Analysis of Combustible Dust Flash Fires on Personal Protective Equipment Fabrics

Sean C. O'Hern, Engineer, Exponent, Inc., 9 Strathmore Road, Natick, MA 01760 USA

Michael C. Stern, Senior Engineer, Exponent, Inc., 9 Strathmore Road, Natick, MA 01760 USA

David M. Anderson, Senior Engineer, Exponent, Inc., 3350 Peachtree Road NE, Suite 1125, Atlanta, GA 30326 USA

Alfonso Ibarreta, Managing Engineer, Exponent, Inc., 9 Strathmore Road, Natick, MA 01760 USA

Timothy J. Myers, Principal Engineer, Exponent, Inc., 9 Strathmore Road, Natick, MA 01760 USA

Combustible dust flash fires present unique hazards to fabrics utilized in personal protective equipment (PPE) garments. NFPA 484 (2015) states that "Testing has shown that the 84 kW/m^2 heat flux used in the NFPA 2112 garment-equipped mannequin flash fire test is only 25 percent to 32 percent of an iron dust flash fire heat flux" and suggests that garments designed to comply with NFPA 1971 or ASTM F2621 may be more appropriate but that there are "no test data to substantiate their performance for metal dust fires." In addition to radiative heat transfer from the flame, combustible dust flash fires also produce high-temperature solid particles that may adhere to fabrics and produce significant and prolonged heat transfer to the garment. While this additional heat transfer unique to combustible dust flash fires may be significant, the prescriptive performance requirements of PPE fabrics required by standards are based primarily on flammable gas-fuelled flash fires and have not been thoroughly evaluated for combustible dust flash fires. Therefore, these standards may not be directly applicable. In an effort to analyse the additional hazards that combustible dusts flash fires pose on PPE fabrics, various PPE fabrics are exposed to combustible dust flash fires using a custom flash fire apparatus. Organic and metal dusts are dispersed using an injection system similar to a standard Siwek 20-L combustion chamber, and subsequently ignited into a flash fire directed at the PPE fabric. The performance of the PPE fabric is evaluated using heat flux measurements and compared to a flash fire from a flammable liquid mist.

Keywords: Deflagration, Combustible Dust, Personal Protective Equipment, Flash Fire

Background

Combustible dust flash fires present unique hazards to fabrics utilized in personal protective equipment (PPE) garments. Unlike a gaseous deflagration, combustible dust deflagrations involve the expulsion of high temperature particles which can (a) increase the amount of radiative heat transfer, and (b) impinge on personnel and clothing, causing contact burns. In addition, certain combustible dusts – such as metal particles – can produce much higher combustion temperatures than those associated with a hydrocarbon deflagration, and may therefore pose increased risk.

In a combustible dust flash fire scenario, injuries to personnel can be caused by (a) flame engulfment, (b) thermal radiation, or (c) contact with burning particles [Ogle, 2016; Grimard, 2011]. The prescriptive performance requirements of PPE fabrics required by consensus standards are based primarily on either flammable gas-fuelled flash fires or arc flash exposures, and have not been thoroughly evaluated for combustible dust flash fires. In the United States (US), flash fire resistance requirements for PPE are governed by NFPA 2112, *Standard on Flame-Resistant Garments for Protection of Industrial Personnel Against Flash Fire*, while arc flash resistance requirements for PPE are governed by NFPA 70E, *Standard for Electrical Safety in the Workplace*. Prior to the 2012 Edition of NFPA 2112, the scope of the standard only covered "short duration thermal exposures or accidental exposure to hydrocarbon flash fires." The current 2012 edition of the standard was edited to remove the word 'hydrocarbon' because according to the NFPA committee: "there are other types of incidents that may be considered when selecting garments." Most of the tests prescribed in NFPA 2112, however, are based on sample exposure to radiative and convective heat transfer from gaseous hydrocarbon flames. The prescribed tests also do not take into account the effect of hot particle impingement.

There is currently no standardized laboratory test that characterizes the hazards of a combustible dust flash fire [Ogle, 2016]. Previous experimental work [Stern, 2015] demonstrates that current confined combustible dust characterization tests, such as the ASTM E1226-12a, *Standard Test Method for Explosibility of Dust Clouds*, do not accurately predict the relative flash fire hazard level of different dusts. This study builds upon that previous work, and uses a novel experimental method to directly measure the consequences of a potential flash fire scenario for a given combustible dust type and concentration. The goal of this experimental technique is ultimately to rank the performance of various PPE fabrics in protecting workers for a potential combustible dust flash fire scenario.

In an effort to analyse the additional hazards that combustible dust flash fires pose on PPE fabrics, four PPE fabrics with varying arc thermal performance values (ATPV) and NFPA 2112 flash fire ratings were exposed to combustible dust flash fires using a custom flash fire apparatus. ATPV is defined as the incident energy (cal/cm²) on a material that results in a 50% probability that sufficient heat transfer through the specimen is predicted to cause the onset of second-degree burn injury. The ASTM F1959, *Standard Test Method for Determining the Arc Rating of Materials for Clothing*, test used to obtain the ATPV rating, however, is based on arc flash exposures. To achieve the NFPA 2112 flash fire rating, fabrics are subjected to heat transfer performance and flame resistance tests, which involve exposure to gaseous hydrocarbon flames. In our current tests organic and metal dusts are dispersed using an injection system similar to a standard Siwek 20-L combustion chamber, then ignited into a flash fire directed at the PPE fabric. The performance of the PPE fabric is evaluated using multiple heat flux measurements. The results are compared to the same PPE fabrics exposed to a flash fire from a flammable liquid mist.

Experimental Setup

PPE Fabric Selection

Four PPE fabrics with varying degrees of personnel protection ratings were investigated:

1) **Fabric A** is a standard laboratory jacket. The manufacturer of Fabric A does not provide ratings based upon NFPA 70E for arc-resistance or NFPA 2112 for flame resistance.

2) **Fabric B** are coveralls that meet the performance requirements of NFPA 70E and have an arc-thermal performance value (ATPV) of 5.7. Fabric B is intended for use in settings in which the worker may be exposed to momentary electrical or thermal hazards; Fabric B does not meet the performance requirements of NFPA 2112.

3) **Fabric C** is a laboratory jacket that meets the performance requirements of NFPA 70E and has an arc-thermal performance value (ATPV) rating of 7.7. Fabric C is intended for use in settings in which the worker may be exposed to momentary electrical or thermal hazards; Fabric C does not meet the performance requirements of NFPA 2112.

4) **Fabric D** is a pair of trousers that meets the performance requirements of both NFPA 70E and NPFA 2112. Fabric D listed for protection against flash fire and electrical hazards. Of the four fabrics tested, Fabric D provides the greatest protection with an ATPV rating of 13.6.

Table 1 is a list of each sample fabric tested, a description, and their fire protection ratings. Figure 1 contains photographs of the four fabrics tested.

Table 1. PPE Fabric sample names and descriptions

Fabric Name	Fabric Type	Fabric Weight (oz/sq yd)	Type of PPE	NFPA 70E ATPV	NFPA 2112 Rated
A	65% Polyester/35% Cotton	7.2	Shop Coat	None	No
B	Nomex IIIA	6.0	Coveralls	5.7	No
C	Fire Rated Cotton	7.2	Laboratory Jacket	7.7	No
D	33% Fire Rated Rayon/25% Aramid/24% Modacrylic/16% TECGEN/2% Nylon	8.9	Trousers	13.6	Yes

Figure 1. Photographs of the four PPE fabrics tested

Dust Flash Fire Apparatus

The custom combustible dust flash fire apparatus as described by Stern et al. [Stern, 2015] was used with slight modifications. The nominally 20-L open-top vessel is designed to replicate many aspects of the 20-L Siwek combustion sphere often used to perform testing per ASTM E1226 and E1515, *Standard Test Method for Minimum Explosible Concentration of Combustible Dusts;* ISO 6184/1, *Explosion Protection Systems: Determination of Explosion Indices of Combustible Dusts in Air*; and VDI 2263, *Dust fires and dust explosions - Hazards, assessment, protective measures*.

Tests are performed by pressurizing a separate chamber with air, then rapidly injecting that air and dispersed dust into the chamber. Inside the 20-L unconfined vessel a spark igniter provides a constant spark. The dust ignites as it travels through the spark and the flames propagate outwards as the dust is propelled out of the vessel by a combination of the air injection and the thermal expansion from the combustion.

Instead of a the 0.6-L dust chamber pressurized to 20-bar gauge common to confined 20-L combustion spheres, a 5.6-L 3.3-bar gauge vessel is used for the pressurized air. The air is released using a solenoid valve which opens the compressed air to a dust-loaded compartment below the injection nozzle. The air and dust mixture travel up and through the injection nozzle and into the open-top vessel. Figure 1 shows a photograph and schematic diagram of the dust flash fire apparatus.

Flammable Liquid Flash Fire Apparatus

A custom flammable liquid flash fire apparatus was constructed from a 19-L (5-gallon) epoxy-coated steel container with a through-wall misting nozzle in the base. With a 3.4 bar (50 psi) pressure source, the misting nozzle discharges 35.9 L (9.49 gallons) per hour and is capable of producing a flash fire upwards of 1.5 meters (5 ft) in length. A representative hydrocarbon solvent, xylene, was selected as the flammable liquid source based on its heat of combustion and its slightly below ambient temperature flash point. Prior to each experiment, a measured volume of xylene is added to a liquid reservoir upstream of the misting nozzle. Upon commencement of the experiment, the xylene is forced through the misting nozzle using an upstream pressure source at 3.4 bar (50 psi). An electric-arc is used to ignite the flammable mist into a flash fire. Figure 3 shows a photograph and schematic diagram of the flammable liquid flash fire apparatus.

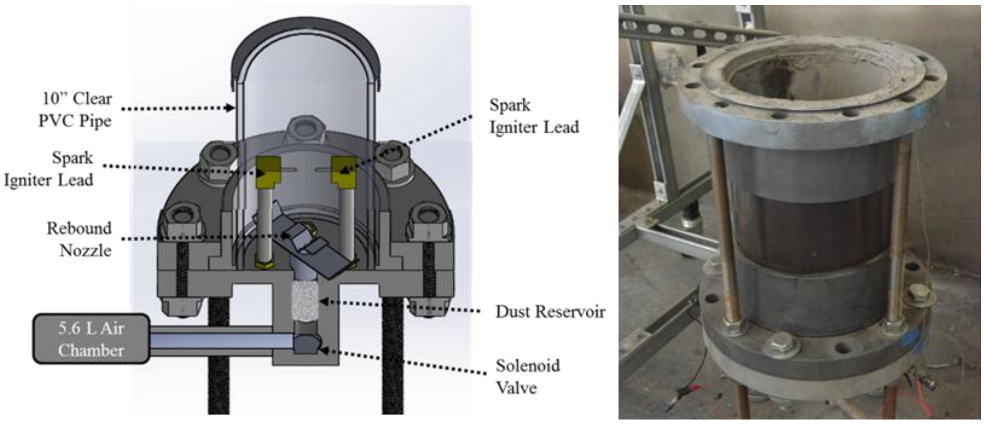

Figure 2. Schematic diagram of the combustible dust flash fire apparatus (left) and a photograph of the apparatus (right).

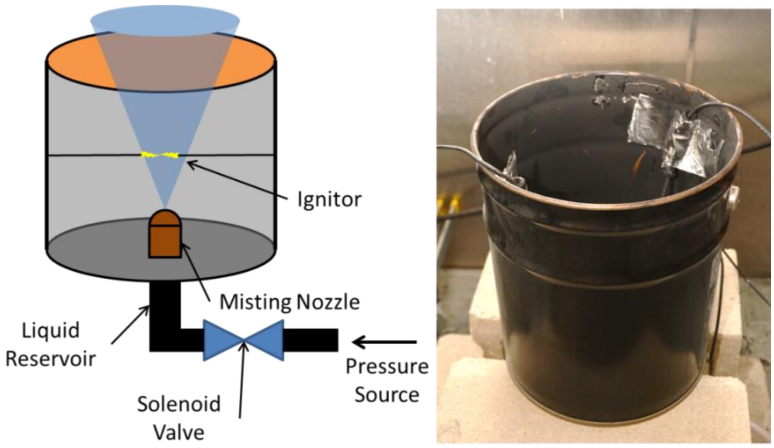

Figure 3. Schematic diagram of the flammable liquid flash fire apparatus (left) and a photograph of the apparatus (right)

Testing Procedure

Each PPE fabric sample is exposed to flash fires fuelled by flammable liquid (xylene), an organic dust (non-dairy coffee creamer), and a metal dust (aluminium) at two different concentrations. Table 2 lists the properties of the tested fuels. Table 3 lists the experimental testing matrix.

For each test, the PPE fabric samples are held 35 cm (14 in.) above the outlet of either the liquid flash fire apparatus or the dust flash fire apparatus. The fabric sample is held in place using two polytetrafluoroethylene (PTFE) gaskets. The PTFE gaskets were selected because the low thermal conductivity would minimize the amount of heat through the gasket collected by the heat flux sensor (as opposed to a metal gasket). A 7 cm (2.9 in.) diameter portion of the fabric is exposed to the flame in the centre of the gasket.

Two heat flux sensors (Hukseflux SBG01-200) collect data during the experiment. Heat flux Sensor #1 collects the heat flux from the flash fire; heat flux Sensor #2 collects the heat flux through the PPE fabric. To provide directionality to the heat flux sensors, each heat flux sensor is mounted to a 10 cm (4 in.) long PTFE cylinder with an inner diameter of 2.54 cm (1 in.). The cylinder is wrapped in insulating foam and aluminium foil to reduce the level of stray heat from the room being collected.

The opening of the cylinder mounted to heat flux Sensor #1 is positioned directly above the outer edge of the flash chamber and directed toward the centre. The opening of the cylinder mounted to heat flux Sensor #2 is in direct contact with the top of the fabric sample, such that only the heat passing through the fabric will be collected. No direct contact measurements between the heat flux sensor and the fabric were made.

Table 2. Properties of tested fuel sources

Fuel Source	Heat of Combustion (kJ/g)	Particle Size (% < 200 mesh)[1]	P_{max} (bar)	K_{St} (bar·m/s)
Xylene	-40.8	N/A	N/A	N/A
Organic Dust (coffee creamer)	-20.5	22	7.2	70
Metal Dust[2] (aluminum)	-55.5	100	8.0	209

[1] Approximately 75 µm
[2] Values obtained from a single series performed based on the methodology described in ASTM E1226-12a

Table 3. Experimental Testing Matrix

Fabric Name	Liquid (Xylene)		Organic Dust (Coffee Creamer)		Metal Dust (Aluminium)	
A	10 mL (8.6 g)	30 mL (25.8g)	10 g	30 g	10 g	30 g
B	10 mL	30 mL	10 g	30 g	10 g	30 g
C	10 mL	30 mL	10 g	30 g	10 g	30 g
D	10 mL	30 mL	10 g	30 g	10 g	30 g

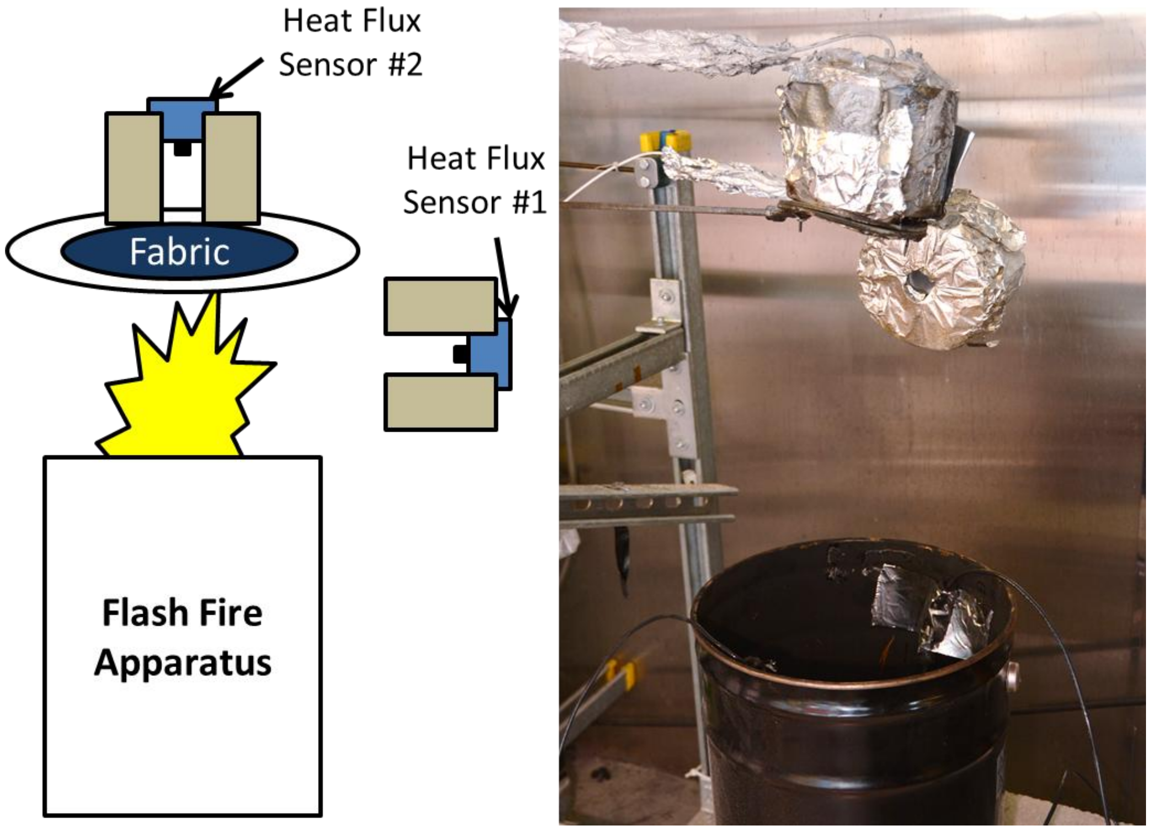

Figure 4. Experimental Setup. PPE fabric sample is placed above the flash fire apparatus. Heat flux Sensor #1 measures the heat flux of the dust or liquid flash fire. Heat flux Sensor #2 measures the heat flux through the fabric.

Results and Discussion

Intensity of Dust and Liquid Flash Fires

The intensity of the flash fire depends upon the type and quantity of fuel used and the dimensions and duration of the flame. For the two tested concentrations of each fuel, the aluminium dust produces the highest peak heat flux, followed by xylene, then by the non-dairy coffee creamer. The heat flux produced by the aluminium flash fire is proportional to the concentration. However, the maximum heat flux produced by both the xylene flash fire and the non-dairy coffee creamer flash fire are independent of the sample mass tested. The duration of the flash fires for the dust samples are also not correlated to the mass of sample. Prior testing has demonstrated, however, that the size of the flash fires is correlated to the sample mass for both dusts tested.

While the aluminium dust flash fire has the highest maximum heat flux of the tested fuels, the xylene flash fire produces the highest integrated heat flux measurement due to the longer length of the flash. The higher concentration produces much longer flash times, which is expected since the misting nozzle increases the time to evacuate the compressed air reservoir, compared to the dust flash fire tests. The aluminium dust produces the second highest level of integrated heat flux measurement.

Table 4 lists the flash fire intensity results. Example frames from video clips of the flash fires for the 30 mL xylene, 30 g coffee creamer, and 30 g aluminium dust are shown in Figure 5. The heat flux measurements are less than the listed NPFA 484 values (84 kW/m^2) and the values calculated by Holbrow et al. [Holbrow, 2000] (25-2900 kW/m^2) due to the view factor of the heat sensors.

After the end of the flash, the xylene flash fire often transitions to a jetting-type fire in which the flammable liquid is entrained with air in the liquid reservoir prior to passing through the misting nozzle. This phenomenon is seen clearly in the first panel of Figure 6. Additionally, residual xylene in the base of the flash fire apparatus during the 30 mL tests continues to burn for several seconds after the initial flash. For the dust flash fires, after the primary flash the combusting dust particles that may impinge upon the surface of the fabric imparting additional heat transfer are visible (Figure 6, centre and right panels). The effects of these particles can clearly be seen in images of the fabrics after exposure. In the case of the non-dairy coffee creamer, the particles tend to clump up and adhere to the surface of the fabric. In the case of the aluminium dust, the particles tend to create burn marks on the fabric. Figure 7 displays close-up photos of the Fabric C after exposure to 30 mL xylene, 30 g of coffee creamer, and 30 g of aluminium dust.

Table 4. Results of the flash fire intensities

Fuel	Amount of Fuel	Average Peak Heat Flux of Flash Fire, W/m^2	Average Length of Flash Fire, s	Integral of Heat Flux, J/m^2
Xylene	10 mL	2,996	5.0	4,088
Coffee Creamer	10 g	1,373	3.2	681
Aluminium	10 g	4,649	3.2	2,784
Xylene	30 mL	3,648	18.9	13,768
Coffee Creamer	30 g	1,204	4.4	913
Aluminium	30 g	16,339	3.2	10,423

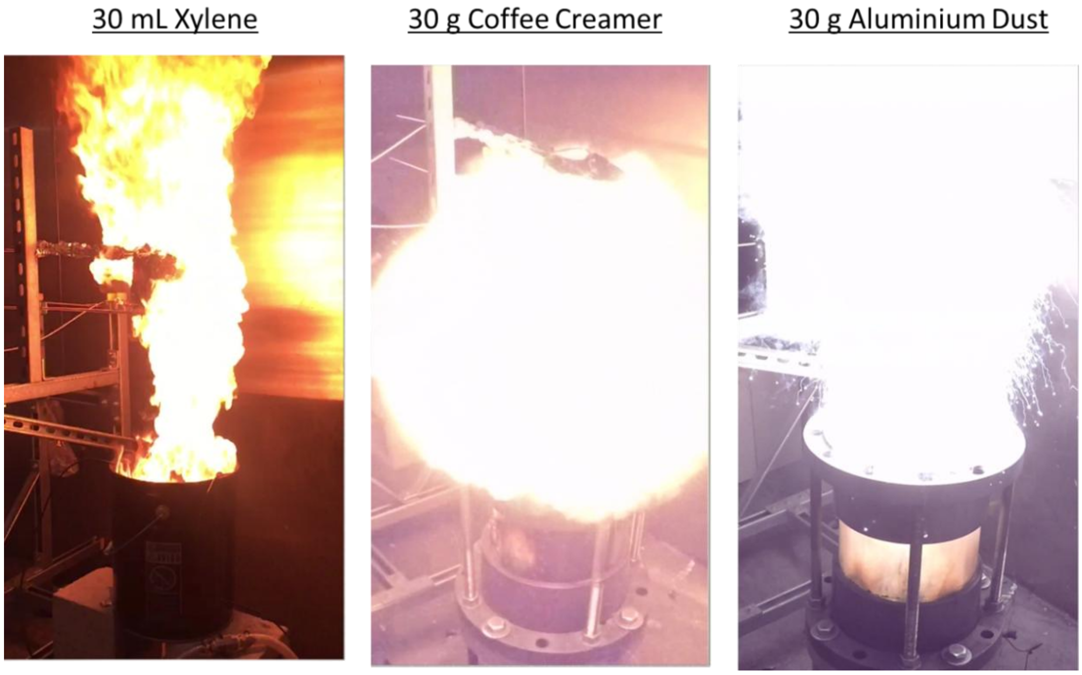

Figure 5. Representative video frames from flash fires

Figure 6. Video frames of flash fires after primary flash has taken place.

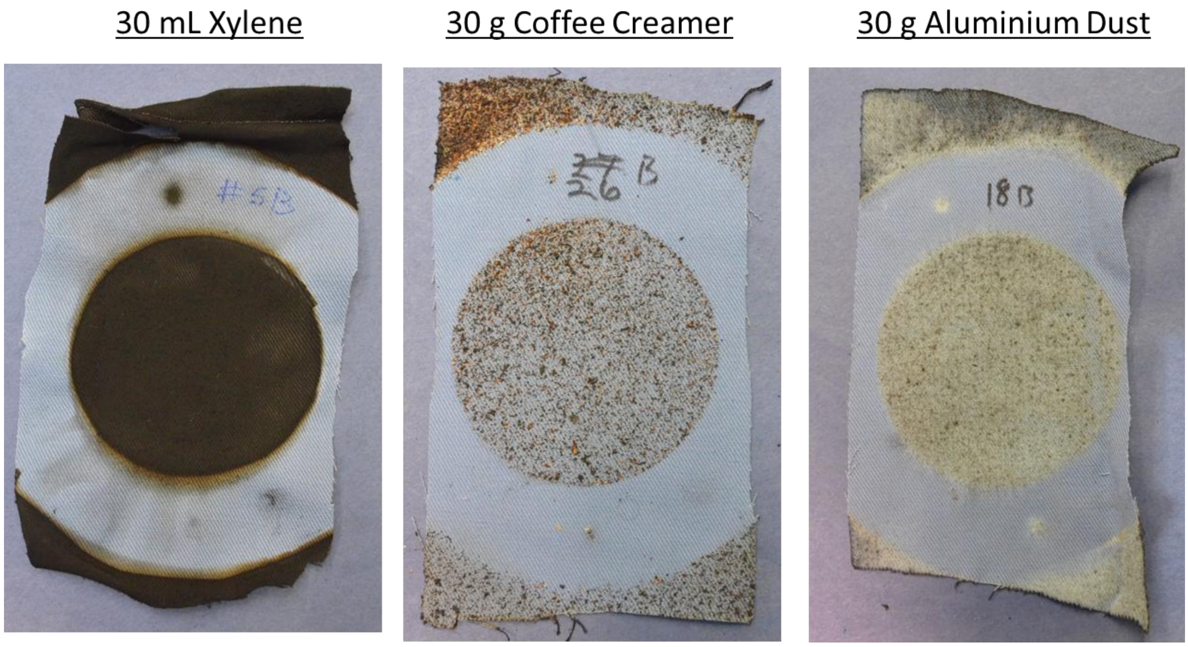

Figure 7. Close-up of Fabric C after exposure to 30 mL of xylene, 30 g of coffee creamer, and 30 g of aluminium dust. Xylene tends to burn the fabric. Coffee creamer particles adhere to the fabric, and aluminium dust particles create distinctive burn marks.

PPE Fabric Performance

Photographs of the fabric samples after exposure to the flash fires are shown in Figure 8 and Figure 9. The bottom side of the fabric faces the flash fire, while the top side faces the heat flux sensor.

The amount of heat transfer through the fabric depends on three factors:

1. The peak heat flux of the flash fire
2. The duration of the flash fire
3. The heat transfer performance of the fabric

The flash fire results in Table 4 show that an aluminium dust fire produces the greatest maximum heat flux, followed by xylene, and lastly coffee creamer. However, because xylene flash fires last longer, the total heat transferred by xylene exceeds that of aluminium in some tests.

An example of this is the relationship between the heat flux with and without the PPE fabric in six example test results shown in Figure 10. Here, we present three different fabric samples (A, B, and D) exposed to either a flash fire from 30 mL of xylene or 30 g of aluminium dust. The aluminium dust produces a maximum heat flux approximately five times that of the xylene (~15,000 W/m^2 to ~3,000 W/m^2). However, the length of the xylene flash fire is approximately six times longer than the aluminium dust (~3 sec to ~ 19 sec), some of which is from the liquid burning in the container. The integral of the heat flux measurements for the six example test results are plotted in Figure 11.

Higher ATPV fabrics tend to have a lower proportion of the heat flux generated by the flash fire transfer across the fabric and a longer time delay between when the bottom side of the fabric is exposed to the heat from the flash fire and when the heat flux is detected by the sensor on the top side of the fabric (Figure 12). In this article, the time delay is defined as the time between the beginnings of the flash to the time at which the heat flux on the top side of the fabric reaches 250 J/m^2.

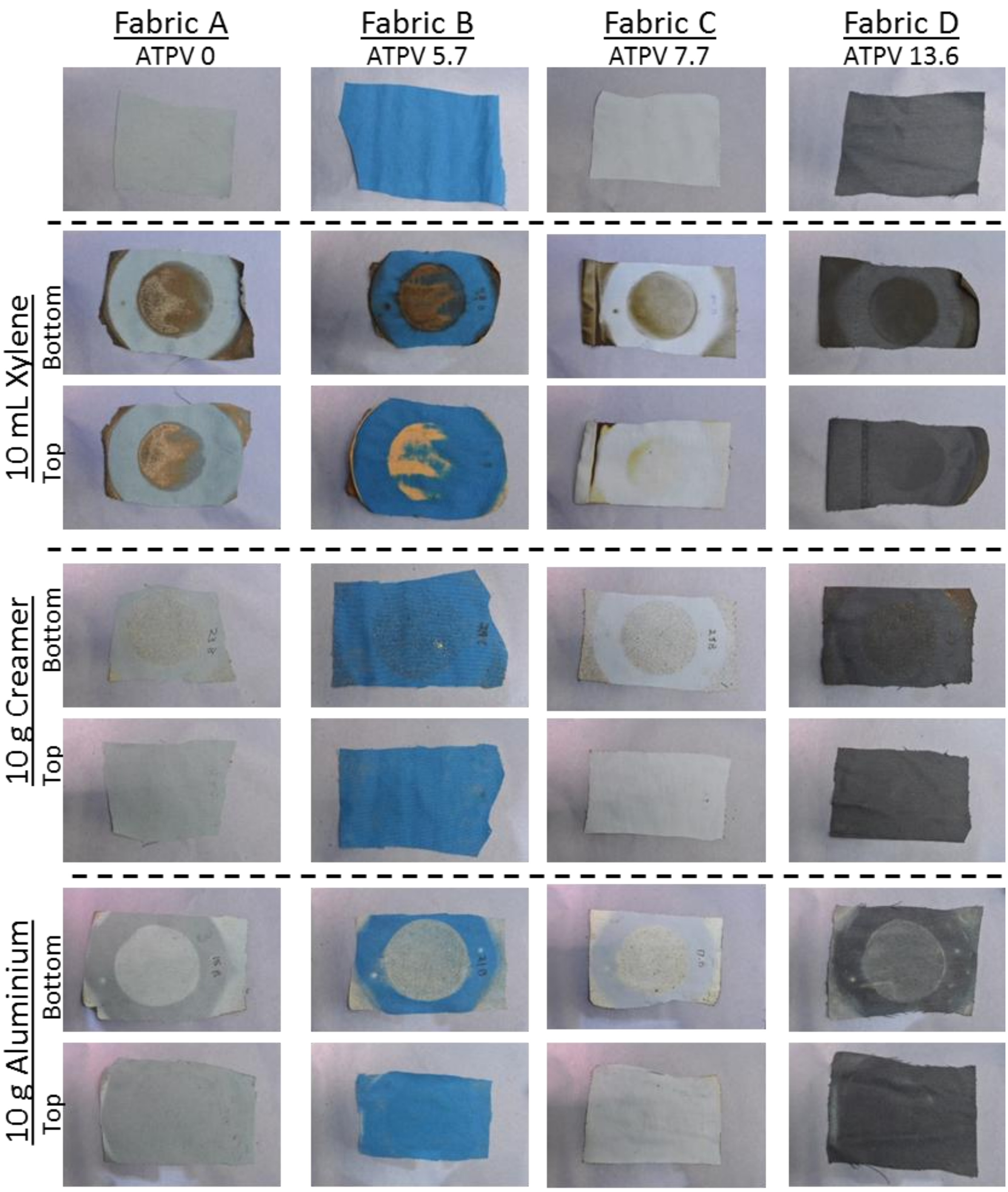

Figure 8. Photographs of fabric samples before and after exposure to 10 mL xylene, 10 g coffee creamer, and 10 g of aluminium dust. Top and bottom of fabric shown.

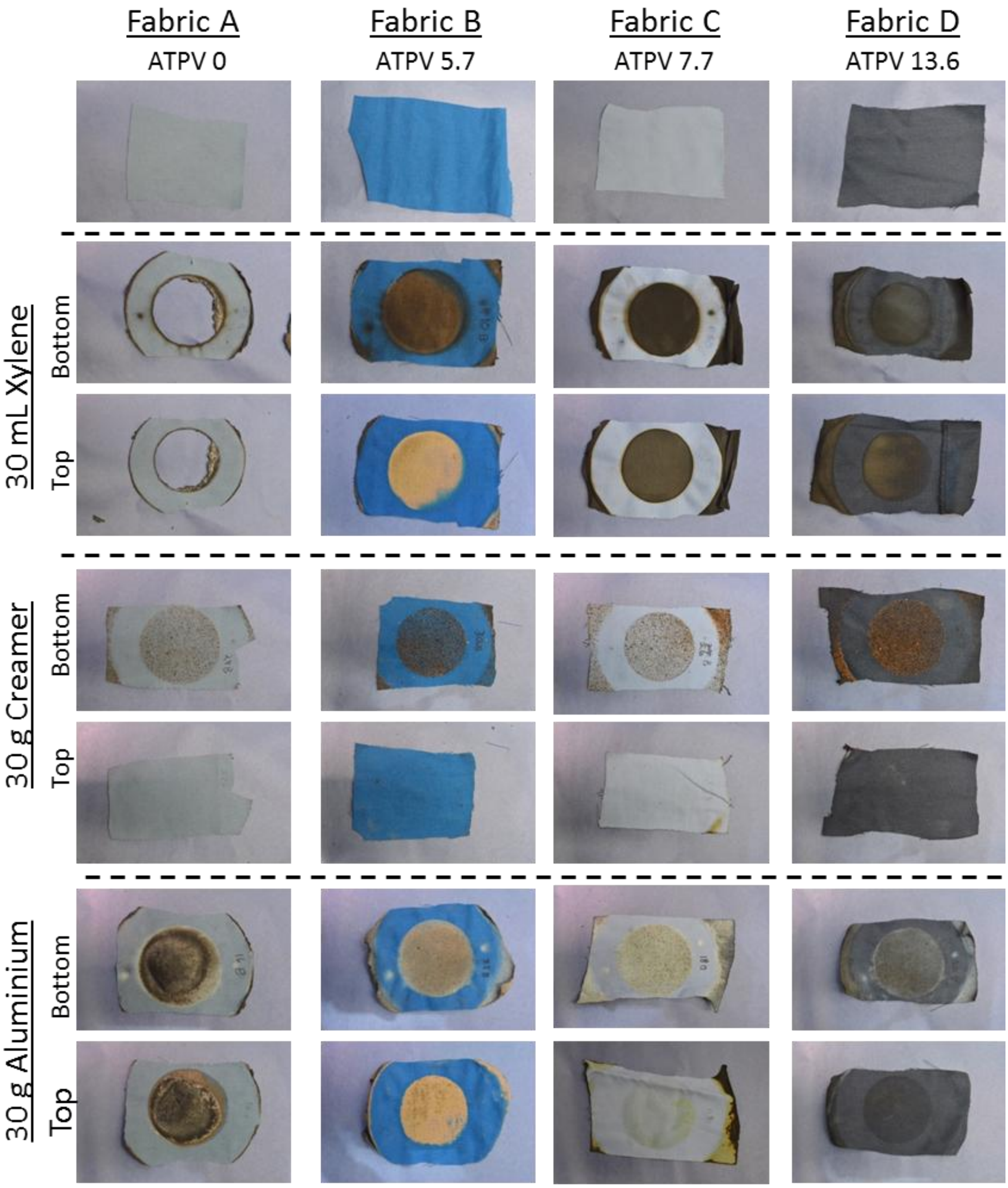

Figure 9. Photographs of fabrics before and after exposure to 30 mL xylene, 30 g coffee creamer, and 30 g of aluminium dust. Top and bottom of fabric shown. Note that Fabric A burned complete through when exposed to the 30 mL xylene test.

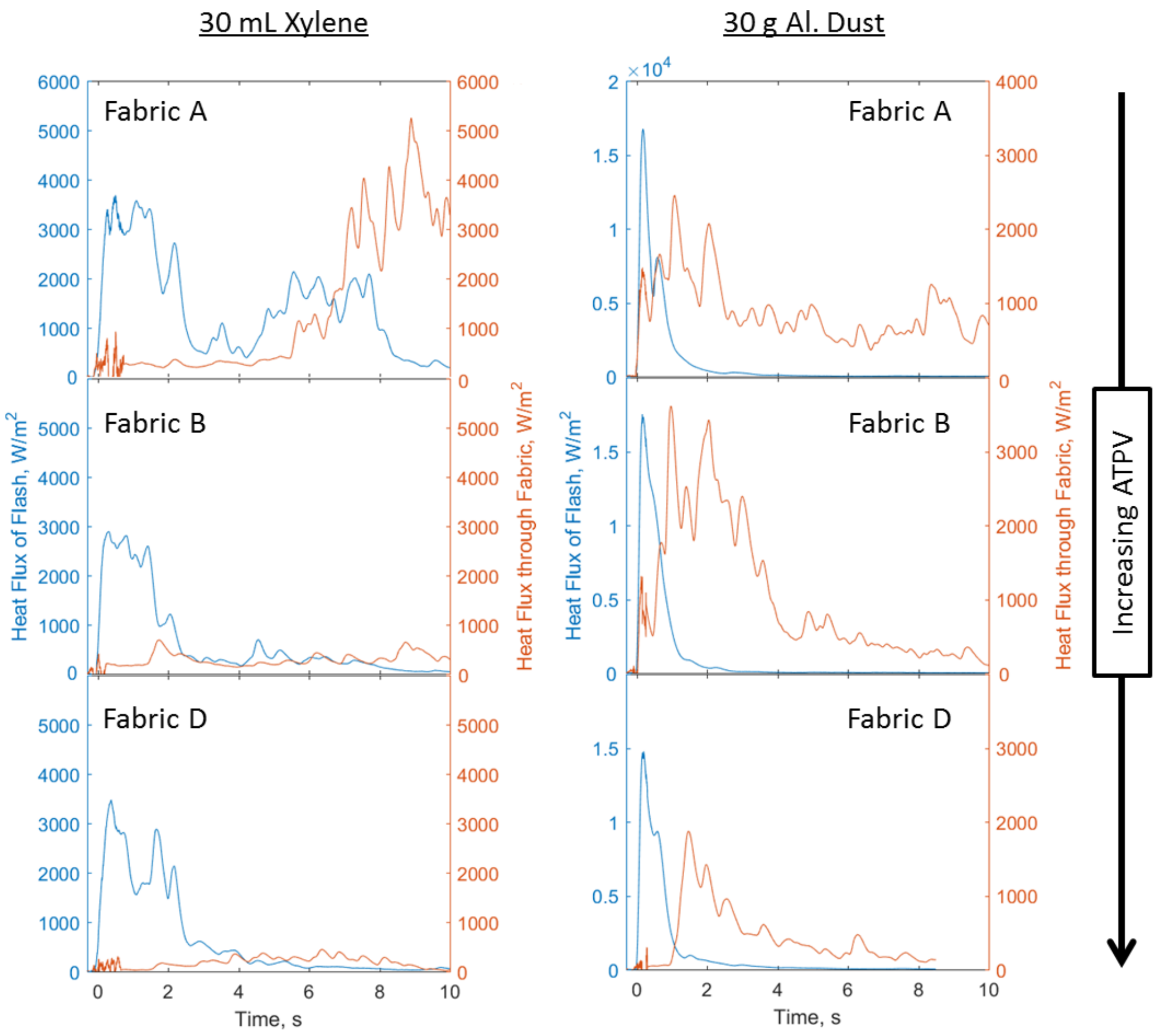

Figure 10. Example heat flux sensor measurements for three samples and two flash fire conditions.

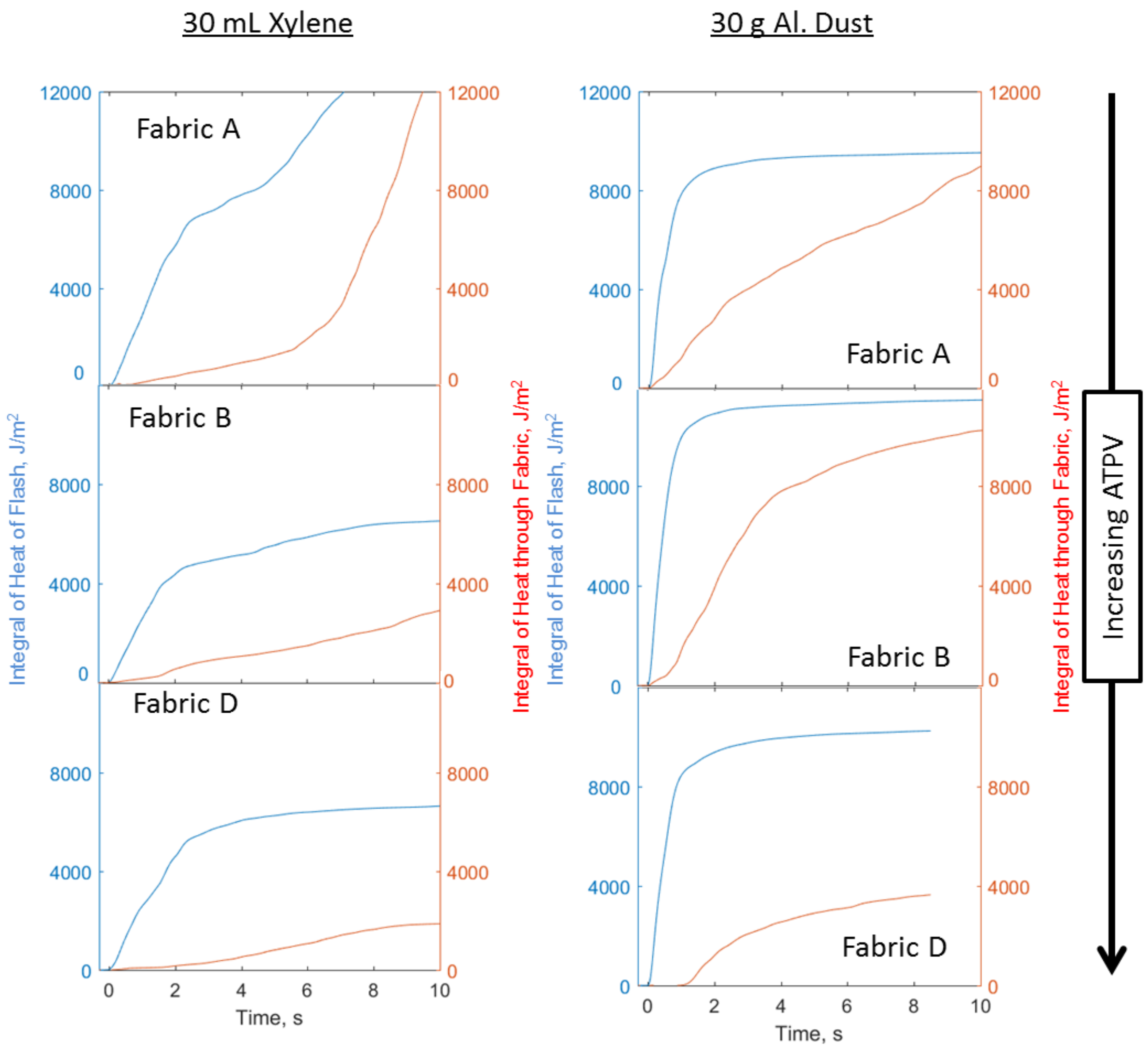

Figure 11. Integral of heat flux measurements for three samples and two flash fire conditions.

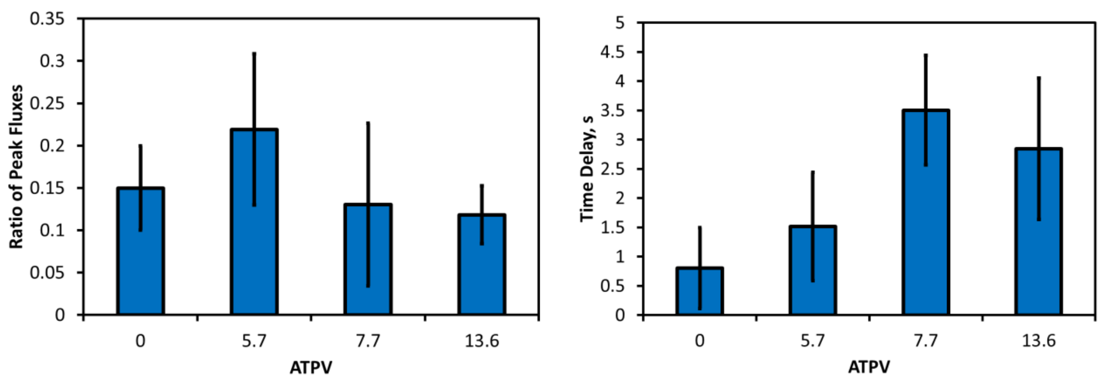

Figure 12. Left Panel: Ratio of peak heat flux of the flash and the peak heat flux detected through the fabric for all fuels and concentrations. Right panel: Time delay between the beginning of the flash fire and the point at which 250 J/m^2 is measured on the top side of the fabric for all fuels and concentrations. Error bars represent standard deviation of measurement.

The above results can be explained by analysing the heat transfer processes occurring during the flash experiment. During the early stages of the flash, radiation can pass through the fabric without substantially increasing the fabric's temperature. As the heat from the flash continues to impinge upon the fabric, the fabric increases in temperature and both re-radiates heat upwards and heats the surrounding air on the top side of the fabric. Continued heating deteriorates and consumes the fabric, permitting the heat from the flash to transmit directly to heat flux sensor (see Figure 10, Fabric A, 30 mL xylene).

During the early stages of the test, before the fabric becomes significantly heated, the thermal protection performance of the fabric is controlled by its transmittance and absorptance of incident radiation. The diffuse spectral absorptance and transmittance of the four fabrics were measured over wave lengths ranging from 0.83 – 20 µm using a Fourier transform infrared spectrophotometer (Nicolet iS50, Thermo-Fisher Scientific) equipped with an integrating sphere using the method outlined by Anderson, et al. [Anderson, 2017]. Table 5 reports the average absorptance (α) and transmittance (τ) values weighed by the expected flame temperature for each fuel type. According to Planck's distribution, as the source temperature increases, the wavelength at which it emits radiation will decrease; hence, the fraction of incident radiation absorbed by or transmitted through a greybody surface will depend on the source temperature. As calculated using the weighting methodology outlined in Anderson, et al. [Anderson, 2017], illustrates that as the flame temperature increases, a higher fraction of radiation is transmitted and a lower fraction of radiation is absorbed. Fabrics A–C are more dramatically impacted by this shift, while Fabric D displays similar transmittance and absorptance regardless of the source temperature. In general, the higher ATPV fabrics tend to have higher absorptance and lower transmittance at all flame temperatures. The presence of no detectable transmission through Fabric D (with the highest ATPV of 13.6) is likely a contributing factor to the longer delay between the peak heat flux of the flash and peak heat flux through the fabric, relative to the other three fabrics, that was demonstrated in Figure 10.

The proportion of the heat flux generated by the flash fire that transfers across the fabric during later stages of the test, once the fabric becomes significantly heated, depends on both the diffuse spectral absorptance and the thermal diffusivity of the fabric. In this analysis, the thermal diffusivity of the fabrics is not measured, but it is expected to be inversely proportional to the weight of the fabric. The fabric with the highest proportion of heat flux that transfers across is also the fabric with the lowest weight (Fabric B); while the fabric with the lowest proportion of heat flux that transfers across is also the fabric with the highest weight (Fabric D).

Table 5. Absorptance and transmittance properties of fabrics

Fabric	Xylene (T_{flame} = 2210°C)		Coffee Creamer (T_{flame} = 2400°C)		Aluminium (T_{flame} = 3790°C)	
	α (%)	τ (%)	α (%)	τ (%)	α (%)	τ (%)
A	45.5	18.4	43.6	19.4	36.5	22.9
B	49.1	21.2	47.1	22.3	39.2	26.8
C	49.3	17.3	47.1	18.3	38.7	22.0
D	83.3	< D.L.*	83.1	< D.L.*	82.7	< D.L.*

*The transmittance for Fabric D was less than the detectable limit, approximately 0.1%

Conclusion

Consistent with gas-fuelled fires, the higher ATPV fabrics are more resilient to flash fires fuelled by either liquid or dust, compared to lower ATPV fabrics. The combustible metal dust tested, aluminium, produces flash fire heat fluxes 2-5 times greater than the representative flammable liquid, xylene. The maximum heat fluxes through the PPE materials are similarly higher from the aluminium dust flash fires, highlighting the additional risk posed by exposure to a brief metal dust flash fire when compared to a hydrocarbon-based flash fire. The effective protection time of PPE materials may be significantly reduced when considering metal dust-fuelled flash fires compared to the hydrocarbon-based flames used in testing. Another important distinction between the materials is the time delay before heat transfer began. While Fabrics C and D were able to prevent heat transfer for 3 to 3.5 seconds during the flash fires, Fabrics A and B allow heat transfer to begin within 1 to 1.5 seconds due to their ability to transmit thermal radiation. This increased heat transfer in Fabrics A and B may also be related to air and particle transport through the knit material. If so, the porosity of materials may become an important factor when selecting PPE fabrics for use in combustible dust hazard areas.

The tests described in this paper only provide qualitative information of the PPE performance in blocking the flash fire thermal radiation consequences. This testing did not measure the conductive heat transfer or contact heat transfer hazards that the wearer would be exposed to. The testing focuses on relatively short-term flash fire exposures. The authors plan to perform additional testing to quantify these parameters in the future.

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