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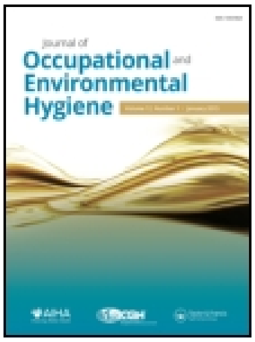

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Respiratory protection for firefighters—Evaluation of CBRN canisters for use during overhaul II: In mask analyte sampling with integrated dynamic breathing machine

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ABSTRACT

According to the National Fire Protection Association there were 487,500 structural fires in the U.S. in 2013. After visible flames are extinguished firefighters begin the overhaul stage where remaining hot spots are identified and further extinguished. During overhaul, a significant amount of potentially hazardous chemicals can remain in the ambient environment. Previous research suggests that the use of air purifying respirators fitted with chemical, biological, radiological, and nuclear (CBRN) canisters may reduce occupational exposure. This study used large scale burns of representative structural materials to perform side-by-side, filtering, and service-life evaluations of commercially available CBRN filters using two head forms fitted with full-face respirators and a dynamic breathing machine. Three types of CBRN canisters and one non-CBRN cartridge were challenged in repetitive post-fire environments. Tests were conducted with two different breathing volumes and rates for two sampling durations (0–15 min and 0–60 min). Fifty-five different chemicals were selected for evaluation and results indicate that 10 of the 55 chemicals were present in the post-fire overhaul ambient environment. Acetaldehyde and formaldehyde were found to be the only two chemicals detected post filter but were effectively filtered to below ACGIH TLVs. Counter to our prior published work using continuous flow filter evaluation, this study indicates that, regardless of brand, CBRN filters were effective at reducing concentrations of post-fire ambient chemicals to below occupational exposure limits. However, caution should be applied when using CBRN filters as the ambient formaldehyde level in the current study was 8.9 times lower than during the previous work.

KEYWORDS
Breathing machine; CBRN; firefighter; overhaul; respiratory protection

Introduction

Firefighters have a greater risk of developing cancer, which increases with duration of employment, highlighting the need to provide adequate workplace protection in all aspects of firefighting.[1,2] In addition to firefighters, research has shown that personnel who investigate the causal factors leading to a structural fire are also at increased risk of developing certain cancers.[3] Fighting a fire can be broken down into three phases; first is the knockdown phase where all visible fires are extinguished; second is overhaul where potential re-ignition sources are identified and further extinguished; and third is the investigation phase when potential causes of the fire are identified.

During knockdown, firefighters are required to wear self-contained breathing apparatus (SCBA), but in many cases are not required to do so during overhaul or investigation. During the overhaul phase, firefighters are exposed to potentially harmful concentrations of residual combustion-related chemicals and particulates. These include carbon monoxide (CO), nitrogen dioxide (NO_2), and volatile organic compounds (VOCs). Within these classifications of chemicals, there are many known carcinogens such as benzene, 1,2-butadiene, formaldehyde, naphthalene, styrene and toluene.[4,5] Within these groups formaldehyde is of particular concern given its status as a known human carcinogen and upper airway irritant.[6,7]

One approach considered by fire departments has been the use of air-purifying respirators (APRs) as a substitute for SCBAs during overhaul. Use of APRs could lessen the physical burden placed on firefighters and in some circumstances potentially be more cost effective than continuing to use SCBAs during the overhaul phase.

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uoeh.

To recognize and understand the potential risks of using APRs during overhaul, Burgess et al.[8] compared the respiratory effects of firefighters who wore APRs with multipurpose cartridges during overhaul. This study identified acute changes in lung function and increased serum pneumoprotein indicating lower respiratory tract damage, signifying that use of APRs fitted with multipurpose cartridges may not completely protect firefighters during overhaul. These findings are further supported by de Vos et al.[9,10] who investigated APR cartridge performance during wild land fire scenarios.

To further clarify APR performance against overhaul contaminants, a study conducted by Anthony et al.[11] demonstrated that the multipurpose cartridges tested in previous studies were not fully protective against combustion smoke contaminants. In an attempt to identify other filters with the potential to 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 as well as one NIOSH-approved canister that was not permitted for CBRN use. This study found that these canisters provided greater protection when challenged with small scale, chamber-based, post-fire, overhaul simulations when compared to the multipurpose cartridges. The canisters were able to reduce downstream concentrations of acetaldehyde, acrolein, benzaldehyde, formaldehyde, glutaraldehyde, butyraldehyde, crotonaldehyde, and cyanide to below NIOSH recommended exposure levels (REL). To further elucidate the performance of CBRN canisters during overhaul, Jones et al.[13] challenged the filters using large scale prescribed burns using common household items. The results of this study were in contrast to the study conducted by Currie at al. in that the CBRN canisters were not effective at reducing formaldehyde below the REL.

The current study expands on the work conducted by Jones et al. by introducing the use of a dynamic breathing machine (DBM) that accurately simulates the rate, volume, and oscillation of normal breathing patterns. It is hypothesized that the introduction of the breathing machine combined with in-mask analyte sampling will better demonstrate the protectiveness of CBRN canisters.

Methods and materials

To determine analyte reduction effectiveness of CBRN canisters/cartridges a series of 12 burns with associated sampling durations was conducted at the Northwest Fire Districts (NWFD) training center (Marana, AZ). Measured quantities of common household items were used during burns to simulate actual overhaul environments (Table 1). During each series of burns, fires were allowed to burn for approximately 15 min until maximum temperature and material combustion was achieved. Fires were then suppressed using water in accordance with standard firefighting procedures. After fire suppression, concentrations of CO were monitored until levels reached 30 ppm using an MSA Altair 4-gas meter (Pittsburgh, PA), at which time sampling began using the dynamic breathing machine, and two head forms fitted with full face respirators. This system allowed for side-by-side evaluation of two canisters/cartridges as well as ambient analyte measurements. Although NWFD standard operating procedures dictate the use of cross-draft ventilation before overhaul to reduce contaminant concentrations, this step was bypassed in an attempt to challenge the APRs with the greatest analyte concentrations possible.[14]

Table 1. List of household materials used during testing.

Material	Quantity	Dimensions
Fiberglass Insulation	1	60.96×121.92×24.136−cm
Laminate Flooring Strip	2	19.8×128.5×0.7−cm
OSB Particle Board	1	122×122×1.9−cm
PVC Pipe	1	2.54cm (dia) × 30.48−cm
Sofa Cushion	1	∼61×61×10−cm
Textiles (cotton, nylon)	∼0.2 kg	
Video Cassette Recorder/ Compact Disc Player	1	∼45.72×45.72×12.7−cm
Vinyl Flooring Strip	3	15.24×91.44−cm
Wood Pallet	1	121.9×101.6−cm

Three commercially available NIOSH-approved CBRN canisters and one non-CBRN cartridge were used during testing. Canisters/cartridge were de-identified and provided a number (1–4). Each filter was used for a single iteration, and replaced with an identical filter prior to the start of each new challenge. For each test iteration, a filter was randomly assigned to one of the two head forms (A or B).

Each head form was drilled to allow insertion of five Tygon tubes (Lima, OH) around the nose and mouth area to allow for in-mask sampling, as well as a large stainless steel pipe for attachment to the breathing machine (Figure 1). Each head form was also fitted with an MSA Millennium full face mask respirator and quantitatively fit tested using an Occupational Health Dynamics (OHD) Quantifit (Pelham, AL, USA). Head form "A" had a mean fit factor (FF) of 1075 and head form "B" had a mean FF of 980 which exceeds the Occupational Safety and Health Administration's (OSHA) requirements (FF = 500) for full face respirators.[15] Sampling from each head form, as well as ambient measurements, used three calibrated SKC personal sampling pumps (Eighty Four, PA) and two Zefon Escort Elf personal sampling pumps (Ocala, FL).

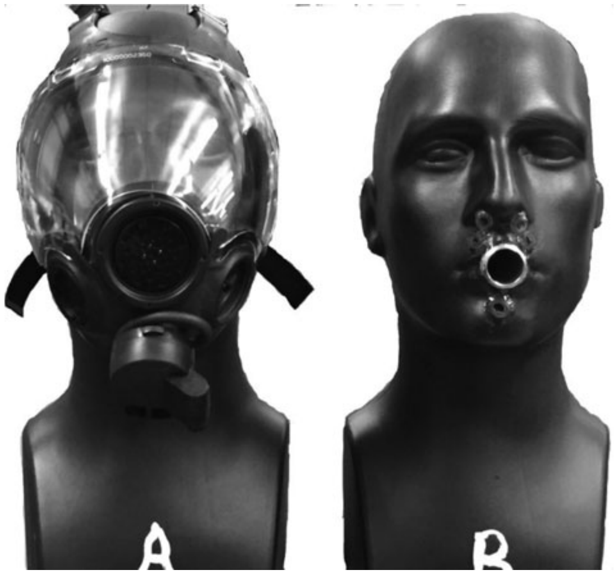

Figure 1. Front view of head forms "A" and "B."

Use of the Dynamic Breathing Machine (Warwich Technology Limited, Warwich, UK) (Figure 2) incorporated two physiologically relevant breathing patterns (80 Lpm, 2.5L tidal volume, 32 breaths per minute/100 Lpm, 2.5L tidal volume, 40 breaths per minute) that were randomized to each sampling iteration. These parameters were calculated using 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)[16] and implemented using LabVIEW System Design Software (National Instruments, Austin, TX). Prior to field use, leakage tests between the upper and lower chambers of the breathing machine were evaluated using laboratory gas. Samples were taken multiple times for 15- and 60-min durations with no leaks detected. Verification was accomplished by increasing the breathing resistance on one of the head forms resulting in quantified leakage. All samples were taken with CBRN canisters in place.

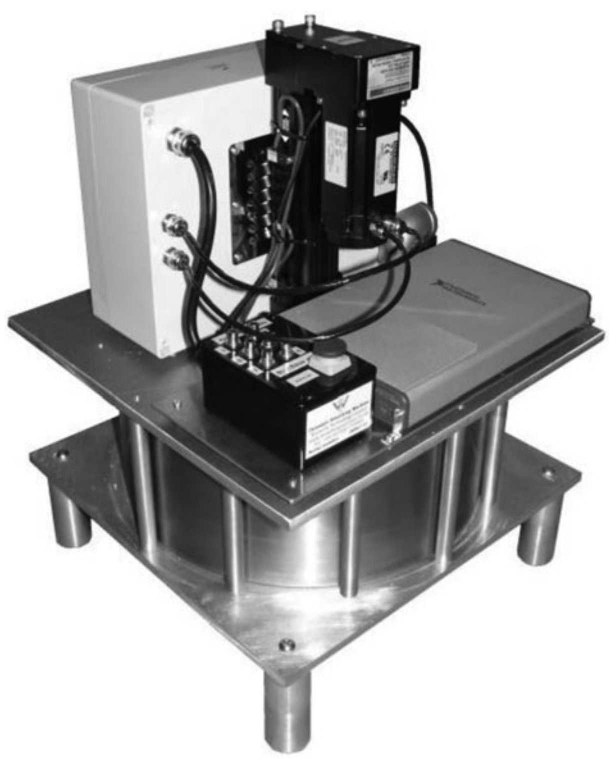

Figure 2. Dynamic breathing machine.

Field assessments occurred after each fire was extinguished and CO concentrations fell to or below 30 ppm. The sampling system was placed inside the burn room via a wheeled cart approximately 1 m from the smoldering materials in a position that approximated a firefighters working breathing zone. Sampling durations were randomized for each test iteration (15 or 60 min). Temperature and relative humidity were also monitored during sampling using a TSI VelociCalc model 9565 (Shoreview, MN). A total of 55 analytes were measured during each of the test iterations, as detailed in Table 2. Analytical samples were sent to Galson Laboratories Inc., (East Syracuse, NY) for analysis.

All statistical analysis was performed using Stata version 12.1 (College Station, TX). Regression analysis was performed to evaluate for statistically significant relationships between analyte concentrations and temperature and/or relative humidity. Two-Tailed T-Tests were also performed to determine if any significant differences existed between analyte concentrations within burn cycles. For all test, an alpha error threshold of 0.05 was applied.

Results

Sampling indicated the presence of 10 (18%) analytes in the ambient overhaul environment detected above the level of quantification (LOQ), including: acenaphthylene, acetaldehyde, benzene, benzaldehyde, crotonaldehyde, formaldehyde, naphthalene, phenanthrene, propionaldehyde, and respirable particulates (Table 3). Only formaldehyde was present above published American Conference of Governmental Industrial Hygienist (ACGIH) threshold limit value ceiling (TLV_C). While CO was relatively elevated, the MSA four-gas meter did not detect hydrogen sulfide, or explosive limits outside of recommended levels.

Of the 10 analytes detected above the LOQ in the post-fire overhaul ambient environment, acetaldehyde and formaldehyde were the only analytes to be detected downstream of any filters on a fairly consistent basis. Benzene was detected downstream of one filter on the last

Table 2. Analytes measured and analysis method.

Analyte		Media/Analysis Method
Aldehydes	Acetaldehyde	ORBO 555/NIOSH 2016
	Benzaldehyde	
	Butyraldehyde	
	Crotonaldehyde	
	Formaldehyde	
	Isovaleraldehyde	
	Propionaldehyde	
	Valeraldehyde	
NO2		226-40-02/NIOSH 6014
PNAH	Acenaphthene	PTFE/ORBO 43/NIOSH 5506
	Acenaphthylene	
	Anthracene	
	Benzo(a)anthracene	
	Benzo(a)pyrene	
	Benzo(b)fluoranthene	
	Benzo(e)pyrene	
	Benzo(g,h,i)perylene	
	Benzo(k)fluoranthene	
	Chrysene	
	Dibenz(a,h)anthracene	
	Fluoranthene	
	Fluorene	
	Indeno(1,2,3-cd)pyrene	
	Naphthalene	
	1-Nitropyrene	
	Phenanthrene	
	Pyrene	
	Acetone	
Respirable Particulate		PW PVC/NIOSH 0600
VOC	Benzene	226–01/multiple NIOSH
	n-Butyl Acetate	
	Chlorobenzene	
	Chloroform	
	Cumene	
	Cyclohexane	
	Cyclohexanone	
	Cyclohexene	
	m-Dichlorobenzene	
	o-Dichlorobenzene	
	p-Dichlorobenzene	
	1,1-Dichloroethane	
	1,2-Dichloroethane	
	Ethyl alcohol	
	Ethyl benzene	
	n-Hexane	
	Methylene chloride	
	Pentane	
	n-Propyl Acetate	
	Tetrachloroethylene	
	Tetrahydrofuran	
	Toluene	
	1,1,2-Trichloroethane	
	Trichloroethylene	
	Trichloroethylene	
	Xylene	

burn cycle. Both analytes were present downstream of filters #3 and #4 while formaldehyde was only detected downstream from filters #1 and #2 (Table 4). Formaldehyde (Figure 3) and acetaldehyde (Figure 4) were reduced to below ACGIH reference thresholds[16] in all cases (Figures 3 and 4).

All filters appreciably reduced concentrations of acetaldehyde during all test iterations. Filters #1, #2, and #3 reduced concentrations by (100%) and filter #4 reduced concentrations by (55%) for the 15-minute sampling duration. Filters #1 and #2 reduced acetaldehyde (100%), #3 (50%), #4 concentration (75%), for the 60-min sampling duration.

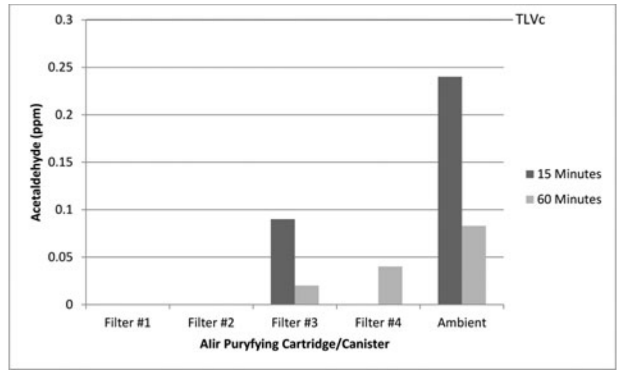

Figure 3. Aggregated mean acetaldehyde concentrations (ppm) by CBRN filter and sampling duration.

All filters appreciably reduced concentrations of formaldehyde during all test iterations. Filter #1 reduced formaldehyde concentrations by (98%), #2 (100%), #3 (81%), and #4 (79%), for the 15-min sampling duration. Filter #1 reduced formaldehyde concentrations by (100%), #2 (94%), #3 (32%), and #4 (82%), for the 60-min sampling duration (Table 5).

Assessment of temperature and relative humidity during sampling showed a mean temperature of 38.7°C and a mean relative humidity (%RH) of 37.3%. Environmental conditions (temperature and relative humidity) had minimal effect on ambient acetaldehyde and formaldehyde concentrations. Regression analysis showed a positive significant correlation between relative humidity (RH) and concentrations of formaldehyde (Figure 5) $R^2 = 0.62$, ($p = 0.004$). Increases in temperature also showed a positive correlation for formaldehyde concentrations ($R^2 = 0.36$); however, this correlation was only marginally significant ($p = 0.052$; Figure 6).

Discussion

Burgess et al.[8] and de Vos et al.[9,10] observed adverse acute health effects associated with exposure to post-fire environment exposure underlining the importance of providing adequate respiratory protection for firefighters. Furthermore, firefighters and fire investigators are at increased risk of developing certain cancers.[3–18] In our live fire overhaul simulation study, formaldehyde was the only analyte measured to be above ACGIH TLVs, while levels of acetaldehyde were present in both the ambient environment and post filter.

Table 3. Post-fire ambient overhaul analyte concentrations (ppm) above LOQ.

Analyte	Burn #1 CONC	Burn #2 CONC	Burn #3 CONC	Burn #4 CONC	Burn #5 CONC	Burn #6 CONC	ACGIH TLV
1. Acenaphthylene	0.0067	0.0035	0.003	0.004	0.003	0.0021	NE
2. Acetaldehyde	0.3	0.08	0.1	0.3	0.4	0.2	25[b]
3. Benzene				1			2.5[c]
4. Benzaldehyde		0.01					NE
5. Crotonaldehyde				**0.07**	0.06	0.02	0.3[b]
6. Formaldehyde	**1.4**	**0.33**	**0.3**	0.3	**0.4**	0.29	0.3[b]
7. Propionaldehyde				0.06	0.07	0.02	20
8. Naphthalene	0.019	0.0088	0.0066	0.02	0.0064	0.0051	NE
9. Phenanthrene		0.0005				0.0016	NE
10. Respirable Particulate*					2.6	1	3
Analyte	**Burn #7 CONC**	**Burn #8 CONC**	**Burn #9 CONC**	**Burn #10 CONC**	**Burn #11 CONC**	**Burn #12 CONC**	**ACGIH TLV**
1. Acenaphthylene	0.001	0.0016	0.003	0.002	0.001	0.0007	NE
2. Acetaldehyde	0.03	0.097	0.1		0.02	0.07	25[b]
3. Benzene		0.1					2.5[c]
4. Benzaldehyde							NE
5. Crotonaldehyde							0.3[b]
6. Formaldehyde	0.07	0.1	0.2	0.2	0.07	0.1	0.3[b]
7. Propionaldehyde							20
8. Naphthalene	0.0053	0.0057	0.012	0.005	0.0033	0.001	NE
9. Phenanthrene	0.0005	0.0008			0.0007	0.0007	NE
10. Respirable Particulate[a]	1	1.1					3

[a] 5.5 µm cutoff- ACGIH TLV and BEI book, Appendix B: Particles Not Otherwise Specified (PNOS), respirable. Concentrations are in mg/m^3.
[b] Indicates ceiling limit
[c] Indicates short-term exposure limit (STEL)
NE-no established threshold limit

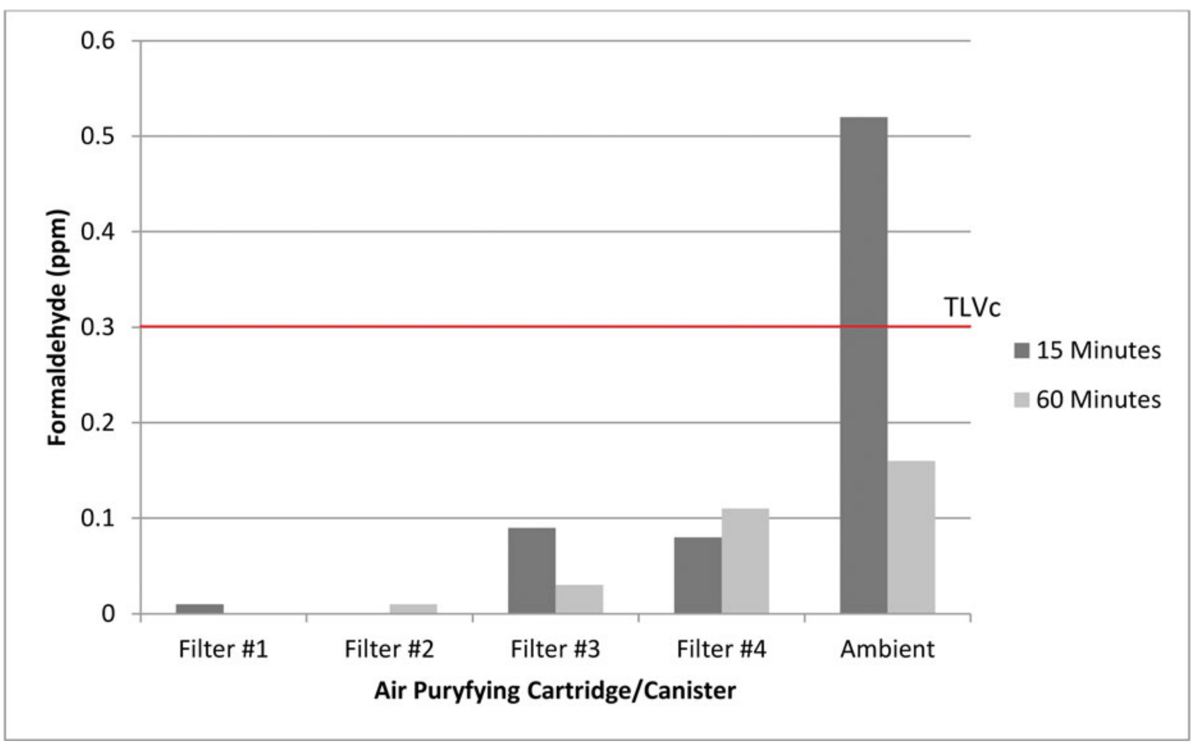

Figure 4. Aggregated mean formaldehyde concentrations (ppm) by CBRN filter and sampling duration.

Table 4. Canister/cartridge breakthrough concentrations by burn number, sampling duraiton, and analyte.

Burn Number	Sampling Duration	Filter	Acetaldehyde CONC	Benzene CONC	Formaldehyde CONC
Burn #1	15 min	Filter #1			0.1
		Filter #2			
Burn #2	60 min	Filter #1			
		Filter #3	0.02		0.04
Burn #3	15 min	Filter #1			
		Filter #4			
Burn #4	15 min	Filter #2			
		Filter #3	0.09		0.1
Burn #5	15 min	Filter #3			0.08
		Filter #4			
Burn #6	60 min	Filter #2			
		Filter #4	0.07		0.18
Burn #7	60 min	Filter #1			
		Filter #2			0.01
Burn #8	60 min	Filter #3			0.02
		Filter #4	0.03		0.04
Burn #9	15 min	Filter #1			
		Filter #4			0.08
Burn #10	15 min	Filter #2			
		Filter #3			
Burn #11	60 min	Filter #1			
		Filter #3			
Burn #12	60 min	Filter #2			
		Filter #3	0.02	0.02	

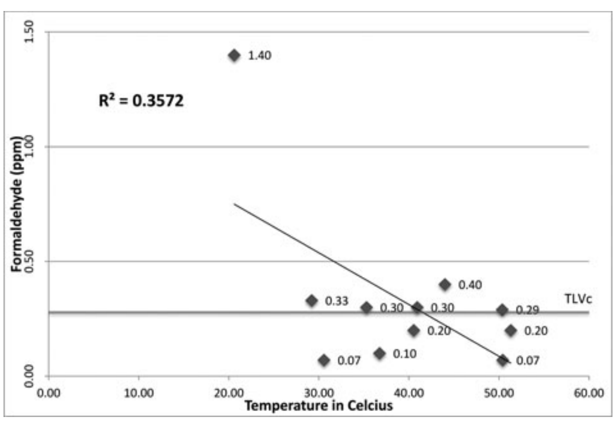

Figure 5. Linear regression of formaldehyde (ppm) and temperature (°C).

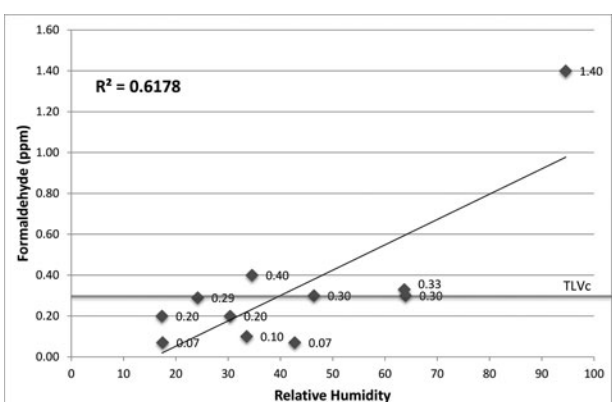

Figure 6. Linear regression of formaldehyde (ppm) and relative humidity.

In 2004, the first NIOSH-approved CBRN canisters became commercially available in the U.S. market. Evaluation of CBRN canister effectiveness at filtering toxic components of smoke during overhaul started with the work conducted by Anthony et al.[11] and Currie et al.[12] These laboratory-scale evaluations of mock overhaul environments using limited quantities of household items in a smoke chamber showed APRs fitted with CBRN canisters held promise in providing an alternative means of respiratory protection when SCBAs were unavailable, or impractical.

Building on the work of Anthony and Currie,[11,12] work conducted by Jones et al.[13] utilized full-scale burns using various common household items and assessed post-fire filtering performance of three CBRN canister and one cartridge identifying performance at 15-, 30-, and 60-min exposures at respiratory relevant rates. This study builds on that previous work conducted by Jones et al. using similar methodologies, but integrating the use of a dynamic breathing machine to accurately simulate physiological breathing patterns (rate, tidal volume, and breath cycle), as well as head forms fitted with full face respirators.

The studies conducted by Anthony et al.[11] and Currie et al.[12] suggested that in laboratory simulated overhaul environments, CBRN canisters effectively reduced all detected analytes to below TLVs. In contrast, the work conducted by Jones et al.[13] found that formaldehyde and respirable particulates were not effectively reduced below TLVs. However, the current work evaluating similar filters during post-fire overhaul using structurally relevant materials shows similar results to the studies conducted by Anthony and Currie, with CBRN filters reducing analytes to below TLVs.

The discrepancies observed for post filter formaldehyde concentrations between this study and the previous study conducted by the same research team[13] could be attributed to several factors. First, this study's internal "ambient" maximum mean temperature during burns was lower than the previous study (167°C vs. 135°C). This could have had the effect of incomplete combustion of materials in turn lowering ambient analyte concentrations. Additionally, because of the time of the year this study was conducted, condensation was present on the burn materials at the beginning of the sampling days which could further reduce combustion. Second, this study used a dynamic breathing machine that integrated oscillatory flow which may have reduced the stress on the CBRN filters when compared to the constant flow of the previous studies. Stress from constant flow could have compromised the integrity of the filter's carbon bed due to its friable nature biasing formaldehyde and respirable particulates resulting in higher breakthrough values. Third,

Table 5. Mean (ppm) and percent reduction from ambient by CBRN filter and sampling duration.

			Filter #1		Filter #2		Filter #3		Filter #4	
Analyte	Sampling Duration (minutes)	Ambient	CONC	%	CONC	%	CONC	%	CONC	%
Acetaldehyde	15	0.2	0	100	0	100	0	100	0.09	55
(ppm)	60	0.08	0	100	0	100	0.04	50	0.02	75
Formaldehyde	15	**0.42**	0.01	98	0	100	0.08	81	0.09	79
(ppm)	60	0.16	0	100	0.01	91	0.11	32	0.03	82

this study's mean ambient formaldehyde concentration (0.22 ppm) was 8.9 times that of the previous study's mean ambient formaldehyde concentration (1.96 ppm).

Although post filter respirable particulate concentrations were reduced to levels below the LOQ, challenge concentrations could have been biased low as overhaul operations were not being conducted (i.e., prodding combusted materials). In a study conducted by Baxter et al.[19] it was reported that respirable particulate concentration were greatly increased during overhaul related activates that disturbed burned materials. It should also be considered that studies conducted by Nelson et al.[20] and Wood[21] reported that increases in temperature and humidity negatively affected the service life and efficacy of APRs. Wood et al.[21] reported that an increase of 5°C above NIOSH bench test methods (25 ± 2.5°C) with corresponding increases in humidity doubled the penetration of methyl iodide. Further, Nelson et al.[20] reported that increasing humidity depressed the service life of APRs especially above 65% relative humidity. Although these studies were not conducted on CBRN filters, analyte breakthrough could be attributed to the environmental conditions observed during sampling.

The methods used in this study to evaluate the effectiveness of CBRN filter capacity intentionally differed from those used by NIOSH for certification. Compared to the NIOSH methods,[22] this study has a mean ambient test temperature of 38.8°C (range 14.3–55.3°C) which is greater than NIOSH's bench test temperature of 25 ± 2.5°C. Additionally, %RH for this study was higher than those used by NIOSH (25 ± 5 and 80 ± 5%RH) with a mean ambient test %RH of 37.3 (range 15.4–98.9%RH) Lastly, this study used oscillatory flow at 80 and 100 Lpm which differs from NIOSH's bench tests of continuous flows of 64 and 100 Lpm. These changes from the standard testing methods of CBRN certification reflect environments and physiological performances reported by firefighters performing overhaul.

Throughout this study every effort was made to ensure variability of burn materials was minimized; but variations in the sizes and types of electronics and textiles were inevitable. Regardless, variability in the concentrations of ambient formaldehyde were not significant ($p = 0.215$). Additionally, this study was conducted in the winter months which may have had an effect on lower ambient sampling temperatures as well as condensation on burn materials hindering complete combustion. These variables could have had the effect of lower analyte challenge concentrations then experienced previously by this research team, in turn reducing filter breakthrough concentrations.

Conclusion

At the ambient analyte concentrations generated during this study, the CBRN filters evaluated effectively reduced levels of hazardous chemicals and respirable particulates to below occupational exposure limits during simulated overhaul. Acetaldehyde and formaldehyde were the only two chemicals present fairly consistently post filter. While filter performance has not been evaluated past 60-min, this study indicates that CBRN filters are effective at reducing typical overhaul chemical compounds. Although reduced to below occupational exposure limits at the currently tested ambient levels, the carcinogenicity of formaldehyde combined with breakthrough observed at higher concentrations warrants the recommendation that firefighters continue to use SCBAs during post-fire activities.

Further research should be conducted that evaluates the effectiveness of CBRN canisters during actual overhaul. Additionally, it has been over a decade since post-fire analyte concentrations were quantified at actual structural fires. These studies should be duplicated as construction materials and common household items have changed to greater quantities of artificial plastics and particle board. Lastly, due to the rising concern of post-fire environmental health on those who investigate fires, quantification of post-fire chemical compounds should be conducted at times relevant to those individuals.

Acknowledgments

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