
Original Article

Evaluation of CBRN Respirator Protection in Simulated Fire Overhaul Settings

Shawn D. Staack¹, Stephanie C. Griffin¹, Vivien S.T. Lee¹, Eric A. Lutz² and Jefferey L. Burgess^{1,*}

¹Department of Community, Environment and Policy, University of Arizona Mel and Enid Zuckerman College of Public Health, 1295 North Martin Ave., Tucson, AZ 85721, USA; ²University of Arizona College of Engineering—Mining and Geological Engineering, 1235 James E. Rogers Way, Tucson, AZ 85719, USA

*Author to whom correspondence should be addressed. Tel: +1-520-626-4918; e-mail: jburgess@email.arizona.edu

Submitted 16 July 2020; revised 16 November 2020; editorial decision 29 December 2020; revised version accepted 16 January 2021.

Abstract

Overhaul is the phase of firefighting after flames have been extinguished but when products of combustion are still being released. While positive pressure self-contained breathing apparatus (SCBA) provide the highest level of respiratory protection during overhaul, use of air-purifying respirators (APRs) with suitable filters could potentially provide a lower weight, longer duration option for first responders. The objective of this study was to assess whether an APR with a chemical, biological, radiological, and nuclear (CBRN) canister could be recommended as substitution for SCBA during overhaul. A total of 15 simulated standard overhaul environments were created by burning household materials. Sampling was conducted using mannequin heads fitted with full facepiece respirators with either a CBRN canister or SCBA. In-mask and personal samples were collected for aldehydes, polynuclear aromatic hydrocarbons, inorganic acids, aromatic hydrocarbons, nitrogen dioxide, and particulate matter. An additional six simulated high-exposure overhaul environments were created in a flashover chamber by continuously adding household materials to a smoldering fire. The sampling train was the same for both the standard and high-exposure environments; however, the facepiece was sealed to the mannequin head in the high-exposure environments. In the standard overhaul environment, the CBRN canister effectively reduced the level of exposure for most contaminants, while in the high-exposure overhaul exposure setting in-mask acetaldehyde and formaldehyde were detected. In both exposure settings, the SCBA prevented almost all exposure, and therefore remains the recommended respiratory protection during overhaul.

Keywords: exposure assessment; extreme environments; firefighter; fit factors; personal protective equipment (PPE) usage

What's important about this paper

Firefighters are at increased risk of exposure to carcinogens. It remains uncertain whether air-purifying respirators can effectively filter toxicants present in the overhaul environment of a structural fire, when hidden flames, hot embers, and other combustion sources are identified and extinguished. Air-purifying respirators with chemical, biological, radiological, and nuclear (CBRN) canisters showed aldehyde breakthrough in the high-exposure environment. Air-purifying respirators with CBRN cartridges and self-contained breathing apparatus (SCBA) reduce exposures during standard overhaul environments, but SCBA should be used in high-exposure overhaul environments.

Introduction

Overhaul is the phase of structural firefighting that occurs after the fire has been knocked down with no visible flames, wherein hidden fires, hot embers, and other combustion sources are identified and completely extinguished to avoid reignition. Though firefighters are the initial first responders to enter the overhaul environment, arson investigators, criminal investigators, coroners, forensic evaluation personnel, and structural damage mitigation personnel are all at risk of exposures in the overhaul environment. Overhaul typically starts when the smoke clears, and in past years firefighters often did not wear respiratory protection during overhaul. However, studies have shown that concentrations of products of combustion may occur at potentially harmful levels during overhaul (Bolstad-Johnson *et al.*, 2000; Austin *et al.*, 2001; Fent *et al.*, 2018).

In a previous study in response to a fire department request, use of a full-face, air-purifying respirator (APR) with multipurpose (high-efficiency particulate, acid gas, and organic vapor) cartridges was found to provide inadequate protection during overhaul, resulting in changes in spirometry and lung permeability, which suggested that chemicals may have broken through the cartridges (Burgess *et al.*, 2001). This led to the current recommendation to use positive pressure self-contained breathing apparatus (SCBA) during overhaul. However, SCBA are tiring to wear due to their weight and time constraints. Thus, there is still a desire among some first responders for an APR with filters (cartridges or canisters) suitable for use in the overhaul setting.

Follow-up evaluation of respiratory protection in laboratory-simulated environments (i.e. smoke chambers) indicated that specific products of combustion including formaldehyde, acrolein, and polynuclear aromatic hydrocarbons passed through combination (high-efficiency particulate, acid gas, and organic vapor) APR cartridges at concentrations that exceed the applicable American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV), and

that chemical, biological, radiological, and nuclear (CBRN) canisters provided a higher level of protection (Anthony *et al.*, 2007; Currie *et al.*, 2009). An additional study used controlled live-fire evaluations of commercially available CBRN canisters and cartridges for performance and time-to-breakthrough at standard respiratory volumes utilizing direct (non-oscillatory) air flow (Jones *et al.*, 2016). Results of this study showed in-mask concentrations of formaldehyde were not consistently filtered below the threshold limit ceiling values (ACGIH TLV-C). Given that breathing patterns are oscillatory, a follow-up evaluation was completed using oscillatory flow (Jones *et al.*, 2015). Results showed that the CBRN canisters substantially reduced formaldehyde concentrations; however, contaminants were still present in in-mask samples. The mixed findings of these previous studies provided the rationale for the current study.

The objective of this study was to assess whether an APR with a CBRN canister could be recommended as substitution for SCBA during overhaul by comparing their exposure reduction performance in simulated overhaul environments using oscillating flow. The study was divided into two parts: first, overhaul settings were simulated with products of combustion concentrations typically found in actual overhaul settings (henceforth termed 'standard' overhaul); second, overhaul settings were simulated with higher exposures (henceforth termed 'high-exposure' overhaul).

Methods

The study was reviewed by the University of Arizona (UA) Institutional Review Board and was deemed exempt.

Standard overhaul

To compare CBRN canister effectiveness in reducing contaminant concentrations to the protection provided by a SCBA, 15 overhaul environments were simulated

by the Yuma Fire Department (YFD) at their Public Safety Training Facility (Yuma, AZ). Overhaul environments were created by burning household materials (Table 1) for 15 min in a burn room at the training facility. Carbon monoxide (CO) measurements were taken by a YFD firefighter using an MSA Altair 4-gas meter (Pittsburgh, PA) to ensure that after fire suppression CO levels were at or below 30 parts per million (ppm) and safe for UA researchers to enter the chamber and place the sampling cart. YFD firefighters used only water to knock down the flames and cool the internal temperature of the building, following standard firefighting procedures. Sampling in the environment was initiated once firefighters deemed the environmental factors, such as temperature and visual combustion levels, suitable for initiation of overhaul activities.

Sampling was conducted using a Dynamic Breathing Machine (DBM; Warwick Technology Limited, Warwick, UK) attached to two Only Mannequin (East Orange, NJ) 15-inch durable plastic flesh colored mannequin heads (item 50013) fitted with full-face respirators. Both mannequin heads and the DBM were fitted to a sampling cart that could be easily moved into the overhaul environment. Samples were simultaneously collected in the mask of each mannequin head; a third sampling train on the cart collected ambient, unfiltered air in the overhaul environment; and a fourth sample train was placed on the body of the firefighter conducting overhaul activities. Holes were drilled in the nasal region of the mannequin heads and five Tygon tubes (Lima, OH) were inserted for in-mask sample collection. A 1-inch stainless steel pipe was inserted in the mouth of the mannequin and connected to the DBM. Both mannequin heads were fitted with Dräger DHS7000 full-face respirator masks (Lübeck, Germany). These masks have both APR and SCBA attachment capabilities, allowing for rotation of an APR with CBRN canisters and SCBA between the

two heads prior to each round of sampling to account for mask and fit-factor variability. Both masks were fit tested using a TSI Portacount 8020 (Shoreview, MN) and the supplied-air adapter to meet or exceed the OSHA fit-factor requirements for a full-face respirator of ≥ 500 ; adjustments (e.g. tightening straps) were made as needed to ensure a protective fit was achieved (OSHA 1910.134 App A, 2004). During the fit test the DBM was activated and seven 60-second samples were taken per OSHA 29 CFR 1910.134 Appendix A fit test requirements.

Physiological breathing patterns were simulated using the DBM. A minute volume of 80 l min^{-1} , with 2.5 l tidal volume at 32 breaths per minute, was utilized for all rounds of sampling. These relatively high rates were chosen to simulate overhauls requiring a higher level of exertion out of the range typically encountered. Firefighter tasks during overhaul include looking for remaining sources of combustion, including opening walls and ceilings, while wearing heavy turnout gear and SCBA. Based on anecdotal reports from firefighters, overhaul involves between 50 and 75% maximal effort. A prior study of firefighters wearing SCBA at 70% maximal effort measured an average minute volumes of 63 l min^{-1} and average heart rate of 170 (Hostler and Pendergast, 2018), whereas 80 l min^{-1} was the lowest minute volume calculated (range $80\text{--}159 \text{ l min}^{-1}$) in a prior treadmill test of firefighters in full turnout gear with heart rates ranging from 149 to 172 (Burgess and Crutchfield, 1995). The flow rate of the DBM was maintained using LabVIEW System Design Software (National Instruments, Austin, TX).

Integrated sampling methods were used to collect in-mask and ambient sample sets on the sampling cart for each contaminant of interest. Concentrations for analysis were represented in parts per million. Four SKC personal sampling pumps (Eighty Four, PA) and one Zefon ELF Escort (Ocala, FL) sampling pump were used on each sample set on the cart, of which there were three: Head 1, Head 2, and Ambient; a fourth set of pumps were worn by the firefighter in the overhaul environment. Pumps were equipped with manifolds allowing for individualized flow adjustment for each sample collected. Samples included 18 analyte PNAH profile using 37 PTFE Amberlite (NIOSH 5506); 6 analyte inorganic acids profile using washed silica gel (OSHA 165SG); 10 analyte aromatic hydrocarbon profile using charcoal (NIOSH 154); 8 analyte aldehyde profile using treated silica gel (NIOSH 2016); and NO_2 using treated molecular sieve (NIOSH 6014). Pre- and postsampling field blanks were collected and analyzed for each sample profile along with one set of lab blanks. TSI Sidepaks AM510 (Shoreview, MN) were used to

Table 1. Burn materials and approximate amounts in each standard overhaul simulated burn.

Household materials	
Laminate wood flooring	0.6 square meters
Vinyl flooring	1.5 square meters
Carpet	1.1 square meters
Couch cushions	3 (1 couch equivalent)
Particle board furniture (e.g. desk, night stand, etc.)	1 piece of furniture
Household electrical appliance (e.g. fan, vacuum)	1 appliance

measure particulate matter for all three sample sets on the cart and on the body of the firefighter. Temperature and percent relative humidity (% RH) measurements of the environment were taken on the cart using HOBO Onset Data Loggers (Bourne, MA). The same integrated and real-time sampling methods were used to collect a personal exposure sample in the breathing zone of a firefighter while performing overhaul activities in the simulated environment. Temperature and RH measurements of the environment were also taken on the body of the firefighter using HOBO Onset Data Loggers (Bourne, MA), placed on the firefighter's shoulder within 12 inches of the where the breathing zone samples were collected.

Prior to activation of the sample pumps and entry into the overhaul environment, one mask was equipped with a new Scott CBRN Cap-1 canister (Monroe, NC) and the other was connected to a Dräger SCBA pack. The Scott CBRN Cap-1 canister was selected based on the results of a previous simulated overhaul study showing that it provided the highest level of protection (Jones *et al.*, 2015). After each sample period, the CBRN

canister was removed and replaced with a new canister, and the SCBA bottle was replaced with a new full bottle. The placement of the CBRN canister and SCBA was rotated between the two heads on each burn to limit potential bias from mask and fit-factor variability.

Samples were collected on the cart once the fire was extinguished and the firefighter was ready to enter the environment to perform overhaul activities. The sample cart was placed approximately 5 feet from the combusted materials (Fig. 1) with both heads and the ambient sample media facing the burned materials. The firefighter performed overhaul activities in the burn room for approximately 10 min, or until the SCBA air supply fell below the National Fire Protection Association (NFPA) standard of 33% remaining (NFPA, 1981). To maximize sampling time, the sample cart remained in the overhaul environment until the mannequin's SCBA was empty. Upon exit of the simulated overhaul, sampling media were capped and stored according to standard NIOSH sampling methods (Table 2) prior to being shipped to Galson Laboratories Inc. (East Syracuse, NY) for analysis.

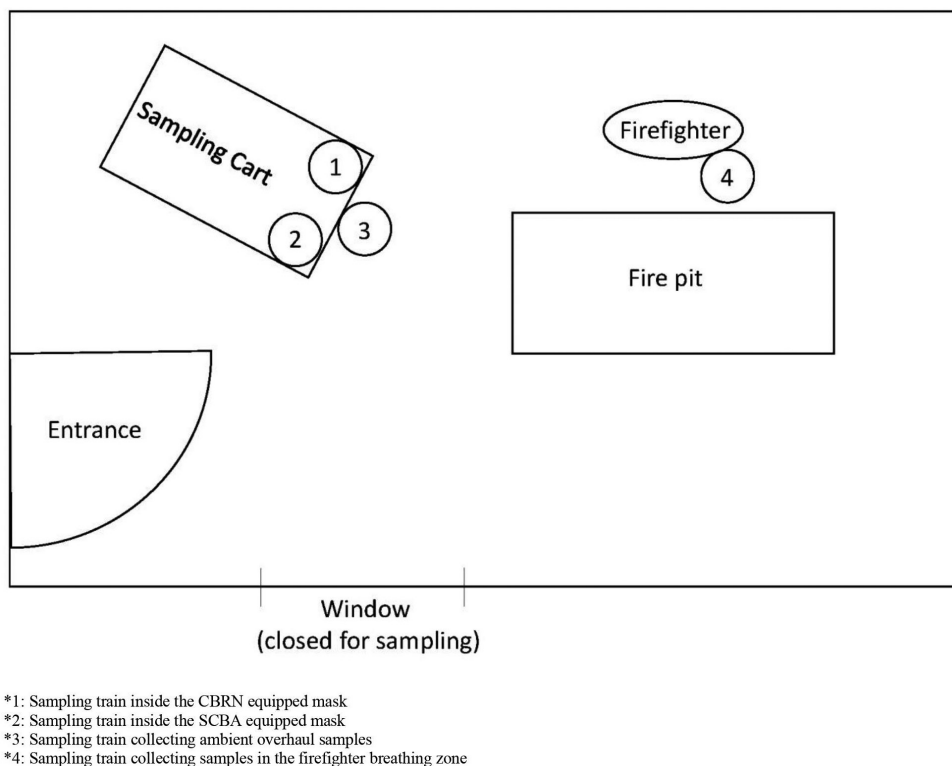


Figure 1. Diagram of the standard overhaul environments sampling setup. 1: sampling train inside the CBRN-equipped mask. 2: sampling train inside the SCBA-equipped mask. 3: sampling train collecting ambient overhaul samples. 4: sampling train collecting samples in the firefighter breathing zone.

Table 2. Analytical limits of detection.

Analyte	NIOSH method	Analytical LOQ (μg) ^a	Sample media	Flow rate (LPM)	Calculated sensitivity per sample (ppm) ^b
PNAHs	NIOSH 5506	0.3	37 PTFE treated Amberlite XAD-2	2.0	
1-Nitropyrene					0.0010
Acenaphthene					0.0016
Acenaphthylene					0.0016
Anthracene					0.0014
Benzo(a)anthracene					0.0011
Benzo(a)pyrene					0.0010
Benzo(b)fluoranthene					0.0010
Benzo(e)pyrene					0.0010
Benzo(g,h,i)perylene					0.0009
Benzo(k)fluoranthene					0.0010
Chrysene					0.0011
Dibenz(a,h)anthracene					0.0009
Fluoranthene					0.0012
Fluorene					0.0015
Indeno(1,2,3-cd) pyrene					0.0009
Naphthalene					0.0019
Phenanthrene					0.0014
Pyrene					0.0012
Inorganic acids	OSHA 165SG	5.0	Washed silica gel	0.2	
Phosphoric acid					0.42
Hydrobromic acid					0.50
Hydrochloric acid					1.12
Hydrofluoric acid					2.04
Nitric acid					0.65
Sulfuric acid					0.42
Aromatic hydrocarbons	NIOSH 1501		Charcoal	0.2	
Benzene		2.0			0.21
Chlorobenzene		5.0			0.36
Cumene		5.0			0.34
Ethylbenzene		5.0			0.38
<i>m</i> -Dichlorobenzene		5.0			0.28
<i>o</i> -Dichlorobenzene		5.0			0.28
<i>p</i> -Dichlorobenzene		5.0			0.27
Toluene		5.0			0.44
Vinyl toluene		200.0			13.8
Xylene		15.0			1.15
Aldehydes	NIOSH 2016		Treated silica gel	0.75	
Acetaldehyde					0.0049
Benzaldehyde					0.0020
Butyraldehyde					0.0030
Crotonaldehyde					0.0031
Formaldehyde					0.0072
Isovaleraldehyde					0.0025
Propionaldehyde					0.0037
Valeraldehyde					0.0025
NO ₂	NIOSH 6014		Treated molecular sieve	0.2	0.1771

^aAnalytical LOQ provided by Galson Laboratories.^bBased on a 15-min sampling time.

High-exposure overhaul

Actual overhaul environment measurements have demonstrated a high degree of variability (Bolstad-Johnson *et al.*, 2000; Burgess *et al.*, 2001). To compare the CBRN canister and SCBA effectiveness at reducing contaminant concentrations in overhaul environments at the upper end of the exposure range, six high-exposure overhaul settings were created by the Tucson Fire Department (TFD) at their Public Safety Training Facility (Tucson, AZ). These environments were created in a flashover chamber by continuously adding household materials including laminate wood flooring, vinyl flooring, particle board furniture (e.g. desk or night stand), and household electrical appliances (e.g. fan or vacuum) to a smoldering fire. To regulate the smolder, two firefighters stayed in the chamber and added water when necessary to knockdown flames that flared up. CO concentrations were not monitored in the high-exposure overhaul as there was active combustion occurring in an enclosed environment, and conditions were deemed by TFD to be hazardous for prolonged exposure by UA researchers.

For both the CBRN canister and SCBA testing in the high-exposure overhaul environment, the facepiece was adhered to the mannequin head through the use of Flame Stopper® 2000 adhesive (Gardner-Gibson Corporation, Tampa, FL), based on concerns of the facepiece seal being compromised that may influence the study results. Adhering the facepiece to the mannequin head ensured that contaminants that were entering the mask were due to canister or system breach, rather than potential leaks between the facepiece and mannequin head. Otherwise all samples were collected using the same equipment and sampling procedures as described in the standard overhaul methods with the exception of those collected on the firefighter. Firefighter samples were not collected in the high-exposure overhaul environment.

Samples collection on the cart began once the flames had been knocked down and the fire had been reduced to a pile of smolder and ash. At this point, household materials were added by a firefighter to continually create smoke without flames. The sample cart was placed in the flashover chamber approximately 25 feet from the smolder and ash. This distance was necessary to keep heat exposure of the sampling cart at safe levels for operation of the DBM. Upon exit of the simulated overhaul, media were capped and stored according to the applicable sampling methods prior to being shipped to Galson Laboratories Inc. (East Syracuse, NY) for analysis.

For both standard and high-exposure overhaul settings, STATA v12 (StataCorp LLP, College Station, TX) was used to manage data and conduct

statistical analyses. Percent reduction was calculated as $1(\text{In-mask concentration}/\text{Ambient concentration})$. Due to the small sample size, a non-parametric Wilcoxon rank sum test was used to test for differences in contaminant concentrations between the means of sample group.

Results

Fit tests of the respirator facepieces were performed on the mannequin heads prior to sampling in both parts of the study. Fit testing was completed in APR configuration using the CBRN canisters that were challenged in the study. Prior to the standard overhaul setting sampling, mannequin Head 1 had a fit factor of 1331 on the first day and 1257 on the second day; Head 2 had a fit factor of 1268 on the first day and 1156 on the second day. In the high-exposure overhaul setting, mannequin Head 1 had a fit factor of 1321 and Head 2 had a fit factor of 1201.

Standard overhaul

Fifteen simulated burns were achieved over 2 days at the Yuma Public Safety Training Facility. Burns 1 through 6 were completed on the first day and Burns 7 through 15 were completed on the second day. The average sampling times were 15.4 ± 1.25 , 14.9 ± 1.42 , and 10.6 ± 0.71 min for Ambient, In-mask (Heads 1 and 2), and firefighter samples, respectively. Ambient cart and in-mask sampling durations were longer than firefighter sampling durations because firefighters were removed from the environment once their SCBA tank reached 33% capacity, while the cart continued to sample until the SCBA expired. All sampling pumps were activated at the same time, differences in sample time between In-Mask and Ambient samples occurred due to the process of recording run times and shutting off the pumps once the cart was removed from the overhaul environment. The average temperature in the sampling environment was $43.9 \pm 3.9^\circ\text{C}$ ($110.8 \pm 9.9^\circ\text{F}$); average RH was $24.6 \pm 6.0\%$.

Of the chemical analytes sampled, 10 were found in the ambient (on-cart or firefighter) samples at concentrations greater than the limit of quantification (LOQ) (Table 3). The highest analyte concentrations for the on-cart ambient samples were acetaldehyde with an average concentration of 0.19 ppm and formaldehyde with an average concentration of 0.14 ppm. Much lower on-cart concentrations of propionaldehyde, acenaphthylene, and naphthalene were measured. Chemical concentrations measured from ambient

Table 3. Average analyte concentrations present in the standard overhaul setting above the LOQ ($n = 15$).

Analyte	Ambient concentration (ppm)	Firefighter concentration (ppm)	In-mask CBRN		In-mask SCBA	
			Concentration (ppm)	Reduction (%) ^a	Concentration (ppm)	Reduction (%) ^a
Acetaldehyde	0.19 ± 0.13	0.61 ± 0.41	0.009 ± 0.022	95	-	100
Crotonaldehyde	-	0.030 ± 0.040	-	-	-	-
Formaldehyde	0.14 ± 0.18	0.51 ± 0.70	-	100	-	100
Isovaleraldehyde	-	0.013 ± 0.024	-	-	-	-
Propionaldehyde	0.0084 ± 0.0218	0.068 ± 0.113	-	100	-	100
Acenaphthylene	0.0022 ± 0.0087	0.0028 ± 0.0019	-	100	0.0012 ± 0.0003	40
Naphthalene	0.0030 ± 0.0017	0.0052 ± 0.0040	-	100	-	100
Sulfuric acid	-	0.31 ± 0.05	-	-	-	-
Hydrochloric acid	-	0.97 ± 0.41	-	-	-	-
Total particulate ^b	7.86 ± 4.66	14.72 ± 4.54	4.11 ± 3.24	48	0.37 ± 0.36	95

(-) results were below the LOQ.

^aPercent reduction calculated as $1 - (\text{In-mask concentration} / \text{Ambient concentration})$.

^bConcentration in mg m^{-3} .

samples collected on the body of the firefighters exceeded those measured on the cart for all analytes. For formaldehyde, the firefighter concentration averaged 0.51 ppm, 1.7 times greater than the ACGIH short-term exposure limit (STEL). Acetaldehyde was measured above the LOQ in only one of the 15 burns for the in-mask CBRN samples, with an average 95% reduction compared with the on-cart ambient samples. The reduction was 100% for all other analytes detected on the ambient on-cart samples. For the in-mask SCBA sample, the only analyte measured above the LOQ was acenaphthylene, detected in 2 of the 15 burns, with a 40% reduction compared with the on-cart samples. The reduction was 100% for all other analytes detected on the ambient on-cart samples.

The mean peak particulate matter exposure for all ambient samples collected on the cart was $7.86 \pm 4.66 \text{ mg m}^{-3}$ (Table 3). The firefighter simulating overhaul activities had a mean peak particulate matter exposure of 14.72 mg m^{-3} . The mean peak particulate matter exposure in the CBRN-equipped mask was $4.11 \pm 3.24 \text{ mg m}^{-3}$. This represents an average 47.7% reduction in particulate matter concentration by the CBRN canister, compared with ambient conditions. The mean peak particulate matter concentration in the SCBA-equipped mask was $0.37 \pm 0.36 \text{ mg m}^{-3}$ ($n = 13$), representing a 95.3% reduction in average peak particulate exposure.

High-exposure overhaul

The average temperature in the high-exposure overhaul setting was $54.2 \pm 6.4^\circ\text{C}$ ($129.4 \pm 15.3^\circ\text{F}$) and the average RH was $40.6 \pm 14.1\%$. In the ambient (on-cart)

environment, 20 chemical analytes were measured at concentrations above the LOQ (Table 4). For the in-mask CBRN samples, in-mask detectable concentrations of acetaldehyde were measured in five of the six burns, with a calculated reduction of 65% compared with the ambient samples. For formaldehyde, CBRN in-mask detectable concentrations were measured in five of the six burns, with a calculated reduction of 89%. The in-mask CBRN percent reduction was 100% for all remaining chemical analytes. In one burn elevated concentrations of benzene and ethylbenzene were found in the in-mask but not in the ambient sample; as these results were unlikely and a potential transposition of results in the analytical laboratory could not be ruled out, these results were excluded from further analysis. In one of the six burns the SCBA o-ring failed (diagnosed by the sound of leaking air coming from the SCBA bottle connection), leaving five burns available for analysis. For the in-mask SCBA samples no chemical analytes were present above the LOQ, resulting in 100% calculated reduction. Ambient total particulate concentrations exceeded 20 mg m^{-3} for the high-exposure overhaul setting. In-mask concentrations averaged 0.82 mg m^{-3} for CBRN and 0.51 mg m^{-3} for SCBA, with exposure reductions of >96 and >97%, respectively.

Discussion

For the simulated standard overhaul setting, both the CBRN filter and SCBA prevented breakthrough of most of the chemicals measured, with the exception of acetaldehyde for the CBRN filter and acenaphthylene

Table 4. Average analyte concentrations present in the high-exposure overhaul setting ($n = 6$).

Analyte	Ambient concentration (ppm)	In-mask CBRN		In-mask SCBA	
		Concentration (ppm)	Reduction (%) ^a	Concentration (ppm) ^b	Reduction (%) ^a
Acetaldehyde	25.67 ± 13.54	8.87 ± 5.54	65	-	100
Benzaldehyde	0.47 ± 0.13	-	100	-	100
Butyraldehyde	0.38 ± 0.12	-	100	-	100
Crotonaldehyde	1.20 ± 0.45	-	100	-	100
Formaldehyde	11.33 ± 5.16	1.28 ± 1.41	89	-	100
Isovaleraldehyde	0.39 ± 0.14	-	100	-	100
Propionaldehyde	4.00 ± 2.56	-	100	-	100
Valeraldehyde	0.12 ± 0.06	-	100	-	100
Acenaphthene	0.0088 ± 0.0008	-	100	-	100
Acenaphthylene	0.07 ± 0.08	-	100	-	100
Anthracene	0.01 ± 0.01	-	100	-	100
Fluoranthene	0.038 ± 0.026	-	100	-	100
Fluorene	0.021 ± 0.021	-	100	-	100
Naphthalene	0.13 ± 0.13	-	100	-	100
Phenanthrene	0.041 ± 0.052	-	100	-	100
Pyrene	0.011 ± 0.016	-	100	-	100
Hydrochloric acid	2.86 ± 3.02	-	100	-	100
Benzene ^b	4.52 ± 2.86	-	100	-	100
Ethylbenzene ^b	0.40 ± 0.05	-	100	-	100
Nitrogen dioxide	0.43 ± 0.66	-	100	-	100
Total particulate ^c	>20.00	0.82 ± 1.67	>96	0.51 ± 1.02	>97

(-) results were below the LOQ.

^aPercent reduction calculated as $1(\text{In-mask concentration}/\text{Ambient concentration})$.

^bAveraged over five burns.

^cUnits are in mg m^{-3} .

for the SCBA. However, the challenge concentrations were relatively low, limiting our ability to evaluate for exposure reduction of most of the analytes measured. For the simulated high-exposure overhaul setting, CBRN in-mask concentrations were detected again for acetaldehyde, and also for formaldehyde, whereas no chemical concentrations were measurable in the SCBA mask. For the CBRN filter in the high-exposure overhaul setting, in-mask formaldehyde samples were greater than the ACGIH STEL (0.3 ppm) in 3 burns and were above the ACGIH TLV-TWA (0.1 ppm) in five burns. For particulates, CBRN in-mask concentrations were higher in the standard than high-exposure simulated overhaul settings, suggesting a potential problem with mask fit addressed by sealing the facepiece to the mannequin head for the high-exposure tests, whereas more consistent lower concentrations were found in mask for the SCBA in both the standard and high-exposure simulated overhaul settings. One inconsistent finding was the measurement of SCBA in-mask concentrations of acenaphthylene in the standard but

not high-exposure overhaul setting, for which a suitable explanation could not be found. Given the higher challenge concentration in the high-exposure setting, we believe that SCBA do provide suitable protection against this contaminant.

The standard overhaul simulated environments in the current study generated concentrations of combustion contaminants on the lower end of real-world overhaul scenarios, based on previous overhaul characterization studies in Arizona (Bolstad-Johnson *et al.*, 2000; Burgess *et al.*, 2001). For example, average ambient on-cart concentrations of acetaldehyde and formaldehyde in the current study, 0.19 and 0.14 ppm, respectively, were lower than the measured averages in actual overhaul, which in Phoenix ranged from 0.34 to 0.38 ppm for acetaldehyde and 0.25 to 0.26 for formaldehyde. In addition, the ambient concentrations in the standard overhaul simulations were substantially lower at the cart compared with measurements in the breathing zone of firefighters performing overhaul activities nearby. However, mean ambient on-cart

formaldehyde concentration still exceeded the ACGIH TLV-TWA of 0.1 ppm, while being below the ACGIH STEL of 0.3 ppm.

Average analyte concentrations in the high-exposure overhaul simulated environments exceeded those previously measured during firefighter overhaul (Bolstad-Johnson *et al.*, 2000; Burgess *et al.*, 2001). The average concentrations in the current study were above the maximum values previously reported, with the exception of nitrogen dioxide which averaged 0.43 ppm in the current study as compared with 3.6 ppm (Bolstad-Johnson *et al.*, 2000). In addition, the high-exposure overhaul concentrations often exceeded occupational standards. Acetaldehyde, crotonaldehyde, formaldehyde, hydrochloric acid, and benzene were present at concentrations above the ACGIH exposure recommendations. Acetaldehyde had an average concentration of 25.7 ppm, 0.7 ppm greater than the ACGIH TLV-C; crotonaldehyde concentrations averaged 1.2 ppm, four times greater than the TLV-C of 0.3 ppm; formaldehyde concentrations averaged 11.3 ppm, 37.7 times greater than ACGIH STEL of 0.3 ppm; hydrochloric acid concentrations averaged 2.86 ppm, 0.86 ppm greater than the ACGIH TLV-C of 2.0 ppm; and benzene concentrations averaged 3.78 ppm, 7.6 times greater than the 0.5 ppm ACGIH TLV-TWA and 1.28 ppm greater than the ACGIH STEL of 2.5 ppm. Although these high-exposure simulated overhaul environment exposure levels are unlikely to be encountered in typical overhauls, they may be present in a small percentage of overhauls in residential and/or industrial fires given the diversity of conditions present in actual fires across the country.

The current study results are consistent with previous APR studies conducted at the University of Arizona, except for the particulate breakthrough. Table 5 provides a summary of prior University of Arizona APR (including CBRN) studies including the percent reduction of challenge concentrations based on in-mask concentrations of acetaldehyde, formaldehyde, and particulate matter. However, these breakthrough concentrations are higher than anticipated based on the published results of the NIOSH testing conditions and results for the Scott CBRN canister; they report a breakthrough of 1 ppm with a challenge concentration of 500 ppm for 60 min (challenge concentrations for acetaldehyde and particulate matter are not available). One potential explanation for our findings is that NIOSH test conditions expose the canister to one contaminant at a time, whereas exposures in the overhaul setting are to multiple contaminants simultaneously. NIOSH CBRN canister performance requirements include single contaminant tests for multiple hazards and were not designed to specifically address multiple contaminants or at high ambient temperatures (NPPTL, 2008). Similar to what was observed in previous simulated overhaul filter studies (Jones *et al.*, 2016), there may be a correlation between increased temperature and post-filter formaldehyde concentrations. In addition, our test conditions involved higher flow rates than used by NIOSH, which may also help explain our divergent results.

As the percent reduction for particulates was high for both the CBRN filter and SCBA at in the simulated high-exposure overhaul setting, we believe that the 48% reduction in particulate matter in-mask observed for

Table 5. Summary of CBRN respirator research in simulated overhaul environments.

Study	Temperature (average °C)	Contaminates	Ambient	In-mask	Reduction (%)
Currie <i>et al.</i> (2009) ^a	28.1	Acetaldehyde (ppm)	0.58	0.05	91
		Formaldehyde (ppm)	0.79	0.02	97
		Particulate (mg m ⁻³)	43.60	0.00	100
Jones <i>et al.</i> (2016) ^b	42.5	Acetaldehyde (ppm)	0.40	0.20	50
		Formaldehyde (ppm)	1.53	0.89	42
		Particulate (mg m ⁻³)	1.83	0.26	86
Jones <i>et al.</i> (2015) ^c	38.8	Acetaldehyde (ppm)	0.20	0.02	90
		Formaldehyde (ppm)	0.50	0.05	90
		Particulate (mg m ⁻³)	1.03	0.00	100
Current study (standard overhaul)	43.3	Acetaldehyde (ppm)	0.19	0.009	95
		Formaldehyde (ppm)	0.14	0.00	100
		Particulate (mg m ⁻³)	7.86	4.11	48
Current study (high-exposure overhaul)	54.2	Acetaldehyde (ppm)	25.67	8.87	65
		Formaldehyde (ppm)	11.33	1.28	89
		Particulate (mg m ⁻³)	20.00	0.82	>96

the CBRN canister compared with ambient conditions in the standard overhaul environment was likely due to leak around the facepiece rather than through the filter itself. Although the initial fit-testing results were consistent with a good seal, the facepiece may have been jostled when the cart was moved into the burn room. While the SCBA proved to be more protective than the CRBN, it did not completely eliminate particulate exposure. It would be anticipated that the reduction would be 100% due to the SCBA creating a positive pressure safeguard against leaks. Unfortunately, the source of this exposure was not determined. Particulates were collected and counted in real time; therefore, it was not possible to complete compositional analysis to determine if there were differences between the in-mask and ambient samples. Future research in this area should consider completing compositional analysis of particulate matter to help determine the possible source of any observed particulate matter.

The results of our study indicate that CBRN respirators provide greater protection for low-level gas concentrations encountered in the standard overhaul simulated exposure setting than the elevated concentrations encountered in the high-exposure overhaul setting; however, it is unclear if the difference was due to changes in effective filtration or lower challenge concentrations in the standard overhaul exposure setting. Concentrations in the high-exposure overhaul environments were more extreme across all toxicants and resulted in 20 toxicants plus particulates being present at concentrations above the LOQ, compared with nine contaminants plus particulates in the standard overhaul setting. The only exception to the reduced performance of the CBRN canisters in the high-exposure overhaul setting was the increased protection against particulates. This difference is likely due to the sealing of the facepiece onto the mannequin head in this setting. It is important also to recognize that CBRN filters are not tested against or expected to be protective against exposure to CO, which is chemical hazard frequently detected during overhaul (Bolstad-Johnson *et al.*, 2000; Burgess *et al.*, 2001).

There are a number of limitations to the current study. It was difficult to determine the effectiveness of the respirators against many products of combustion as only ten were present above the LOQ in the standard overhaul setting, compared with 21 in the high-exposure setting. On-cart ambient measurements in the standard overhaul setting were lower than those measured concurrently in the breathing zone of firefighters, a limitation that was addressed in part through subsequent high-exposure overhaul testing. A mannequin respirator rate of 32 breaths per minute and a tidal volume of 2.5 l were

used, which models strenuous exertion in relation to the International Organization for Standardization (ISO) standard for Respiratory Protective Devices-Human Factors-Part 1: Metabolic rates and respiratory flow rates (ISO/DTS 16976-1). Although firefighters can certainly breathe at a higher rate or larger tidal volume (Burgess and Crutchfield, 1995), exertion rates and minute volume may be lower for many actual overhauls. It is important to note that the high flow rates used in the current study exceed those used by NIOSH for testing CBRN filters, which as previously noted may help explain the divergence between the NIOSH testing results and those of the current study. The selected breathing rate executed in the sampling may have exceeded the rate necessary for select toxicants to have been removed via sorptive mechanisms in the CBRN filter. This may explain the in-mask CBRN exposure to formaldehyde and acetaldehyde. The facepiece was sealed to the mannequin heads in the high-exposure setting to prevent leakage around the facepiece and to better measure contaminants breaking through the canister, but leakage into the mask from between the facepiece and the face is always possible in actual firefighter use when positive pressure in the facepiece (such as provided by SCBA) is not present. Use of simultaneous integrated particulate sampling along with the real-time instruments used would have helped validate the higher than anticipated in mask particulate measures, particularly in the CBRN mask. It should be noted that CBRN canisters would not provide protection against CO and that monitoring for this contaminant should always be done on the fireground to assure that exposures are within applicable occupational exposure limits prior to removal of SCBA. Finally, the testing was limited to use of a CBRN canister attached to the firefighters' mask; use of a powered air-purifying respirator with a CBRN canister may have yielded different results.

Conclusion

SCBA was highly protective for all measured chemical analytes regardless of the conditions in the sampling environment. Given the aldehyde breakthrough with the CBRN canisters in the high-exposure overhaul setting, the use of CBRN canisters is not recommended as respiratory protection in overhaul environments when SCBA is an option, particularly when a high-exposure overhaul setting is anticipated. However, in the standard overhaul environment CBRN canisters reduced contaminant exposures to levels below occupational exposure limits and could be used in the event that SCBA is not a viable option, as long as CO levels are below occupational exposure limits. Our study findings also suggest that the protective

values found for CBRN canisters during NIOSH approval testing may not be representative of actual protective values when used in a firefighter overhaul setting, particularly in settings with high exposures, high ambient temperatures, and high flow rates due to strenuous exertion.

Acknowledgements

We would also like to thank Northwest Fire District (northwest Tucson metropolitan area, AZ) for their expertise and support provided during the study.

Funding

Funding for this project was provided by the Department of Homeland Security Standards and Technology Directorate through an Interagency Agreement with the National Personal Protective Technology Laboratory (NPPTL), a division of the National Institute for Occupational Safety and Health (NIOSH). Burn simulations were conducted at Tucson Fire Department and Yuma Fire Department training facilities. This project would not have been possible without their willingness to participate.

Conflict of interest

The authors declare no competing interests.

References

- Anthony TR, Joggerst P, James L *et al.* (2007) Method development study for APR cartridge evaluation in fire overhaul exposures. *Ann Occup Hyg*; 51: 703–16.
- Austin CC, Wang D, Ecobichon DJ *et al.* (2001) Characterization of volatile organic compounds in smoke at municipal structural fires. *J Toxicol Environ Health A*; 63: 437–58.
- Bolstad-Johnson DM, Burgess JL, Crutchfield CD *et al.* (2000) Characterization of firefighter exposures during fire overhaul. *AIHAJ*; 61: 636–41.
- Burgess JL, Crutchfield CD. (1995) Quantitative respirator fit tests of Tucson fire fighters and measurement of negative pressure excursions during exertion. *Appl Occup Environ Hyg*; 10: 29–36.
- Burgess JL, Nanson CJ, Bolstad-Johnson DM *et al.* (2001) Adverse respiratory effects following overhaul in firefighters. *J Occup Environ Med*; 43: 467–73.
- Currie J, Caseman D, Anthony TR. (2009) The evaluation of CBRN canisters for use by firefighters during overhaul. *Ann Occup Hyg*; 53: 523–38.
- Fent KW, Evans DE, Babik K *et al.* (2018) Airborne contaminants during controlled residential fires. *J Occup Environ Hyg*; 15: 399–412.
- Hostler D, Pendergast DR. (2018) Respiratory responses during exercise in self-contained breathing apparatus among firefighters and nonfirefighters. *Saf Health Work*; 9: 468–72.
- Jones L, Burgess JL, Evans H *et al.* (2016) Respiratory protection for firefighters—evaluation of CBRN canisters for use during overhaul II: In mask analyte sampling with integrated dynamic breathing machine. *J Occup Environ Hyg*; 13: 177–84.
- Jones L, Lutz EA, Duncan M *et al.* (2015) Respiratory protection for firefighters—evaluation of CBRN canisters for use during overhaul. *J Occup Environ Hyg*; 12: 314–22.
- Occupational Safety and Health Administration. (c1998–2004) 1910.134 App A. Washington, DC: Fit Testing Procedures—General Requirements. Available at <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.134AppA>. Accessed 13 February 2019.
- Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services 2013 Edition (1981) NFPA. Available at <https://submittalsarchive.nfpa.org/TerraViewWeb/ViewerPage.jsp?id=1981-2013.ditamap&pubStatus=FDR>. Accessed April 2016.
- The National Personal Protective Technology Laboratory (NPPTL). (2008) Pittsburg, PA: Standard Respirator Testing Procedures: Air-Purifying Respirators with Chemical, Biological, Radiological, and Nuclear Protection. Available at <https://www.cdc.gov/niosh/npptl/stps/aprespcbrn.html>. Accessed 31 October 2019.