Engineering Research Report

Rapid Dry Field Decontamination Method for Firefighters

Barbara M. Alexander, PhD, PE, CIH
Division of Applied Research and Technology
Engineering and Physical Hazards Branch

Matthew M. Dahm, MPH, REHS/RS
Division of Surveillance, Hazard Evaluations, and Field Studies
Industrywide Studies Branch
Lieutenant Commander, U.S. Public Health Service

Division of Applied Research and Technology
Engineering and Physical Hazards Branch
EPHB Report No. 374-11a

September 2017

DEPARTMENT OF HEALTH AND HUMAN SERVICES
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Site Surveyed: N/A

NAICS Code: 922160

Survey Dates: N/A

Surveys Conducted By: Barbara M. Alexander and Matthew M. Dahm

Contractor Representatives: N/A

Disclaimer

Mention of any company or product does not constitute endorsement by NIOSH. In addition, citations to websites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products. Furthermore, NIOSH is not responsible for the content of these websites. All Web addresses referenced in this document were accessible as of the publication date.

Table of Contents

Abstract

This report describes the development of a prototype system for use by firefighters at a fire scene, the rapid dry firefighter field decontamination system (RDFFDS). Some diseases occurring at higher rates in firefighters than in the general population, including cardiovascular disease and certain cancers, may result from firefighters' exposure to hazardous substances in the workplace. The new RDFFDS utilizes air jets to remove particulate contamination from firefighter turnout gear and equipment. Multiple studies have shown that, during fire response, firefighter gear becomes contaminated with hazardous substances including heavy metals, polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs). Many of these substances may be adsorbed onto particulate matter and carried back to firehouses, as shown by analysis of vacuum cleaner dust collected in California fire stations. Field decontamination before entering vehicles may reduce the amount of contamination brought back to the fire station and reduce continuing personnel exposures when the gear is re-worn. Results of laboratory testing of prototype decontamination methods identified several methods capable of removing 70-80% or more of a test soil from cloth swatches. One prototype method field tested during firefighter training activities required only about 1 minute for decontamination of firefighter turnout coat and pants. Further field testing is necessary to confirm the acceptance and effectiveness of this technology.

Introduction

Background for Control Technology Studies

The National Institute for Occupational Safety and Health (NIOSH) is the primary Federal agency engaged in occupational safety and health research. Located in the Department of Health and Human Services, it was established by the Occupational Safety and Health Act of 1970. This legislation mandated NIOSH to conduct a number of research and education programs separate from the standard setting and enforcement functions carried out by the Occupational Safety and Health Administration (OSHA) in the Department of Labor. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering and Physical Hazards Branch (EPHB) of the Division of Applied Research and Technology has been given the lead within NIOSH to study the engineering aspects of health hazard prevention and control.

Since 1976, EPHB has conducted a number of assessments of health hazard control technology on the basis of industry, common industrial process, or specific control techniques. Examples of these completed studies include the foundry industry; various chemical manufacturing or processing operations; spray painting; and the recirculation of exhaust air. The objective of each of these studies has been to document and evaluate effective control techniques for potential health hazards in the industry or process of interest, and to create a more general awareness of the need for or availability of an effective system of hazard control measures.

The reports from these studies are then used as a basis for preparing technical reports and journal articles on effective hazard control measures. Ultimately, the information from these research activities builds the data base of publicly available information on hazard control techniques for use by health professionals who are responsible for preventing occupational illness and injury.

Background for this Study

Firefighter Health

In 2013, there were an estimated 30,052 U.S. fire departments (all career: 2,477; mostly career: 1,971; mostly volunteer: 5,797; all volunteer: 19,807) and an estimated 1,140,750 U.S. firefighters (career: 354,600; volunteer: 786,150) [Haynes and Stein 2014]. Firefighters are exposed to a wide range of hazardous substances, both during firefighting activities, and from substances remaining on protective clothing and gear after the fire [Alexander and Baxter 2014; Evans and Fent 2015; Fent et al. 2015; Kirk and Logan 2015; Stull et al. 1996]. These exposures may contribute to firefighters' elevated risks of cardiovascular disease and certain types of cancer [Daniels et al. 2014; LeMasters et al. 2006; Sen et al. 2016; Smith et al. 2013]. Small and volunteer fire departments, in particular, lack the funds to frequently launder firefighter turnout gear. A compact, inexpensive and quick method for field decontamination at fire scenes would be advantageous to reduce firefighter exposure from contaminants on turnout gear and equipment. This project is intended to develop such a method.

Cardiovascular Disease

Cardiovascular Disease (CVD) is common in the general population and among municipal and wildland firefighters, likely due to underlying personal risk factors combined with unique occupational risk factors, such as physiological and psychological stress, shift work and sleep disruption, and exposures to hazardous substances [Fahy et al. 2016; Kales et al. 2007; Smith et al. 2013]. Heart attacks are one of the leading causes of line-of-duty death for wildland and municipal firefighters (both career and volunteer) [Fahy et al. 2016]. Many variables contribute to CVD risk. Acute physiological changes in the human body, including stress and thermal and cardiac strain, especially during emergency situations (i.e. fire response), can increase firefighters' risk of sudden cardiac death [Smith et al. 2013]. Additionally, firefighters have a higher reported incidence of cardiac difficulties, hypertension, and myocardial infarction than the general population, which contribute to elevated cardiovascular risk and disease among this response workforce [Baxter et al. 2010]. Evidence from both epidemiological and laboratory research indicates that fine particulate exposure (e.g. fire smoke) is associated with acute changes in cardiovascular function [Baxter et al. 2010; Evans and Fent 2015]. Exposure to chemical asphyxiants and lipophilic substances may also increase the risk of acute cardiovascular events or CVD [Alarie 2002].

Cancer

Occupational carcinogens are an important cause of death and disability. It is estimated that 3-6% of all cancers worldwide are caused by exposures to carcinogens in the workplace [Driscoll et al. 2005]. Based on U.S. cancer incidence rates, in 2010 there were 43,695 - 87,390 new cancer cases caused by past exposure in the workplace [CDC 2015]. This is probably an underestimate, partly because we don't yet know about all of the agents in the workplace that may cause cancer. As new occupational carcinogens are discovered and behaviors like smoking are reduced within the population, it is likely that the proportion of occupationally related cancers will increase.

The number of firefighters who died from cancer or are battling this disease is alarming. During 2005-2014 the International Association of Firefighters (IAFF) lists 1136 members who passed away as a result of cancer [IAFF 2015]. Firefighters have an increased risk of several cancers compared to the general population. A recent NIOSH cohort study of 30,000 career firefighters employed from 1950 to 2009 found an excess risk of developing digestive, oral, pharyngeal, and laryngeal cancers, as well as mesothelioma, when compared with the general U.S. population [Daniels et al. 2014].

Reproductive Health

Workplace hazards can lead to many different types of adverse reproductive outcomes (such as impacting the ability to become pregnant, health problems of unborn children, and adverse effects on child development). While most adverse reproductive outcomes are related to a number of different etiologic factors, occupational exposures likely play an important and perhaps under-recognized role. For example, it is estimated that 3% of major malformations among live births are due to toxicant exposures [Lawson et al. 2003]. Additionally, a discrepancy exists between the number of chemicals in commerce (approximately 84,000) and the number that have been evaluated for reproductive toxicity potential (4,000) [Lawson et al. 2003]. Firefighters are known to be exposed to endocrine disruptors, which are associated with reproductive toxicity [Alexander and Baxter 2014].

Firefighter Exposures

Exposure to carcinogens is a significant problem in the fire service. The International Agency for Research on Cancer (IARC) classifies occupational exposure as a firefighter as possibly carcinogenic to humans (Group 2B) [IARC 2010]. Reducing exposure to hazardous substances, especially fine particulate, may help to protect firefighter health.

Exposures proposed to be responsible for increased rates of certain diseases in the fire service include toxic gases, particulates and a wide variety of organic chemicals in the vapor state or adsorbed onto protective gear and particulate matter [Baxter et al. 2010; Bolstad-Johnson et al. 2000; Fabian et al. 2014]. In several studies, contaminants were identified on firefighter personal protective gear, including heavy metals, plasticizers and polycyclic aromatic hydrocarbons (PAHs) [Alexander and Baxter 2014; Fabian et al. 2014; Stull et al. 1996].

In a study performed at Underwriters Laboratories (UL), it was found that gloves and protective hoods worn by firefighters at residential fires become contaminated with a wide range of organic and inorganic compounds, some of which are known to be carcinogens. High levels of heavy metals, including lead and mercury, were measured. The organic chemicals found in the largest quantities on firefighter gloves and hoods were phthalate diesters, especially di-(2-ethylhexyl) phthalate (DEHP), a plasticizer used primarily in polyvinyl chloride (PVC) plastics, and certain PAHs [Fabian et al. 2014].

Multiple flame retardant chemicals, PAHs and polychlorinated biphenyls (PCBs) were identified in dust collected at California fire stations [Brown et al. 2014; Shen et al. 2015]. Some of these hazardous substances are postulated to be present because firefighter gear is treated with flame retardant chemicals, but some of the contamination may also be brought back to the fire station from fire events by way of contaminated boots, turnout gear and equipment [Shen et al. 2015].

Exposure to these agents may occur through inhalation, but deposition onto protective gear, with subsequent skin contact, creates a further possibility of exposure by transdermal absorption. Hydrocarbons such as certain flame retardants, PAHs and phthalate diesters are highly lipophilic and expected to readily absorb through the skin, especially at the elevated skin temperatures experienced in firefighting situations [Chang and Riviere 1991].

In a study by Shaw et al., blood samples from 12 San Francisco (SF) firefighters, who had responded to a fire within the previous 24 hours, contained a range of chlorinated, fluorinated and brominated chemical species, including flame retardants. Measured levels of polybrominated diphenyl ether (PBDE) flame retardants were 2 to 3 times the levels detected in the general US population [Shaw et al. 2013]. In a more recent study by Park et al., blood samples were collected from 101 Southern California firefighters. PBDE levels in the blood serum were very similar to those found for the SF firefighters [Park et al. 2015].

PBDEs are a class of brominated aromatic organic chemicals which may contain from 1 to 10 bromine atoms arranged in different configurations, with each chemical being assigned a congener number from 1 to 209 (e.g., PBDE-209). Adverse health effects of PBDE exposure are not well characterized, but include neurotoxicity and endocrine disruption [Siddiqi et al. 2003]. PBDEs are also suspected of thyroid toxicity and carcinogenicity [Schecter et al. 2005]. In 2004, 21% of flame retardants produced globally were PBDEs and other brominated flame retardant chemicals, but PBDEs are since being phased out worldwide due to concerns over environmental persistence, bioaccumulation and toxicity [Brandsma et al. 2013; Stapleton et al. 2011]. PBDEs are still found commonly in consumer items made before the bans were instituted [Stapleton et al. 2011].

Given the excessive exposure of firefighters to respiratory irritants and toxicants, it is essential that firefighters recognize the importance of respirator use, and take steps to minimize their risk of acute and chronic pulmonary disease, CVD, and cancer. This includes proper training, use of protective clothing and approved respiratory protection during all phases of firefighting, and keeping their protective clothing and gear clean. Because contaminants on firefighter gear and equipment could be re-aerosolized and inhaled (e.g. particulate matter such as asbestos) or transferred to skin and absorbed (e.g. hydrocarbons such as PAHs), it is imperative that firefighters employ effective decontamination methods following a fire response.

Hazardous substances remaining on firefighter personal protective gear following fire response are often in the form of particulate matter [Baxter et al. 2010; Evans and Fent 2015]. Particulates brought back to fire stations after fire response are a likely source for the elevated levels of PBDE flame retardants found in vacuum cleaner dust from fire stations in California [Shen et al. 2015]. Decontamination at the scene of a fire response would help to prevent bringing hazardous substances into fire vehicles and fire stations. The purpose of this research is the development of a prototype system for use by firefighters at a fire scene, the rapid dry firefighter field decontamination system (RDFFDS).

Stakeholder Information

This research was supported by funding from the CDC Innovation Fund (iFund). The iFund is designed to make it possible for CDC researchers to test and develop creative, new ideas addressing CDC’s Winnable Battles and strategic public health priorities. This is intended to promote innovation within CDC. As a first step in the project, participation in the “I-Corps Bootcamp” was required. The I-Corps Bootcamp is a course intended to help participants create innovative solutions that meet the needs of stakeholders and partners. A large part of the course involved interviewing stakeholders and partners to ascertain their circumstances, and the need for the innovation being proposed.

Thirty-six interviews were performed with stakeholders and potential partners in March and April, 2015. These interviews helped to determine the challenges faced by fire departments in decontaminating and laundering their turnout gear, as well as the resources available to firefighters that could be used in decontamination. Interviews with fire department personnel, firefighter union representatives and firefighter support groups revealed that, although full-time professional fire departments often have a second set of turnout gear for firefighters to wear, small and volunteer fire departments usually have only one set of turnout gear for their members. Most fire department personnel stated that turnouts are laundered about once or twice per year, and after major fires or hazmat events. During interviews with personnel from sixteen different fire departments, only one person stated that turnout coats and pants are laundered after every fire.

After discussing the concept of using air jets as a potential decontamination intervention, one firefighter urged that the use of a self-contained breathing apparatus (SCBA) breathing air cylinder as the air source for the decontamination system be considered, emphasizing that all fire departments had these air cylinders on hand. Other stakeholders stated that 110 Volt electric power and compressed air were widely available on fire apparatus (vehicles), which could potentially be used to power equipment to supply air for decontamination. Currently, firefighters may occasionally be hosed off or brushed off at the scene of a major fire, however, traditional hazardous material decontamination is very rarely performed.

Traditional hazardous material decontamination is a multi-step process requiring bulky equipment and a lengthy setup. It leaves clothing and equipment wet and not suitable for immediate reuse. In the iFund research activity covered by this report, NIOSH researchers developed and investigated an innovative method—the RDFFDS—using air jets in a compact, inexpensive system to accomplish quick field decontamination while the firefighter is still wearing an SCBA. Personal protective gear remains dry and ready for reuse. Stakeholders and potential partners interviewed were all enthusiastic about the prospect of having such a decontamination system available at the scene of a fire, and predicted that it would be widely used if it were simple and quick.

This decontamination method was inspired by the NIOSH Clothes Cleaning System [Pollock et al. 2006], which is used in the mining industry to remove dust from workers' clothing. However, the NIOSH Clothes Cleaning System is large, expensive and non-portable. For many fire departments, a lack of funding and space would make it unlikely for such a system to be adopted for firefighter decontamination. It was endeavored to develop a similar technology that was small, inexpensive and portable, so that each fire department could afford to purchase an RDFFDS for use at fire scenes, thus reducing contamination on personal protective gear before firefighters re-enter vehicles and firehouses.

NIOSH research has contributed to an improved understanding of work-related etiologic factors for acute and chronic diseases. Employing engineering controls to reduce these exposures should result in improved health. Adoption and implementation of exposure controls, PPE cleaning and decontamination procedures, and improved work practices will minimize respiratory, cardiovascular, reproductive and carcinogenic risk in firefighting. Because the RDFFDS under development by NIOSH is rapid and low-cost, it has a high probability of adoption throughout the fire service, even in underfunded departments such as small and volunteer fire departments.

Cancers that occur as a result of exposures in the workplace are preventable. Exposures to known or suspected carcinogens in the fire service can be reduced, and this study is an important step in that direction. This study contributes data important to future workplace recommendations for avoiding hazardous exposures. The fire service is a key industrial sector in which to perform interventions to reduce exposure to substances suspected of causing occupational disease. Research from NIOSH can play a significant role towards the development and evaluation of engineering control interventions for the prevention of these occupational health effects. The technology can also find application in other industries where particulate contamination is an issue.

Plant and Process Description

Occupational Exposure Limits and Health Effects

As a guide to the evaluation of the hazards posed by workplace exposures, NIOSH investigators use mandatory and recommended Occupational Exposure Limits (OELs) when evaluating chemical, physical, and biological agents in the workplace. Generally, OELs suggest levels of exposure to which most workers may be exposed up to 10 hours per day, 40 hours per week for a working lifetime without experiencing adverse health effects. It is, however, important to note that not all workers will be protected from adverse health effects even though their exposures are maintained below these levels. A small percentage may experience adverse health effects because of individual susceptibility, a pre-existing medical condition, and/or hypersensitivity (allergy). In addition, some hazardous substances may act in combination with other workplace exposures, the general environment, or with medications or personal habits of the worker to produce health effects even if the occupational exposures are controlled at the level set by the exposure limit. Combined effects are often not considered in the OEL. Also, some substances are absorbed by direct contact with the skin and mucous membranes, and thus can increase the overall exposure. Finally, OELs may change over the years as new information on the toxic effects of an agent become available.

Most OELs are expressed as a time-weighted average (TWA) exposure. A TWA exposure refers to the average airborne concentration of a substance during a normal 8- to 10-hour workday. Some substances have recommended Short-term Exposure Limit (STEL) or ceiling values which are intended to supplement the TWA, where there are recognized toxic effects from higher exposures over the short-term.

In the U.S., OELs have been established by Federal agencies, professional organizations, state and local governments, and other entities. The U.S. Department of Labor OSHA Permissible Exposure Limits (PELs) [OSHA 2006] are occupational exposure limits that are legally enforceable in covered workplaces under the Occupational Safety and Health Act. NIOSH Recommended Exposure

Limits (RELs) are OELs that are based on a critical review of the scientific and technical information available on the prevalence of health effects, the existence of safety and health risks, and the adequacy of methods to identify and control hazards [NIOSH 2010]. They have been developed using a weight of evidence approach and formal peer review process. Other OELs that are commonly used and cited in the U.S. include the TLVs® recommended by ACGIH®, a professional organization [ACGIH 2015]. ACGIH TLVs are considered voluntary guidelines for use by industrial hygienists and others trained in this discipline "to assist in the control of health hazards." WEELs are recommended OELs developed by AIHA, another professional organization. WEELs have been established for some chemicals "when no other legal or authoritative limits exist"[AIHA 2014].

OSHA requires an employer to furnish employees a place of employment that is free from recognized hazards that are causing or are likely to cause death or serious physical harm [OSHA 2004]. Thus, employers are required to comply with OSHA PELs. Some hazardous agents do not have PELs, however, and for others, the PELs do not reflect the most current health-based information. Thus, NIOSH investigators encourage employers to consider the other OELs in making risk assessment and risk management decisions to best protect the health of their employees. NIOSH investigators also encourage the use of the traditional hierarchy of controls approach to eliminating or minimizing identified workplace hazards. This includes, in preferential order, the use of: (1) substitution or elimination of the hazardous agent, (2) engineering controls (e.g., local exhaust ventilation, process enclosure, dilution ventilation) (3) administrative controls (e.g., limiting time of exposure, employee training, work practice changes, medical surveillance), and (4) personal protective equipment (e.g., respiratory protection, gloves, eye protection, hearing protection).

Firefighting Procedures

Structural firefighting usually takes place in two phases: knockdown or fire attack, and overhaul. During knockdown, fires are extinguished, and firefighters are typically wearing full turnout gear and using SCBA units for respiratory protection. During overhaul, smoldering materials are broken up to prevent re-ignition of the fire. Respiratory protection may or may not be worn during the overhaul phase, although toxic substances may still be present in the air [Bolstad-Johnson et al. 2000].

Following knockdown and overhaul, firefighters typically reenter their vehicles and return to the firehouse without performing any field decontamination. Many times, they are still wearing their turnout coats and pants when they enter their vehicles, bringing with them the contaminants that have accumulated while fighting the fire. Use of the RDFFDS at the scene of the fire would reduce the amount of hazardous particulate material brought into firefighter vehicles and living spaces. This would reduce exposure potential and help to protect firefighter health.

Particulate Removal

The particulate matter to which a firefighter may be exposed will vary by circumstances and cannot be precisely characterized as to size or composition. Fire events may include many different types of burning structures, such as office buildings, warehouses, manufacturing plants, high-rise buildings and homes, as well as wildfires, trash fires and vehicle fires. The materials of construction and the contents of the structures will also vary. The amount, size and composition of particulate matter produced during a fire event will also depend on the temperature of the fire, the amount of oxygen present, and the turbulence in the environment [Baxter et al. 2010; Fabian et al. 2014].

Particulate matter adhering to a surface, such as a firefighter helmet or turnout gear, is held in place by molecular-level forces. These adhesion forces may include van der Waals forces, electrostatic forces (especially in non-conductive materials), chemical bonds and the capillary action of moisture on the surface [Fletcher et al. 2008; Ranade 1987; Ziskind et al. 1995]. The strength of these forces is dependent on the particle size, the properties of the particle and the surface, the relative humidity of the air and the length of time that the particle has resided on the surface [Ibrahim et al. 2004; Ibrahim et al. 2008]. Longer residence time on a surface may allow moisture to condense in small gaps between the particle and the surface, increasing the adhesion force. Even if this moisture is subsequently dried, crystallized impurities may remain, helping to “cement” the particle to the surface [Ranade 1987]. This highlights the need for firefighters to remove contamination from surfaces quickly, at the scene of a fire, before contamination dries on protective gear and adhesion forces increase.

In a flowing air stream, the forces acting to detach a particle from a surface include lift, drag and torque. These hydrodynamic forces are dependent on the size of the particle and the speed of the air stream [Harris and Davidson 2008]. When the particle starts to detach, it may move by lift-off, sliding or rolling [Phares et al. 2000]. Experimentally, particles have been observed to roll before detaching from a surface, so torque may be an important component of the forces involved in removing a particle from a surface, especially because rolling detachment occurs at a much lower shear stress than sliding detachment [Harris and Davidson 2008]. Several researchers have additionally noted a time-dependence of particle suspension from a surface by an air jet [Smedley et al. 1999; Ziskind et al. 1995].

In order to remove particles from surfaces using air jets, the speed and impact force of the air jet must be sufficient for the hydrodynamic forces working to detach the particle to exceed the adhesion forces tending to keep the particle on the surface. Experimentally, particle removal efficiency has been shown to increase with increasing air jet pressure, decreasing jet height above the surface, and increasing particle diameter [Smedley et al. 1999]. These results have also been verified for particles adhering to cloth [Fletcher et al. 2008]. Development of the RDFFDS takes advantage of these hydrodynamic forces.

Methodology

NIOSH researchers developed a technique to quantitatively measure the effectiveness of different decontamination methods in the laboratory. This technique utilizes a fluorescent powder, Dust Chaser Leak Detection Compound (W.H. Kingsmill, Ltd., Burlington, ON, Canada), distributed onto the surface of a 6” x 6” (15.24 cm x 15.24 cm) swatch of firefighter turnout coat fabric, as a simulated soil. An LED blacklight flashlight, Scorpion Master 100 LED Blacklight Flashlight (Shawshank LEDz Inc., Chandler, AZ), is used to illuminate the fluorescent powder. This flashlight was modified to provide AC power in place of battery power to eliminate light output variation due to battery voltage variation. The lux of the fluorescence stimulated is measured using a light meter, Extech Model SDL400-NIST (FLIR Systems, Inc., Nashua, NH). The arrangement of the instruments is shown in Figures 1 and 2.

Approximately 0.2 grams of the fluorescent powder were weighed out in a scintillation vial on a Mettler AT261 DeltaRange analytical balance (Mettler-Toledo, Greifensee, Switzerland). The vial was reweighed after it was emptied to determine the weight transferred to the fabric, because some of the powder was observed to cling to the vial. The powder was evenly spread over a 6” x 6” (15.24 cm x 15.24 cm) black TenCate Advance fabric sample consistent with that used in the outer layer of firefighter turnout coats and pants (TenCate Protective Fabrics, Union City, GA). (See Figure 3.) Particulate may be less likely to “stick” to brand new fabric, so the test fabric was laundered without the use of fabric softener and machine-dried, before being cut into squares for testing. The back of a Scoopula™ (Thermo Fischer Scientific, Waltham, MA) was used to press the particulate lightly into the fabric surface. By doing this, the powder adhered well to the fabric and did not fall off when the fabric was held vertically.

After the “before” fluorescence measurement was taken, each “soiled” fabric square was attached to a square of corrugated cardboard using four binder clips, so that it would be unable to flap around when it was treated with a jet of air. The cardboard square was mounted vertically on the inside of the access door of a small glovebox. Figure 4 shows the cardboard square used in the testing, and Figure 5 shows the glovebox. The glovebox door was closed, and the evaluated decontamination method was tested for a period of 10 seconds of treatment on the fabric sample, while the air nozzle was held as close as possible and at an angle of approximately 45^{o} to the fabric surface. After the decontamination treatment, the fluorescence of the fabric sample was measured again. Four samples were decontaminated using each combination of treatment method and nozzle, for a total of 48 samples. In addition, an uncontaminated control fabric sample was evaluated for its fluorescence before/after each set of trial runs.

Thirty-two measurements of the fluorescence of an uncontaminated blank sample of fabric were made over a period of 8 months. The mean of these measurements was 86 lux and the standard deviation was 2.88 lux. For decontamination effectiveness analysis, the contamination-attributed fluorescence (lux) on a given test sample was determined by subtracting this 86 lux baseline from the total fluorescence measured. In this manner, the baseline-corrected reduction in fluorescence between pre- and post-decontaminated fabric test samples was calculated using the equation shown in Equation 1.

$$\%\ Fluorescence\ Reduction = \left[1 - \left[\frac{(M_{v\,after} - 86)}{(M_{v\,before} - 86)}\right]\right] * 100 \qquad (1)$$

where:

$$M_v = luminous\ emittance\ of\ the\ surface\ (lux)$$

Several measurements of different characteristics of the decontamination methods were made to determine which factors were important in good decontamination performance. System static pressure of each air-delivery system was measured using a Magnehelic® pressure gauge (Dwyer Instruments, Michigan City, IN) when the air flow path was blocked so that no air was flowing.

Volumetric flowrate of evaluated compressed air delivery systems was measured using a Model 6200 mass flow meter (CDI Meters, Woburn, MA) (See Figure 6.). At lower air pressures, the volumetric flowrate of air was measured using a 2" FVT venturi flowmeter (Primary Flow Signal, Cranston, RI) (See Figure 7.). Discharge air velocities were estimated by dividing measured volumetric flowrates by the cross-sectional area for flow at the exit of the nozzle or air knife as follows:

$$v = \frac{Q}{A} \qquad (2)$$

where:

v = air velocity, m/sec

Q = volumetric flowrate of air, m^3/sec, and

A = cross-sectional area for flow, m^2

Control Technology

Five commercially-available air delivery systems were tested in an effort to determine the most suitable and effective for the RDFFDS. Tested sources of air included:

SCBA cylinder

Leaf blower

High-speed hand dryer blower

Pet dryer blower

Cage dryer blower

The SCBA cylinder was tested using 9 different configurations of commercially available nozzles or "air knives". The blowers were tested using the nozzles provided and/or nozzles designed at NIOSH using Solidworks software (Dassault Systemes, Vélizy-Villacoublay, France). Nozzles were fabricated from acrylonitrile-butadiene-styrene (ABS) plastic using the Dimension uPrint Plus 3-D printer

(Stratasys, Eden Prairie, MN), to determine which configuration would remove the simulated soil most effectively.

SCBA Cylinder

The use of an SCBA breathing air cylinder was recommended as the decontamination air source during stakeholder surveys, as such cylinders are on hand in every fire department. SCBA cylinders contain breathing air at a pressure of up to 5500 psig (37,900 kPa) or a volume of 111 scf (3.14 cubic meters) [Scott Safety 2012]. One cylinder is intended to provide breathing air for up to 75 minutes, although the actual length of time depends on the breathing rate of the user.

OSHA regulation 29CFR1910.242 does not permit the use of compressed air at pressures above 30 psi (207 kPa) for cleaning purposes [OSHA 1978]. To use the SCBA cylinder as an air source for cleaning, the air pressure was regulated down to 30 psi (207 kPa) at the outlet, using two pressure regulators in series. A Concoa regulator model 4921801-84-347 (Concoa, Virginia Beach, VA) regulated the full cylinder pressure down to 200 psig (1379 kPa) (See Figure 8.), and a Norgren R73G-2AK-RMN (IMI Precision Engineering, Birmingham, UK) regulated the 200 psig (1379 kPa) air down to 30 psig (207 kPa).

The air was delivered to the decontamination nozzles via a 3/8" x 25' long (1 cm x 7.6 m) Flexzilla air hose (Legacy Manufacturing Co., Marion, IA) attached to a Spraying Systems model 60 Gun Jet 3/8" (1 cm) spray gun (Spraying Systems Co., Wheaton, IL). Figure 9 shows the Norgren regulator attached to the Spraying Systems spray gun. Nine configurations of spray nozzles and "air knives" were tested for this application, as listed in Table I, and shown in Figure 10.

Leaf Blower

The leaf blower used for this research was a Black & Decker model BV6000 with AC power (Stanley Black & Decker, New Britain, CT). The manufacturer rates it at an air velocity of 250 mph (27 m/min), and a volumetric flow rate of 400 cubic feet per minute (11.4 m^3/min). A shorter nozzle than the one provided was designed and 3-D printed for the leaf blower, so that the leaf-blower could be used as a hand-held decontamination device. The static pressure measured for this device was 28 inches of water (6970 Pa).

The leaf blower was also tested using a 10-foot (3 m) length of 2-1/2" (6.4 cm) Flex-Tube® TR hose (Flexaust, Warsaw, IN) with the same nozzle. In this configuration, the leaf blower "body" would rest on the ground, while the nozzle was used for decontamination. Both tested leaf blower configurations are shown in Figure 11.

High-Speed Hand Dryer Blower

The high-speed hand dryer motor used for this study was an American Dryer replacement blower, model #GTX216 (American Dryer, Livonia, MI). The motor reportedly rotated at a maximum of 24,000 revolutions per minute (RPM). Housings for the blower were designed and 3-D printed so that the motor could be used for hand-held decontamination. Three different housings were tested, as shown in Figure 12.

The first housing had round holes arranged in a rectangular pattern to deliver the air for decontamination. The second housing incorporated a wide-slot nozzle to direct decontamination air, with a slot opening 11/16" (1.75 cm) wide x 2" (5.08 cm) long. The third housing incorporated a narrow-slot nozzle, with a slot opening ¼" (0.635 cm) wide x 1-3/4" (4.445 cm) long. The static pressure measured for this blower was 53 inches of water (13,200 Pa).

Pet Dryer

The pet dryer tested in this study was an Air Force® Commander® AFTD 4-HP (2.9 kW) blower (Metropolitan Vacuum Cleaner Company, Oakland, NJ). This blower remains on the ground while a nozzle on the end of a hose is used for decontamination. The original housing on the pet dryer had a 1-1/2" (3.8 cm) diameter outlet to accommodate a 1-1/2" (3.8 cm) inside-diameter (I.D.) hose attached to a slightly fan-shaped nozzle, 5/8"-wide (1.59 cm) x 2-1/4" (5.715 cm) long. To increase system airflow, part of the blower discharge housing was redesigned to have a 2-1/2" (6.4 cm) diameter outlet and 3-D printed. The redesigned housing was tested using a 10-foot (3 m) length of 2-1/2" (6.4 cm) I.D. Flex-Tube® TR hose (Flexaust, Warsaw, IN) in combination with each of two nozzle designs: a wide-slot 1" (2.54 cm) nozzle, and a narrow-slot ¼" (0.635 cm) nozzle. Both nozzles were also designed in-house and 3-D printed. The three tested configurations are shown in Figure 13. The pressure of this blower was measured as 80 inches of water (19,900 Pa).

Cage Dryer

The cage dryer tested for this study was an XPower X800TF-MDK dryer (XPower Pet Dryers, San Gabriel, CA). The cage dryer is also intended to remain on the ground. It was supplied with an adapter for connection to 3: 8-foot long x 4.5 inch diameter (2.4 m x 11.4 cm) hoses. The connection ports for two of the hoses were blocked off for this research. Two nozzles were designed and 3-D printed: a wide-slot nozzle 1" wide x 2-7/16" long (2.54 cm x 6.19 cm) and a narrow-slot nozzle ¼" wide x 2-5/8" long (0.635 cm x 6.67 cm). One 4.5" hose was connected to the unblocked connection port and used with a nozzle for this research. The evaluated wide-slot nozzle and narrow-slot nozzle configurations are shown in Figure 14. The pressure of this blower was measured at 2.3 inches of water (573 Pa).

Results

SCBA Cylinder

The decontamination effectiveness of all nine configurations of the SCBA cylinder and attachments (See Figures 8 – 10.) were tested early in the project. At that time, battery power was used for the black light flashlight. It was later recognized that these tests were not reproducible, because the light output of the flashlight was continually decreasing with time as the batteries aged. These tests did indicate that two of the nozzle/air knife configurations performed better than the rest.

These two nozzle configurations, #2 and #9, were retested under the same quantitative evaluation protocol used with the other air-source technologies, using AC power. Measurements of the luminous emittance (M_v) of the fabric swatch before and after treatment with the SCBA cylinder, along with the average of the four trials, are given in Tables 2 and 3. Equation (1) was used to calculate the percent fluorescence reduction for each configuration. Configuration 2 reduced M_v by an average of 66%. One of the trials for configuration 9 appeared to be an outlier from the other three, resulting in much poorer soil removal. The results of the other three trials were averaged to result in a 58% reduction in M_v.

Leaf Blower

The leaf blower was tested with and without a hose leading to the nozzle, as shown in Figure 11. Results of these tests are shown in Tables 4 and 5. Four trials were performed using each arrangement. Using equation (1), the average reduction in M_v was 81% without the hose, and 76% with the hose. An example of a soiled fabric swatch before and after treatment with the leaf blower is shown in Figure 15.

High-Speed Hand Dryer Blower

Three air-discharge housings were designed and tested for the high-speed hand dryer blower, as shown in Figure 12. Four trials were performed for each housing with the results shown in Tables 6, 7 and 8. The housing that delivered air through an array of small holes reduced M_v by an average of 47%. The wide-slot nozzle reduced M_v by an average of 50%, and the narrow-slot nozzle reduced M_v by an average of 71%.

Pet Dryer

The pet dryer was tested using three air-discharge configurations, as shown in Figure 13. Four fabric samples were treated with each configuration. Results of these tests are shown in Tables 9, 10 and 11. The pet dryer in its original form reduced M_v by an average of 73%. The pet dryer with the 2-1/2" (6.4 cm) diameter hose and wide-slot nozzle reduced M_v by an average of 51%, and with the same hose and a narrow-slot nozzle, M_v was reduced by an average of 77%.

Cage Dryer

The Xpower cage dryer was tested using one of the three 4.5" (11.4 cm) hoses supplied with the unit. Two nozzle designs were tested with the hose, as shown in Figure 14. Four soiled fabric samples were treated with each nozzle and the results of testing are shown in Table 13. The wide-slot nozzle reduced M_v by an average of 35%, and the narrow-slot nozzle reduced M_v by an average of 33%. An example of a soiled fabric square before and after treatment by the cage dryer with wide-slot nozzle is shown in Figure 16.

Discussion

It was initially difficult to obtain a reliable M_v reading using the LED blacklight flashlight. Because the flashlight was battery-powered, the intensity of its light was constantly decreasing. In order to obtain a steady light source, an AC power supply was used with the flashlight. After this modification, we obtained consistently reproducible results from the light source.

The average results for all the methods tested are shown in Figure 17. The leaf blower and the pet dryer with a narrow-slot nozzle showed the best results in reducing the fluorescence of a fabric sample, followed by the hand dryer blower using a narrow-slot nozzle.

Most of the methods seemed to remove all the powder that was going to be removed almost instantly, with very little additional powder being removed for the rest of the time period in which the fabric squares were being treated. The exceptions to this rule were the SCBA cylinder methods. They appeared to still be actively removing visually apparent quantities of powder at the end of the treatment time.

The different treatment technologies were originally selected based on the volume of air that they could deliver, but other factors were also found to be important for dry decontamination effectiveness. Several variables were evaluated in trying to account for the differences in decontamination efficiency between the technologies. These variables included volumetric flowrate and static pressure. Discharge air velocity was estimated from volumetric flowrate as shown in the Methodology section. These measurements and calculations are listed in Table 14.

The volumetric flow rate of air delivered was obviously important, but narrow-slot nozzles were often observed to perform better than wide-slot nozzles that can deliver higher volumes of air. The velocity of the air in feet per second or meters per second is also an important factor in removing particulate contamination from fabric. For a given air mass, a higher velocity results in a higher force exerted on particles at the surface. The advantage of a narrower nozzle is that for a given volumetric air flow rate, it delivers a higher velocity air stream.

The cage dryer was the only technology tested that did not exhibit better performance when using a narrower nozzle. This can be explained by its extremely low static pressure. Adding the resistance of the narrower nozzle to the flow path reduced the airflow from the cage dryer significantly.

The adhesive forces on particles have been described by a log-normal distribution, with some particles being easier to remove than others [Ziskind et al. 1995]. This explains why none of the methods tested were capable of removing 100% of the model soil. The force exerted by the air jet on the surface particles is proportional to a threshold surface shear, τ, which is the change in air velocity with distance from the surface. The shear, in turn, is dependent on the air velocity leaving the nozzle [Smedley et al. 1999]. When percent reduction in fluorescence is plotted vs. air velocity for the blower-based methods (See Figure 18.), a clear correlation is seen.

In the case of SCBA cylinder-based methods, the air jets were so small in diameter, coming through small round holes in a nozzle, that they only impacted a small area of the test swatch, unlike the blower methods that utilized broad oblong openings in the nozzles. As observed, powder was still being removed with SCBA cylinder methods at the end of the 10-second test period. If the SCBA cylinder methods had been tested for a longer period of time, it is possible that they would have removed more soil. As there is a limited quantity of air in an SCBA cylinder, the length of time that it could be used for decontamination is limited. Cylinders used in laboratory decontamination testing could be emptied in as little as 6 minutes of use.

Field Testing

Early in this study, there was an opportunity to test one of the technologies as part of a large field exercise at the Illinois Fire Service Institute. During the field exercise, firefighters wore new sets of turnout gear while fighting training fires. Wipe samples were obtained from the sleeves of the turnout jackets before and after the fire was extinguished, and after a decontamination treatment. The decontamination methods tested were (1) dry decontamination using an RDFFDS, (2) a dry brush, or (3) soapy water applied with a brush and rinsed off with a garden hose. Soapy water might be considered the gold standard for decontamination, but it involves multiple steps and leaves turnout gear wet.

The leaf blower with short nozzle was chosen to represent the RDFFDS during the field exercise, due to its promising laboratory results. A photo of one of the training fires is shown in Figure 19. A photograph of an RDFFDS decontamination being performed on a researcher wearing a firefighter turnout jacket and pants is shown in Figure 20. The average time needed to decontaminate each set of turnout gear with the RDFFDS was just over one minute.

Wipe samples were sent to an analytical laboratory to be tested for the presence of PAHs. Unfortunately, the small quantities of PAHs detected made it difficult to precisely determine the effectiveness of decontamination using the leaf blower.[Fent et al. 2017] Further testing will be needed to conclusively evaluate the effectiveness of the RDFFDS.

Similar to the testing of turnout gear from the Illinois training fire, the RDFFDS (leaf blower with short nozzle) was tested for decontamination of fire-worn turnout coats and pants in ongoing service, borrowed from a local fire department. Turnout gear is shown being worn by a researcher for decontamination in Figure 21. Once again, wipe samples showed a low level of PAHs both before and after decontamination, making it difficult to evaluate the effectiveness of the decontamination. Several sets of the borrowed turnout gear were also placed inside an enclosure so that air samples for offgassing could be collected. Almost every air sample tested for offgassing of hydrogen cyanide (HCN) was below the limit of detection, whether the turnout gear had been decontaminated or not. Thermal diffusion tubes were used to collect offgassing samples of VOCs as well, but results were inconclusive and potentially impacted by VOCs coming from the plastic enclosure used to collect the offgassing samples. (See Figure 22.)

Relative merits of the methods

Each of the tested RDFFDS decontamination methods had advantages and disadvantages. Methods without a hose are more compact and easy to transport to the scene of a fire. However, they are somewhat more unwieldly and heavy to use.

The addition of a hose allows the heavy blower to remain on the ground during use. The leaf blower weighs 8.1 pounds. While the hand dryer replacement blower, at only 3 pounds, may be easier to manipulate, its use also resulted in a reduction of decontamination efficiency. The methods with hoses could present a tripping hazard during use, and there are also more ways in which they can fail, for example, by a hose becoming disconnected during use or being stepped on and flattened.

Almost all of the methods require a 110 Volt electrical outlet to be available to power the decontamination, but the advantage of these methods is that the supply of air is essentially unlimited. Electrical power is usually available on fire vehicles present at the scene of a fire event. The methods based on use of an SCBA cylinder do not require an external source of power, but they can supply only a limited amount of air before a new cylinder will be required. They also require the use of pressure regulators that are relatively fragile and must be adjusted periodically to maintain the proper air pressures during use.

The hand dryer blower operates at high rotational speeds, and is intended to be used only for 30 seconds at a time. It will need to run for several minutes at a time for decontamination purposes. Field trials will be necessary to verify its long-term suitability for this service. The cage dryer did not perform well with either of the two nozzles tested, and probably does not merit further study.

Conclusions and Recommendations

Several promising technologies for use as the RDFFDS were identified in laboratory testing. These methods could remove from 70% to over 80% of a test soil from a 6” x 6” (15.24 cm x 15.24 cm) test swatch within 10 seconds. Results of field testing of one of the RDFFDS prototypes, the leaf blower with short nozzle, were inconclusive. Dry field decontamination of a firefighter turnout coat and pants could be accomplished in about 1 minute.

The low concentrations of PAHs observed in wipe samples taken from firefighter turnout gear made it difficult to measure the effectiveness of the RDFFDS technology using this performance metric. Selection of more abundant chemical species as an indicator for contamination on turnout gear, may help in quantifying the effectiveness of field decontamination. Some chemicals that have been detected in higher quantities than PAHs on firefighter turnout gear include di-(2-ethylhexyl) phthalate (DEHP) and lead [Alexander and Baxter 2014; Stull et al. 1996]. Additional field testing by fire departments will be necessary before final selection of a technology for further development and use in the fire service. This field testing will establish the ease and acceptance of use, dependability and effectiveness of the RDFFDS technology.

Acknowledgements

The authors would like to express their appreciation to the following NIOSH personnel for significant assistance in performing this research: Donnie Booher, Andy Cecala, Kenny Fent, Daniel Farwick, Duane Hammond, Ron Kovein, Jerry Kratzer, Dawn Ramsey Farwick and Kenny Sparks. Essential support was also received from Chief Thomas Lakamp of the Cincinnati Fire Department and from Gavin Horn of the Illinois Fire Service Institute at the University of Illinois.

References

ACGIH [2015]. *2015 TLVs® and BEIs®: threshold limit values for chemical substances and physical agents and biological exposure indices.* . Edited by American Conference of Governmental Industrial Hygienists (ACGIH). Cincinnati, Ohio: American Conference of Governmental Industrial Hygienists (ACGIH),

AIHA [2014]. WEELs. edited by American Industrial Hygiene Association (AIHA). Falls Church, Virginia: American Industrial Hygiene Association (AIHA), https://www.aiha.org/get-involved/AIHAGuidelineFoundation/WEELs/Pages/default.aspx.

Alarie Y [2002]. Toxicity of fire smoke. Crit Rev Toxicol *32* (4):259-89.

Alexander BM, and Baxter CS [2014]. Plasticizer Contamination of Firefighter Personal Protective Clothing - A Potential Factor in Increased Health Risks in Firefighters. J Occup Environ Hyg *11* (5):D43-D48.

Baxter CS, Ross CS, Fabian T, Borgerson JL, Shawon J, Gandhi PD, Dalton JM, and Lockey JE [2010]. Ultrafine Particle Exposure During Fire Suppression-Is It an Important Contributory Factor for Coronary Heart Disease in Firefighters? J Occup Environ Med *52* (8):791-796.

Bolstad-Johnson DM, Burgess JL, Crutchfield CD, Storment S, Gerkin R, and Wilson JR [2000]. Characterization of firefighter exposures during fire overhaul. AIHA J *61* (5):636-641.

Brandsma SH, de Boer J, Cofino WP, Covaci A, and Leonards PEG [2013]. Organophosphorus flame-retardant and plasticizer analysis, including recommendations from the first worldwide interlaboratory study. Trends Analyt Chem *43*:217-228.

Brown FR, Whitehead TP, Park JS, Metayer C, and Petreas MX [2014]. Levels of non-polybrominated diphenyl ether brominated flame retardants in residential house dust samples and fire station dust samples in California. Environ Res *135*:9-14.

CDC [2015]. "United States Cancer Statistics: 1999–2012 Incidence and Mortality Web-based Report." Centers for Disease Control and Prevention Accessed 01/07/2016. https://nccd.cdc.gov/uscs/.

Chang SK, and Riviere JE [1991]. Percutaneous absorption of parathion in vitro in porcine skin: effects of dose, temperature, humidity, and perfusate composition on absorptive flux. Fundam Appl Toxicol *17* (3):494-504.

Daniels RD, Kubale TL, Yiin JH, Dahm MM, Hales TR, Baris D, Zahm SH, Beaumont JJ, Waters KM, and Pinkerton LE [2014]. Mortality and cancer incidence in a pooled cohort of US firefighters from San Francisco, Chicago and Philadelphia (1950-2009). Occup Environ Med *71* (6):388-397.

Driscoll T, Takala J, Steenland K, Corvalan C, and Fingerhut M [2005]. Review of estimates of the global burden of injury and illness due to occupational exposures. Am J Ind Med *48* (6):491-502.

Evans DE, and Fent KW [2015]. Ultrafine and respirable particle exposure during vehicle fire suppression. Environ Sci Process Impacts *17*:1749 - 1759.

Fabian T, Borgerson J, Gandhi P, Baxter CS, Ross C, Lockey J, and Dalton J [2014]. Characterization of Firefighter Smoke Exposure. Fire Technology *50* (4):993-1019.

Fahy RF, LeBlanc PR, and Molis JL [2016]. Firefighter Fatalities in the United States - 2015. edited by National Fire Protection Association (NFPA). Quincy, Massachusetts, http://www.nfpa.org/~/media/files/news-and-research/fire-statistics/fire-service/osfff.pdf?la=en.

Fent KW, Alexander B, Roberts J, Robertson S, Toennis C, Sammons D, Bertke S, Kerber S, Smith D, and Horn G [2017]. Contamination of firefighter personal protective equipment and skin and the effectiveness of decontamination procedures. J Occup Environ Hyg:0.

Fent KW, Evans DE, Booher D, Pleil JD, Stiegel MA, Horn GP, and Dalton J [2015]. Volatile Organic Compounds Off-gassing from Firefighters' Personal Protective Equipment Ensembles after Use. J Occup Environ Hyg *12* (6):404-14.

Fletcher R, Briggs N, Ferguson E, and Gillen G [2008]. Measurements of Air Jet Removal Efficiencies of Spherical Particles from Cloth and Planar Surfaces. Aerosol Sci Technol *42* (12):1052-1061.

Harris AR, and Davidson CI [2008]. Particle Resuspension in Turbulent Flow: A Stochastic Model for Individual Soil Grains. Aerosol Sci Technol *42* (8):613-628.

Haynes HJG, and Stein GP [2014]. US Fire Department Profile 2013. edited by NFPA. Quincy, Massachusetts: NFPA, http://www.nfpa.org/~/media/files/research/nfpa-reports/fire-service-statistics/osfdprofile.pdf?la=en.

IAFF [2015]. "Line of Duty Deaths Database." Accessed 01/07/2016. http://www.iaff.org/hs/lodd/advancedSearch.asp.

IARC [2010]. Painting, Firefighting, and Shiftwork. In *IARC Monographs on the Evluation of Carcinogenic Risks to Humans.*, edited by International Agency for Research on Cancer. Lyon, France, http://monographs.iarc.fr/ENG/Monographs/vol98/index.php.

Ibrahim AH, Dunn PF, and Brach RM [2004]. Microparticle detachment from surfaces exposed to turbulent air flow: Effects of flow and particle deposition characteristics. J Aerosol Sci *35* (7):805-821.

Ibrahim AH, Dunn PF, and Qazi MF [2008]. Experiments and validation of a model for microparticle detachment from a surface by turbulent air flow. J Aerosol Sci *39* (8):645-656.

Kales SN, Soteriades ES, Christophi CA, and Christiani DC [2007]. Emergency duties and deaths from heart disease among firefighters in the United States. N Engl J Med *356* (12):1207-15.

Kirk KM, and Logan MB [2015]. Structural Fire Fighting Ensembles: Accumulation and Off-gassing of Combustion Products. J Occup Environ Hyg *12* (6):376-83.

Lawson CC, Schnorr TM, Daston GP, Grajewski B, Marcus M, McDiarmid M, Murono E, Perreault SD, Schrader SM, and Shelby M [2003]. An occupational reproductive research agenda for the third millennium. Environ Health Perspect *111* (4):584-92.

LeMasters GK, Genaidy AM, Succop P, Deddens J, Sobeih T, Barriera-Viruet H, Dunning K, and Lockey J [2006]. Cancer risk among firefighters: A review and meta-analysis of 32 studies. J Occup Environ Med *48* (11):1189-1202.

NIOSH [2010]. NIOSH Pocket Guide to Chemical Hazards. Washington, DC: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, http://www.cdc.gov/niosh/npg/.

OSHA [1978]. 29 CFR 1910.242 Hand and portable powered tools and other hand-held equipment. edited by OSHA. Washington, DC: U.S. Department of Labor, Occupational Safety and Health Administration, https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9849.

OSHA [2004]. Occupational Safety and Health Act of 1970, Public Law 91-596. By Department of Labor. Washington, DC: U.S. Department of Labor, Occupational Safety and Health Administration, https://www.osha.gov/pls/oshaweb/owasrch.search_form?p_doc_type=OSHACT.

OSHA [2006]. OSHA 1910.1000 Air Contaminants. By US Department of Labor. Washington, DC: U.S. Department of Labor, Occupational Safety and Health Administration, https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9991.

Park JS, Voss RW, McNeel S, Wu N, Guo T, Wang Y, Israel L, Das R, and Petreas M [2015]. High exposure of California firefighters to polybrominated diphenyl ethers. Environ Sci Technol *49* (5):2948-58.

Phares DJ, Smedley GT, and Flagan RC [2000]. EFFECT OF PARTICLE SIZE AND MATERIAL PROPERTIES ON AERODYNAMIC RESUSPENSION FROM SURFACES. J Aerosol Sci *31* (11):1335-1353.

Pollock DE, Cecala AB, Zimmer JA, O'Brien AD, and Howell JL [2006]. "A new method to clean dust from soiled work clothes." 11th U.S./North American Mine Ventilation Symposium.

Ranade MB [1987]. Adhesion and Removal of Fine Particles on Surfaces. Aerosol Sci Technol *7* (2):161-176.

Schecter A, Papke O, Tung KC, Joseph J, Harris TR, and Dahlgren J [2005]. Polybrominated diphenyl ether flame retardants in the US population: Current levels, temporal trends, and comparison with dioxins, dibenzofurans, and polychlorinated biphenyls. J Occup Environ Med *47* (3):199-211.

Scott Safety [2012]. "Cylinders for use with Scott Safety self-contained breathing apparatus." Accessed March 17. https://www.scottsafety.com/en/us/DocumentandMedia1/Bro_Cylinders_HS_7012_0312.pdf.

Sen S, Palmieri T, and Greenhalgh D [2016]. Cardiac Fatalities in Firefighters: An Analysis of the U.S. Fire Administration Database. J Burn Care Res *37* (3):191-5.

Shaw SD, Berger ML, Harris JH, Yun SH, Wu Q, Liao C, Blum A, Stefani A, and Kannan K [2013]. Persistent organic pollutants including polychlorinated and polybrominated dibenzo-p-dioxins and dibenzofurans in firefighters from Northern California. Chemosphere *91* (10):1386-94.

Shen B, Whitehead TP, McNeel S, Brown FR, Dhaliwal J, Das R, Israel L, Park JS, and Petreas M [2015]. High levels of polybrominated diphenyl ethers in vacuum cleaner dust from California fire stations. Environ Sci Technol *49* (8):4988-94.

Siddiqi MA, Laessig RH, and Reed KD [2003]. Polybrominated diphenyl ethers (PBDEs): new pollutants-old diseases. Clin Med Res *1* (4):281-90.

Smedley GT, Phares DJ, and Flagan RC [1999]. Entrainment of fine particles from surfaces by gas jets impinging at normal incidence. Exp Fluids *26*:324-334.

Smith DL, Barr DA, and Kales SN [2013]. Extreme sacrifice: sudden cardiac death in the US Fire Service. Extrem Physiol Med *2* (1):6.

Stapleton HM, Klosterhaus S, Keller A, Ferguson PL, van Bergen S, Cooper E, Webster TF, and Blum A [2011]. Identification of flame retardants in polyurethane foam collected from baby products. Environ Sci Technol *45* (12):5323-31.

Stull JO, Dodgen CR, Connor MB, and McCarthy RT [1996]. "Evaluating the Effectiveness of Different Laundering Approaches for Decontaminating Structural Fire Fighting Protective Clothing." In *Performance of Protective Clothing: Fifth Volume*, edited by J.S. Johnson and S.Z. Mansdorf. American Society for Testing and Materials.

Ziskind G, Fichman M, and Gutfinger C [1995]. Resuspension of particulates from surfaces to turbulent flows—Review and analysis. J Aerosol Sci *26* (4):613-644.

Appendices

Figures

Figure 1. The blacklight flashlight and light meter sensor used in testing were attached to a ring stand to obtain reproducible readings of light intensity.

Figure 2. Fabric strips attached to the base of the ring stand allowed fabric squares to be positioned in the same location for each reading.

Figure 3. Unsoiled 6” x 6” (15.24 cm x 15.24 cm) square of Tencate Advance fabric.

Figure 4. Corrugated cardboard square used for mounting fabric squares for testing.

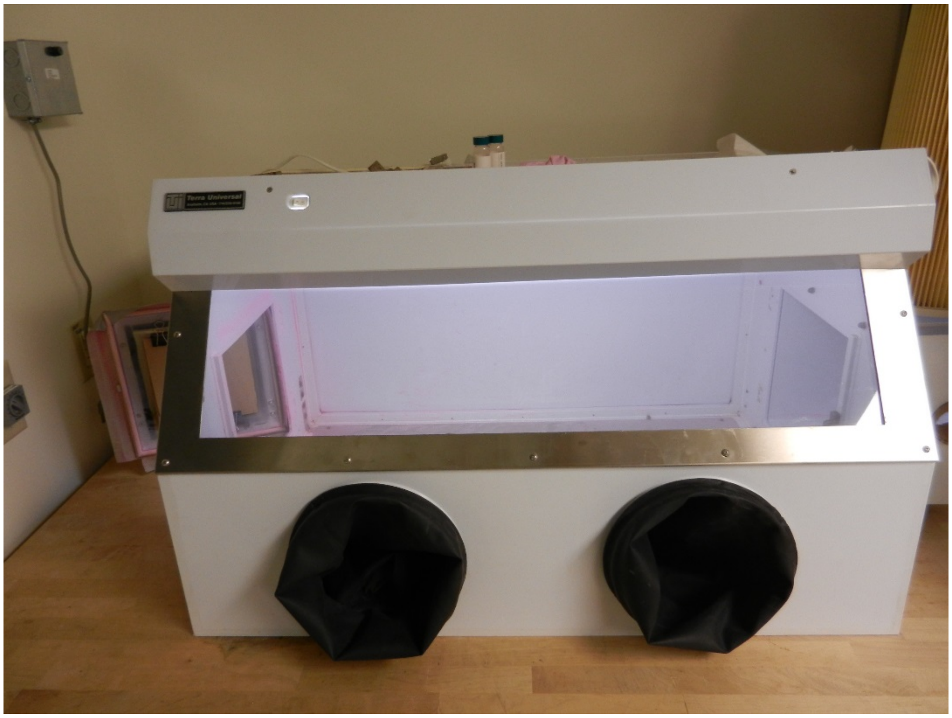

Figure 5. Glovebox used for lab testing, showing access door open at left.

Figure 6. CDI mass flowmeter used to measure the flow rate of compressed air.

Figure 7. Primary Flow Signal flowmeter, used to measure the flow rate of low-pressure air.

Figure 8. Concoa regulator attached to a Scott breathing air cylinder.

Figure 9. Norgren pressure regulator and Spraying Systems spray gun attached to a manifold with 3 Air TX spray nozzles (configuration 1).

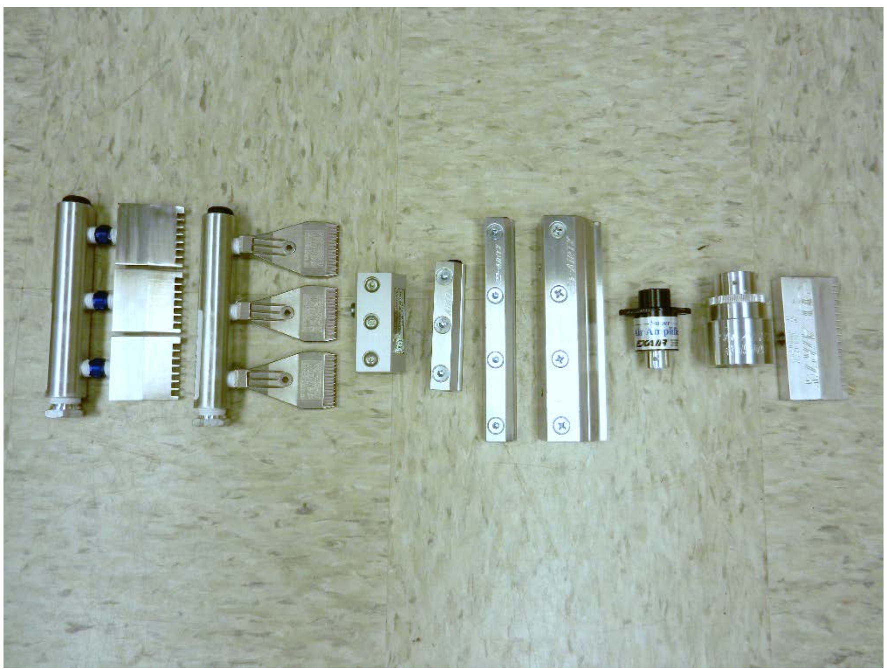

Figure 10. From left to right, air spray configurations 1 - 9, tested with an SCBA cylinder for dry decontamination.

Figure 11. Modified leaf blower used for dry decontamination, with and without hose.

Figure 12. Three different housings tested with high-speed hand dryer blower: outlet holes, wide-slot nozzle and narrow-slot nozzle.

Figure 13. Three different configurations of the Metro pet dryer were tested: as sold with a narrow hose and fan-shaped nozzle, with a larger hose and a wide -slot nozzle, and with the larger hose and a narrow-slot nozzle.

Figure 14. The XPower cage dryer was tested with a wide-slot nozzle and with a narrow-slot nozzle.

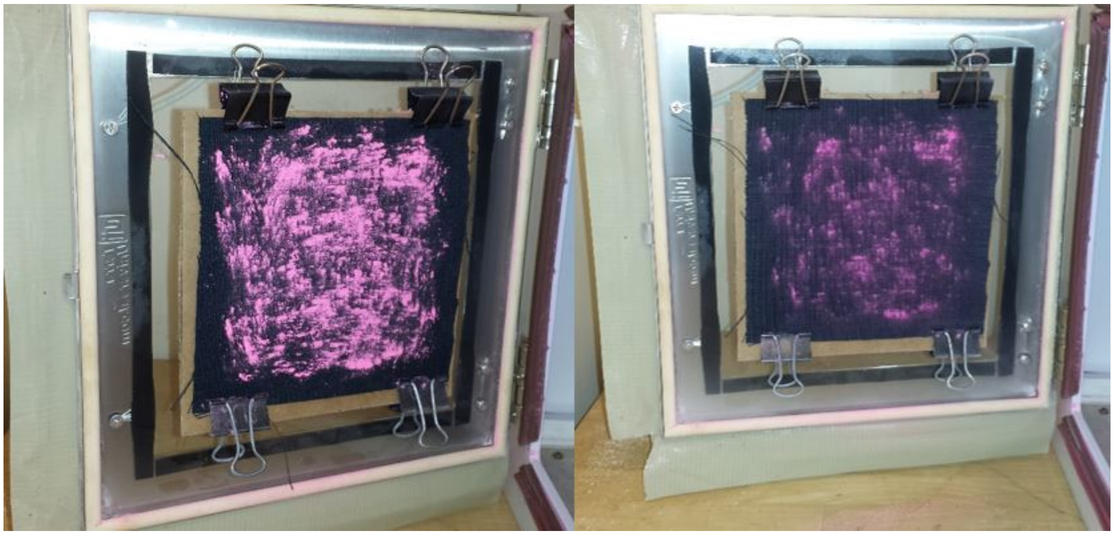

Figure 15. An example of the appearance of the test swatch before and after one of the most successful decontamination trials, using the leaf blower without hose.

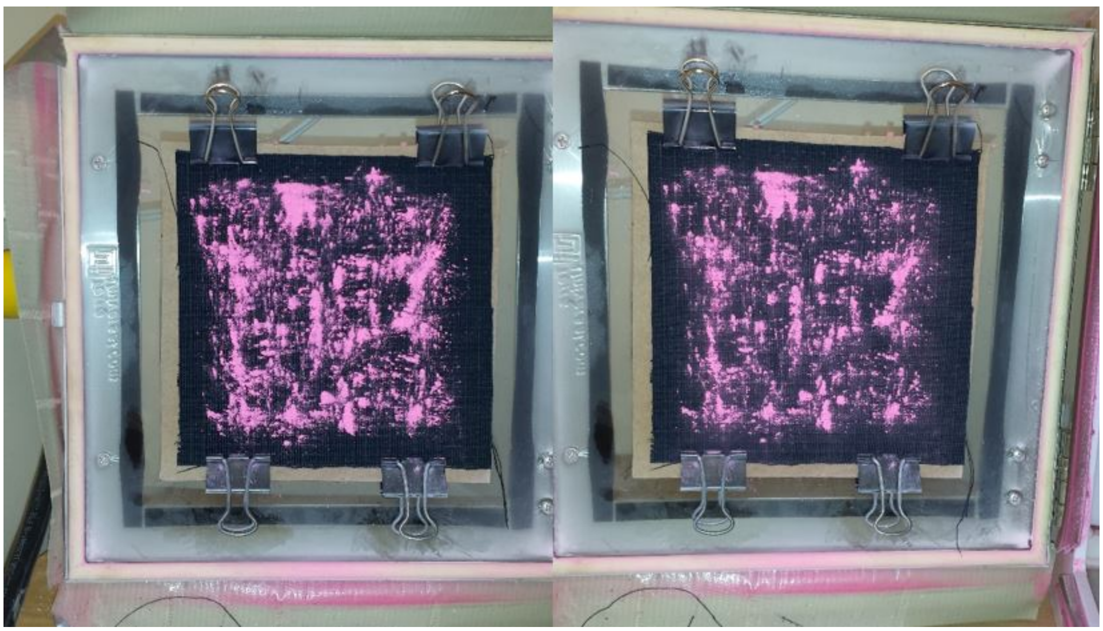

Figure 16. An example of the appearance of the test swatch before and after one of the least successful decontamination trials, using the cage dryer with wide nozzle.

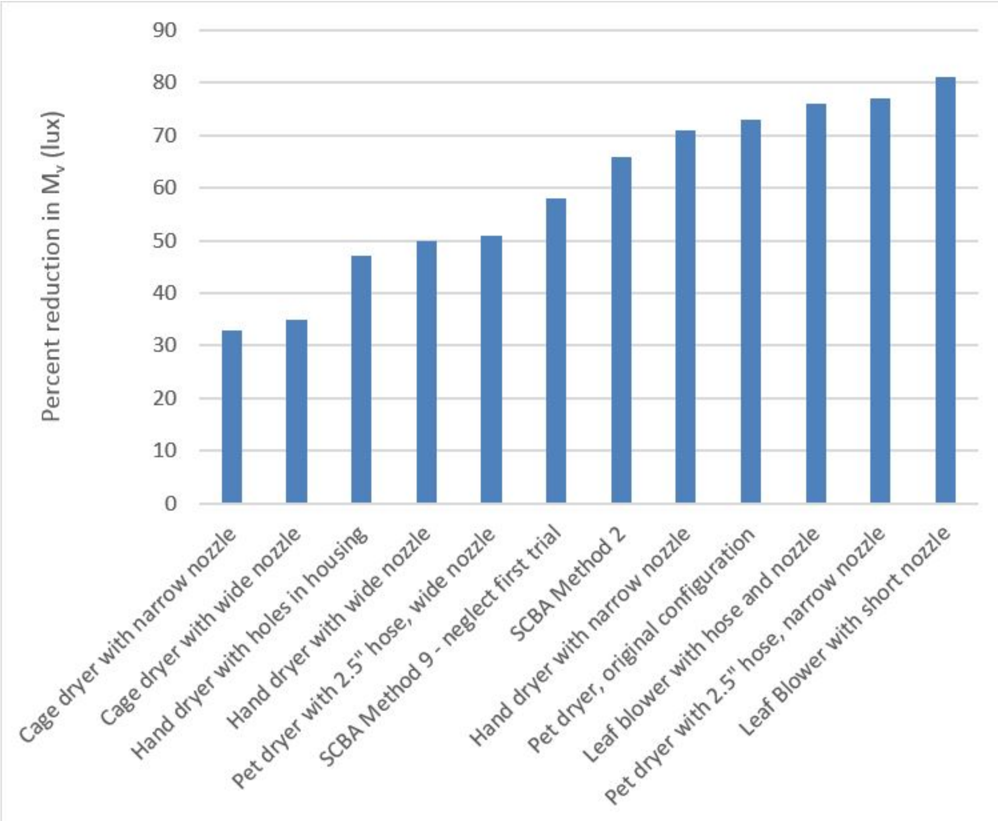

Figure 17. Percent reduction in fluorescence by decontamination methods tested, in order of increasing effectiveness.

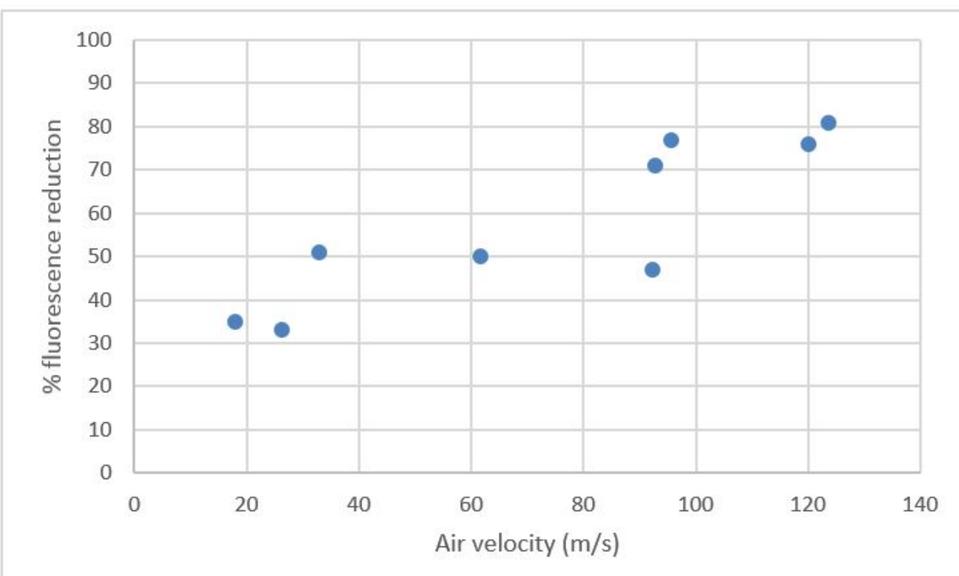

Figure 18. Percent fluorescence reduction of blower-based decontamination methods plotted vs. air velocity.

Figure 19. Firefighters and researchers at a training fire at the Illinois Fire Service Institute, June, 2015.

Figure 20. Decontamination trial using leaf blower with short nozzle at the Illinois Fire Service Institute.

Figure 21. Researcher wearing fire-worn turnout gear to be decontaminated with dry air jets.

Figure 22. Fire-worn turnout gear inside an enclosure during collection of air samples for offgassing analysis.

Tables

Table 1. Nozzle/air knife systems used with breathing air (SCBA) cylinders for decontamination.

Configuration	Nozzle System
1	Air TX Model 38006 manifold (AirTX International, Cincinnati, OH) with 3 Air TX 38050 nozzles
2	Air TX Model 38006 manifold with 3 Spraying Systems 727-SS-11 Windjet nozzles (Spraying Systems Co., Wheaton, IL)
3	Spraying Systems 3” Air Knife, #57070-#-AL
4	Air TX 3” Air Knife
5	Air TX 6” Air Knife
6	Air TX 6” Super Air Knife
7	Exair Super Air Amplifier (Exair Corp., Cincinnati, Ohio), 5/8” ID
8	Air TX Air Amplifier #15008, 1” ID, adjustable (used in closed position)
9	Air TX 4” Hurricane Wedge Jet #38154

Table 2. Decontamination results using SCBA cylinder and configuration 2.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	272	186	46%
2	263	134	73%
3	223	129	69%
4	262	125	78%
Average	255	143.5	66%

Table 3. Decontamination results using SCBA cylinder and configuration 9.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	383	281	34%
2	263	168	54%
3	212	130	65%
4	235	153	55%
Average			52%
Average		Neglecting 1st run	58%

* Performance outlier during first run, possibly due to inconsistent user technique.

Table 4. Decontamination results using leaf blower and short nozzle.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	269	119	82%
2	272	119	82%
3	285	124	81%
4	253	122	78%
Average			81%

Table 5. Decontamination results using leaf blower, hose and short nozzle.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	308	136	77%
2	266	123	79%
3	286	135	76%
4	282	143	71%
Average			76%

Table 6. Decontamination results using high-speed hand dryer blower with holes for air outlet.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	276	198	41%
2	307	199	49%
3	277	197	42%
4	315	188	55%
Avg			47%

Table 7. Decontamination results using high-speed hand dryer motor with wide-slot (11/16"/1.75 cm) nozzle.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	305	188	53%
2	254	176	46%
3	265	176	50%
4	304	197	49%
Average			50%

Table 8. Decontamination results using high-speed hand dryer motor with narrow-slot (1/4"/0.635 cm) nozzle.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	277	150	66%
2	233	125	73%
3	245	131	72%
4	289	145	71%
Average			71%

Table 9. Decontamination results using Metro pet dryer, original configuration.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	259	140	69%
2	265	129	76%
3	239	127	73%
4	263	134	73%
Average			73%

Table 10. Decontamination results using Metro pet dryer with 2-1/2" (6.4 cm) hose and wide-slot (1"/2.54 cm) nozzle.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	260	176	48%
2	266	167	55%
3	260	173	50%
4	285	183	51%
Average			51%

Table 11. Decontamination results using Metro pet dryer with 2-1/2" (6.4 cm) hose and narrow-slot (1/4"/0.635 cm) nozzle.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	306	147	72%
2	270	123	80%
3	322	141	77%
4	292	127	80%
Average			77%

Table 12. Decontamination results using Xpower cage dryer with 4-1/2" (11.4 cm) hose and 1” (2.54 cm) wide nozzle.

Trial #	M_v (Lux) before	Mv (Lux) after	% fluorescence reduction
1	315	237	34%
2	258	207	30%
3	294	220	36%
4	242	181	39%
Average			35%

Table 13. Decontamination results using the Xpower cage dryer with the 4-1/2" (11.4 cm) hose and 1/4" (0.635 cm) nozzle.

Trial #	M_v (Lux) before	M_v (Lux) after	% fluorescence reduction
1	220	179	31%
2	284	218	33%
3	260	202	33%
4	248	191	35%
Average			33%

Table 14. Properties of decontamination technologies.

Technology	Rated volumetric flow rate	Measured volumetric flow rate	Linear flow velocity	Static pressure
SCBA Cylinder (max)	NA	12 SCFM (0.34 m^3/min)	958 fps (292 m/s)	830 inches of water (30 psig or 206,800 Pa)
Leaf blower without hose	400 scfm (11.3 m^3/min)	66.5 SCFM (1.9 m^3/min)	406 fps (124 m/s)	28 inches of water (6970 Pa)
Leaf blower with hose	400 scfm (11.3 m^3/min)	64.5 SCFM (1.8 m^3/min)	394 fps (120 m/s)	28 inches of water (6970 Pa)
High-speed hand dryer - holes	NA	64.5 SCFM (1.8 m^3/min)	303 fps (92.4 m/s)	53 inches of water (13,200 Pa)
High-speed hand dryer – wide nozzle	NA	67.5 SCFM (1.9 m^3/min)	202 fps (61.6 m/s)	53 inches of water (13,200 Pa)
High-speed hand dryer – narrow nozzle	NA	69 SCFM (2.0 m^3/min)	304 fps (93 m/s)	53 inches of water (13,200 Pa)
Pet dryer – wide nozzle	130 scfm (3.7 m^3/min)	120 SCFM (3.4 m^3/min)	108 fps (33 m/s)	80 inches of water (19,900 Pa)
Pet dryer – narrow nozzle	130 scfm (3.7 m^3/min)	89.3 SCFM (2.5 m^3/min)	314 fps (96 m/s)	80 inches of water (19,900 Pa)
Cage dryer – wide nozzle on 1 hose	3000 scfm (with 3 hoses) (85 m^3/min)	55.5 SCFM (1.6 m^3/min)	59 fps (18 m/s)	2.3 inches of water (573 Pa)
Cage dryer – narrow nozzle on 1 hose	3000 scfm (with 3 hoses) (85 m^3/min)	28.5 SCFM (0.8 m^3/min)	86 fps (26 m/s)	2.3 inches of water (573 Pa)

Delivering on the Nation's promise: Safety and health at work for all people through research and prevention.

To receive NIOSH documents or other information about occupational safety and health topics, contact NIOSH at

1-800-CDC-INFO (1-800-232-4636)

TTY: 1-888-232-6348

E-mail: cdcinfo@cdc.gov

or visit the NIOSH Web site at www.cdc.gov/niosh

For a monthly update on news at NIOSH, subscribe to NIOSH eNews by visiting www.cdc.gov/niosh/eNews

SAFER • HEALTHIER • PEOPLE