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Development of small-scale testing for the particle penetration of personal protective equipment using a standardised combustion from a cone calorimeter

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Several studies have established a connection between the firefighter occupation and the elevated chance of cancer and illnesses attributed to the harsh environment and exposure to airborne combustion products. This especially concerns airborne particles small enough to penetrate protective garments and human skin. These particles also often contain polycyclic aromatic hydrocarbons (PAHs), which are known carcinogens. When developing new textiles for personal protective equipment (PPE), it is therefore important to document their particle and PAH penetration-blocking ability. Despite this, currently, no relevant, standardised and cost-efficient test method exists. This study introduces a novel method specifically designed for screening PPE textiles, filling critical gaps in available test methods, to facilitate future improved understanding of the protective ability of firefighter garments in preventing carcinogen exposure. In the proposed method, the PPE textiles are exposed to fire smoke from burning PVC plastic, polyurethane foam, and spruce wood in a standardised setup using the cone calorimeter. The smoke passes through an exposure tunnel with a PPE textile mounted on it while particle concentration, PAH content and temperatures are systematically measured on each side of the textile. The method shows promising results for the generation of "standardised" smoke and for documenting particle penetration through PPE textiles. Some remaining challenges related to repeatability and the costs involved are discussed.

Keywords: firefighter exposure, firefighter health, experimental, test method, development

1. Introduction

Firefighters are exposed to airborne particles and gases from fires, which is connected to an increased chance of several types of diseases and increased mortality for firefighters, as summarised in a recent systematic review by Laroche and L'Espérance (Laroche and L'Espérance 2021). In addition, harsh environments related to fires, cold, and heat exposures generate physiological strain on the human body. Studies have shown that airborne particles generated in fires penetrate protective garments and deposits on human skin, including particles containing polycyclic aromatic hydrocarbons (PAHs) (Boström et al. 2002). These airborne toxins can penetrate the skin and are shown to cause cancer and cardiovascular diseases (Fabian et al. 2010). It has also been shown that in a warm and humid environment, where the skin gets wet from perspiration and other water sources, the amount of particles depositing on the skin increases (Wingfors et al. 2017). All the above-mentioned factors prompt high requirements for the personal protective equipment used by firefighters during fire extinguishing efforts. Not only must the equipment protect against the elements and falling debris, but it must also create a tight seal around the body to ensure lower exposure to heat and combustion particles. This seal is meant to keep particles from penetrating both through openings in the garment and through the textile itself. It is important for the garment parts of the equipment to block as many combustion particles as possible.

Despite the extensive research on firefighter exposure to smoke particles (Baxter et al. 2014; Alexander 2012; Fent et al. 2014; Fernando et al. 2016), no easy and cheap test methods exist that producers can use in an early stage of textile development for the particle penetration screening. Related development work on test methods for determining the particle penetration in garments is not easy to find, although some work exists, such as by (Hill et al. 2013). However, these works are very often quite theoretical, with complicated equipment and non-fire smoke particle sources.

In this study, we hypothesised that it was possible to develop a realistic, cost-efficient, repeatable and reproducible small-scale test method for personal protection equipment (PPE) garments that can test the textiles' performance of blocking particle penetration. This test method can be used in the early-stage development of textiles for PPE as an easy way of screening performance. To achieve this, we developed a small-scale test setup based on a standardised method (the cone calorimeter, ISO 5660-1:2015 (ISO 2015) with an attached smoke tunnel and exposure tunnel, and developed a relevant and realistic fuel. Preliminary results from this study were first presented at Interflam in 2019 (Storesund and Mikalsen 2019), and this paper presents the full study. The results from the study include both a technical data set and practical considerations related to experiences and challenges with the developed setup and method.

2. Materials and methods

To ensure reproducibility and to be representative of a domestic fire scenario, a standardised fuel mixture was used in this study, which contains three different typical materials found in regular dwellings: rigid PVC plastic (made from water drainage pipes), flexible polyurethane foam (specified in IMO Res. MSC:265(84) (International Maritime Organization 2008)) and spruce wood (defined in FM 5560-2016 (FM Approvals 2016)). The materials were cut into cubes and placed in an aluminium sheet container, which in turn was placed in a sample holder according to the cone calorimeter method, ISO 5660-2:2002 (International Organization for Standardization 2002). Three cube sizes and two orientations were studied in a series of pretests (discussed later), with the main experimental series using 10 mm cubes, which were randomly mixed.

The experimental setup was based on the cone calorimeter setup according to ISO 5660-1:2015, with an attached exposure tunnel and exposure box. The sample holder with the fuel was placed under the irradiation heater, which was set to 35 kW/m^2. The duration of the experiment was 880 seconds.

Two variants of textile specimens were used, which were cut-outs of firefighter PPE garments (triple layer) and industrial woollen undergarments (single layer).

In the experimental setup, the textile specimen was mounted in a purpose-built smoke exposure box attached to an exposure tunnel connected to a cone calorimeter's hood and pump, as shown in Fig. 1. Smoke generated from the combustion of the fuel mixtures was collected by the extraction hood, transported through the exposure tunnel and exposure box, and vented out via the extraction pump and subsequent ventilation as with regular testing. The smoke piping was made of a 125 mm in diameter flexible aluminium pipe transitioning via a conical, square tunnel and subsequent 500 × 500 mm rectangular cross-section exposure tunnel, both made of 2 mm thickness steel plates. The tunnel length from the extraction hood to the end of the piping was approximately 6 m in total, with an airflow of 24 ± 0.4 L/s.

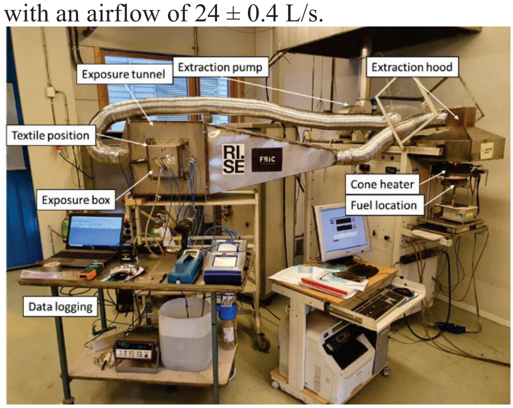

Fig. 1. The experimental setup with a smoke tunnel connected to the exhaust duct of the cone calorimeter.

On the side of the exposure tunnel, the exposure box was mounted with 8 M6 bolts. These bolts and an air-tight rubber sealing strip ensure that only air from the exposure tunnel travels to the exposure box through the textile specimen mounted in between them. The exposure box had a 200 × 200 mm cross-section and was 150 mm deep. The overlapping opening between the exposure tunnel and the exposure box was 13 × 16 mm. The exposure box was also fitted with a humidity generating unit, consisting of a 70 × 120 mm 12V heating foil mounted in the bottom of the exposure box with an aluminium bowl measuring 135 × 65 mm and 20 mm deep, containing 150 mL water. The typical humidity and temperature measured in the exposure box were around 70 % and 30 °C, respectively, which simulated the actual conditions (100 % and 48 °C) occurring inside the PPE garment when firefighters are exposed to a fire scene (Rossi 2003).

Heat release rate (HRR), total heat release (THR), smoke production rate (SPR), total smoke production (TSP) and mass loss were recorded according to ISO 5660. Time to ignition and time to flameout were registered manually, according to ISO 5660.

Temperatures were measured mid-air with 1.5 mm encapsulated K-type thermocouples on both sides of the textile specimen (exposed and unexposed side). The pressure difference between the exposed and unexposed sides was measured using tubes connected to a Pascal measuring unit. Temperature and pressure difference data was collected by a data acquisition unit with a 1-second logging interval. Fine smoke particles (15 µm – 0.02 µm, from here referred to as PM15 and PM0.02) were measured 5 cm from the textile on both sides of the specimen using two TSI 8533 Dusttrak DRX Aerosol Monitors (one on each side) and one TSI P-TRAK 8525 on the unexposed side. The study was limited to "fine mode particles" (≤2.5 µm (Kim et al. 2015)) since these are the most dangerous to human health due to their ability to penetrate deep into the human respiratory system (Robinson et al. 2011; Zhang et al. 2013)). Due to the high particle concentration on the exposed side, a dilution rig was necessary. The rig consisted of tubes and a flowmeter, ensuring the sampled air was mixed with fresh air from 1 to 10. To measure PAH (polycyclic aromatic hydrocarbons) content on the smoke particles, they were extracted with a pump (SKC AirCheck, a flow of 2 L/min) and accumulated on filters (SKC 225-1713 and SKC 226-30-04).

A handheld hygrometer, SDL550 from Extech Instruments, was utilised and logged at 1-second intervals to monitor the humidity and temperature inside the exposure box. The hygrometer also functioned as a valve and could be used to control the flow of fresh air into the exposure box, controlling the pressure difference between the exposure tunnel and the exposure box.

Selected textile specimens (1 for scenarios A and C, and 2 for scenarios B and D) were sent to PAH21 accumulation analysis according to NIOSH 5515, issue 2 (GC-MS) (National Institute for Occupational Safety and Health 1994).

A total of 35 experiments were performed, including 5 pretests and 30 experiments in the main experimental series. The experiments were divided into 4 different scenarios: with and without the humidity-generating unit and with one or two layers of textile specimens (Table 1). Experiments with the humidity-generating unit were prioritised (10 of each) since this represents the human body.

Table 1 Overview of the four scenarios in the experimental campaign and the number of repetitions performed for each scenario.

	Without humidity generating unit	With humidity generating unit
One textile layer (PPE)	Scenario A (N=5)	Scenario B (N=10)
Two textile layers (PPE and wool)	Scenario C (N=5)	Scenario D (N=10)

3. Results and discussion

3.1. *Pre-study with different fuels*

The effect of fuel size and organisation of the fuel bed was explored in a pre-study. Six scenarios were explored, with fuel cube sizes of 5, 7, and 10 mm used and two fuel arrangements: one organised/stacked and one randomly mixed. The fuel beds were exposed to heating, and the resulting heat release rate (HRR) and rate of smoke production from each fuel configuration are found in the supplementary material available at. https://risefr.no/media/dokumenter/suppl-aamodt.pdf.. It was hypothesised that the differences in the exposed surface area between the scenarios would impact the burning of the fuel bed. However, the results showed no clear difference in peak HRR between the scenarios. The smallest cubes of 5 mm did differ from the others in terms of having an earlier decrease towards zero smoke production rate (SPR) at 600 seconds. The larger cubes had a longer burning time. It was therefore decided to avoid using 5 mm cubes, as a longer burning time would be beneficial for the purpose of the method, to expose the textiles to smoke for some period of time. There was no clear difference between 7 and

10 mm cubes, nor between organised/stacked and randomly mixed. The fuel that was least time-consuming to make was 10 cm randomly mixed cubes, and thus, this was selected to allow for the method to be as cost-efficient as possible.

3.2. Fuel combustion characteristics and repeatability

In this section, the collected data averages with standard deviations for fuel combustion and smoke production are presented, showing relatively good repeatability between experiments for the method with the given fuel.

For the 30 experiments, the time to ignition (avg.=97s, SD=58s), time to flameout (avg.=653s, SD=129s) and duration of flame (avg.=540s, SD=116s) were measured. The time to ignition for the fuel has a relatively large standard deviation (58s). This was most likely due to the random mixing of the fuel in the sample holder, which gave differences in the amount of exposed mattress foam, PVC, and wood. Mattress foam ignites more easily than other fuels, and samples with more mattress foam exposed will have the shortest time to ignition. However, having a less random fuel surface would require a significant increase in the time to prepare the fuel, which in turn would weaken the method's cost-effectiveness.

It could be expected that samples that ignited late also would have the longest times to flameout, but no such correlation was found. This was most likely due to the nature of fires burning, which at times display large variations. There were also some variations in the duration of flame, which could give variations in the smoke production and the consumption of the fuel.

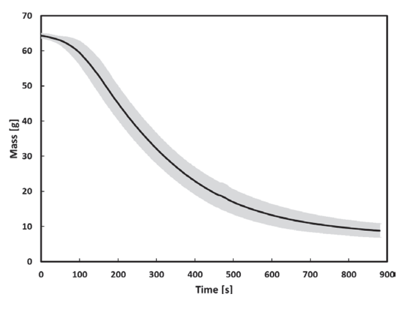

Fig. 2. Average measured mass loss of the fuel in 29 experiments and their corresponding standard deviation as grey shadowing. In one experiment, the mass logging was faulty.

The fuel consumption during combustion is given in Fig. 2. The mass loss data shows satisfying repeatability of the fuel consumption between experiments, as the standard deviation at any given time never exceeds 4.5 grams (2 grams in the end).

Average values of Heat Release Rate (HRR), Total Heat Released (THR), Smoke Production Rate (SPR), and Total Smoke Produced (TSP) with their corresponding standard deviation in grey shadow are shown in Fig. 3. Note that experiments 2, 12, 13, 15 and 16 are not included for the HRR and THR as measurements of the gas analyser were faulty, which gives N=25.

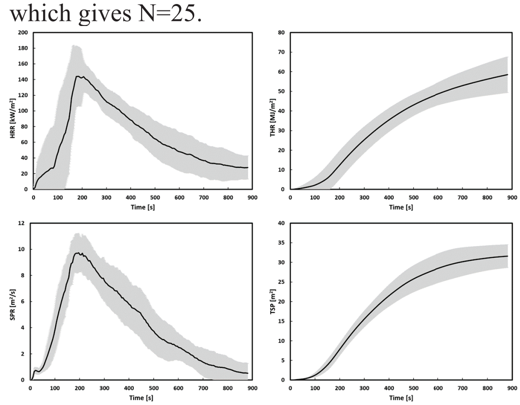

Fig. 3. Heat release and smoke production from the fuel. (Top left) Heat release rate, HRR for 25 experiments with the corresponding standard deviation in grey. (Top right) Total heat release, THR for 25 experiments with the corresponding deviation in grey. (Bottom left) Smoke production rate, SPR for 30 experiments with the corresponding standard deviation in grey. (Bottom right) Total smoke production, TSP 30 tests with corresponding standard deviation in grey.

The overall trend for the HRR between experiments was similar. The relatively large standard deviation in the beginning was due to the variations in time to ignition. At the time of the peak HRR, the spread in the data was ± 37.3 kW/m^2, and the maximum standard deviation was 69.6 kW/m^2. The standard deviation of the HRR naturally also impacted the integrated heat release (the THR), having the highest standard deviation at the end of ± 9.1 MJ/m^2.

The smoke production follows the same trends as the HRR, with smaller standard deviations for the SPR of up to ± 2.0 m^2/s. The total smoke production (TSP) had a standard deviation of ± 2.9 m^2 in the end.

Given the stochastic nature of fires, we consider the repeatability between experiments with the given setup and choice of fuel to be satisfactory, although there is always room for improvement.

3.3. Experimental conditions in the exposure chamber and exposure box

3.3.1. Temperature

The temperatures on the exposed and unexposed sides of the textile are shown in Fig. 4. When the fuel ignites and produces hot smoke that is transported into the smoke tunnel, a rise in temperature may be observed on the exposed side. The registered smoke temperatures (~45-55 °C) are similar to heat exposures of firefighters engaged in fighting wildfires but low compared with flashover room fires (typical temperatures can be several hundred degrees Celsius). It could, however, represent temperature exposures during smoke diving in a part of a building where the firefighter is not in close proximity to a fire or where there is a small flaming fire in the room (typical temperature increase can be limited to 10-20 °C in the room (Fjærestad et al. 2023)).

The temperatures on the unexposed side were quite constant (~30 °C), with a small increase as the warmer air from the smoke tunnel penetrated through the textile. There was no noticeable temperature difference between experiments with and without the humidity-generating unit with heating foil.

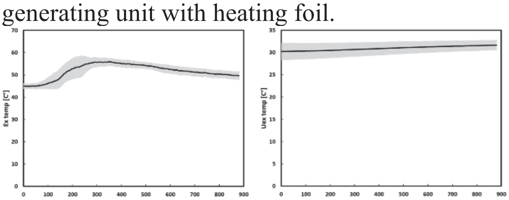

Fig. 4. Temperatures from 19 experiments on the exposed side (left) and 18 experiments on the unexposed side (right) of the textile specimen. Their corresponding standard deviation is marked as grey shadowing. The rest of the experimental results were lost.

3.3.2. Pressure

Fig. 5. shows the pressure difference between the exposed and unexposed sides of the textile specimen. The pressure difference was set to 25 ± 2 Pa. This was intentionally kept relatively low to facilitate some draft through the textile specimen. The slight drift upwards during the experiment was due to the textile specimen being saturated with particles. The pressure difference was difficult to keep constant, and some adjustments were needed at the start of some of the experiments, resulting in large fluctuations during the first ~50 seconds.

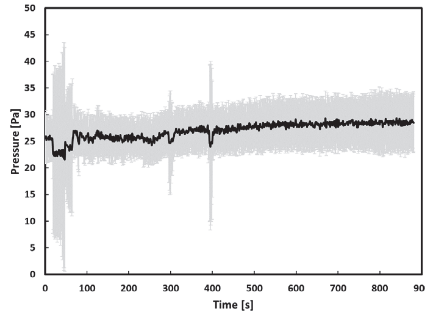

Fig. 5. The measured pressure difference from 26 experiments between the exposed and unexposed sides of the textile specimen. The pressure was set to be a constant 25 Pa for each experiment. The corresponding standard deviation is marked as grey shadowing.

3.3.3. Humidity

There was a significant difference in the relative humidity (in Fig. 6.) for the experiments with and without the humidity-generating unit activated. When activated, the relative humidity starts at 74.8 % and ends at 64.4 %. The drop in 10 % humidity can be explained by the constant extraction of air out of the exposure box for the particle measurements. The unit did not have the capacity to counter this extraction, and this should be considered for further development. The same trend can be observed for the relative humidity in the experiments without the active unit, starting at 27.1 % and ending at 23.3 %.

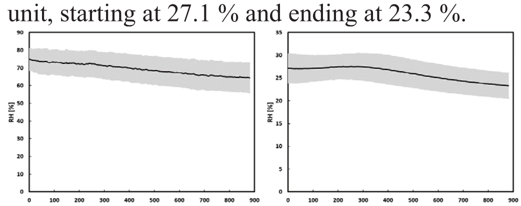

Fig. 6. The measured relative humidity, RH, for 17 experiments with the humidity generating unit activated (left). Measurement of the relative humidity of 7 experiments without humidity generating unit (right). Their corresponding standard deviation is makred as grey shadowing. Notice the different y-scales.

3.4. Protective performance of textiles

3.4.1. Particles

The particle data from the exposed side showed that the fuel combustion generated smoke with the desired fine mode particles (≤2.5 µm) that are dangerous to human health. During the first ~1000 seconds, the amount of particles steadily increased, with peak values in the range of around 10-150 mg/m3. The apparent large variation between experiments was caused by 4 experiments showing particularly low maxima and 1 particularly high, with no apparent explanation for the variation. The remaining were intermediate at ~50-120 mg/m3 of fine-mode particles. As expected, the exposed side was not influenced by the scenario (described in section 1.1).

For each experiment, the number of particles on the exposed side may be compared with the number of particles on the unexposed sides to study the protective performance of the textile. The trends in the number of particles on the unexposed side follow the trends on the exposed side, but with the number of particles on the unexposed side being significantly lower than on the exposed side, with 0-1 mg/m3 for all scenarios except scenario D which was higher (~0-4 mg/m3). Scenario D also had the largest spread in data. It was surprising to find that the scenario with two layers of textile gave the highest penetration of particles, but the spread in the data means that this could be coincidental, which should be explored further in future studies. The data are found in the supplementary material available at this link: https://risefr.no/media/dokumenter/suppl-aamodt.pdf.

The method was found to be suitable for demonstrating differences between exposed and unexposed sides. If the method is to be used for quantitative comparison between textile products, some key improvements need to be made to the setup. The main challenges were the dilution rig not being able to keep a constant flow of fresh air and particles that got stuck in the tubes and, therefore, not reaching the accumulation logger.

3.4.2. PAH

The results from the PAH measurements can be seen in Table 3, presented step by step as the smoke travels from exposed to unexposed side: First from the exposed side of the textile specimen, through the outer and inner layer (if any) of the textile and ending up on the unexposed side The results show that both the outer and the inner layer of the garment catch some PAH particles.

Table 3. Results from the PAH analysis. Scenario A-D, with no humidity (nH) or humidity (H) and the number of textile layers (1 or 2) in the given scenarios. Exposed and unexposed measurements in experiment 22 were lost.

Experiment number	Scenario	Exposed (mg/kg)	Outer (triple layer) (µg/m^3)	Inner (single layer) (µg/m^3)	Unexposed (mg/kg)
3	A: nH, 1	2100	18	No inner layer in test	0,36
7	C: nH, 2	2400	7,3	0,34	1,3
21	B: H, 1	170	5,7	No inner layer in test	13
22	D: H, 2	Faulty	7	5,4	Faulty
23	D: H, 2	290	5,4	19	36
24	B: H, 1	300	4	No inner layer in test	42

There is a clear difference between the amount of PAH on the exposed and the unexposed side, giving a clear indication that the textile specimens are blocking a significant amount of PAH. This is in line with recent findings by (Mitchell et al. 2024), who found the presence of PAHs in the three different layers of firefighter garments. They found that particularly the moisture barrier layer of the garments inhibited the PAH penetration, and it was therefore hypothesised that this trend could also be observed in the current data set, with the outer layer having higher PAH levels than the inner layer. However, it was not possible to observe any such trend differing between the outer and inner layer of the garment based on the presented data due to the limited extent of the data set. Finally, the humidity on the unexposed side could potentially impact the amount of PAH penetrating the textiles. However, it was not possible, based on the current data set, to conclude this.

3.5. Discussion of the setup and potential areas for method improvement

With time to ignition being one of the parameters showing the largest variations, a more uniform fuel bed could potentially be a mitigating measure. One approach to mitigate this could be to have only one fuel, but this would, in turn, not give a realistic smoke composition relevant to fires in dwellings. Another approach, as previously described, is using smaller cubes, which would make the fuel bed production more time-consuming and thus less cost-efficient. An approach that was not explored in this study is to use a grinder to make a uniform fuel that still may consist of several different materials.

Utilising the cone calorimeter was found to be a benefit, both in terms of reproducibility and potential future needs, e.g., changing the irradiance heat flux level to alter the combustion intensity. The exposure tunnel and exposure box were rather easy to weld together, and the dimensions were easy to fabricate. Through the experimental campaign, all the components proved to hold their quality and did not deform or rupture.

The exposure box had a simple design. However, it was fastened by 8 M6 bolts, which took time to fasten and resulted in uneven sealing. The sealing was done by sealing strips of foam that were self-adhesive but needed replacing. A more practical sealing system should be considered.

The production of higher temperature and relative humidity in the exposure box was made difficult due to the extraction of sampling air to the particle and PAH instruments. As discussed in Chapter 2.1, both temperature and humidity did not meet the predefined criteria due to the lack of capacity of the heating foil to increase the temperature inside the exposure box further than 31 °C and relative humidity to ~70-80 %. Improving the method has been found to be challenging but should be considered in future studies. It could also be considered to avoid having a humidity-generating unit altogether, as this greatly complicates the setup.

The pressure differential was difficult to keep constant. For future method development, a mechanism for the inlet of air to the exposure box, which can ensure constant pressure difference across the textile, should be considered.

Particle measurement instruments gave some indicative results, but for a method where the most important measurements are the particles penetrating the textile specimen, the accuracy of the measurements should be improved. The utilised instruments were vulnerable to humidity, high temperatures and high particle concentrations, and re-calibrations were needed during the experimental campaign. An industrial instrument should be a better option.

As mentioned, to obtain accurate quantitative data for the particle penetration, a more reliable dilution system was needed, with a flow control valve to keep the dilution of the particles on the exposed side constant. Also, in the current setup, particles were prone to stick to the tubes when humidity was present. Avoiding humidity would, in other words, give a less realistic scenario in terms of mimicking the human body inside the textile, but at the same time, it would most likely provide more accurate quantitative data for particle penetration.

An identified challenge when sampling PAH's on the exposed side was blocking of the filter due to too heavy smoke. This restricted the sampling time. Options to avoid this to give the required sampling time should be explored.

Finally, we recommend that further development of the method should focus on particle penetration rather than sampling and analysis of PAHs. The latter was time-consuming, had practical challenges, and high costs associated with analysis. Higher concentrations of particles will subsequently indicate higher concentrations of PAH for fire smoke.

4. Conclusion

A novel method for screening personal protective equipment textiles' ability to block particle penetration is proposed, developed and experimentally studied. We systematically investigate all the most important aspects of the experimental method in the search for a relevant, repeatable and reproducible method. The method is found to be relevant for the purpose, with promising results regarding the ability to generate "standardised" smoke and to document the penetration of smoke and particles through firefighter garments. The method has some challenges linked with repeatability, in particular with the time to ignition of the fuel between experiments. Challenges are also identified with the costs involved with running the method for it to be feasible as a low-cost, easy screening test method for suppliers of PPE textiles. In its current format, the method also has practical challenges with many instruments involved in the experimental setup. Points of improvement of the setup, the experimental method, and the lower costs associated with the method have been proposed.

Our initial hypothesis that it is possible to develop a realistic, cost-effcient, repeatable and reproducible small-scale test method for PPE garments that can document the textiles' performance of blocking particle penetration is, in other words, partly strengthened and partly rejected.

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