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Hierarchy of contamination control in the fire service: Review of exposure control options to reduce cancer risk

Gavin P. Horn[a,b], Kenneth W. Fent[c], Steve Kerber[a], and Denise L. Smith[b,d]

[a]Fire Safety Research Institute, UL Research Institutes, Columbia, Maryland; [b]Illinois Fire Service Institute, Champaign, Illinois; [c]National Institute for Occupational Safety & Health, Cincinnati, Ohio; [d]Skidmore College, Saratoga Springs, New York

ABSTRACT

The international fire service community is actively engaged in a wide range of activities focused on development, testing, and implementation of effective approaches to reduce exposure to contaminants and the related cancer risk. However, these activities are often viewed independent of each other and in the absence of the larger overall effort of occupational health risk mitigation. This narrative review synthesizes the current research on fire service contamination control in the context of the National Institute for Occupational Safety and Health (NIOSH) Hierarchy of Controls, a framework that supports decision making around implementing feasible and effective control solutions in occupational settings. Using this approach, we identify evidence-based measures that have been investigated and that can be implemented to protect firefighters during an emergency response, in the fire apparatus and at the fire station, and identify several knowledge gaps that remain. While a great deal of research and development has been focused on improving personal protective equipment for the various risks faced by the fire service, these measures are considered less effective. Administrative and engineering controls that can be used during and after the firefight have also received increased research interest in recent years. However, less research and development have been focused on higher level control measures such as engineering, substitution, and elimination, which may be the most effective, but are challenging to implement. A comprehensive approach that considers each level of control and how it can be implemented, and that is mindful of the need to balance contamination risk reduction against the fire service mission to save lives and protect property, is likely to be the most effective.

KEYWORDS

Cancer; contamination control; firefighter; firefighting; hierarchy of controls; occupational exposure; PPE

Introduction

Firefighting poses acute occupational hazards and is associated with long-term health risks including cancer. A number of epidemiology studies have been conducted to determine the risk of cancer in the fire service, and several meta-analyses have been conducted on these studies (Table 1; LeMasters et al. 2006; Jalilian et al. 2019; Soteriades et al. 2019; Casjens et al. 2020; Laroche and L'Esperance 2021). National Institute for Occupational Safety and Health (NIOSH) conducted one of the largest cohort mortality studies on firefighters in the United States and found statistically significant increases in mortality and incidence rate estimates for firefighters compared with the general population (Daniels et al. 2014; Pinkerton et al. 2020). Researchers also found evidence of exposure-response relationships for lung cancer and leukemia among firefighters (Daniels et al. 2015; Glass et al. 2016).

One of the most studied aspects of firefighters' occupational risk of cancer is potential exposure to fireground contaminants (products of combustion and other contaminants released from burning fuels) (Table 2). Firefighters may be exposed to numerous compounds produced by burning materials on the fireground, including polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), aldehydes, particulate matter, and other products of incomplete combustion. Several studies have been conducted to assess firefighters' exposure to products of combustion (Jankovic et al. 1991; Feunekes et al. 1997; Bolstad-Johnson et al. 2000; Austin et al. 2001; Fent et al. 2014, 2018, 2019a; Keir et al. 2017, 2020;

CONTACT Gavin P. Horn gavin.horn@ul.org Fire Safety Research Institute, UL Research Institutes, 6200 Old Dobbin Lane, Suite 150, Columbia, MD 21045.

Table 1. Overview of recent meta-analysis of epidemiology studies that have been conducted to assess the risk of cancer in the fire service.

Author, year	# studies	Associated cancers
LeMasters et al. 2006	26	Testes, prostate, non-Hodgkin's lymphoma, multiple myeloma
IARC, 2010b	44	Testes, prostate, non-Hodgkin's lymphoma
Soteriades et al. 2019	49	Testes, prostate, non-Hodgkin's lymphoma, bladder, colorectal, melanoma, central nervous system
Jalilian et al. 2019	48	Testes, prostate, non-Hodgkin's lymphoma, bladder, colorectal, melanoma, thyroid, mesothelioma
Casjens et al. 2020	25	Testes, prostate, bladder, colorectal, pancreas, melanoma, mesothelioma
Laroche and L'Esperance 2021	104 (from 11 systematic reviews)	Testes, prostate, non-Hodgkin's lymphoma, bladder, colorectal, melanoma, mesothelioma

Table 2. Types of contaminants commonly studied in the fire service and associated cancer risk.

Contaminant	Description/definition	Cancer risk[a]
Products of combustion		
PAHs	Polycyclic aromatic hydrocarbons (PAHs), containing two or more benzene rings. PAHs with four or more rings have low volatility, while shorter chain PAHs are semi-volatile. Naphthalene (two rings) is the most volatile.	IARC known and probable carcinogens include benzo[a]pyrene, cyclopenta[cd]pyrene, dibenz[a,h] anthracene, and dibenzo[a,l] pyrene
VOCs	Volatile organic compounds (VOCs), typically containing hydrocarbon chains or a single benzene ring with branching organic or inorganic elements. As the name suggest, they are volatile and typically present as gas or vapor. Examples include benzene, toluene, and styrene.	IARC known and probable carcinogens include benzene, formaldehyde, 1,3-butadiene, styrene, and acrolein.
PM	Particulate matter (PM) that may be composed of organic or inorganic elements. Combustion particulate is typically in the fine (<2.5 um) or ultrafine (<0.1 um) size range. Combustion PM will have high surface area and is likely to contain other adsorbed chemicals.	Although PM is not classified as a carcinogen, a variety of carcinogens may be adsorbed to PM.
Released from materials during combustion		
FRs	Chemical flame retardants (FRs), including polybrominated diphenyl ethers (PBDEs), other brominated FRs, organophosphate FRs, and chlorinated FRs. Examples include deca-BDE (BDE-209) and chlorinated tris (TDCPP).	According to the National Toxicology Program (NTP), certain types of PBDEs have been shown in animal studies to cause liver and thyroid tumors (deca-BDE). Chlorinated tris is labeled as a carcinogen in California.
PFAS	Per- and polyfluoroalkyl substances (PFAS) are a class of synthetic chemicals that have been used in various consumer products for their stain and water repellant properties, including carpeting, furniture, and fabric. PFAS have also been used in Aqueous Film-Forming Foams (AFFF). Examples of long-chain PFAS include perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA).	IARC classifies PFOS and PFOA as probable carcinogens.
Other occupational exposures		
Diesel exhaust	Diesel exhaust is composed of PM, PAHs, and oxides of carbon, nitrogen, and sulfur. It is usually characterized by measuring airborne elemental carbon. Exposure is possible at the fire station or fire incident where diesel apparatus or other vehicles or equipment are operated.	IARC classifies diesel exhaust as a known human carcinogen.

[a]Associated cancer risk according to the International Association for Research on Cancer (IARC 2010a, 2012a, 2012b, 2019, 2021), the National Toxicology Program (National Toxicology Program (NTP) 1986), and California Office of Environmental Health Hazard Assessment (OEHHA 2016).

Stec et al. 2018; Wingfors et al. 2018; Sjostrom et al. 2019; Oliveira et al. 2020; Poutasse et al. 2020). Elevated biological levels of PAHs and benzene have been consistently found in firefighters after firefighting activities (Caux et al. 2002; Laitinen et al. 2010; Fent et al. 2019b, 2020b). These studies show that structural fires may expose firefighters to known (group 1—e.g., benzene, formaldehyde, 1,3-butadiene), probable (group 2A—e.g., acrolein, styrene) or possible (group 2B—e.g., naphthalene) carcinogens according to the International Agency for Research on Cancer (IARC 2010a, 2012a, 2012b, 2019, 2021). In 2022, IARC evaluated the occupation of firefighting and classified it as "carcinogenic to humans" (Demers et al. 2022).

In addition to products of combustion, firefighters may be exposed to flame retardants (FRs) and per- and polyfluoroalkyl substances (PFAS) that are released during combustion events. FRs are added to many household items such as furniture, carpet padding, electronics, and other consumer products to reduce fire risk, but FRs may also be released when these substances burn, which is a concern due to their known detrimental health effects (Linares et al. 2015; Hoffman et al. 2017; Vuong et al. 2020). Similarly, human health risks have been identified from exposure to PFAS (Agency for Toxic Substances and Disease Registry (ATSDR) 2018, 2020; Sunderland et al. 2019; Interstate Technology Regulatory Council 2021), which are present in items such as stain resistant upholstery and carpeting. Firefighters may also be exposed to PFAS contamination when using aqueous film-forming foam (AFFF) and concern has been raised about the use of firefighting personal protective

Table 3. Control options for the fire service based on the hierarchy of controls approach.

Potential effectiveness	Types of controls	Options that are being researched
Least	PPE	
↓	Inhalation	Consistent use of respiratory protection during all phases of a response
	Dermal	Tightening the interfaces of turnout gear, use of particulate-blocking hoods
	Administrative controls	Use of specific fire attack tactics, crew rotation, PPE donning and doffing practices, PPE decontamination, PPE retirement/removal from service, skin cleaning, fire apparatus cleaning, fire station cleaning
	Engineering controls	Fire station design, diesel exhaust capture, training prop design
	Substitution	Training fuel selection, use of simulated smoke and flame, replacing hazardous chemicals in products with less hazardous chemicals (e.g., fluorine-free foams), replacing diesel apparatus with electric or hybrid-electric apparatus
Most	Elimination	Public education programs (increased installation of smoke alarms and sprinklers), fuel reduction efforts to prevent exterior fires transitioning to structure fires

equipment (PPE) that is manufactured from textiles containing PFAS (Peaslee et al. 2020).

Finally, there are important sources of occupational chemical exposure that firefighters may encounter that do not come from fires. Emissions from diesel exhaust can contribute to exposures on the fireground or at other emergency incidents where firefighters are operating near a diesel engine. Exposure to diesel exhaust is also possible at fire stations (Pronk et al. 2009). Despite all the research characterizing firefighters' chemical exposures, actual exposures and risk may be underestimated due to incomplete characterization of all the airborne compounds and the potential synergistic effects of those exposures.

While there are many potential sources and a wide range of compounds that firefighters may be exposed to, there are three primary routes of entry: inhalation, ingestion, and dermal absorption. Airborne contaminants that enter the lungs are readily absorbed through the pulmonary capillaries directly into the blood stream. Contaminants may also end up on a firefighters' skin and be available for dermal absorption. Several important products of combustion, including PAHs, benzene, and styrene can be absorbed through the skin (Franz 1984; VanRooij et al. 1993; Thrall et al. 2000; Fent et al. 2022). Finally, ingestion can occur when inhaled contaminants are captured by the mucociliary escalator in the upper respiratory system or are transferred from contaminated hands onto food and are then swallowed.

In the United States, NIOSH leads the national Prevention through Design initiative (American National Standards Institute (ANSI) 2021) incorporating a strategy called the Hierarchy of Controls. This framework supports decision making by considering five broad levels where strategies can be implemented for protecting workers from occupational hazards (National Institute for Occupational Safety and Health (NIOSH) 2015). This framework can also provide a rational paradigm to integrate current research and understanding into sound guidance on exposure control options for the fire service (Table 3). Each level of the hierarchy will be examined in detail beginning with PPE, which the fire service has the most local control over, and ending with elimination, which may require higher level action, collaboration, and policy to implement.

PPE—protect the worker with PPE

In the fire service, PPE is essential to protect the wearer from known and unknown hazards arising from the variability and often unpredictable conditions at the emergency scene. PPE is used to protect the firefighter against multiple hazards, including environmental heat, water, and physical abrasion. Given the risks associated with exposures, increasing attention is being paid to the ability of PPE to protect against particulate, vapor, and gases in smoke. However, firefighting PPE also imposes a physiological burden to the wearer, increasing metabolic heat

Table 4. Summary of PPE control options and considerations.

PPE control options	Important considerations or need for additional research
Turnout gear manufactured with tighter interfaces around the neck, wrists, waist, and boots	May impact thermal strain and ability to quickly don and doff protective equipment.
Station gear made of long-sleeves and pants *vs.* short-sleeves and/ or shorts	May impact thermal strain, comfort, and mobility; although, encapsulating gear is expected to be the dominant factor for heat stress.
Turnout gear that incorporates a zipper vs. hook & dee closure	Zippers may not be as durable as hook & dee closures, but they are actually more common in the marketplace today.
Particulate-blocking hoods	Like all hoods, must seal properly around respiratory facepiece to provide most protection. Particulate barrier could make hearing difficult.
Wearing SCBA during all phases of the fire response, including in the fireground, especially in smoky conditions.	Need adequate resources to provide SCBA and air-packs for all impacted personnel. Wearing SCBA is heavy and contributes to physical strain. The SCBA facepiece can impact incident command's ability to communicate.

production, trapping heat and moisture next to the skin, as well as impairing mobility, speech intelligibility and field of vision. While firefighters can mitigate their contamination exposure risk through proper use of PPE (Jahnke et al. 2016), gaps in protection against chemical contamination remain. Table 4 summarizes several PPE control options along with important consideration and areas where additional research may be needed.

Dermal protection

Dermal protection in the modern structural firefighting protective ensemble is typically provided by jacket and pants (referred to as 'turnout gear' in this manuscript), interface elements (for example, the "hood" worn between the jacket and SCBA facepiece) gloves, boots, and helmet. Structural firefighters typically wear turnout gear that includes three layers: outer shell, moisture barrier, and thermal liner.

Turnout gear

Only a few studies have examined the penetration of fireground contaminants to the interior of the turnout gear. To date, much of the research on contaminants penetrating firefighter turnout gear has focused on the solid phase products of combustion, namely, higher molecular weight PAHs (Baxter et al. 2014; Fernando et al. 2016; Fent et al. 2017; Keir et al. 2017; Wingfors et al. 2018; Mayer et al. 2020). Kirk and Logan (2015) measured air concentrations of total PAHs that were on average 12 times lower under turnout gear than outside gear. In contrast, Wingfors et al. (2018) found that total PAHs were 146 times lower under firefighters' base layer and turnout gear. This higher protection factor (than what was reported by Kirk and Logan) was attributed in part to additional protection provided by the base layer. However, compared to particles, gases, and vapors such as benzene can more readily penetrate the small gaps in protective ensemble interfaces (Mayer et al. 2020, 2022). The relative importance of protecting against gases, vapors, and/or solid-phase substances remains an important area of research.

Studies have identified vulnerabilities that can lead to dermal contamination in the neck region (Fent et al. 2014; Hill and Hanley 2015; Maness and Ormond 2017) and around the gloves (Fent et al. 2017; Stec et al. 2018). However, one study found similar levels of PAHs on five different body sites, including fingers, back, forehead, neck, and wrist (Fernando et al. 2016). These different findings among studies may be explained, at least in part, by differences in study design as well as possible cross contamination during PPE doffing. However, the disparate findings indicate the clear need for additional research.

Firefighter PPE will continue to evolve, and studies are underway to understand opportunities to improve turnout gear that resist ingress of contaminants. Park et al. (2014) identified that the integrity of interface protection between PPE elements was an important consideration for firefighter comfort, mobility, and thermal protection. Ormond et al. (2019) demonstrated improved particle protection in turnout gear with modified jacket-to-pant, jacket-to-glove, and pant-to-boot interfaces using a fluorescent aerosol screening test (FAST). Mayer et al. (2020) found that the jacket-closure mechanism can also impact protection, with median PAH concentrations under hook & dee style closures that were 1.5-fold higher than zippered closures. Turnout gear works best when sized and worn properly. To provide the fullest protection against fireground contamination, firefighters should don all PPE carefully and properly close interfaces including at the collar, gloves, sleeves, and waistline.

As new designs and concepts are introduced to improve PPE's ability to further control contamination exposures in the fire service, studies must be conducted to understand the holistic impacts of PPE design changes on other performance characteristics to avoid unintended consequences. For example, Bogerd et al. (2018) have shown that increased protection against gases and vapors may also increase thermal strain. Physical reinforcements to PPE may also impact heat stress, thermal comfort, task performance, range of motion, and gait characteristics (Coca et al. 2010; Park et al. 2011; Ciesielska-Wrobel et al. 2017, 2018; McQuerry et al. 2018).

Hoods

To improve dermal protection in the neck area, PPE manufacturers have developed new fire hoods aimed specifically at blocking particle penetration (particulate-blocking hoods). Using FAST, Ormond et al. (2019) found qualitative reductions in exposure in the head and neck region when particulate blocking hoods were worn compared to the traditional two-ply knit hood. Mayer et al. (2020) reported that particulate-blocking hoods reduced PAHs reaching a stationary mannequins' necks by more than 30% compared to knit hoods.

Kesler et al. (2021) measured lower PAH levels from neck skin when firefighters were wearing a particulate-blocking hood compared to a knit hood. However, contamination reaching the skin was not eliminated even though no detectable levels of PAHs were found on the inner layer of particulate-blocking hoods. This finding suggests that there may be other avenues for contamination to reach the neck skin, such as penetration through interfaces and cross contamination from doffing procedures. Firefighters tended to have more negative perceptions of particulate-blocking hood wearability compared to the knit hood, particularly related to noise level and hearing difficulties. Thus, it is important to balance protection against fireground contamination with practical requirements of PPE usage.

Respiratory protection

The concentration of contaminants available for inhalation depends on both the job assignment and whether a positive pressure self-contained breathing apparatus (SCBA, which has an assigned protection factor of 10,000) is consistently used for the assignment. Firefighters assigned to attack or search and rescue job assignments are likely to work in an area of the highest airborne concentration, followed by firefighters assigned to overhaul and outside ventilation, incident commanders, fire apparatus operators, and other exterior support members (Fent et al. 2018). However, because of the trends in usage of SCBA (i.e., prioritized for attack, search and rescue functions), the actual exposure risk may be higher for those who operate farther from the fire, because they often do not wear respiratory protection during all work activities despite being exposed to smoke on the fireground.

Burgess et al. (2020) implemented an intervention with fire apparatus operators (referred to as engineers in their study) including having engineers don an SCBA as soon as practicable when exposed to smoke. The fireground interventions significantly reduced the engineers' mean total post-fire urinary PAH metabolites (PAH-OHs) by more than 40%. In a separate study, Andersen et al. (2018) determined that SCBA usage was effective at preventing inhalation exposure to particulate matter (PM); however, exposures still occurred if firefighters removed SCBA when they thought conditions no longer necessitated its use.

Firefighters may choose to doff their SCBA during overhaul once the apparent risk from visible smoke is not present. Using a mouse model, Gainey et al. (2018) assessed the risk to the lungs by measuring gene expression in mice exposed to the overhaul environment without airway protection. The researchers found that exposure to the overhaul environment without respiratory protection was associated with transcriptional changes impacting proteins potentially related to inflammation-associated lung disease and cancer even though gases that are commonly monitored during overhaul using handheld meters (e.g., carbon monoxide, oxygen) were well below NIOSH ceiling limits. Because SCBA is heavy and its use increases thermal strain, there is interest in finding alternatives during physically demanding overhaul operations. Chemical, Biological, Radiological, and Nuclear (CBRN) and multi-gas canisters have been evaluated for use in post live-fire overhaul environments (Anthony et al. 2007; Currie et al. 2009; Jones et al. 2015). While CBRN canisters provide protection from many of the contaminants that were sampled, some contaminants (e.g., formaldehyde, carbon monoxide) were found to break through in each study.

Post-fire investigators often work during or shortly after overhaul activities and respiratory protection use is inconsistent. While limited research has been conducted with this segment of the fire service population, Kinnes and Hine (1998) noted that several fire investigators who did not wear full-face respiratory protection experienced both eye and respiratory irritation during investigations. Horn et al. (2022) measured elevated particulate levels up to 5 days after fire suppression during fire investigation activities, and also found formaldehyde concentrations that exceeded recommended exposure limits in several phases of the investigation. These data highlight the need to protect

Table 5. Summary of administrative control options and considerations.

Administrative control options	Important considerations or need for additional research
Utilizing exterior attack or transitional attack *vs.* interior attack at structure fires	Choice of attack will depend on a variety of factors, including life-safety and preservation of property.
Rotating crews of firefighters through positions to lessen their exposure and physiological burden	Need enough personnel available to rotate through positions. Rotating crews may also provide staggered times for managing decontamination efforts.
Rotating trainers through live-fire exercises to lessen their exposure time	Need enough qualified trainers available to rotate through live-fire training exercises.
Careful doffing of turnout gear, especially hoods and gloves, to minimize the transfer of contaminants to the skin	Doffing procedures are ingrained in the firefighting workforce. Changing doffing procedures will require training and reinforcement from leadership.
Cleaning skin immediately after firefighting	Effectiveness is likely to vary depending on how and when skin is cleaned. Several options available for cleaning skin at the fireground, including various types of skin wipes and traditional soap and water. Infrared saunas have been proposed as a way of excreting contaminants from skin, but more research is needed, including studies that examine heat stress and dehydration.
Gross decontamination of PPE	Studies indicate that using detergent along with water and scrubbing will increase the efficacy of decontamination. Setting up a decon line requires adequate resources, training, and personnel, although the materials can be as simple as a garden hose, bucket, dish soap, and scrub brush. Firefighters should ideally breathe through their SCBA while going through decon. All PPE (helmets, boots, SCBA packs, radios, and tools) should also be decontaminated.
Laundering of turnout gear (jacket, pants) and hoods after firefighting	Laundering will remove many contaminants, but the efficacy for specific types of contamination continues to be studied. Cross-contamination during the laundry cycle is possible. Research is needed to determine the optimal parameters and conditions to more fully clean turnout gear.
Routine cleaning of the fire apparatus interior	Several contaminants have been found inside the cabins of fire apparatus. Routine cleaning of apparatus interior surfaces and upholstery will reduce surface contamination.
Routine cleaning of the fire station	Several studies have documented higher levels of certain types of contaminants (including PBDEs, OPFRs, and metals) in dust collected from fire stations. Routine cleaning of surfaces should lower firefighters' potential exposure to those contaminants.

fire investigators' airways from airborne contaminants any time investigations are conducted.

Administrative controls—change the way people work

While the use of PPE alone is a powerful tool for contamination control, changing the way firefighters work while wearing the PPE and how they handle and care for PPE after the emergency response may be equally important for contamination control. Table 5 provides a review of administrative control options that may be available to the fire service.

Fire attack tactics

Changing the way firefighters apply water to residential structure fires has shown promise as a control measure to reduce contamination exposure. Fent et al. (2018, 2020b) studied two distinct approaches to fire suppression: (1) interior attack (firefighters immediately enter the structure to suppress fire from inside the building) and (2) transitional attack (firefighters initially apply water to the fire through a window before entering the building to completely extinguish the fire). Firefighters who performed transitional attack had lower post-fire urinary concentrations of hydroxyfluorenes, hydroxyphenanthrenes, and 1-hydroxypyrene, compared to firefighters using the interior attack tactic (Fent et al. 2020b). These findings indicate that transitional attack could be used as an administrative control to reduce firefighters' exposures to PAHs, when such an attack is appropriate based on fireground needs. Of course, fire attack tactics must consider a broad range of factors, particularly life safety of occupants and firefighters (Kerber et al. 2019). Providing members with training on how and when to use different tactics based on a wide range of factors can allow firefighters to best adapt to conditions present on the fireground (NFPA 1700 2021a).

Crew rotation

Assembling enough firefighters to address the fire/emergency/training situation is critical to a successful outcome and to allowing crew rotation to reduce exposures to individual firefighters (Moore-Merrell et al. 2021). As described earlier, firefighters should wear SCBA to protect their airway throughout the firefight but enforcing SCBA usage during overhaul can result in increased heat strain (Horn et al. 2018). With enough staffing, a fresh crew can be utilized for overhaul and SCBA usage can be feasibly enforced without further increasing the risk for heat-related injuries to the initial attack crews. This approach will also reduce the time required to implement decontamination and hygiene practices for the initial crews.

Additionally, increased personnel available during live-fire training may be able to reduce peak exposures to instructors. Fent et al. (2019b) compared instructors' change in urinary concentrations of PAH metabolites after three training exercises to firefighters' changes after one exercise and found statistically significant greater increases for the instructors for some PAH-OHs. These findings provide evidence for instructors' cumulative exposures to PAHs from overseeing multiple training exercises in a day.

PPE doffing practices

Although PPE provides significant protection against dermal exposure, improper PPE doffing practices can result in secondary exposures to fireground contaminants. For example, the traditional methods firefighters use to doff hoods and gloves, can lead to cross contamination from the outside of the PPE to bare skin (Illinois Fire Service Institute (Producer) 2017, 2018). While there has been limited study of firefighting PPE doffing practices, important lessons can be learned from health care (e.g., Reidy et al. 2017; Phan et al. 2019), hazmat (e.g., Oudejans et al. 2016), and EMS operations (e.g., Northington et al. 2007). Kesler et al. (2021) assessed the impact of a hazmat style hood doffing technique in addition to the importance of hood design and repeated laundering. By employing a controlled overhead doffing method, firefighters had significantly lower neck skin PAH levels compared to those using a traditional doffing method. Overall, modifying the process of removing the hood resulted in a larger reduction in contamination than the hood design modification.

Post fire skin cleaning

Despite the use of PPE, firefighter's skin can be exposed to elements of fireground contamination. The longer a contaminant is present on skin, the more time it has available for dermal absorption and biological uptake (Baxter et al. 2014; Fent et al. 2014, 2020b; Keir et al. 2017). Importantly, Fent et al. (2017) found that cleansing wipes were able to reduce PAH contamination on neck skin by a median of 54%. Considering that ~50% of the contamination may remain on the skin, showering, hand washing, and other means of more thorough cleaning of the skin should be conducted as soon as feasible. To date, no studies have examined how the timeliness of showering impacts the biological uptake of fireground contamination. Because firefighters have competing responsibilities, especially after a fire, it is not uncommon for showering to occur hours later.

In recent years, the fire service has been debating the use of saunas to remove contaminants from the body via sweat following firefighting. Burgess et al. (2020) evaluated the use of infrared saunas following live fire training and found a reduction in total mean hydroxylated PAH concentrations in the urine by 43.5%, but this difference was not statistically significant. Additional studies that characterize the use of saunas to reduce the body burden of chemicals should consider tradeoffs between benefits achieved and potential risk for heat strain and dehydration.

PPE cleaning practices

PPE cleaning practices (NFPA 1851 2020) can be considered in terms of on-scene preliminary exposure reduction (PER) techniques, commonly referred to as *on-scene decontamination* or gross decon, and more thorough, advanced cleaning that may occur during machine washing at the fire station or by sending PPE to an outside vendor, which will be referred to as *laundering* in this review.

On-scene decontamination

Research has suggested that taking measures to remove contamination on-scene could limit firefighter exposure due to PPE cross-contamination. Fent et al. (2017) conducted wipe sampling of the exterior of contaminated turnout gear immediately post-fire and from a subset of the gear after on-scene decontamination. On-scene decontamination using dish soap, water, and scrubbing was found to reduce PAH contamination on turnout jacket outer shells by a median of 85%, compared to a reduction of 23% for dry brush decon. Fent et al. (2020a) also found that on-scene decontamination reduced many polybrominated diphenyl ether (PBDE) contaminants but results for organophosphate flame retardants (OPFRs) were mixed. Calvillo et al. (2019) found that water only decontamination had limited effectiveness in reducing PAHs. It is likely that the surfactant in dish soap, designed to liberate lipid-soluble compounds from surfaces, is important for removing PAHs.

Burgess et al. (2020) studied a number of fireground interventions to reduce exposures for entry teams including post-fire on-scene decontamination and skin cleaning. By measuring urinary PAH-OHs before and after implementation of these interventions, these administrative controls were found to be associated with a 36% reduction in urinary PAH-OHs. Engelsman et al. (2019, 2020) suggested that exposure to semi-volatile organic compounds in Australian fire stations may be mitigated through increased decontamination on the fireground and increased laundering frequency.

It is important to acknowledge that implementation of on-scene decontamination has occasionally been met with challenges and resistance in the field (Harrison et al. 2018a). Hopefully these challenges can be overcome through targeted messaging/education (Harrison et al. 2018b) and/or future improvements in tools, processes, and training

Laundering

Laundering of firefighting PPE is an important measure to further reduce contamination. Keir et al. (2020) found that laundering removed 61–98% of surface contamination from firefighters' PPE. Mayer et al. (2019) observed that laundering reduced up to 81% of PAH contamination, up to 98% for certain OPFRs, and up to 44% of brominated FRs (not including PBDEs) in firefighting hoods used in simulated structure fire responses, but these findings were not consistent across all compounds. Surprisingly, in this study, median PBDE contamination levels increased in hood samples collected after laundering. This finding was attributed to cross contamination from other highly contaminated hoods during the laundering (Mayer et al. 2019). Banks, Wang, et al. (2021) found little difference in PAH, PBDE, and OPFR contamination before and after laundering. Researchers supporting the fire service are actively engaged in studying and validating cleaning procedures for firefighter PPE including studying laundry settings (e.g., water temperature, detergents, and so on) and alternative cleaning methods (e.g., oxidizing agents (Stull 2018, 2019).

Tradeoffs

While improvement in PPE cleaning methods continue to be studied, it is important to understand the relative tradeoffs between removing contaminants after the firefight and potential compromise to the protective properties of the gear that may put firefighters at risk during their next firefight. Horn et al. (2021) employed a protocol that included repeated simulated fireground exposures and/or repeated laundering and wet or dry decontamination techniques. They concluded that some important protective properties of turnout gear such as tear strength, total heat loss, and thermal protective performance can be impacted after repeated exposure/cleaning cycles relative to their levels when tested in a new condition. On the other hand, laundering and/or on scene decontamination for up to 40 exposure/cleaning cycles did not appear to negatively impact the fireground particulate protection capability of turnout gear (Mayer et al. 2020).

Fire apparatus cleaning

Vehicles that are present on the fireground may be exposed to contaminants in the air and/or from contaminated PPE, tools, hoses, and implements utilized on the fireground. Engelsman et al. (2019) found metals present on wipe samples collected from several items within vehicle cabins. Keir et al. (2020) measured airborne concentrations of PAHs and antimony in fire truck cabs and found elevated levels compared to air samples collected from the vehicle bay. The authors suggest elevated air concentrations in the truck cab may be reduced through protocols to minimize cross-contamination and more frequent cleaning of these areas. Similar concerns may also apply to command or personal vehicles that may be responding to a fire scene from home and may ultimately track contaminants back to their residence.

Fire station cleaning

Contamination from the fireground can deposit on firefighting tools, PPE, and apparatus, and may then be transferred to surfaces in the fire station. Fire station dust has been identified as a potential source for inhalation and even ingestion exposure, particularly if hands are not washed prior to eating. Oliveira et al. (2017) found that Portuguese firefighters were exposed to PAH contamination in the fire station at levels that could increase their risk of adverse health outcomes. Dust samples collected from vacuum cleaner bags used in select California fire stations were analyzed for PAHs, PBDEs, polychlorinated biphenyls, and phosphorous-containing flame retardants (Shen et al. 2015, 2018). The authors reported that BDE-209 concentrations were among the highest of any previously documented residential or occupational settings in the world. They hypothesized that this may be attributed

Table 6. Summary of engineering control options and considerations.

Engineering control options	Important considerations or need for additional research
Isolating contaminated PPE from personnel and passenger cabins	VOCs are expected to volatilize quickly in open air, but semi-volatiles will off-gas slower. Transporting contaminated PPE in enclosed containers or unoccupied compartments in vehicles will help reduce air concentrations of off-gassing contaminants and the transfer of particulate to other surfaces.
Fire station design (e.g., delineation of clean and dirty areas, maintaining positive pressure in living quarters relative to the engine bay, and other designs for contamination control).	Some design elements may be implemented without incurring substantial costs, but others may require significant investments. How these design elements relate to biological exposure is largely unknown.
Diesel exhaust capture systems	Installation of local exhaust ventilation systems in engine bays will help control diesel exhaust emissions, however, it is critical that these systems are maintained and function properly. It is also important that the vehicles are maintained so that they run optimally.
Vehicle-mounted diesel exhaust filtration systems	These systems are designed to provide filtration of diesel particulate before being emitted from the tailpipe into the environment and would likely reduce exposures for personnel at an incident.
Training prop design at fire academies	Instructors and firefighters can be exposed during live-fire training. Training props may be designed to reduce exposure. For example, some training structures include exhaust ventilation systems to quickly remove smoke.

to contamination tracked back to the fire station from the fireground. Similarly, an Australia study quantified PAHs, PBDEs, and OPFRs in fire station dust and air samples and hypothesized that they were brought back from the fireground (Banks et al. 2020). Additionally, PFAS and total fluorine have been characterized in dust from Massachusetts fire stations and higher levels of total fluorine and three PFAS were reported in PPE locker rooms compared to station living rooms (Young et al. 2021). The authors propose that firefighters' turnout gear may be an important source of PFAS due to contamination from firefighting activities and/or compounds added to the gear during its manufacture. Regardless of the source, more regular cleaning of fire stations and more cleanable surfaces (including floor coverings), particularly in turnout gear locker rooms and apparatus bays may be effective in reducing contamination available to expose the firefighter.

Engineering controls—isolate people from the hazard

Table 6 provides a summary of select fire service engineering control options.

Isolating contaminated PPE from vehicle passenger cabins

Once firefighting PPE and tools become contaminated, they present a secondary contamination risk for unprotected firefighters. During fireground use, PPE may pick up or absorb contaminants, some of which may be volatile or semi-volatile. Contaminated PPE may then begin to release these compounds back to the air in vapor form through "off-gassing." Fent et al. (2017) reported off-gassing of VOCs and hydrogen cyanide that increased after firefighting but returned to near baseline concentrations after 17–36 min. Banks, Wang, et al. (2021) found measurable concentrations of PAHs, OPFRs, and PBDEs off-gassing from the outer shell of laundered firefighting PPE in a private vehicle on a summer day and recommended storage techniques that encapsulate the PPE. Hwang et al. (2019) collected wipe samples from various surfaces in vehicles that responded to the fireground and found that PAH levels in the vehicles were significantly reduced by use of containers to transport PPE. To reduce exposure to off-gassing contaminants, firefighting PPE could be left outdoors to off-gas for as long as practicable and then enclosed in an air-tight container or transported in an unoccupied compartment of the vehicle.

Fire station design

Due to the amount of time firefighters work, eat, sleep and live in their fire stations, contamination control in this building may provide important benefits. Fire station design can allow isolation of firefighters' living quarters from hazards that may be present in the more heavily contaminated apparatus and gear storage areas. Sparer et al. (2017) found levels of contamination (e.g., PM, PAH) in the truck bays were higher than the kitchen. Of note, the station with the highest contamination in the truck bay had the lowest levels in the kitchen, which was partially attributed to effective separation between building zones. Banks et al. (2020) identified correlations between concentrations of a number of PAHs, OPFRs, and PBDEs and firefighting PPE storage locations, indicating that the proximity of contaminated PPE determines the extent to which it contribute to contamination in fire stations. Chung et al. (2020) reported that exposure risks in the vehicle bays can be higher in stations with a back-in vehicle bay design compared to drive-through. Anecdotal evidence has also suggested that isolating ice machines from diesel exhaust in apparatus bays may also reduce firefighters' exposure risk.

Rogula-Kozłowska et al. (2020) sampled gaseous and particulate-bound PAHs in the common room, changing room, truck bay, and outside of two Polish fire stations. PM concentrations were highest in the truck bay, while the highest mean PAH concentrations were in the changing rooms at both fire stations. The estimated incremental lifetime cancer risk related to PAH exposure exceeded the acceptable risk level for firefighters and office employees at each station. Recommendations include not placing dispatch centers, office rooms, common rooms, or bedrooms near truck bays or changing rooms, shortening the time fire station employees spend in these rooms, installing ventilation systems and systematically cleaning.

Diesel exhaust control

While in the fire station, firefighters may also be exposed to diesel exhaust emissions. Pronk et al. (2009) included "emergency workers in fire stations" as situations where intermediate exposure to diesel exhaust may occur. Recommendations for control of diesel exhaust emissions in the fire service have been presented for many years (e.g., Froines et al. 1987; Echt et al. 1995; Roegner et al. 2002) and a variety of engine exhaust ventilation technologies have been employed. However, recent studies in Australia (Bott et al. 2017), Canada (Chung et al. 2020), and the U.S. (Sparer et al. 2017) suggest exposure concerns persist. Bott et al. (2017) found operational checks of fire apparatus during start of shift contributed more strongly to overall engine bay diesel PM than the number of times the fire apparatus departed and returned in a study where no mechanical ventilation was used. This study describes a number of potential strategies for reducing firefighter exposures to diesel exhaust such as improving engine bay ventilation, improving vehicle design and emission controls, reviewing equipment check procedures and minimizing air movement between the engine bay and other areas of the station. Exhaust capture systems, which attach directly to the apparatus exhaust and controls the flow of emissions until they reach the outside of the fire station are widely used in today's fire service. Kim et al. (2019) reported that concentrations of some pollutants in fire station bays exceeded Korean standards, but that installation of an exhaust capture system (referred to as exhaust reduction system) effectively mitigated these pollutants in the bays. However, these exhaust capture systems are most effective when properly maintained and used. Exposure risks may increase if ventilation units are not performing to manufacture recommendations (Chung et al. 2020) or if the capture system is not attached prior to apparatus entering the fire station bay (Sparer et al. 2017). Vehicle-mounted diesel exhaust filtration systems are also available in the market that can be used to reduce diesel particulate emissions where exhaust capture is not possible, including at incidents.

Substitution—replace the hazard

For many of the situations to which the fire service must respond, it is not feasible to replace the hazard. However, replacement controls may be possible in training and through advocacy and equipment selection. Table 7 describes several substitution control options that may be available to the fire service

Training environment

In conducting hands-on training, the fire service may be able to substitute historically common live fire environments with those using different fuels or different sources of environmental simulation to mitigate health and safety concerns. Of course, the requirements of the necessary training environment will be dictated largely by training objectives, but it is also prudent to balance what will be gained from training with the risk it poses.

Fuel selection

Firefighters' exposures during live-fire training exercises have been studied in research projects that used solid wood, particleboard/chipboard, plywood, oriented strand board (OSB), diesel fuel, and heating oil as fuel sources (Hill et al. 1972; Atlas et al. 1985; Feunekes et al. 1997; Moen & Ovrebø 1997; Laitinen et al. 2010, 2012; Kirk and Logan 2015, 2019; Fernando et al. 2016; Abrard et al. 2019; Stec et al. 2018; Wingfors et al. 2018; Fent et al. 2019a, 2019b; Rossbach et al. 2020; Banks, Thai, et al. 2021). Two of these studies directly compared firefighters' exposure to contaminants when working in different training fire environments (fuels used and the training

Table 7. Summary of substitution control options and considerations.

Substitution options	Important considerations or need for additional research
Using training fuels for live-fire training that can achieve training objectives but lessen exposures	Studies indicate that burning different types of wood products at different orientations and different amounts with different ventilation parameters can impact the concentrations of hazardous substances produced. The training fire environment should balance risk of exposure with the intended benefit of the training objective.
Using simulated smoke and fire *vs.* live fire to achieve training objectives.	Simulated smoke (e.g., glycol-based aerosols) and digital flame can produce conditions for certain types of training without combustion. This type of training would not eliminate other hazards (e.g., slips, trips, falls, and thermal and physiological strain). These systems can range in cost and sophistication.
Supplementing live fire training with virtual/augmented reality training	This type of training would eliminate many hazards, including exposure to combustion byproducts. However, more research is needed to determine how to effectively achieve desired learning objectives.
Replacing chemical flame retardants (FRs) with nontoxic alternatives	Many chemical FRs (e.g., PBDEs) have been phased out of production and use in furniture. Barrier layers, including natural materials, have been incorporated in some products for fire retardancy. Other products have switched to new or other FR formulations (e.g., organophosphate FRs). Research to understand performance characteristics, exposure and toxicity of these new FRs is ongoing.
Replacing long-chain PFAS with other compounds, including non-fluorinated compounds	Class B foams are being manufactured that do not contain any fluorinated compounds, however, PFAS-containing foams are still being used in some settings. Turnout gear manufacturers may use long-chain PFAS in the manufacture of textiles and to achieve certain properties. However, some manufacturers are moving away from the use of PFAS.
Replacing aging diesel apparatus with electric or hybrid-electric apparatus	Just like the rest of the automotive industry, manufacturers are starting to develop apparatus that are powered by rechargeable batteries. Although the initial investment may be much higher than a diesel apparatus, exposure to diesel exhaust could be eliminated, or in the case of a hybrid, dramatically reduced.

structure) (Laitinen et al. 2010, 2012; Fent et al. 2019a, 2019b).

Laitinen et al. (2010, 2012) compared firefighter chemical exposures from training in a gas-fired simulator to exposures in a "conventional simulator" using different fuel: chipboard (and polyurethane foam), plywood, or spruce wood. Exposure to pyrene was assessed through metabolites in the urine and was found to be highest in firefighters following the plywood scenario. On the other hand, the highest airborne concentration of formaldehyde was measured in the gas simulator training prop. And while overall chemical exposures were typically lower with the gas simulator, the authors noted that the behavior of the smoke differed from a "real fire," which can impact training objectives (Laitinen et al. 2012).

Fent et al. (2019a, 2019b) studied different training environments in which firefighters completed a common training scenario. Training environments were created using (1) pallet & straw fuels in a concrete structure, (2) two different types of OSB and pallet & straw in a metal structure, or (3) simulated smoke and digital flame in a metal structure. Personal air levels of benzene and PAHs were higher for one type of OSB in the metal structure scenario compared to the other scenarios. Median area air concentrations of aldehydes and isocyanates were also highest during this OSB in metal structure scenario, while the pallet and straw in concrete structure scenarios resulted in the highest median concentrations of certain VOCs and acid gases. Firefighters and instructors who participated in the one type of OSB in the metal structure scenario also experienced the greatest median increase in urinary metabolites of pyrene and other PAHs. This study did not isolate the impact of training fuel alone, so these results may be attributed to some combination of fuel selection, fuel orientation and training structure design.

Training simulation instead of live-fire; increased use of virtual reality

One potential means for reducing exposure during training is to replace live-fire training scenarios with simulation-based training scenarios, as a way to safely learn skills in a fire environment, or to otherwise supplement live-fire training. Commercially available technologies exist for creating theatrical smoke and digital flames which can be deployed in traditional training structures or buildings that are acquired specifically for training. Work is also underway to advance virtual reality techniques to support hands-on training for the fire service such as the Enhanced Dynamic Geo-Social Environment (EDGE) from the United States Department of Homeland Security (2022).

The effect of simulated smoke based training on exposures was quantified in the aforementioned study by Fent et al. (2019a, 2019b). While firefighters had a significant increase in PAH-OH concentrations 3-hr after training for all scenarios, the increase from simulated smoke was much lower than from the live-fire scenarios. Uptake of PAHs during the simulated smoke exercises was unexpected, and partially attributed to residual contamination that remained on the turnout gear. It should be noted that other risks may still be present even if combustion has been eliminated. In this same study, firefighters' peak core temperatures, heart rates, and hemostatic responses were not statistically different among the training environments despite the differences in ambient conditions (Horn et al. 2019). It was concluded that physiological responses experienced by firefighters working in turnout gear are based largely on intensity and duration of work, not ambient conditions.

Virtual reality (VR) based fire training simulators have been of interest to both the fire service and the academic community for years. For example, Cha et al. (2012) proposed a framework for creating a three-dimension VR based training system that integrates fire dynamics with their initial simulation focusing on a road-tunnel fire scenario. Xu et al. (2014) developed a VR simulator focusing on smoke hazard assessments in subway and school scenarios. However, recently Monteiro et al. (2021) pointed out the challenges in delivering the correct stimuli for decision making during firefighter training and determined that better performance when only visual cues are provided in simulation may not be representative of the real-life performance.

Replacing toxic flame retardants with other methods to reduce flame spread

FRs have been shown to be released into the fire environment and deposited onto firefighters' PPE during combustion events (Fent et al. 2020a) and to make their way into the firefighter's body (Mayer et al. 2021). Several other studies have found a variety of FR contamination on turnout gear and in fire station dust (Shen et al. 2015; Alexander and Baxter 2016; Easter et al. 2016; Mayer et al. 2019). Furthermore, research has found elevated levels of certain FRs (or their metabolites) in specimens collected from firefighters compared to the general population (Dishaw et al. 2011; Shaw et al. 2013; Jayatilaka et al. 2017). As a result of this growing evidence, the fire service has been engaged in activities with legislative bodies in an attempt to replace certain classes of FRs in specific cases, particularly where the risk of their use may outweigh the benefit of their presence. New types of FR materials and alternative fire-prevention measures continue to be developed as a possible substitution for additive chemical FRs (Harris et al. 2021), though the relative trade-offs between risk and benefits of any replacement control should be studied in a holistic manner.

Replacing fluorinated compounds with equally effective alternatives

Replacing AFFF with fluorine free foam, where appropriate

AFFF has historically been used by firefighters to control and suppress flammable liquid fires such as those from fuel spills (Class B). However, firefighters' use of AFFF can lead to elevated concentrations of PFAS in firefighter blood and contribute to PFAS contamination of ground and surface water in the general population (Houtz et al. 2013; Hu et al. 2016). Over the past several decades, the formulation of AFFF has evolved to move away from longer chain PFAS (e.g., PFOA, PFOS) and fluorine-free foams have been introduced to the market (Hawthorne and Grant 2022). However, AFFF is still being used for certain types of fires while further evaluation of fluorine-free foams proceeds to determine which foams meet performance requirements. As with any chemical substitution, it is important to choose replacement chemicals that are effective for their intended purpose and do not pose increased or different health and safety risks that cannot be properly managed.

Replacing fluorinated compounds in PPE

Firefighters have also raised concern about the use of PFAS to provide durable water and oil resistance in textiles used in firefighting PPE. Several studies (Peaslee et al. 2020; Young et al. 2021; Muensterman et al. 2022) have found evidence that firefighters' turnout gear may be a contributor to PFAS contamination in stations, potentially due to fireground contamination and/or materials used in PPE production. Current research and development is focused on replacing PFAS materials in firefighting PPE with fluorine-free alternatives. Until the potential risks of PFAS can be better delineated and viable substitutes found, administrative and engineering control measures such as cleaning PPE thoroughly, washing hands and skin after handling turnout gear, and isolating PPE from living quarters may help to mitigate risks (Peaslee et al. 2020).

Table 8. Summary of elimination control options and considerations.

Elimination options	Important considerations or need for additional research
Community Risk Reduction	How effective are fire safety messaging strategies at reducing the number of fire starts? What impact does early notification of fires through smoke detectors have on helping to eliminate large fires and the need for occupant rescue?
Installation of residential sprinklers	What impact does early control of fires through automatic sprinklers have on eliminating large fires and the subsequent smoke production and contamination risk?
Exterior fuel treatments	Careful removal/elimination of unnecessary and/or easily ignitable exterior fuels near homes and communities can reduce the risk of exterior fires transitioning into the structure. Implementation of the Home Ignition Zone concept has been shown to improve fire safety which can eliminate smoke production from household items.

Replacing aging diesel apparatus with electric or hybrid-electric vehicles

The aforementioned risks to firefighters from diesel exhaust emissions are important at the fire station and on the fireground. Fire departments may consider substituting traditional diesel apparatus for recently developed electric and hybrid-electric fire apparatus (Avsec 2021). While such substitutions must be made with a holistic view of the fire department activities, policies, and financial realities, the possible reduction in firefighter exposure is an important parameter to consider.

Elimination—physically remove the hazard

While complete elimination of accidental fires is currently impossible, the Fire Service's efforts in Community Risk Reduction can pay dividends by eliminating some of the local fire risk. Table 8 describes a few elimination control considerations for the fire service.

Public education programs can raise awareness of local occupants for risky materials, products, and/or behaviors. Each ignition eliminated through public awareness can result in one less exposure to fireground contaminants for responding firefighters. *Smoke alarms* can provide early warning for occupants of a structure, providing an important opportunity for evacuation from the structure, improving department response times and, hopefully, eliminating the need for rescue at the fire incident. The installation of *automatic fire sprinklers* can control fires at the incipient stage, eliminating the occurrence of larger, more complicated post-flashover fires that create increased risk for exposure to carcinogenic contamination.

In order to mitigate the risk of external fires (e.g., vegetation, mulch) igniting a structure fire, risk reduction practices include local fuel treatments which can eliminate dangerous fuels near residential neighborhoods and remove high risk fuels in the home ignition zone. These practices create defensible space through zoned removal of exterior fuels and have been shown to improve fire safety (e.g., Cohen 2000).

While the primary goal of these community risk reduction practices is to lower the risk for the general public and reduce the potential for their loss of life and property, there are also important benefits for the fire service including reduced fireground exposures. These community risk reduction practices should be integrated into a holistic view of reducing firefighter exposure risk.

Summary and conclusions

By characterizing fire service contamination control options through the lens of the NIOSH Hierarchy of Controls, we have identified evidence-based measures that can be implemented to reduce exposures and protect firefighters during an emergency response, in the fire apparatus and at the fire station. This information is also valuable to better understand firefighters' potential routes of exposure, where they are most likely to be encountered, and highlights examples of protective measures to lessen exposure (e.g., Figure 1). Despite the important advancements made in recent years, several gaps in understanding remain, particularly at the higher levels of the Hierarchy of Controls, which are generally the most effective at decreasing exposure risk. For example, many of the control options described in this review are based on air or surface sampling or even professional judgment, but additional studies are needed to quantify the impact of specific control options on biological uptake of hazardous substances and to document the mechanistic link between exposure and health outcomes. Additionally, the scenarios that the fire service must respond to and the activities, tools and technologies they employ will continue to evolve, which will likely lead to the potential for further reduction in contamination and exposures. However, new hazards may be produced and encountered, which could require different control measures to be developed (Jakobsen

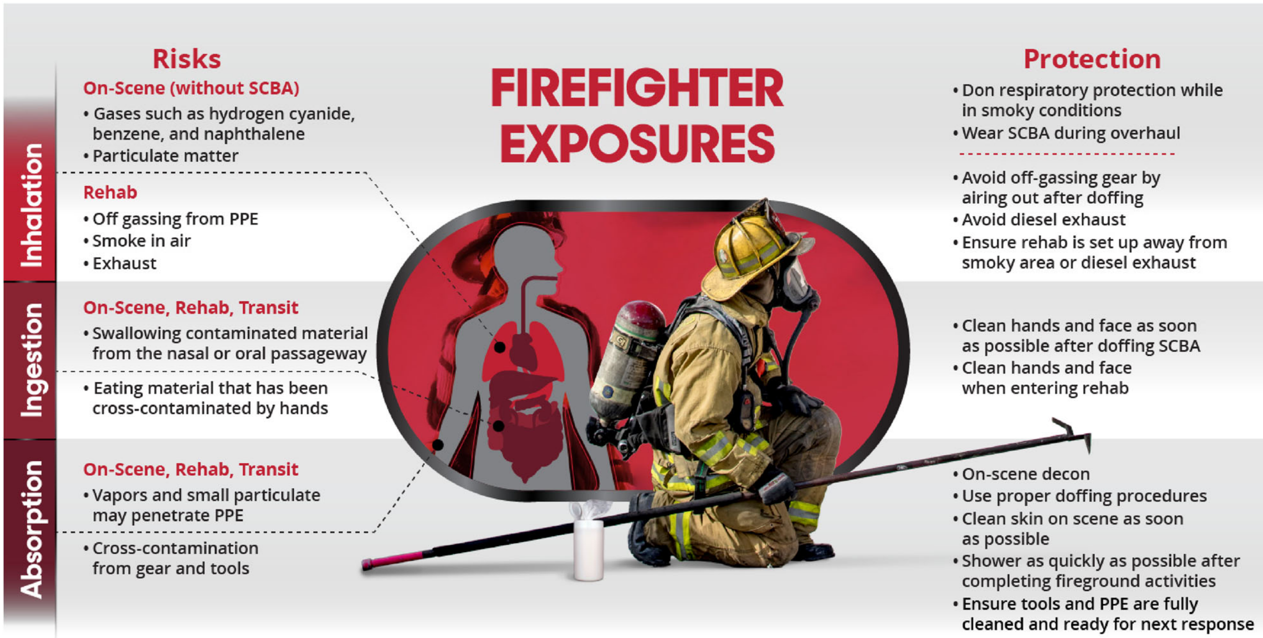

Figure 1. Firefighter exposure risks and protection.

et al. 2020). A few major trends that have been highlighted in this review include:

- Much of the existing research has focused on improving PPE for the various hazards faced by the fire service. However, as contamination control concerns are incorporated into PPE design, the impacts on thermal protection, wearability, and heat stress must also be considered.
- Several studies have evaluated administrative and engineering controls that can be used during the firefight, as well as during recovery from the emergency incident. However, more research is needed on the most effective and efficient means to work on the fireground and clean equipment, apparatus, and individuals after emergency and training fires.
- Relatively little research has been conducted on quantifying the benefits, both immediate and long term, for higher-level control measures (in the hierarchy), such as substitution and elimination. Implementing these controls may require compelling scientific evidence, local policy shifts, and potentially larger political action.

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ORCID

Gavin P. Horn http://orcid.org/0000-0002-4364-9673
Kenneth W. Fent http://orcid.org/0000-0003-4978-7839
Steve Kerber http://orcid.org/0000-0002-4951-6927

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