulated metal filaments that can be used as basic transmission lines or whole circuits (Marculescu *et al*., 2003). The Georgia Tech Wearable Motherboard (GTWM™) (Park and Jayaraman 2004), one of the earliest e-textiles, is an example of this woven architecture of a textile-based computer motherboard for special purpose chips and processors. As indicated on the GTWM™ website (GTWM, n.d.), the wearable motherboard served as a flexible information infrastructure and a system for monitoring the vital signs of individuals. The third generation of GTWM™ was a smart shirt in which the plastic optical fiber (POF) was spirally integrated into a single-piece undershirt during the fabric weaving process. It was the first woven full-fashion garment with no 'cut and sew' operations, so the POF does not have any discontinuities at the armhole or the seams. Sensors, such as electrocardiogram (EKG) sensors, can be connected to the smart shirt and vital sign data such as temperature, heart rate, and respiration rate, and information about wounds, can be collected and transmitted to monitoring equipment or DARPA's (Defense Advanced Research Projects Agency) personal status monitor. The GTWM™ project was funded by the U.S. Department of Navy, so the original application was for military protection, but the wearable information infrastructure can be easily customized for applications in personalized information processing, healthcare and telemedicine, space exploration, and others (GTWM, n.d.).

Other woven e-textile research can be found in Virginia Polytechnic Institute and State University (Virginia Tech) (Martin *et al*., 2004) and Carnegie Mellon University (Stanley-Marbell *et al*., 2003). e-Textiles have three common design goals: low cost, durability and long running (Marculescu *et al*., 2003). Inexpensive, off-the-shelf electronic components are often used in e-textiles to ensure low manufacturing costs. The communication among processing elements is by wired in e-textiles. This is more power efficient than wireless communications (Marculescu *et al*., 2003). It was found that energy consumption of wireless communication is about 14 times that of wired communication (Jones *et al*., 2003). The low energy consumption in communication ensures long running of e-textiles. Durability is often a concern for the wired communication e-textiles. Because of manufacturing defects, and normal wear and tear on the fabric, it is likely that wires will be broken or shorted in the e-textile over the course of its lifetime (Martin *et al*., 2004). Several fault tolerance research studies (Martin *et al*., 2004; Stanley-Marbell *et al*., 2003) have been conducted to improve the durability and reliability of e-textiles; however, e-textiles still have higher failure rates than non-textile based sensor networks (Marculescu *et al*., 2003).

8.4 Conclusion and future trends

The production, use and maintenance of PPE are highly regulated, with numerous national, multi-national, and international standards. The application of smart technology or integration of electronics in PPE is still relatively new. Improving user safety is the most important purpose for PPE and safety should never be impaired in any PPE. However, none of the existing standards has dealt with the safety aspect of integrating electronics into PPE. Buchweiller *et al*. (2003) indicated that no methodology has been developed to answer the safety questions arising from integrating electronic circuits into PPE, and proposed a new method to address this issue. To make smart clothing succeed in the PPE market, a safety assessment methodology for different PPE products must be developed. Following the assessment methodology, the standards for smart PPE need be developed and approved by government agencies, international nonprofit organizations, or industrial trade associations.

Buchweiller *et al*. (2003) raised a few questions on the level of protection, confidence and reliability, and new risks associated with integrating electronics into PPE. The future design and development of smart PPE must address these questions. Smart PPE should provide an equivalent level of protection to traditional PPE, and smart PPE standards must meet the same safety criteria as the existing PPE standards. Smart PPE should provide sufficient reliability for the lifetime of the product. The application and environment should not adversely affect the reliability of the electronic circuits or devices used in PPE. This is extremely important for PPE used in hostile environments, such as firefighter's PPE. For example, in firefighter's PPE, the electronic circuits or devices may need to be protected against water, fire or heat, so they will not fail during use. The incorporation of electronic devices should not introduce new risks, especially in hostile environments.

The design of smart PPE must assure easy use and maintenance. Some PPE users such as HAZMAT workers or firefighters have a very short time to don their PPE, so that they can have the quickest response time to an incident. This requires that the electronic devices be seamlessly integrated into PPE and that the smart PPE does not require a complicated calibration or 'turn-on' procedure. Some electronic devices may need to be removed from PPE during maintenance, cleaning, or care. After that, they must be capable of being easily returned to their correct position by the users.

8.5 Sources of further information and advice

- OSHA's general overview on PPE can be found at www.osha.gov/Publications/osha3151.pdf.
- PPE guidance for welding and cutting professionals can be found at www.aws.org/technical/facts/FACT-33.pdf. U.S.
- CDC guidance on PPE selection, and use in healthcare setting can be found at www.cdc.gov/HAI/pdfs/ppe/PPEslides6-29-04.pdf.
- Most of the leading PPE manufacturers are member companies of International Safety Equipment Association (ISEA). The ISEA website www.safetyequipment.org has useful information on PPE.
- The 'PPE Update' column in FireRescue1.com by Jeffery and Grace Stull provides a useful summary of firefighter PPE. These articles can be found at www.firerescue1.com/Columnists/Jeffrey-O-Stull/.

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