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

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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. 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 lower in the Hierarchy of Controls, which 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

Contamination control; firefighter; firefighting; PPE; hierarchy of controls; occupational exposure

DISCLOSURE

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INTRODUCTION

Firefighting poses acute occupational hazards and there is mounting evidence that it may also lead to 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; Casjeans et al. 2020; Laroche 2021). NIOSH conducted one of the largest cohort mortality studies in firefighters in the United States and found statistically significant increases in mortality and incidence rates 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 carcinogenic compounds produced by burning materials on the fireground, including polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), aldeydes, particulate matter and other products of incomplete combustion. Several studies have been conducted to assess firefighters' exposure to products of combustion (Austin et al. 2001; Bolstad-Johnson et al. 2000; Fent et al. 2014, 2018, 2019a; Feunkes et al. 1997; Jankovic et al. 1991; Keir et al. 2017, 2020; Oliveira et al. 2020; Sjöström et al. 2019; Poutasse et al. 2020; Stec et al. 2018; Wingfors et al. 2018). 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) (International Agency for Research on Cancer 2010a, 2012a, 2012b, 2019, 2021). In 2010, IARC evaluated the occupation of firefighting and classified it as "possibly carcinogenic to humans" (International Agency for Research on Cancer 2010b).

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. Exposure to FRs—present in many types of furnishings—is a concern during structural firefighting because of their known detrimental health effects (Hoffman et al. 2017; Linares et al. 2015; Vuong et al. 2020). Similarly, human health risks have been identified from exposure to PFAS (Sunderland et al. 2019; Agency for Toxic Substances and Disease Registry 2018, 2020; 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 equipment (PPE) that is manufactured from textiles containing PFAS (Peaslee et al. 2020). Certain types of FRs and PFAS are considered persistent organic pollutants and can accumulate in human tissues (Engelsman 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).

While there are many potential sources and 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. While positive-pressure self-contained breathing apparatus (SCBA) can essentially eliminate inhalation of these contaminants, firefighters do not always wear SCBA. Contaminants may also end up on a firefighters' skin and be available for dermal absorption. Although protecting the airway is the most important control measure to implement on the fireground, it has become increasingly apparent that dermal absorption plays a key role in systemic exposure for firefighters. Several important products of combustion, including PAHs, benzene, and styrene can be absorbed through the skin (Fent et al. 2022; Franz 1984; Thrall et al. 2000; VonRooij et al. 1993). 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 Hierarchy of Controls model, there are five broad levels where strategies can be implemented for protecting occupations from the hazards in the workplace. This framework can be used to provide a rational paradigm to integrate current research and understanding and provide 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. There are a number of modifiable lifestyle factors that can increase firefighters' risk of cancer (Jahnke et al. 2017), but for this paper, we will focus primarily on occupational exposure to contaminants and ways to reduce those exposures.

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 abrasion; and increasingly there are calls to add requirements for protection against contaminant ingress. However, firefighting PPE also imposes a physiological burden to the wearer, increasing metabolic heat production, trapping heat and moisture next to the skin, and impairing mobility. 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 PPE control options along with important consideration and areas where additional research may be needed in the fire service.

Dermal protection

The modern structural firefighting protective ensemble typically includes 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 3 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; Fent et al. 2017; Fernando et al. 2016; Keir et al. 2017; Mayer et al 2020; Wingfors et al. 2018). 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—the larger magnitude attributed in part to protection provided by the additional base layer. However, compared to particles, gas molecules such as benzene can more readily penetrate the small gaps in PPE interfaces. Mayer et al (2020) recently found almost no reduction in benzene concentrations under PPE in a study using a standardized exposure prop and stationary mannequins. The relative importance of protecting against gas or solid-phase substances remains an important area of research.

By measuring PAHs on firefighters’ skin locations, studies have identified vulnerabilities in the neck region (Fent et al. 2014) 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 differences may be explained, at least in part, by differences in study design. 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 infiltration 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 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. Reinforcements to PPE, often provided for improved abrasion performance, thermal protection, visibility and/or load carriage may also impact heat stress (McQuerry et al. 2018) and thermal comfort, task performance, range of motion and gait characteristics (Ciesielska-Wrobel et al. 2017, 2018; Coca et al. 2010; Park et al, 2011).

Hoods—To improve dermal protection in the neck area, PPE manufacturers have developed new fire hoods aimed specifically to block particle penetration (particulate-blocking hoods). Using the FAST, Ormond et al (2019) found qualitative improvements in the particulate blocking hood to reduce the risk of exposure in the head and neck region over 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. Furthermore, 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, again it is important to balance protection against fireground contamination with other requirements of the PPE.

Respiratory protection

There are multiple times when a firefighter might experience airborne hazards while working at a structure fire. Fortunately, respiratory protection programs have been implemented in most fire departments. Positive-pressure SCBA, which have an assigned protection factor of 10,000, can essentially eliminate inhalation of the fireground contaminants described above. The concentration of contaminants available for inhalation depends on the job assignment and the use of SCBA. Firefighters assigned to attack and search job assignments are likely to work in an area of the highest airborne concentration, followed by firefighters assigned to overhaul, outside vent, incident commanders and 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 and search 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.

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 practical when exposed to smoke. The fireground interventions significantly reduced (more than 40%) mean total post-fire urinary PAH metabolites (PAH-OHs) in engineers. While other interventions were tested in this study, the authors theorized the reduction in the engineers' urinary PAH-OHs was primarily due to increased SCBA use. 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.

Anecdotally, firefighters often doff their SCBA during overhaul once the apparent risk from visible smoke is gone. Gainey et al (2018) characterized the impact of unprotected overhaul exposure using a mouse model without airway protection to assess risk to the lungs in the form of gene expression. Although gases that are commonly monitored during overhaul were well below NIOSH ceiling limits, 3,852 lung genes were differentially expressed in the mice exposed to the overhaul environment compared with mice that did not enter the overhaul environment. These findings indicate a potential increased risk for firefighters who conduct overhaul without airway protection. Because SCBA is heavy and increases thermal strain, there is interest in finding alternatives during physically demanding overhaul operations. Jones et al (2015) evaluated Chemical, Biological, Radiological and Nuclear (CBRN) canisters in repetitive post live-fire overhaul exposure tests and found that while CBRN canisters provide protection from many contaminants, formaldehyde did breakthrough. These results indicate that CBRN canisters may not provide complete protection against possible airborne hazards during overhaul.

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 they studied. Horn et al (2022) measured particulate levels well above background 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 fire investigators' airways from airborne particulate any time fire-cause 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 summarizes administrative control options along with important consideration and areas where additional research may be needed in the fire service.

Fire attack tactics (interior vs transitional attack)

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 through the front door 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 20%, 36%, and 50% lower post-fire urinary concentrations of hydroxyfluorenes, hydroxyphenanthrenes, and 1-hydroxypyrene, respectively, 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 occupants' life safety (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.

Crew rotation

Assembling enough firefighters to address the fire/emergency/training situation is critical to a successful outcome and can also be important in allowing crew rotation to reduce peak 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—an activity that often requires long periods of physical activity—can result in increased heat stress (Horn et al. 2018). With enough staffing on the scene, 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 who were working in highest concentration of smoke and contamination.

Additionally, increased personnel available during live-fire training may be able to reduce peak exposures to instructors. Fent et al (2019b) compared instructors' cross-shift (approximately 8 hours with multiple training exercises) change in urinary concentrations of PAH metabolites to firefighters' pre to 3-hr post-training (1 exercise) change in urinary concentrations 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 donning/doffing practices

Although PPE provides significant protection against dermal exposure, and improvements are continuing to be developed, improper PPE doffing practices can result in secondary exposures to fireground contaminants. For example, the traditional methods firefighters use to doff hoods and gloves in particular, can lead to cross contamination from the outside of the PPE to bare skin (Illinois Fire Service Institute 2017, 2018). While there has been little 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 on protection from contamination depositing on the neck 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 design modification. The relative importance of donning/doffing of contaminated PPE contributes to dermal and inhalation exposure and biological uptake remains an important area of research.

Post fire skin cleaning

Despite the use of PPE, firefighter's skin can be exposed to elements of firegound 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%. Because this indicates 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. Wildland firefighting presents a unique challengefor post-fire skin cleaning, so skin wipes may be especially useful in this environment (Cherry et al. 2021).

A sauna has been proposed as a novel method to remove contaminants in skin via sweat following firefighting. Burgess et al (2020) evaluated the use of infrared saunas following live fire training as a potential strategy to reduce or mitigate exposure to carcinogens. Sauna treatment was found to reduce total mean hydroxylated PAH concentrations in the urine by 43.5%, but this difference was not statistically significant. Additional firefighter sauna studies may be useful to include a range of sauna types and settings along with potential exercise conditions and consideration of other exposures. Such studies could consider heat strain and dehydration, as well as quantification of contaminants in sweat and urine.

PPE cleaning practices

PPE cleaning practices 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 at the fire station or by sending PPE to an outside vendor (i.e. Independent Servcie Provider (ISP)), 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 appeared to reduce many polybrominated diphenyl ether (PBDE) contaminants but results for organophosphate flame retardants (OPFRs) were mixed. In a separate study, 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) 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 Ottawa 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, which was attributed to cross contamination from other highly contaminated hoods during the laundering (Mayer et al. 2019). Evidence of cross contamination during laundering was also found in a study of firefighter PPE contamination in Australia, where very little difference in PAH, PBDE, and OPFR contamination was found before and after laundering (Banks et al. 2021). Researchers supporting the fire service are actively engaged in studying and validating cleaning procedures for firefighter PPE (e.g. Stull 2018, 2019), and important advances in understanding are expected in the near future.

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. Outer shell and thermal liner tear strength was significantly reduced when laundered as compared to wet or dry decontamination. Total Heat Loss was reduced for all samples that underwent any form of cleaning while Thermal Protective Performance was increased only in the gear that was laundered. These results suggest that some important protective properties of turnout gear can be decreased 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 and/or from contaminated PPE and tools 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 Chief's or personal vehicles that may be responding to a fire scene from home and may ultimately track contaminants back to their home.

Fire station cleaning

Contamination on 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 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 to contamination tracked back to the fire station from the fireground. Similarly, in Australia, Banks et al (2020) quantified PAHs, PBDEs and OPFRs in fire station dust and air samples and hypothesized that they were brought back from the fireground. 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 rigorous cleaning of fire stations, 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 summarizes engineering control options along with important consideration and areas where additional research may be needed in the fire service.

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 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 minutes. Banks et al (2021b) 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 on the apparatus or other 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 and higher than outdoors. Of note, the station with the highest exposures 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 storage locations of firefighting PPE, indicating that the proximity of contaminated firefighting PPE to the rest of the station determines the extent to which they contribute to concentrations 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).

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. In this study, 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, which have been classified as carcinogenic to humans by IARC. 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. Echt et al. 1995; Froines et al. 1987; Roegner et al. 2002). 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. Importantly, 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. 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. Interestingly, Sparer et al (2017) noted that the age and layout of the stations may impact the implementation of exhaust capture systems. Kim et al (2019) reported that concentrations of some pollutants in fire station bays exceeded Korean standards, but that installation of an exhaust reduction system effectively mitigated these pollutants in the bays. Somewhat surprisingly, data from Chung et al (2020) indicated that vehicle bay exposures were higher in stations with local exhaust ventilation; however, several of the ventilation units performed well below manufacturer recommendations. These data suggest that the mitigation efforts may have provided a false sense of security and further demonstrate the importance of assessing these units regularly for efficiency. Vehicle-mounted diesel exhaust filtration systems are also available in the market. While these systems may not be a replacement for exhaust capture systems in bays, they 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, there are specific situations where this may be possible. Table 7 summarizes substitution control options along with important consideration and areas where additional research may be needed in 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 & Ovrebo 1997; Laitinen et al. 2010, 2012; Kirk & Logan 2015, 2019; Fernando et al. 2016; Abrard et al. 2018; Stec et al. 2018; Wingfors et al. 2018; Fent et al. 2019a, 2019b; Rossbach et al. 2020; Banks 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 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 fuels and environments in which firefighters completed a common coordinated attack fire training scenario. In this study, training environments were created using (1) pallet & straw fuels in traditional concrete structure or (2) two different types of oriented strand board (OSB), 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 scenario compared to the other scenarios. Median area air concentrations of aldehydes and isocyanates were also highest during this OSB scenario, while the pallet and straw scenarios resulted in the highest median concentrations of certain VOCs and acid gases. Firefighters and instructors who participated in the one type of OSB scenario also experienced the greatest median increase in urinary metabolites of pyrene (and other PAHs).

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. 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.

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 possibly 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 fully encapsulating personal protective equipment is 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 Monterio 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 in furnishing with other risk reducing methods

FRs have been added to many home furnishings such as furniture, carpet padding, electronics and other consumer products to reduce fire risk. However, FRs also pose health risks as some FRs can accumulate in the body and are associated with a variety of adverse health effects. 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 (Alexander & Baxter 2016; Easter et al. 2016; Mayer et al. 2019; Shen et al. 2015). 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; Jayatilaka et al. 2017; Shaw et al. 2013). 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 tradeoffs between risk and benefits of any replacement or elimination control should be studied in a holistic manner.

Replacing fluorinated compounds with equally effective alternatives

The fire service has become increasingly aware of risks from PFAS, which have been associated with adverse health effects. These substances are often used in upholstery and other materials for their stain and moisture resistance properties, and may be liberated from these materials during combustion, potentially exposing firefighters in a manner similar to FRs. However, we are not aware of any studies that have documented biological uptake of PFAS from burning materials.

Replacing AFFF with fluorine free foam—Aqueous film-forming foam (AFFF) has historically been used by firefighters to control and suppress flammable liquid fires such as those from fuel spills. 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). New fluorine-free foams have been introduced to the market and many communities have banned the use of PFAS-containing AFFF. 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 at 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 (Muensterman et al. 2022; Peaslee et al. 2020; Young et al. 2021) 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).

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. *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 *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.

For wildland and wildland-urban interface (WUI) fires, risk reduction practices include local fuel treatments such as prescribed burns which can eliminate dangerous fuels near residential neighborhoods and removing 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 Hierarchy of Controls we have identified evidence-based measures that can be implemented to 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. The scenarios that the fire service must respond to and the activities, tools and technologies they employ will continue to evolve. This evolution 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 (Jakobsen et al. 2020). A few major trends that have been highlighted in this review include:

- Much of the 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.
- Notably less 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.
- While biological monitoring has provided support for some types of control measures, many of the control options described in this review are based on air or surface sampling or even professional judgement. 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.

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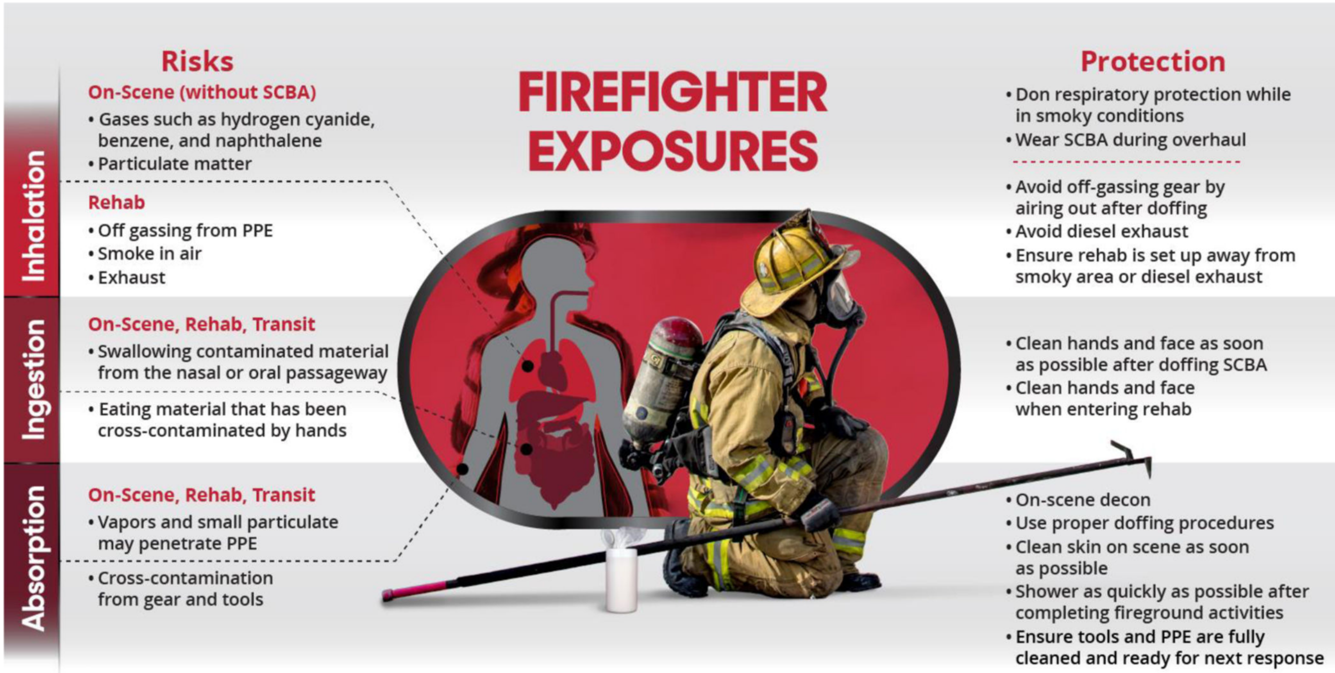

Figure 1.

Firefighter exposure risks and protection.

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, NHL, MM
IARC. 2010	44	Testes, prostate, NHL
Soteriades et al. 2019	49	Testes, prostate, NHL, bladder, colorectal, melanoma, CNS
Jalilian et al. 2019	48	Testes, prostate, NHL, bladder, colorectal, melanoma, thyroid, mesothelioma
Casjens et al. 2020	25	Testes, prostate, bladder, colorectal, pancreas, melanoma, mesothelioma
Laroche et al. 2021	104 (from 11 systematic reviews)	Testes, prostate, NHL, bladder, colorectal, melanoma, mesothelioma

NHL = non-hodgkin's lymphoma, MM = multiple myeloma, CNS = central nervous system

Table 2.

Types and classes of contaminants commonly studied in the fire service.

Contaminant	Description/definition	Health effects and association with cancer risk
Products of combustion		
PAHs	Polycyclic aromatic hydrocarbons (PAHs), containing two or more benzene rings. PAHs with 4 or more rings have low volatility, while shorter chain PAHs are semi-volatile. Naphthalene (2 rings) is the most volatile.	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.	Known and probable carcinogens include benzene, formaldehyde, 1,3-butadiene, styrene, and acrolein. Some VOCs are also known to cause neurological effects, irritation, sensitization, and asphyxiation.
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.	Exposure to high concentrations of PM can exacerbate heart and lung conditions. Respirable PM can be inhaled deep into the lungs where it is difficult to clear, more likely to be absorbed, and can cause inflammation. Other hazardous compounds (including 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).	PBDEs have long biological half-lives (e.g., years). Certain types of PBDEs have been shown in animal studies to cause effects on thyroid, liver, and immune system, as well as neurobehavioral and development effects, and even liver and thyroid tumors (deca-BDE). Certain organophosphate and chlorinated FRs have also been associated with developmental effects. Chlorinated tris is labelled as a carcinogen in California.
PFAS	Per- and polyfluoroalkyl substances (PFAS) are a class of synthetic chemicals that have been used in various 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)	Longer-chain PFAS (e.g., C8) have long biological half-lives (e.g., years). Studies suggest some PFAS may adversely affect the immune, endocrine, and reproductive systems; result in organ toxicity; and increase the risk of kidney and testicular cancers. PFOS and PFOA are IARC Group 2B probable human 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.	Diesel exhaust is an IARC Group 1 known human carcinogen.

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 particle-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 for the wildland-urban interface

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 versus 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 versus hook & dee closure	Zippers may not be as durable as hook & dee closures, but they are actually more common in the marketplace today.
Particle blocking hoods	Like all hoods, must seal properly around respiratory facepiece to provide most protection. Particle 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.

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 versus 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. Other 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.

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 the tailpipe 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.

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 versus 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.
Using virtual reality for training	This type of training would eliminate many hazards, including exposure to combustion byproducts. However, more research is needed to determine if or when this training is effective in achieving learning objectives.
Replacing chemical flame retardants (FRs) with non-toxic 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 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.