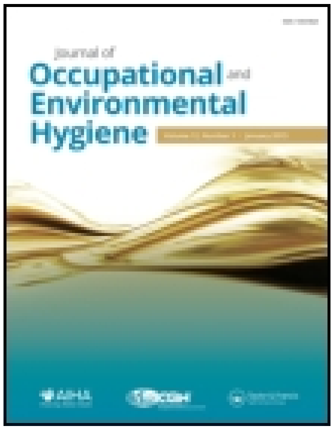

Journal of Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uoeh20

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Leaton Jones[a], Eric A. Lutz[a], Michael Duncan[a] & Jefferey L. Burgess[a]

[a] Division of Community, Environment, and Policy, Mel and Enid Zuckerman College of Public Health, University of Arizona, Tucson, Arizona

Accepted author version posted online: 04 Mar 2015.Published online: 15 Apr 2015.

Journal of Occupational and Environmental Hygiene, 12: 314–322
ISSN: 1545-9624 print / 1545-9632 online

DOI: 10.1080/15459624.2014.989363

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Leaton Jones, Eric A. Lutz, Michael Duncan, and Jefferey L. Burgess
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In the United States, there are approximately 366,600 structural fires each year. After visible flames are extinguished, firefighters begin the overhaul stage of firefighting to smother remaining hot spots and initiate investigations. Typically during overhaul significant ambient concentrations of chemical contaminants remain. However, previous research suggests that the use of air purifying respirators (APR) fitted with chemical, biological, radiological, and nuclear (CBRN) canisters may reduce occupational respiratory exposures. This pilot study used large-scale prescribed burns of representative structural materials to perform simultaneous, side-by-side, filtering and service-life evaluations of commercially available CBRN filters. Three types of CBRN canisters and one cartridge were challenged in repetitive post live-fire overhaul exposure tests using a sampling manifold apparatus. At a flow rate of 80L/min, nine tests were conducted in the breathing zone for three different exposure durations (0–15 min, 0–30 min, and 0–60 min). Fifty different chemicals were identified for evaluation and results indicate that 21 of the 50 chemicals tested were in the air of the overhaul environment. Respirable particles and formaldehyde were consistently present above the American Conference of Governmental Industrial Hygienists (ACGIH®) recommended exposure level (REL) and threshold limit ceiling value (TLV_c), respectively. Each filter effectively reduced concentrations for respirable particulates below the maximum recommended level. Formaldehyde was reduced, but not consistently filtered below the TLV_c. These results were consistent across all exposure durations. This study indicates that, regardless of brand, CBRN filters provide protection from the vast majority of particle and gas-phase contaminants. However, due to formaldehyde breakthrough, CBRN filters do not provide complete protection during firefighter overhaul.

Keywords firefighter, overhaul, protection, respiratory

Address correspondence to: Leaton Jones, Division of Community, Environment, and Policy, Mel and Enid Zuckerman College of Public Health, University of Arizona, Tucson, Arizona 1295 N. Martin Ave., Tucson, AZ, 8572; e-mail: leatonjo@email.arizona.edu
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INTRODUCTION

Firefighters have elevated cancer rates which increase with duration of employment highlighting the need for adequate workplace protection.[1,2] During a fire, firefighters wear self-contained breathing apparatus (SCBA) to protect against acutely toxic concentrations of products of combustion. After a fire has been extinguished, firefighters start overhaul, a phase when potential reignition sources are extinguished and site investigations begin. During overhaul, firefighters are exposed to potentially harmful concentrations of residual combustion-related particulates, gases, and vapors such as carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and more than 120 volatile organic compounds (VOCs), including carcinogens such as benzene, 1,2-butadiene, formaldehyde, naphthalene, styrene, and toluene.[3,4] Formaldehyde is of particular concern in this group, given its status as a known human carcinogen and upper airway irritant.[5,6]

Although it is recommended that firefighters use SCBA during overhaul, many fire departments either do not require or do not enforce this procedure.[7] For these departments, a common practice incorporates real-time field quantification of CO as the primary metric for determining when to doff SCBA and begin overhaul. When post-fire CO concentrations decrease below a pre-established threshold, typically 30 ppm, firefighters remove their SCBA and enter the structure, typically without respiratory protection. [8]

One approach considered by fire departments has been the use of APRs during overhaul. To more fully understand and mitigate associated risks, Burgess et al.[7] compared the respiratory effects of firefighters who wore APRs fitted with multipurpose cartridges during overhaul to those who did not. They identified acute changes in lung function and increased serum pneumoprotein in both groups, indicating lower respiratory tract damage, concluding that use of APRs fitted with multipurpose cartridges may not completely protect firefighters during overhaul. This lack of firefighter respiratory protection using APRs with multipurpose cartridges is supported by the findings of de Vos et al.[9,10] who investigated APR cartridge performance in various wildland fire scenarios.

TABLE I. List of Household Material Used During Testing

Material	Quantity	Dimensions
Fiberglass Insulation	1	60.96 × 121.92 × 24.136- cm
Laminate Flooring Strip	3	19.8 × 128.5 × 0.7 - cm
OSB Particle Board	1	122 × 122 × 1.9- cm
PVC Pipe	1	5.1cm (dia) x 30.5 cm
Sofa Cushion	1	∼61 × 61 × 10- cm
Textiles (cotton, nylon)	∼0.2 kg	
Video Cassette Recorder (VCR)	1	∼45.72 × 45.72 × 12.7- cm
Vinyl Flooring Strip	3	15.24 × 91.44- cm
Wooden Pallet	1	121.9 × 101.6- cm

To further elucidate the performance of APR filters against overhaul contaminants, a study by Anthony et al.[11] demonstrated that the multipurpose cartridges used in the previous overhaul study by Burgess et al.[7] were not fully protective against all smoke contaminants. To determine if other filters could provide greater protection, Currie et al.[12] tested the effectiveness of three, commercially available, National Institute of Occupational Safety and Health (NIOSH)-approved, chemical, biological, radiological, and nuclear (CBRN) canisters and one NIOSH-approved cartridge that was not approved for CBRN, but was of similar shape and size. This study found that they were effective in reducing acetaldehyde, acrolein, benzaldehyde, formaldehyde, glutaraldehyde, butyraldehyde, crontonaldeyde, and cyanide to below NIOSH recommended exposure levels (RELs). The results of this work indicated improved performance of CBRN canisters over multipurpose and CBRN cartridges when challenged with a small-scale, chamber-based, post-fire, overhaul simulation. However, the performance of the commercially available CBRN canisters and cartridges in field post-fire environments is unclear. As such, we hypothesized that commercially available CBRN canisters/cartridges will provide adequate respiratory protection when challenged at overhaul-relevant exposure times at a physiological plausible flow rate consistent with actual overhaul environments following live-fire burns.

METHODS AND MATERIALS

To determine exposure reduction effectiveness of CBRN canisters/cartridges, a series of burns cycles with associated sampling durations [n = 9 sampling durations x 4 sampling trains (3 canisters/cartridge plus 1 ambient) = 36)] were conducted at the Northwest Fire District (NWFD) Fire Training Center (Marana, AZ) (Figure 1). Measured quantities of common residential structural and household items were used during the burns to simulate actual overhaul environments (Table I). During each cycle, fires burned for approximately 10 minutes until a maximum temperature was achieved and suppressed with water per standard firefighter procedures. Internal maximum "ambient" temperatures of the burn room averaged 167°C, with a range of 50°C–614°C during the combustion period. Ambient temperatures at the beginning of sampling averaged 42.3°C, with a range of 26.7°C–56.7°C. After fire suppression, carbon monoxide concentrations were monitored until levels reached 30 ppm, at which time sampling began using a custom air sampling manifold. The sampling manifold allowed for simultaneous side-by-side canister/cartridge and ambient assessment (Figures 2 and 3). Although a NWFD standard operating procedure dictates the use of cross draft ventilation before and during overhaul to minimize contaminant exposure,[8] this was not done during this study in an attempt to challenge the APRs with the greatest chemical concentrations possible.

The three commercially available NIOSH-approved APR CBRN canisters and one non-CBRN cartridge were used during testing. Each canister/cartridge was assigned a number (1-4) for identification purposes. Each filter was used for a

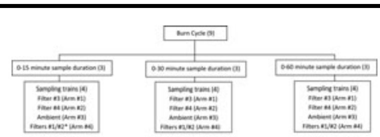

FIGURE 1. Sampling plain flow chart.

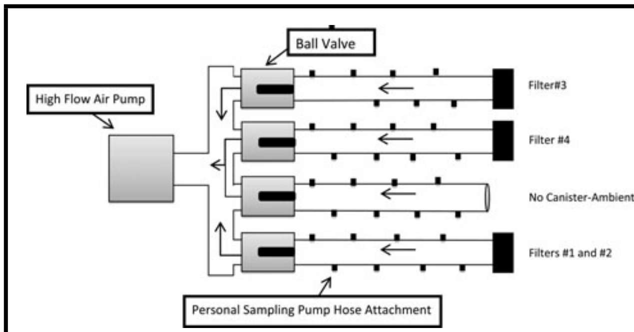

FIGURE 2. Top view of the sampling manifold.

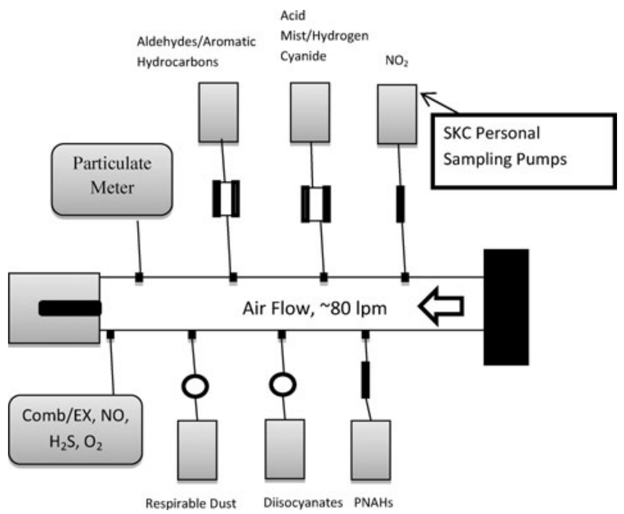

FIGURE 3. Sampling schematic for one arm of the sampling manifold.

single iteration, and replaced with a new identical filter, in the same manifold location, prior to the start of each new test.

Each filter was randomly assigned to one arm of the sampling manifold for all nine test iterations while one arm of the sampling manifold remained open during testing to measure ambient conditions. Due to randomization of canisters/cartridge, the cartridge not NIOSH approved for CBRN (filter #2) was not evaluated at the 30-minute sampling duration. With the filter in place, each arm of the sampling manifold was adjusted for a flow rate of approximately 80 L/min, representing respiratory rates for males, ages 31–41 years, above the 50th percentile during high-intensity activity, per the Environmental Protection Agency's (EPA) *Exposure Factors Handbook*.[13] Flow rates were confirmed using a TSI VelociCalc (TSI, Inc., Shoreview, MN). Three different sampling durations, repeated in triplicate, were used during testing, namely: 0–15 min, 0–30 min, and 0–60 min. All sampling durations were randomized for each post-burn test to control for confounding associated with variation in residual heat in the burn room.

After each fire was extinguished and CO concentrations dropped below 30 ppm, the sampling manifold was placed inside the burn room via a wheeled cart approximately 1 m from the smoldering materials in a manner that approximated the breathing zone of a working firefighter. Analyte sampling was performed using six calibrated SKC personal sampling pumps (SKC, Inc., Eighty Four, PA), a TSI Sidepak personal aerosol monitor (TSI Inc., Shoreview MN), and a MSA four-gas meter (Mine Safety Appliances, Pittsburgh, PA) on each arm of the manifold. The pumps and direct read instruments remained in the same location on the arm for all sampling durations. The sampling system is depicted in Figure 3. A total of 50 analytes were measured during each of the test durations, as detailed in Table II. Analytical samples were sent to Galson Laboratories Inc., of East Syracuse, NY, for analysis.

TABLE II. Contaminants Measured and Analysis Method

Contaminants	Method/Collection Alignment
Aldehydes (8 compounds)	
Acetaldehyde	NIOSH 2016/
Benzaldehyde	Treated Silica Gel
Butyraldehyde	
Crotonaldehyde	
Formaldehyde	
Isovaleraldehyde	
Propionaldehyde	
Valeraldehyde	
Aromatic HC (10 compounds)	
Benzene	NIOSH (Various)/
Chlorobenzene	Charcoal
Cumene	
m-Dichlorobenzene	
o-Dichlorobenzene	
p-Dichlorobenzene	
Ethyl benzene	
Toluene	
Vinyl toluene	
Xylene	
Inorganic Acid (6 compounds)	
Hydrobromic acid	NIOSH 7903/
Hydrochloric acid	Washed Silica Gel
Hydrofluoric acid	
Nitric acid	
Phosphoric acid	
Sulfuric acid	
Diisocyanates (6 compounds)	
HDI	OSHA PV2092/
HMDI	Treated GFF
IPDI	
MDI	
2,4-TDI	
2,6-TDI	
Hydrogen Cyanide	NIOSH 6010/
	Soda Lime
PNAHs (18 compounds)	
Acenaphthene	NIOSH 5506/
Acenaphthylene	37 PTFE/Treated Amberlite
Anthracene	XAD-2
Benzo(a)anthracene	
Benzo(a)pyrene	
Benzo(b)fluoranthene	
Benzo(e)pyrene	
Benzo(g,h,i)perylene	
Benzo(k)fluoranthene	
Chrysene	
Dibenzo(a,h)anthracene	

(Continued on next page)

TABLE II. Contaminants Measured and Analysis Method *(Continued)*

Contaminants	Method/Collection Alignment
Fluoranthene	
Fluorene	
Indeno(1,2,3-cd)pyrene	
Naphthalene	
1-Nitropyrene	
NO_2	NIOSH 6014/ Treated Molecular Sieve

MSA 4 Gas Meter (O_2, SO_2, H_2S and Combustibles)

All statistical tests used Stata version 12.1 (StataCorp., College Station, TX). A Kruskal-Wallis test was performed to evaluate median differences in measured contaminants between each filter and between each sampling duration. If statistical significance resulted, a Wilcoxon Rank Sum test with Bonferroni correction was performed to assess significance within the individual filter groups. A linear regression was performed to determine if there was any relationship between sampling duration/temperature and analyte concentrations. For all tests, an alpha error level of 0.05 was applied.

RESULTS

Sampling indicated the presence of 21 (42%) analytes in the ambient overhaul environment detected above the level of quantification (LOQ), including: 2,6-TDI monomer, acenaphthylene, acetaldehyde, anthracene, benzaldehyde, benzene, butyraldehyde, crotonaldeyhde, formaldehyde, HDI monomer, hydrochloric acid, hydrogen cyanide, IPDI monomer, isovaleraldehyde, MDI monomer, naphthalene, NO_2, phenanthrene, propionaldehyde, respirable particulates, and valeraldehyde (Table III). Formaldehyde and respirable particulates were present above the published American Conference of Governmental Industrial Hygienists (ACGIH®) threshold limit value ceiling (TLV_c), short-term exposure limit (STEL), or time-weighted average (TWA) values[14] Analytes with only TLV®-TWA limits were calculated to represent an 8-hour work day. While CO was relatively elevated, the MSA four-gas meter did not detect O_2, hydrogen sulfide, or explosive limits outside recommended levels.

Of the 21 analytes detected above the LOQ in the post-fire overhaul ambient environment, as many as 15 were also

TABLE III. Post-fire Overhaul Analyte Concentrations (ppm) above LOQ

Analyte	Mean	Max	Min.	ACGIH® TLV®
1. 2,6-TDI Monomer	0.01	0.01	0.01	0.02^A
2. Acenaphthylene	0.0004	0.0004	0.0004	NE
3. Acetaldehyde	0.4042	0.71	0.2	25
4. Anthracene	0.0017	0.0062	0.002	0.05^B
5. Benzaldehyde	0.0387	0.057	0.02	NE
6. Benzene	0.2	0.3	0.2	2.5^B
7. Butyraldehyde	0.0163	0.3	0.009	NE
8. Crotonaldeyhde	0.0924	0.072	0.02	0.3^C
9. Formaldehyde	1.53	2	0.01	0.3^C
10. HDI Monomer	0.0004	0.002	0.0005	0.005^B
11. Hydrochloric Acid	0.12	0.14	0.1	2^C
12. Hydrogen Cyanide	0.85	1.3	0.4	4.7^C
13. IPDI monomer	0.00003	0.0003	0.0003	0.005^B
14. Isovaleraldehyde	0.02	0.03	0.007	NE
15. MDI monomer	0.002	0.003	0.0008	NE
16. Naphthalene	0.0008	0.0009	0.0008	15^A
17. NO_2	0.2	0.63	0.5	0.2^B
18. Phenanthrene	0.016	0.03	0.0078	NE
19. Propionaldehyde	0.04	0.06	0.02	NE
20. Respirable Particulates	1.83	14.88	0.11	$3(mg/m^3)^D$
21. Valeraldehyde	0.00001	0.02	0.008	50^t

Note: NE - no established TLVs
^{A}Indicates short term exposure limit (STEL) no ceiling limit available.
^{B}Indicates time-weighted average (TWA) no ceiling limit available.
^{C}Indicates ceiling limit
^{D}Ref. no. [14] Appendix B: Particles, not Otherwise Specified (PNOS), respirable.

TABLE IV. Mean downstream concentrations (ppm) by CBRN brand and sampling duration

		Filter #1	Filter #2	Filter #3	Filter #4
Analyte	Sampling Duration (minutes)	CONC	CONC	CONC	CONC
2,6- TDI Monomer	15				
	30				
	60				0.0005
Acenaphthylene	15				
	30				
	60		0.004	0.003	0.0047
Acetaldehyde	15	0.29	0.1	0.28	0.3
	30	0.2		0.13	0.22
	60	0.35	0.075	0.14	0.3
Benzaldehyde	15	0.03		0.04	0.03
	30	0.02		0.02	0.03
	60	0.01	0.03	0.02	0.043
Benzene	15	0.2		0.3	0.3
	30	0.1		0.02	
	60	0.1	0.1	0.15	0.2
Butyraldehyde	15				
	30				
	60				0.0085
Crotonaldeyhde	15	0.07		0.08	0.07
	30	0.04		0.03	0.03
	60	0.05	0.04	0.03	0.06
Formaldehyde	15	**0.96**	**0.58**	**1.03**	**1.4**
	30	**1.1**		**0.84**	**1.4**
	60	**0.72**	**0.44**	**0.64**	**1.6**
Isovaleraldehyde	15	0.06		0.02	0.03
	30				
	60	0.007	0.008	0.006	0.005
Naphthalene	15	0.003			
	30				
	60		0.012	0.01	0.011
NO2	15				
	30				
	60			0.001	0.073
Phenanthrene	15				
	30				
	60		0.002		0.0019
Propionaldehyde	15	0.04		0.06	0.07
	30	0.02		0.01	0.03
	60	0.01	0.009	0.01	0.03
Respirable Particulates	15	0.3	0.06	0.28	0.9
	30	0.01		0.01	0.8
	60	0.05	0.8	0.53	0.05
Valeraldehyde	15			0.02	
	30	0.01			0.01
	60	0.1	0.01	0.09	0.005

detected downstream of CBRN canisters/cartridge. Twelve analytes were detected downstream of the filter #3, nine from the filter #1, 12 from filter #2, and 15 downstream of filter #4 (Table IV). None of the analytes detected downstream of the canisters/cartridge was detected above ACGIH reference thresholds, with the exception of formaldehyde. Formaldehyde was detected downstream at concentrations above ACGIH TLV_c for all the filters through all test iterations and sampling

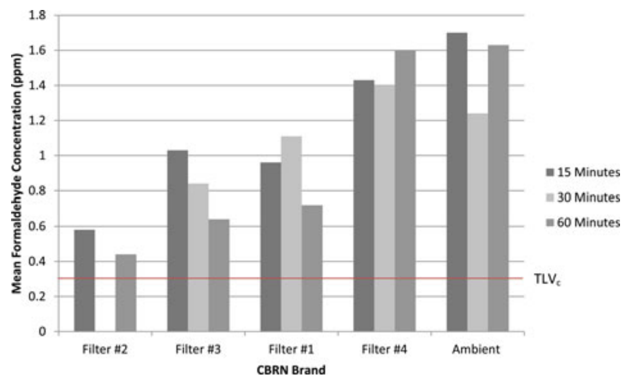

FIGURE 4. Aggregated mean formaldehyde concentrations (ppm) by CBRN brand and sampling duration.

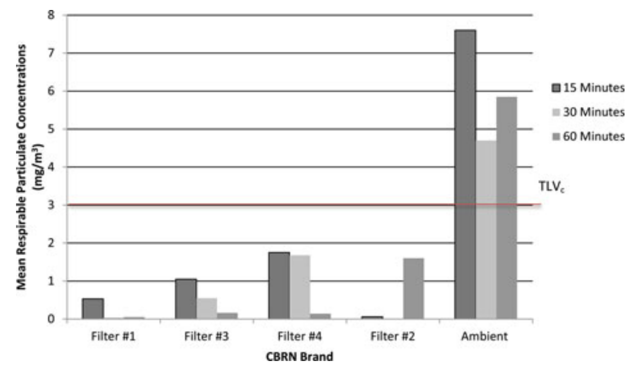

FIGURE 6. Aggregated mean respirable particulate concentrations (mg/m^3) by CBRN brand and sampling duration.

durations (Figure 4). Greater formaldehyde concentrations were associated with the temperature at the start of sampling ($R^2 = 0.610$; $p = 0.013$) (Figure 5). In all cases, concentrations of respirable particles were reduced downstream below TLV_c (3.0 mg/m^3) for the filter, while maximum concentrations exceeded the TLV_c for ambient concentrations (Figure 6). There was no association between respirable particulates and temperature at the start of sampling.

Although formaldehyde breakthrough concentrations remained above ACGIH TLV_c during all sampling durations, all CBRN canisters/cartridge appreciably reduced downstream formaldehyde concentrations. Filter #1 reduced formaldehyde concentrations by (44%), filter #2 (66%), filter #3 (18%), and filter #4 (18%) for the 15minute sampling duration. Filter #1 reduced concentration by (40%), filter #3 (55%), and filter #4 (25%) for the 30-minute sampling duration; whereas, the filter #1 reduced concentrations by (55%), filter #2 (72%), filter #3 (60%), and filter #4 (3%) for the 60-minute sampling duration.

In most cases, concentrations of respirable particulates decreased as sampling duration increased. For respirable particulates, filter #1 reduced concentration by (93%), filter #2 (99%), filter #3 (87%), and filter #4 (77%) for the 15-minute sampling duration. Filter #1 reduced concentration by (99%), filter #3 (89%), and filter #4 (65%) for the 30-minute time duration. Filter #1 reduced concentrations by (99%), filter #2 (72%), filter #3 (89%), and filter #4 (98%) for the 60-minute sampling duration (Table V).

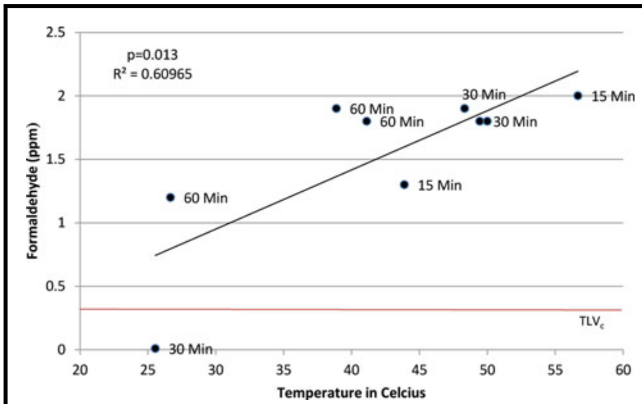

FIGURE 5. Linear regression of formaldehyde (ppm) and temperature (ºC).

The aggregate mean formaldehyde concentrations between each filter were significantly different ($p = 0.0092$), yet the aggregate mean formaldehyde concentrations for each sampling duration indicated no difference between brands ($p = 0.8105$). For respirable particulates, the aggregate mean concentrations showed a significant difference in means between both CBRN brands and sampling durations ($p = 0.0003$), respectively (Table VI).

There was a significant difference between filters #3 and #4 ($p = 0.0400$) and filters #2 and #4 ($p = 0.0400$) for formaldehyde. Significant differences were seen between filters #1 and #2 ($p = <0.0001$), filters #1 and #3 ($p = <0.0001$), filters #1 and #4 ($p = 0.0003$), and filters #2 and #4 ($p = 0.004$) for respirable particulates. For sampling durations, significant differences were seen between each sampling duration, as 60- and 30-minute durations, the 60- and 15-minutes durations, and the 30- and 15-minute durations ($p = <0.0001$), respectively (Table VI).

When evaluating CBRN brand by sampling duration, no significant differences were seen for formaldehyde breakthrough. Breakthrough by brand and sampling duration for respirable particulates showed a significant difference between filter #1 and ambient, filters #1 and #4, filter #3 and ambient, and filters #3 and #4 ($p = <0.0001$), respectively for the 15-minute sampling duration. Statistical significance was observed for filters #1 and #3, filter #1 and ambient, filters #1 and #4, and filter #3 and ambient ($p = <0.0001$) respectively for the 30-minute sampling duration. Statistically significant differences were observed between filter #1 and ambient ($p = <0.0001$), filters #1 and #4 ($p = 0.0006$), filters #1 and #2 ($p = 0.0012$), filter #3 and ambient ($p = <0.0001$), filters #3 and #4 ($p = <0.0001$), filters #3 and #2 ($p = 0.0006$), and filters

TABLE V. Mean and percent reduction from ambient by CBRN brand and sampling duration

Analyte	Sampling Duration (minutes)	Ambient	Filter #1		Filter #2		Filter #3		Filter #4	
			CONC	%	CONC	%	CONC	%	CONC	%
Formaldehyde (ppm)	15	1.70	0.96	44	0.58	66	1.03	40	1.43	18
	30	1.85	1.11	40	—	—	0.84	55	1.37	25
	60	1.63	0.72	55	0.44	72	0.64	60	1.69	3
Respirable	15	7.61	0.53	93	0.06	99	1.04	87	1.75	77
Particulate	30	4.77	0.04	99	—	—	0.55	89	1.68	65
(mg/m3)	60	5.86	0.05	99	1.59	72	0.16	97	0.14	98

#4 and #2 (p = <0.0001) for the 60-minute sampling duration (Table VII).

DISCUSSION

Burgess et al.[7] and de Vos et al.[9,,10] demonstrated the importance of providing firefighters with respiratory protection during overhaul due to adverse acute health effects associated with post-fire environment exposures. Further, firefighters are at increased risk of developing a variety of cancers.[15] In our study, the ambient analytes in air above the ACGIH TLV included both formaldehyde and respirable particulates.

A study conducted by Baxter et al.[16] reported that ultrafine particles accounted for more than 70% of the particles measured during fire suppression. Particles ranging from 0.11 – 1.0 microns markedly increased during the overhaul phase when firefighters are less likely to wear respiratory protection. Baxter et al.[16] noted that these ultrafine particles are not observable to the human eye and may produce a false sense of safety, leading firefighters to remove respiratory protection.

Beginning in 2004, the first commercially available NIOSH-approved CBRN canisters came to market in the United States. APRs fitted with CBRN canisters held promise for improved respiratory protection for first responders when SCBAs were unavailable or impractical. To evaluate CBRN effectiveness at filtering the toxic components of smoke during overhaul, Anthony et al.[11] and Currie et al.[12] conducted laboratory-scale controlled evaluations of mock overhaul environments using limited quantities and types of household items and a smoke chamber.

Building on the work of Anthony and Currie,[11,12] the present study assessed full-scale, post-fire, filtering performance of commercially available, NIOSH-approved, CBRN canisters and one non-CBRN cartridge, identifying performance at 15-, 30-, and 60-min exposures at a respiratory-relevant flow rate (~80 L/min). These challenge durations were selected to determine end-of-service life for each filter during realistic overhaul conditions.

Work done by Anthony et al.[11] and Currie et al.[12] suggested that in laboratory overhaul simulations CBRN canisters effectively reduced formaldehyde and respirable particulates to below TLVs. However, the current study's evaluations of similar filters during post-fire overhaul from residential structure representative materials found that, for respirable particulates and formaldehyde (the only post-filter components exceeding TLVs), all filters effectively reduced respirable

TABLE VI. Significant results (p-value) of K-Wallis and Rank-Sum tests for aggregated concentrations for all CBRN brand and sampling duration

Analyte	CBRN Filter	Sampling Duration	K-Wallis	Rank-Sum
Formaldehyde	All	—	0.0092	
	#3/#4			0.0400
	#2/#4			0.0400
Respirable	All	—	0.0003	
Particulates	—	All	0.0003	
	#1/#2			< 0.0001
	#1/#3			< 0.0001
	#1/#4			0.0003
	#2/#4			0.0040
		60Min/30Min		< 0.0001
		60Min/15Min		< 0.0001
		30Min/15Min		< 0.0001

TABLE VII. Significant result (p-value) of K-Wallis and Rank-Sum for respirable particulates by CBRN brand and sampling duration

CBRN Brand	Sampling Duration	K-Wallis (combined)	Rank-Sum
#1/Ambient	15 Minutes	<0.0001	< 0.0001
#1/#4			< 0.0001
#3/Ambient			< 0.0001
#3/#4			< 0.0001
#1/#3	30 Minutes	<0.0001	< 0.0001
#1/Ambient			< 0.0001
#1/#4			< 0.0001
#3/Ambient			< 0.0001
#1/Ambient	60 Minutes	<0.0001	< 0.0001
#1/#4			0.0006
#1/#2			0.0012
#3/Ambient			< 0.0001
#3/#4			< 0.0001
#3/#2			0.0006
#4/#2			< 0.0001

particulates to below TLVs, but failed to filter formaldehyde to below TLVs, regardless of exposure time.

The discrepancies observed for post-filter formaldehyde concentrations between this study and the study conducted by Currie et al.[12] could be attributed to several factors. First, this study burned greater quantities and broader variety of household materials at higher mean temperatures (42.3°C versus 28°C). Second, this study used a slightly greater flow rate of ~80 L/min, about 5 L greater when compared to Currie's study (74 – 76 L/min). Third, this study's mean ambient formaldehyde concentration (1.96 ppm) was twice that observed in Currie's study (0.79 ppm), although Currie's and this study both had similar maximum formaldehyde concentrations of >1.6 and 2 ppm, respectively. Fourth, there was limited airflow in the burn house during sampling. Lastly, although relative humidity (RH) was not measured in this study, it could have been a factor for the high breakthrough concentrations of formaldehyde. Due to formaldehyde's polarity, it may have adsorbed onto water molecules passing through the filters, or the carbon sites were blocked by adsorbed water. These factors may indicate that under realistic fire conditions, the CBRN canisters and cartridge are less effective when ambient conditions are at greater temperatures or when analyte concentrations are elevated.

Although there was a statistically significant difference observed in the filtering abilities of all CBRN brands for formaldehyde, filters #2 and #3 outperformed filter #4. There was also no statistically significant difference observed between the CBRN canisters/cartridge across sampling times. This indicates that, excepting formaldehyde, the filtering capacity of each CBRN canister/cartridge remains sustainable when challenged for up to 60 minutes.

All CBRN APRs performed effectively at reducing concentrations of respirable particulates, although filter #1 outperformed filter #2 and filters #3 and #4. Although this remained true when results where parsed by sampling time, additional significant differences were observed at 15 min (#3/#4) and 60 min (filter #3 and #2 and filter #4 and #2).

Further, aggregated respirable particulate concentrations were effectively reduced when approaching 60 minutes. This could signify either that when exposure time increases, the filtering ability of the filters improves, or that when exposure time increases filter media becomes saturated and thereby reduces the ability to accurately quantify downstream concentrations. However, all filter brand comparison results should be viewed with consideration that the sample size of this pilot work was limited.

Although concentrations of respirable particulates were reduced to below ACGIH ceiling limits, penetration was greater than what is allowed per NIOSH testing methods. NIOSH uses di-ocytyl phthalate (DOP) at concentrations up to 200 mg/m^3 at a flow rate of 85 L/min and requires no greater than 0.03% penetration of the most penetrating particle size.[17] The greatest penetration percentage seen in this study was 35% with mean percent penetration across all sampling durations and CBRN brands of 13.3%.

These discrepancies could be attributed to several factors. First, although the seals that attached the filters were evaluated for leaks, there was the possibility that small-diameter particles could have penetrated the seal artificially inflating concentrations. Second, activated carbon is used in filters as a chemical absorbent and is friable. Due to outside forces, the activated carbon could have been crushed and fine dust might have broken through. Third, the TSI Sidepak correction factor was set to 1.00. Not using an established correction factor for aerosols generated from combustion could have artificially inflated the respirable particulate concentrations observed. Lastly, although unlikely, because water was used to extinguish the fires, elevated humidity could have prematurely broken down the absorbent material allowing greater penetration. Studies conducted by Nelson et al.[18] and Wood[19] found that high humidity and temperature negatively affected the service life and efficacy of air-purifying respirator cartridges. For example, Wood found that increasing testing temperatures by 5°C above the bench test standards (25 ± 2.5°C) with corresponding increases in humidity amounted to doubling the penetration of methyl iodide and general reduction in cartridge service life. Further, Nelson et al.[18] found that increasing humidity depressed the service life of cartridges, especially above 65% relative humidity, and that increasing temperature by 10°C reduced time-to-breakthrough by 1 – 10%. Although these studies were not conducted using CBRN filters, it is possible that the effects of temperature and humidity seen in air-purifying respirators also affect canisters/cartridges used in this study.

The study methods used to evaluate the filters in the current study intentionally differed from those used by NIOSH to approve CBRN canisters. When compared to NIOSH methods, which uses ambient exposure temperature of 25±5°C, this study had an average ambient air testing temperature of 39.7°C to reflect actual overhaul conditions. Additionally, the ~80 L/min flow rate through the canisters differed from the NIOSH method of 64 and 100 L/min to reflect likely respiratory intake of working firefighters.[13–17] These changes from the standard methods of challenging CBRN filters better reflect actual environments and physiological performance of firefighters during overhaul operations.

Throughout this study every effort was made to reduce the variability of combustion materials used for each burn, but some variability by type of textiles and electronics was inevitable. Regardless, this variability did not result in a statistically significant difference in ambient concentrations across burns for formaldehyde ($p = 0.086$) or respirable particulates ($p = 0.956$). Additionally, while the airflow pulled through each filter was at an overhaul-relevant respiratory rate, the test system did not allow for oscillatory flow typical of respiration. While it is not expected that the lack of inhalation/exhalation flow would impact filter performance, our system fails to elucidate the downstream "in APR" environment for any compounds that pass through the filters.

CONCLUSION

The commercially available CBRN products evaluated in this study were each effective in reducing concentrations of hazardous chemicals and respirable particulates during simulated overhaul. The compounds with the greatest contribution to exposure above TLVc were identified as formaldehyde and respirable particulates. While questions remain related to filter performance during actual overhaul beyond 60-min exposures, and for "in-mask" post-filter contaminant concentrations, this study indicates that, regardless of brand, the filters tested effectively filter typical overhaul chemical compounds, except formaldehyde, to below TLV levels. As the significance of formaldehyde breakthrough on the chronic health status of firefighters performing overhaul is clear, use of SCBAs during post-fire activities is recommended.

Further research should be conducted into the effectiveness of CBRN canisters for use during overhaul. It is recommended that future studies incorporate the use of a breathing machine to simulate actual breathing patterns and volume in conjunction with quantifying in mask analyte concentrations. Relative humidity should be assessed to determine its effects on CBRN canister/cartridges efficacy and service life. Lastly, if possible, increasing the number of burn cycles should be included to provide greater significance with statistical analysis.

ACKNOWLEDGMENTS

This work could not have been conducted without the partnership of professional firefighters of the Northwest Fire District and scientific collaboration of the National Institute of Occupational Safety and Health, National Personal Protective Technology Laboratory team (Contract #200-2012-M-53198). Also, a special thanks to Tony "TMFR" Raley for the fabrication of the sampling manifold.

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