Smoke Exposure and Firefighter Risk in the Wildland Urban Interface

Assistance of Firefighters Grant Program
Fire Prevention and Safety Grants
EMW-2013-FP-00621

Prepared by:
Dr. Matt Rahn California State University San Marcos
Nelson Bryner – National Institute of Standards and Technology

In Collaboration with:
Rick Swan – International Association of Fire Fighters
Curtis Brown – CAL FIRE
Tim Edwards – CAL FIRE Local 2881
George Broyles – US Forest Service

Table of Contents

1.0 Summary

Collaborators with California State University San Marcos and the University Auxiliary Research Services Corporation worked in partnership with the United States Department of Agriculture-Forest Service, CAL FIRE, CAL FIRE Local 2881, the International Association of Fire Fighters, and the National Institute of Standards and Technology to evaluate the physiological and working conditions of wildland firefighters and smoke exposure in the wildland urban interface (WUI). Funding for this work was provided by the Federal Emergency Management Agency (FEMA) Fire Prevention and Safety Program (FPS).

Conditions dictate that wildland firefighters are often required to work for extended periods in intense heat and brutal environmental conditions. Today, a WUI incident represents a dynamic, complex environment where wildland, structure, and vehicle fires often merge. As a result, we do not clearly understand of the risks and hazards this synthesis creates. Moreover, protection standards for firefighters are specific to each incident type, and often overlook the concomitant risks that firefighters face when responding to an incident in the WUI.

This study assesses air pollutants during wildland and urban interface fires, develops protocols and sensor platforms for measuring and assessing smoke exposure in the WUI, monitors the physiological condition of wildland firefighters on duty, and assesses common materials in a WUI incident under controlled laboratory burns and actual WUI incidents to identify and understand constituents of concern in the smoke. Overall, the exposure to wildland firefighters is significant, and often exceeds occupational exposure limits, particularly on those incidents that include combusted materials from the urban environment (e.g. homes, vehicles, and infrastructure). While CO and PM were commonly observed in both the laboratory and field testing, other constituents pose a significant threat to wildland firefighters. In those incidents where manmade materials were included (for both training burns and WUI incidents), key constituents were observed that were otherwise absent or below occupational exposure levels in the other vegetation-only burns. While the laboratory tests provided similar results, the data collected in the field on actual WUI and training fires demonstrated a much more consistent and elevated exposure risk in certain constituents. In general, PM, CO, SO2, VOCs, NO, cyanide, and benzene were commonplace when these combusted materials were included in the smoke exposure, while PAHs, HCN, and HCL were also detected (however these occurrences were typically at lower levels of occurrence and minimal exceedances of occupational levels).

Ninety-five wildland firefighters with CAL FIRE volunteered to participate in this study, including personnel at training events (extended hose lays), controlled burns, and actual wildland fires. The results show that wildland firefighters regularly exceeded safe physiological conditions (regardless of the event type). Nearly 65% of the firefighters had sustained peak heart rates above 200 beats per minute (bpm), with nearly 20% exceeding 220bpm (all but three of the volunteers regularly exceeded the recommended maximum hearts rate for work (220bpm minus your age). Likewise, measured core body temperatures exceeded 102F in roughly 70% of the firefighters, with 10% exceeding 103F. Furthermore, nearly two-thirds of the firefighters started their shifts at or near a level of dehydration. Dehydration rates significantly increased across all firefighters at the end of duty, with only 25% of the firefighters that started off at or near dehydration self-correcting and becoming more hydrated by the end of the shift. Finally, the type of personal protective equipment (PPE) worn by wildland firefighters has a significant influence on their physiology. The results suggest that the traditional double-layer PPE produces significantly higher core body temperatures, higher incidence of dehydration, and higher heart rates than single-layer PPE.

2.0 Literature Review on Primary Constituents of Concern

Today, a WUI incident represents a dynamic, complex environment where wildland, structure, and vehicle fires often merge. As a result, we do not clearly understand of the risks and hazards this synthesis creates. Moreover, protection standards for firefighters are specific to each incident type. This report seeks to rectify this situation by improving our understanding of the exposure risks across the myriad of incident types, providing a synthesis of existing literature and reports associated with wildland, structure, and vehicle fires. This can serve as a springboard for evaluating tools for assessing and predicting hazards, and recommending safeguards for improving health and safety.

The paradigm shift from wildland to WUI firefighting has transformed conventional risk. Traditionally, fire studies focused on the three broad categories: wildland, structure, and vehicle. Each incident type comes with distinctive exposures, hazards, and risks with protocols, tactics, and PPE specific to each scenario. A WUI fire represents a dynamic and complex incident where these incident types merge. Firefighters may respond to a wildland fire, but often focus on community defense where structures and vehicles can become involved. The evolution of modern wildfires fires suggests that this is not only a common scenario, but is a virtual certainty. The result is a transition from a wildland fire (where firefighters may be reasonably prepared and protected) to an atmospheric mix of pollutants that can have severe risks and consequences.

While smoke exposure at some wildfires and prescribed burns can be no more than a nuisance, on occasion it approaches or exceeds legal and recommended occupational exposure limits. The composition of the smoke depends on variables such as fuel type, moisture content, temperature, and wind with different fuels containing variable levels of cellulose, lignin, polyphenols, oils, fats, resins, waxes, and starches. The smoke is a highly variable and complex mixture of carbon dioxide, water vapor, carbon monoxide (CO), particulates (PM), unburned fuel, polycyclic aromatic hydrocarbons (PAHs), nitrogen oxides, trace minerals and diverse hazardous air pollutants (HAPs). While this is daunting in itself, when wildland fires become WUI fires, the range of natural and synthetic materials from structures and vehicles release additional pollutants, many of which are highly hazardous, carcinogenic, and toxic.

Many safeguards for structure and vehicle fires are not part of WUI standards; customary protocols and PPE may actually be incompatible. For example, extended duty on many wildland/WUI fires means that traditional the breathing apparatus used for these incidents would provide only a fraction of the protection needed during a 12-, 16-, or 24-hour shift where exposure can be unpredictable. This device is further limited simply due to the physical constraints it places on the firefighter in the field. Similarly, turnout gear for structure fires is designed to afford adequate protection for an interior attack, not the exterior attack more typical of WUI firefighting. The thick, heavy, urban gear induces serious heat stress for firefighters conducting exterior or vegetative fire suppression. Proper WUI safeguards are imperative.

This project compiled nearly two hundred sources of literature and reports related to exposure hazards and risks related to wildland, structure, and vehicle fires. The goal is to provide an assessment of the types or hazards and exposure risks that can occur in the outside environment for a WUI fire (where traditional wildland, structure, and vehicle fires can occur simultaneously). The findings included herein can be used to inform firefighting agencies and firefighters with responsibility for WUI fires. This synthesis helped identify gaps in information, as well as which constituents of concern we should focus on for our broader exposure study.

2.1 Methods

In order to assess the current understanding of hazards and risks related to wildland, structure, and vehicle fires, we conducted an exhaustive search of the literature and reports available on this topic, with an emphasis on those studies that have been competed since 2000. Our literature search included keyword searches with both and "OR" and "AND" qualifier using combinations of terms, including: firefighter, structure fires, vehicle fires, wildland fires, wildland urban interface fires, smoke, exposure, air pollution, contaminants, and emissions. We searched key databases including: Web of Science, PubMed, Medline, BIOSIS, PubMed, JSTOR, Google Scholar, and the Cal State and University of California Databases with San Diego State University and UC San Diego. We also conducted general Internet searches and key agency contacts including the US Forest Service, the National Institute for Occupational Health and Safety, Centers for Disease Control and Prevention, National Institute of Standards and Technology, and the Motor Vehicle Fire Research Institute. Additional references were identified in key papers that were screened for relevant articles that were not identified in the original search. All articles were compiled in an EndNote database (Version 8), with annotations and digital copies of the source (where available).

2.2 Results

In total, the searches resulted in 2,028 potential articles that met our search criteria. We then evaluated these articles for accessibility and validity, selecting literature that was either published by reputable sources, agencies, or peer reviewed literature. We then read through the articles to identify those that were relevant to this particular study and human exposure. This resulted in 194 sources: 85 for wildland fires, 67 for structure fires, and 49 for vehicle fires (fifteen articles spanned both structure and wildland fire topics). These sources were then further analyzed to identify specific hazards and exposure risks that can reasonably be related to firefighters in the wildland urban interface.

A database was compiled, evaluating each article on several key factors (Table 1):

- The type of study conducted (e.g. whether it was an exposure study, assessment of combustible materials, or an analysis of a particular injury-related incident)
- Whether the study specifically included or referenced firefighting and firefighters
- Whether the study addressed smoke related issues (generally and specifically)
- Key constituents included in the study including hazardous air pollutants (HAPs), polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), particulates, carbon monoxide, carbon dioxide, nitrogen species, sulfur dioxide, benzene, cyanide, and acids (hydrochloric and sulfuric)
- Whether the study included an assessment of heat as part of the analysis
- Whether the study specifically addressed wood and/or wood related products
- Whether the study addressed the use of SCBA or respirators as part of the evaluation
- For vehicle fires, the evaluation also identified whether the study was specific to tunnel fires and/or whether they included tire combustion in the assessment

Appendix A provides a complete table and evaluation criteria for each resource included in this analysis. **Appendix B** provides a complete list of the literature included in the literature review.

Table 1. Number and type of studies that addressed specific categories of combustion constituents

Incident Type	HAPs	PAHs	VOCs	PM	CO	CO2	NOx	SO2	Benzene	Cyanide	Acids
Structure Fire Total	14	8	8	9	16	5	5	3	3	14	4
Vehicle Fire Total	4	5	6	2	8	5	2	1	4	3	3
Wildland Fire Total	2	8	19	26	25	2	3	1	9	6	2
GRAND TOTAL (N=194)	**20**	**21**	**33**	**37**	**49**	**12**	**10**	**5**	**16**	**23**	**9**

Table 2. Number and type of studies that included key criteria (discussed above)

Incident Type	Firefighter Study	Heat	Wood Combustion	SCBA and/or Respirator Use	Tunnel Study	Tire Fires*
Structure Fire Total	27	5	8	4	NA	NA
Vehicle Fire Total	8	6	1	1	12	5
Wildland Fire Total	49	0	17	4	NA	NA
GRAND TOTAL (N=194)	**84**	**11**	**26**	**9**	**12**	**5**

*This criteria only applies to vehicle fires included in this assessment

Results of this review led us to identify the key physiological measurements that we collected on the firefighters as well as the key constituents of concern to assess in our WUI smoke exposure assessment (described in the following sections).

3.0 Laboratory Analysis and Sensor Assessment

Significant research has been conducted to better understand the conditions that fire fighters and occupants are exposed to during structure fires and to a somewhat lesser extent, during wildland fires. Less research has been conducted to understand the exposure to WUI fires. This study was designed to better characterize smoke generated by wildland-urban interface fires to better understand the exposure of fire fighters and the public to WUI smoke. A portable gas and particulate sampling system was developed to collect data both at laboratory- and full-scale for smoke from combinations of structural and vegetative fuels.

This study focuses on the exposure of fire fighters, but the data collected by the sensor package is also applicable to characterizing the exposure of the public during WUI fires. This study extends the work of previous studies (including those conducted by NIST) on the physical and chemical characterization of smoke, laboratory experiments, and field assessments to identify key constituents of smoke [1-16].

3.1 Smoke Sampling

Combustion smoke can be sampled and analyzed using a range of technologies including gravimetric sampling, optical and paramagnetic sensors, gas chromatographs, photoionization detectors, and electrochemical diffusion cells. Some of these techniques can track species or particulate concentrations in real time while others collect an integrated or batch sample which is analyzed off-line to report concentrations. Although batch sampling typically requires less equipment in the field because the sample is returned to the laboratory for analysis, batch samples provide concentrations averaged over the entire collection period, not time-resolved data.

Smoke can be characterized in terms of chemical composition, concentration, and aerodynamic size. Identifying the chemical components of smoke is necessary to determine what compounds, both inorganic and organic, that fire fighters could potentially be exposed to on the fire ground. Organic compounds may include toxic gases (hydrogen cyanide and carbon monoxide), asphyxiants (carbon dioxide [17]), carcinogens (benzene and polycyclic aromatic hydrocarbons [18]) and unburned fuel (soot, vegetation, and volatile organic compounds). Inorganic compounds may include toxic gases (hydrogen sulfide and sulfur dioxide), irritant gases (hydrogen chloride, hydrogen bromide, nitrogen oxides), and particulates (soil). Quantifying how much or the of the specific compounds are present in the smoke is necessary to assess the potential impact of the chemical compounds. For gaseous species concentration is often expressed as parts per million (ppm) or volume percent while solid particulates are reported in mg/m^3.

3.2 Soot and Particulate Sampling

3.2.1 Mass Concentration

Soot and particulate sampling can be conducted using gravimetric filters, either batch or real time, or optical light cell based techniques. The simplest approach is gravimetric batch where a pump is used to pull smoke through a filter media. Filter media can be cellulosic or quartz fibers or polymeric membranes. The filter is weighed before collection, smoke at a known flow rate is pulled through the filter, and the filter is re-weighed after collection. Dividing the total mass collected on the filter by the total volume provides an average concentration. Soot and particulates can also be sampled gravimetrically in real-time using a tapered element oscillating microbalance (TEOM). The TEOM techniques involves causing a small filter to vibrate at a known frequency, and pulling a known volume of smoke sample through the filter media. Although this technology can be deployed to the field, As the mass accumulates on the filter,

the frequency of the vibration changes, and the accumulated mass can be calculated from the frequency change in real time. Again, dividing the instantaneous mass by the flow rate provides real-time mass concentration. However, the relatively small EOM filter (< 1.3 cm diameter) can become clogged in high mass concentrations requiring frequent filter changes. For low concentrations of smoke, a single filter can collect for many hours, but for higher concentrations of smoke, such as those in close proximity to active fires, a single filter may only collect for several minutes before necessitating a filter change.

In additional to TEOM techniques, light- or optical-cells can also be used to monitor soot and particulates in real-time. Smoke is pulled into a small volume while a beam of light is transmitted through the smoke. The light source which can be a laser, an incandescent filament, or light emitting diode, is typically in the visible and/or infrared portion of the electromagnetic spectrum. Smoke can either absorb or scatter light within the cell volume. The amount of light adsorbed and scattered is a function of mass concentration, size distribution, index of refraction, and the wavelength of the light. Optical cells can be small portable hand held models or more complex 10 liter cells mounted on an optical board or frame.

3.1.2 Size Distribution

The size distribution of soot and particulates can be conducted using aerodynamic impactors (batch), or optical light cell based techniques (real-time). A pump is used to pull smoke through a multi-stage impactor. At each stage the smoke is accelerated and required to negotiate 90 degree changes in direction. At each stage, the particles with larger aerodynamic diameter are less able to follow the flow lines of the gas and impact a thin foil collection media. As the smoke is accelerated more at each subsequent stages, the smoke particulates are collected on the different foils according to aerodynamic size. The size distribution of the particulates is calculated by weighing the mass of particles on each sizing stage. Some impactors are designed to simulate how deep the particulates would penetrate the human respiratory system. Large particles would be deposited in nose/throat, smaller particles in the bronchial tree, and still smaller particles would be carried deeper into the lungs.

Optical light cell particle counters can use light scattering, light obscuration, or direct imaging to count and/or size smoke particulates. Typically, a pump pulls a smoke sample into a sensing chamber where a high intensity light (LED, laser, or halogen) illuminates the particles. Photo detectors track the scattered light and/or obscured light and the amplitude of the light scattered or light blocked allows particles to be counted and tabulated into standardized counting bins. For direct imaging, the sensing chamber is illuminated by a high intensity light and digital images of the particles are recorded for subsequent analysis by imaging software. While light scattering or light blocking particle counters can display data in real-time, direct imaging counters typically do not report data in real time.

3.2 Gas Species

Combustion smoke gas species can be sampled and analyzed using a range of technologies including light absorption cells, paramagnetic sensors, electrochemical cells, photoionization detectors, and gas chromatographs. Many of these monitors provide real-time or near real-time gas concentrations while others utilize batch collection and off-line analysis.

3.2.1 Light Absorption Optical Cells

Within Carbon monoxide and carbon dioxide, within the smoke can be individually detected using non-dispersive infrared sensors. After passing the smoke through a cold trap to remove water and a filter to remove particulates, smoke is pumped through a small cell. A beam of infrared light is split and transmitted through the sample cell and a reference cell which contains the gas species of interest at a

known concentration. Both the sample and reference cells absorb portions of the transmitted light in proportion to the gas species being detected. The ratio of the two signals provides real-time concentration of gas species in the reference cell.

3.2.2 Paramagnetic Detectors

Oxygen concentrations can be tracked in real-time because oxygen has the unique paramagnetic properties which cause a flow of oxygen containing gas to induced an internal magnetic field when placed in an externally applied magnetic field. Since the induced magnetic field is proportional to amount of oxygen molecules, oxygen concentrations can be tracked in real-time. Typically, the smoke is pumped through a cold trap to remove water vapor and a filter to remove particulates.

3.2.3 Electro-Chemical Cells

The gas diffuses into the sensor, through the back of the porous membrane to the working electrode where it is oxidized or reduced. This electromechanical reaction results in an electric current that passes through the external circuit. In addition to measuring, amplifying and performing other signal processing functions, the external circuit maintains the voltage across the sensor between the working and counter electrodes for a two electrode sensor or between the working and reference electrodes for a three electrode cell. At the counter electrode an equal and opposite reaction occurs, such that if the working electrode is an oxidation, then the counter electrode is a reduction.

3.2.4 Photoionization Detectors

Photoionization detectors measure volatile organic compounds and other gases in concentrations. In a photoionization detector high energy photons, typically in the vacuum ultraviolet range, break molecules into positively charged ions. As compounds enter the detector they are bombarded by high energy UV photons and are ionized when the absorb the UV light, resulting in ejection of electrons and the formation of positively charged ions. The ions produce an electric current, which is the signal output of the detector. The greater the concentration of the component, the more ions are produced, and the greater the current. PIDs are non-destructive and can be used before other sensors in multiple-detector configurations.

3.3 Sorbent Tubes

Sorbent tubes are widely used collection media for sampling gases and volatile compounds in air or smoke. Sorbent tubes are small glass tubes packed with various types of sold adsorbent materials. The medium is tailored to the component(s) of interest. Activated charcoal and a crosslinked polystyrene copolymer resin are often used to capture benzene and polycyclic aromatic hydrocarbons, respectively. Smoke is pulled through a sorbent tube and the chemicals are trapped onto the sorbent material during the sampling period. Sorbent tubes are returned to a laboratory for desorption and subsequent analysis. Often the analysis is completed using a gas chromatograph. Once analyzed, often done via a gas chromatograph, the total amount of chemical is reported. Dividing the total amount by the volume pulled by the pump through the sorbent tube provides an integrated value over the entire sampling period.

3.4 Chromatography

Chromatography is an analytical technique which can be used to quantify compounds in smoke. Samples are introduced typically into a small diameter column which is packed with a specific medium. The medium is tailored to the component(s) of interest. The sample is moved through the medium within the column by either a carrier gas or liquid solvent. Compounds move through the medium at different rates because of specific material properties. For example, large molecules may take more time than

small molecules to elude from the end of the column. Detectors at the end of the column sense when specific compound emerge as a function of time. The amount of time required for sample to move through medium is dependent on compound, carrier/solvent flow, and length of column. Portable chromatographs and micro-chromatographs can be deployed to the field, but do not provide real-time data. By selecting different medium, columns, carriers/solvents, and detectors, chromatographs can identify a broad range of compounds, but not simultaneously.

4.0 Instrumentation Package

On the fire ground, whether it be an urban, wildland, or wildland-urban interface fire, fire fighters are exposed a range of combustion products. A field deployable instrumentation package would allow smoke to be sampled on the fire ground. Deployment of multiple packages would allow smoke exposure to be characterized at multiple location simultaneously. Smoke sampling technologies, both commercial off-the-shelf systems as well as laboratory prototypes, each system was reviewed to assess the suitability of sensors and monitoring devices for potential precision/accuracy, reliability/repeatability, durability, length of deployment, portability (size/weight), data distribution and communications compatibility, real-time capabilities, and ease of use and interpretation. It was also critical that the selected instruments be compatible with other systems in order to allow all the sampling to be assembled, powered, and deployed in a single rugged system.

4.1.1 Smoke Sampling Capabilities

The system needed to include the capability of monitoring multiple combustion products including toxic and irritant gases, polycyclic aromatic hydrocarbons, volatile organic compounds, particulate materials as well as temperature and relative humidity. Smoke components, sensors, and analysis techniques are tabulated in Table 3.

Table 2. Smoke Components, Sensors, and Analysis Techniques.

Smoke Component	Sample Type	Detection Method	Reported Data
Carbon Monoxide	Real time	Optical Cell – light absorption	Concentration Volume Percent (Parts Per Million)
Carbon Dioxide	Real time	Optical Cell – light absorption	
Hydrogen Cyanide	Real time	Electrochemical Cell	
Hydrogen Chloride	Real time	Electrochemical Cell	
Hydrogen Flouride	Real time	Electrochemical Cell	
Nitric Oxide	Real time	Electrochemical Cell	
Nitrous Oxide	Real time	Electrochemical Cell	
Sulfur Dioxide	Real time	Electrochemical Cell	
Benzene	Integrated Batch	Sorbent Tube Chromatography	Mass Concentration Mg/m3
Polycyclic aromatic hydrocarbons	Integrated Batch	Sorbent Tube Chromatography	
Volatile Organic Compounds	Real time	Photo ionization	

Particulate Material	Integrated Batch	Gravimetric	Average Mass Concentration
	Integrated Batch	Gravimetric	Particle Size Distribution
	Real Time	Optical Cell – Light Scattering	Particle Size Distribution

Smoke monitoring analyzers are commercially available as single gas or multiple gas systems. In order to minimize weight and size as well as power required, multiple-gas analyzers were selected. Two multi-gas systems were configured to monitor carbon dioxide, carbon monoxide, volatile organic com dedicated to tracking one gas or compound or as multiple analyzer

Table 3. Smoke Component and Sample Configuration

Smoke Component		Sample Configuration
Hydrogen Cyanide		Multi-Gas System1
Hydrogen Chloride		
Hydrogen Flouride		
Nitrous Oxide		
Sulfur Dioxide		
Carbon Monoxide		Multi-Gas System 2
Carbon Dioxide		
Nitric Oxide		
Volatile Organic Compounds		
Benzene		Sorbent Tube & portable pump
Polycyclic aromatic hydrocarbons		Sorbent Tube & portable pump
Particulate Material	Average Mass Concentration	Filter & portable pump
	Particle Size Distribution	Cascade Impactor & portable pump
	Particle Size Distribution	Particle Analyzer with built-in pump

4.1.2 Active Smoke Sampling

The key feature of active smoke sampling is that a sample is extracted from the fire conditions or smoke plume. Typically, a pump is employed to pull the sample through the probe at a calibrated flow rate through tubing to a detector. The probe and tubing can be glass, metal, or plastic. The smoke may or may not be conditioned to prepare it for analysis. Filters are used to remove particulates, cold traps to remove water, and specific adsorbents, to scrub carbon dioxide. Gravimetric analysis for particulates

almost always requires that a volume be pulled through a filter media in order to separate out the solid component of the smoke. When sampling for multiple compounds, it can be useful to use the same probe to pull all the samples. If multiple probes and sample locations are used, it can introduce uncertainty as to whether or not there was variability in chemical composition related to different sample locations. Since active sampling involves moving a sample from the sampling point to an analyzer, electrical power, either hardwired or battery, is needed.

4.1.3 Passive Smoke Sampling

Rather than using pumps to extract a sample, passive sampling relies on wind or air currents to move or convect the smoke to the detector. The smoke may or may not be well mixed, so multiple sensors located small distances apart may be immersed and thus sampling in smoke of different concentrations. However, since passive sampling does not require a pump to extract a sample, the need for electrical power requirements are significantly reduced.

4.2 Smoke Sampling Package

In order to monitor and track multiple components of smoke which were identified during the early stages of this study, the design of this instrumentation package needed to meet a number of requirements including 1) real-time concentration measurements of 8 different gas species, 2) real-time concentrations of volatile organic compounds, 3) batch sample collection for polycyclic aromatic hydrocarbons and benzene, 4) real-time monitoring of size distribution of particulates, 5) gravimetric measurement of soot and particulate mass concentrations, 6) portable and relatively low weight, 7) battery powered, 8) data logging for real-time data streams, and 9) able to survive brief exposure to flame radiation and embers.

4.2.1 Analyzer Enclosure

The enclosure for the analyzers is a thin wall stainless steel duct of 24 cm (9 inch) diameter and 40 cm (16 inch) long(Figure 1). An end cap at the exhaust or lower end a centered mounting column, battery pack, and exhaust fans (Figure 2). Another end cap at the entrance or upper end is perforated with twenty holes of 2.5 cm (1 inch) diameter. The 20 orifices help ensure that the smoke drawn into the main body of the cylinder is well mixed and prevents large embers from entering (Figure 3).

4.2.2 Multi-Gas Systems

Multi-gas systems 1 and 2 are positioned parallel to and mounted to the center support (Figure 4). Temperature and relative humidity sensors are incorporated into both of the multi-gas systems. As the smoke is pulled into the cylinder and through the perforated end cap, the smoke volume appeared well-mixed within the cylinder. The gravimetric and sorbent tube sampling trains were located after the electro-chemical, photoionization, and light absorption optical cells.

4.2.3 Gravimetric and Sorbent Tube Sampling

Filter holder for gravimetric soot mass concentration and small funnel shaped entrance tip to soot particle size analyzer are mounted in between the multi-gas systems (Figure 5). Sorbent tubes for benzene and polycyclic aromatic hydrocarbons (PAH) are mounted on the opposite side from the multi-gas analyzers (Figure 6). Both sorbent tubes have a filter located before the sorbent tube to remove soot and other particulates. The PAH sorbent tube is larger diameter and filled with white XAD-2 adsorbent (Figure 7). The benzene sorbent tube is a smaller diameter filled with black coconut charcoal (Figure 7).

4.3.4 Pumps, Particle Size Analyzer and Data Acquisition System

Once the stainless steel cylinder has been re-installed over the analyzers, filters, and sorbent tubes, the portable battery-powered pumps are mounted on the outside of the cylinder (Figure 8). Each pump is connected via 6 mm (0.25 inch) diameter plastic tubing to a sample train which includes a filter and sorbent tube. The flow rate for the benzene and polycyclic aromatic hydrocarbon sampling trains were set at 0.2 l/m and 2.0 l/m, respectively. In addition to the sample pumps, the battery-powered particulate sizing analyzer is also mounted on the outside of the cylinder and connected to the sampling tip on the inside of the cylinder by a small diameter 3 mm (0.125 inch) plastic tube (Figure 9). A battery-powered data acquisition system was also mounted on the outside of the cylinder. It was connected to the multi-gas analyzers and other instruments inside the cylinder and the particle analyzer on the outside (Figure 10).

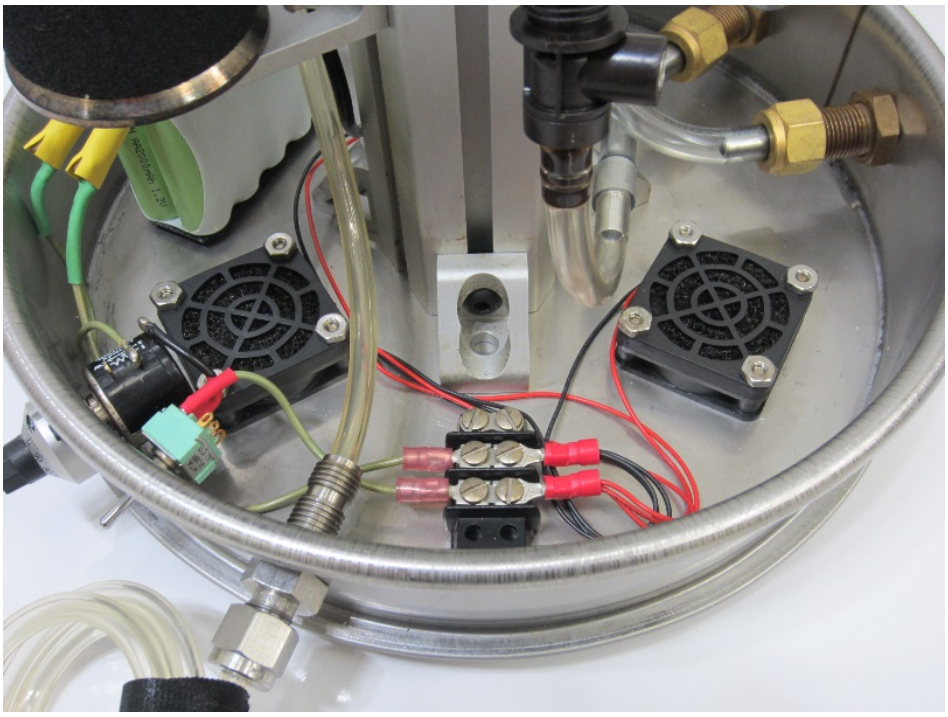
4.3.5 Final Sensor Measurement Matrix

The following table shows the final sensors used to assess smoke samples in both the laboratory and in the field.

Table 4. Wildland-Urban Interface Fire Exposure Selected Measurement Technology

Energy					
	Temperature	Air / Gas	Thermocouple	Chromel-Alumel	
	Thermal Flux	Thermal Radiation	Heat Flux Transducer	Conduction cooled	
Mass					
	Chemical Component	Type of Measurement		Sample Acquisition	GrayWolf Analyzer
	Cabon Monoxide		Opto-chemical	Real Time	IQ-610
			Biomimetic	Assisted Convection	
			Electrochemical		
			Semiconductor		
	Carbon Dioxide		Non-Dispersive Infrared	Real Time	IQ-610
				Assisted Convection	
	Nitrogen Dioxide, NO2		Electro-Chemical Diffusion Cell	Real Time	IQ-501
				Assisted Convection	
	Nitric Oxide, NO		Electro-Chemical Diffusion Cell	Real Time	IQ-501
				Assisted Convection	
	Sulfur Dioxide		Electro-Chemical Diffusion Cell	Real Time	IQ-501
				Assisted Convection	
	Cyanide		Electro-Chemical Diffusion Cell	Real Time	IQ-610
				Assisted Convection	
	Sulfuric Acid		Electro-Chemical Diffusion Cell	Real Time	
	H2SO4			Assisted Convection	
	Hydrochloric Acid		Electro-Chemical Diffusion Cell	Real Time	IQ-501
	HCl			Assisted Convection	
	Hydrobromic		Electro-Chemical Diffusion Cell	Real Time	
	HBr			Assisted Convection	
	Hydroflouric		Electro-Chemical Diffusion Cell	Real Time	IQ-501
	HF			Assisted Convection	
	VOC's		Electro-Chemical Diffusion Cell	Real Time	IQ-610
				Assisted Convection	
	Benzene		Sorbent Tubes	Integrated Sample	SKC Sorbent Tube Cat No. 222-3-50
				Offline analysis	
	PAHs		Sorbent Tube/	Integrated Sample	SKC PUF/XAD/PUF
			Foam	Offline analysis	Cat No. 226-129
	Inhalable		Optical Scattering	Real Time	PC-3016A
	Coarse Particles			Assisted Convection	
	PM10				
	Inhalable		Optical Scattering	Real Time	PC-3016A
	Fine Particles			Assisted Convection	
	PM 2.5				
Weather					
	Temperature			Single Point Real Time	IQ-610
	Wind Speed & Direction			Single Point Real Time	
	Humidity			Single Point Real Time	IQ-610

Figure 1. Stainless steel duct analyzer enclosure.



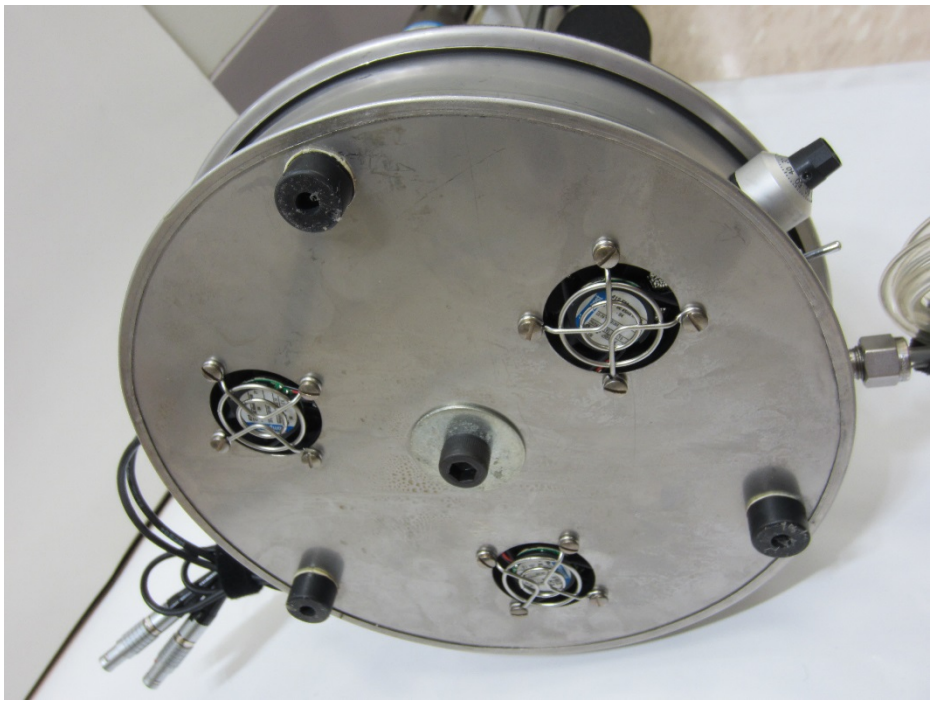


Figure 2. End cap with centered mounting column, battery pack and exhaust fans. Top image sampling side and lower image from exhaust side.

Figure 3. Perforated entrance plate.

Figure 4. Multi-gas systems 1 and 2 are positioned parallel to and mounted to the center support.
Impact of Ventilation

Figure 5. Filter holder for gravimetric soot mass concentration and small tip for soot particle size analyzer are mounted in between the multi-gas systems

Figure 6. Sorbent tubes for benzene and polycyclic aromatic hydrocarbons (PAH) are mounted on the opposite side from the multi-gas analyzers.

Figure 7. Sorbent tubes for polycyclic aromatic hydrocarbons (top) and benzene (bottom).

Figure 8. Portable battery-powered pumps are mounted on the outside of the cylinder.

Figure 9. Battery-powered particulate sizing analyzer is also mounted on the outside of the cylinder.

Figure 10. A battery-powered data acquisition system was also mounted on the outside of the cylinder.

5.0 Laboratory Testing of WUI Materials

Smoke assessments were conducted at the Fire Research Division of the Engineering Laboratory at the National Institute of Standards and Technology (NIST), located in Gaithersburg, Maryland. Vegetation was collected from areas in southern and northern California (ponderosa pine, California cedar, and chaparral), Texas (grassland), Florida (palmetto) and Colorado (pine). Materials were burned as stand-alone vegetation or mixed with standard PVC, gypsum (wall board), or wooden planks (e.g. standard construction lumber) to simulate a wildland fire or a fire with mixed materials as would be found in a WUI incident. The basic premise was twofold: first to assess the viability of the sensor platform and its ability to assess smoke at wildland incidents, and second, to isolate these materials in a laboratory setting to assess the key constituents of concern. The following figures shows the laboratory conditions and protocols used. The samples were placed into metal bins, with a natural gas burner at the bottom of the material (for initial ignition). The smoke is collected by the shroud located above the material, and then funneled into a chamber where the smoke sensors are able to measure the various constituents.

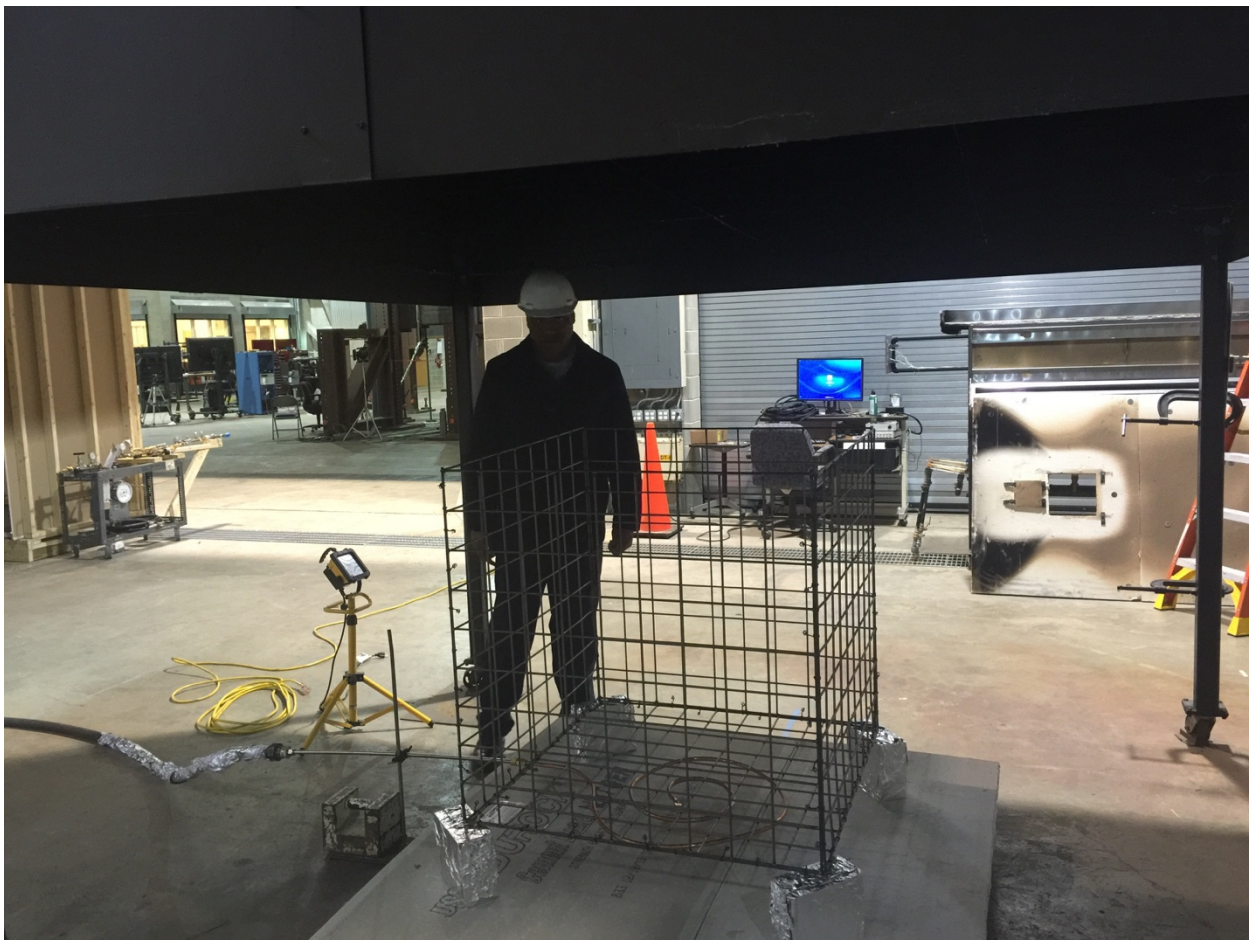


Figure 11. Metal cage and gas coil burner used for vegetation testing.

.

Figure 12. Weighing the plant material placed into metal cage.

Figure 13. Metal hood used to collect smoke from the burn, and funnel it to the sensor array.

Figure 14. Sensor platform connected to metal tubes that send smoke through to be analyzed.

Figure 15. Real-time monitoring of material burn.

Figure 16. Active burning of pine, gypsum, and PVC to simulate a WUI fire.

5.1 Laboratory Results

The following tables and figures represent some of the raw data collected during the laboratory sampling. Following the initial testing of the chaparral, it was determined that the sensor array needed to be modified to allow for the detection of higher levels of and increased range for total VOCs. The other gas sensors were also not operating with accurate results. Therefore, limited data were collected on the chaparral. Additionally, some of the plant materials were unusable for burning as they were contaminated with mite outbreaks, or became too dry during the shipping process (no longer reflecting actual vegetation conditions). However, once these issues were resolved, laboratory data were collected on materials sent on the Saw Palmetto, California Cedar, Texas Grass, Ponderosa Pine, and White Pine (with gypsum, PVC, and pine wood being combined to these materials to simulate a WUI fire incident.

Table 5. Fuel packages and mass tested in the fire lab.

Test ID	Fuel Package	Initial Fuel Mass (g)
WETS160112c	Saw Palmetto	23.3
WETS160113a	Saw Palmetto	45.4
WETS160113b	Saw Palmetto	44.4
WETS160113c	Saw Palmetto	55
WETS160113d	Saw Palmetto	54.5
WETS160114a	Saw Palmetto	46.6
WETS160114b	Saw Palmetto	37.7
WETS160114c	Saw Palmetto	47.3
WETS160114d	Saw Palmetto	42.2
WETS160115a	Texas Grass	21.4
WETS160115b	Texas Grass	19.8
WETS160115c	Texas Grass	29.3
WETS160115d	Ponderosa Pine	58.2
WETS160115e	Ponderosa Pine	28.5
WETS160115f	Ponderosa Pine	83.2
WETS160128a	California Cedar	77.6
WETS160128b	California Cedar	91.4
WETS160128c	California Cedar	88.6
WETS160129a	California Cedar + Gypsum (6) + Pine Wood (8)	67.1
WETS160129b	California Cedar + Gypsum (6) + Pine Wood (8)	65.2
WETS160129c	California Cedar + Gypsum (5) + Pine Wood (7) + PVC (2)	86
WETS160129d	Grass + Gypsum (5) + Pine Wood (7) + PVC (2)	59.7
WETS160201a	White Pine	63.1
WETS160201b	White Pine	74
WETS160201c	White Pine	83.9
WETS160201d	White Pine + Gypsum (5) + Wood (7) + PVC	96.1
WETS160201e	Gypsum (22) + Wood (28) + PVC (6)	156.1

In general, there was a variability in the particle size that was observed when non-vegetation materials were added to the burn, with smaller particles showing up earlier in the smoke column with the introduction of gypsum and typically occurring throughout the burn test.

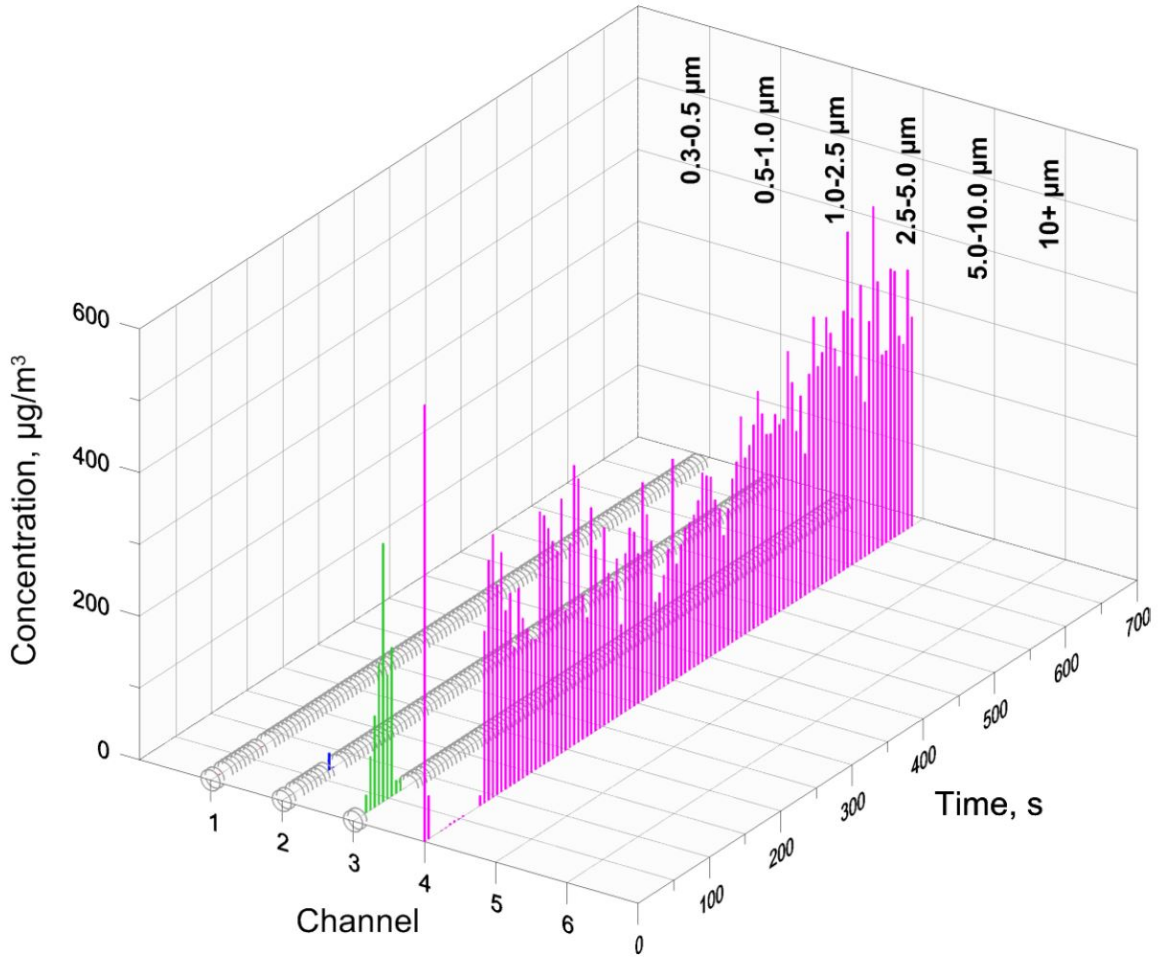


Figure 17. Particle Size Distribution- California Cedar/Gypsum/Pine Wood Test WETS160129b.

With regard to particle sizes, across all vegetation types, the dominant and persistent particle sizes that were observed throughout the laboratory tests consisted largely of PM 2.5-5.0, with some samples showing period releases of PM 1.0-2.5. Additional particle size distribution figures are provided in Appendix A.

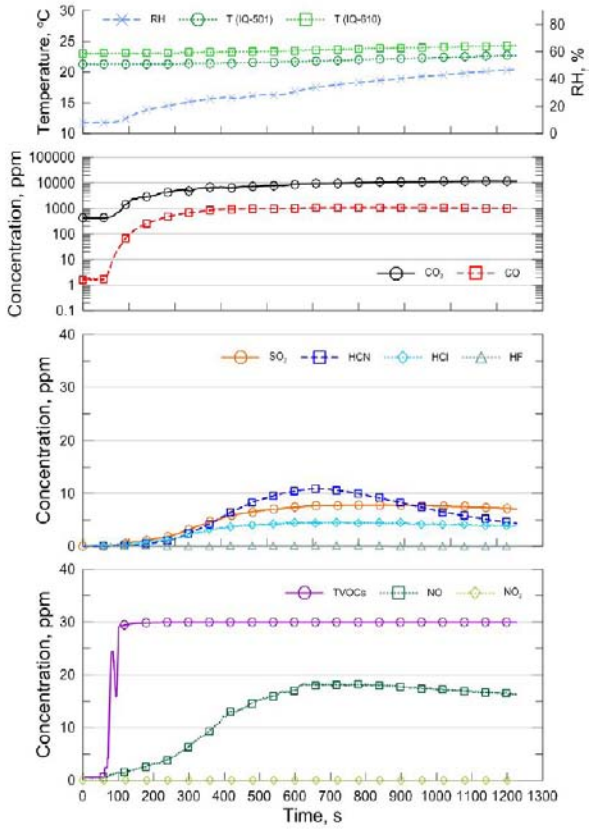
The tests showed that the concentrations of carbon monoxide were generally above 1,000 ppm, and tended to carry a stable concentration throughout the burn. Concentrations of SO_2, NO, HCN, HCI, and HF all peaked at the early stages of the burn and then slowly dissipated, with SO_2 taking longer (in general to dissipate). Concentrations of total VOCs showed a similar pattern of high early concentrations that took longer to dissipate compared to the other constituents. Finally, NO_2 was found in relatively low levels throughout the burns. It is also important to note that the concentrations of total VOCs were likely much higher than what was

recorded in the lab tests simply because the sensor had limits to its peak detection capabilities. Graphs of the cone data reports for laboratory testing is provided in Appendix B.

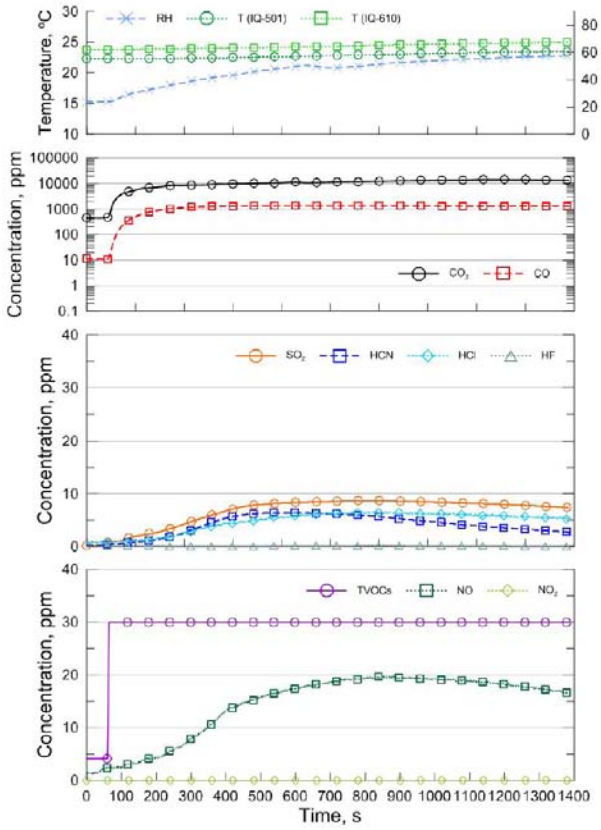
When comparing the data collected from laboratory burns that included just the natural vegetation, versus those that included materials to simulate a WUI scenario, several observations were made. First, not significant differences were detected with regard to the relative humidity, temperature, or concentrations of carbon dioxide or carbon monoxide when WUI materials were introduced to test burns. This was true across all types of vegetation tested. With regard to SO2, concentrations were relatively consistent across both vegetation, and WUI + vegetation burn experiments, however time to reach peak concentrations was often more rapid when WUI materials were introduced into the burn tests. Concentrations of Cyanide for strictly vegetation burns tended to have slightly higher peaks when compared to test burns that included WUI materials. Airborne acids (HCl) were also typically found in higher concentrations when WUI materials were introduced into the test burns, when compared to vegetation alone. With regard to VOCs, no significant differences were observed between test burns with or without WUI materials, however in many cases initial levels of TVOCs were more variable at the beginning of the burn when WUI materials were not present. Finally, NO was typically higher in test burns that included WUI materials when compared to vegetation-only tests (although these differences tended to somewhat variable and only slightly higher).

The following figures show a side-by-side comparison between vegetation-only test burns versus test burns that included WUI materials (including pine board, PVC, and gypsum). Additional graphs of test burns under various conditions are provided in Appendix B.

FIGURE 18. COMPARISON OF WHITE PINE AND WUI MATERIALS

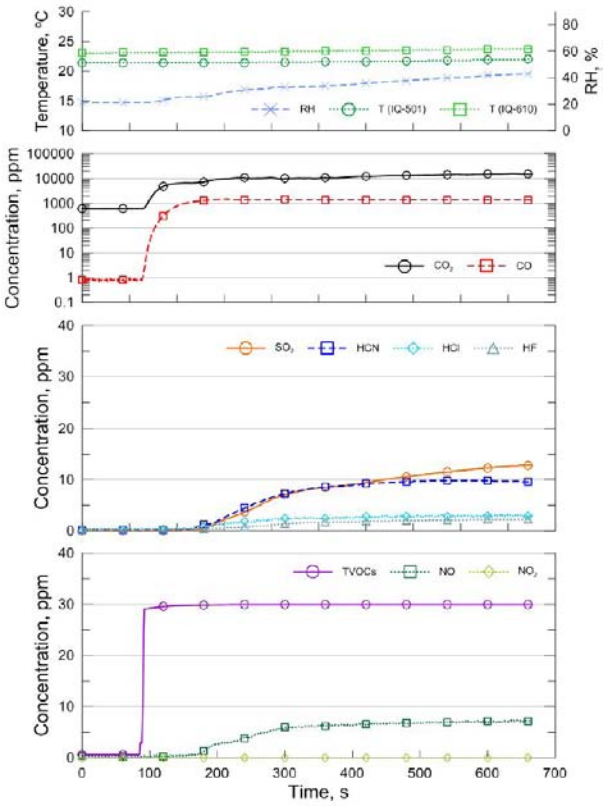


Gas Species Concentration
White Pine **Only**

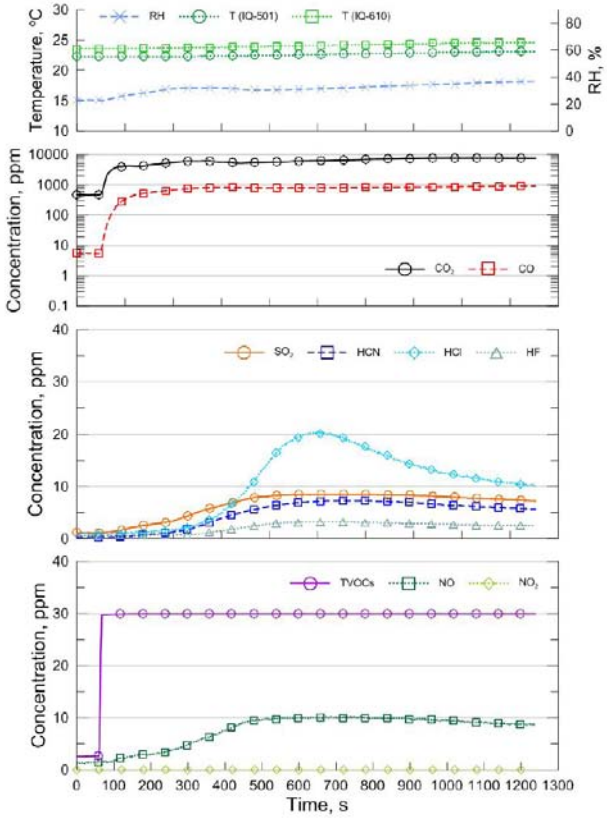


Gas Species Concentration
White Pine and **WUI** Material
Gypsum, Wood Pine, PVC

FIGURE 19. COMPARISON OF TEXAS GRASS AND WUI MATERIALS

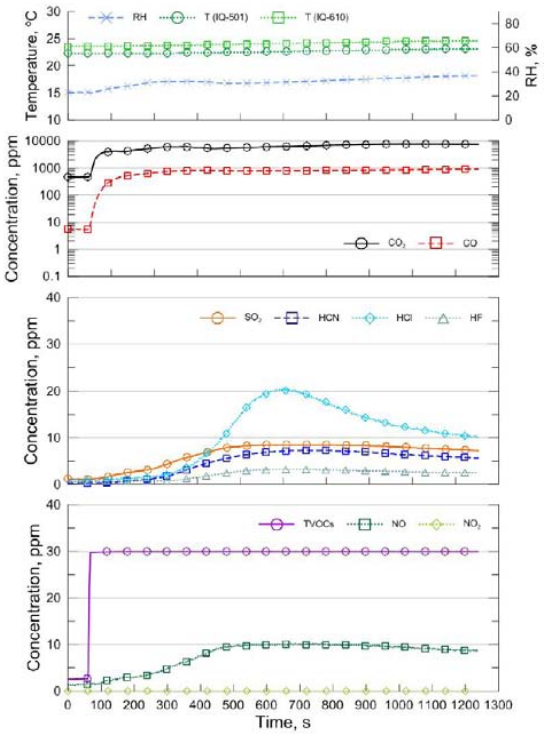


Gas Species Concentration
Grass **Only**

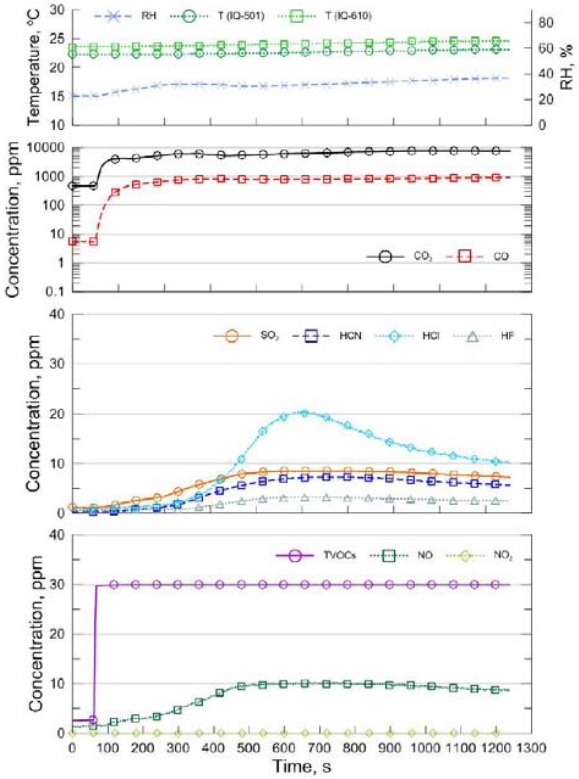


Gas Species Concentration
Grass and **WUI** Material
Gypsum, Wood Pine, PVC

FIGURE 20. COMPARISON OF CALIFORNIA CEDAR AND WUI MATERIALS



Gas Species Concentration
Cedar **Only**



Gas Species Concentration
Cedar and **WUI** Material
Gypsum, Wood Pine, PVC

The data collected through the sorbent tubes included concentrations of both Benzene and PAHs. In general, the Benzene concentrations tended to be significantly higher for those test burns that included both the vegetation and the WUI materials.

Table 6. Benzene Concentration by sample type – Coconut Charcoal Sorbent Tube

Sample	Sample Volume L	Sample Time s	Concentration		Reportable Limit mg/m3	Notes
			mg/m3	ppm		
White Pine WETS160201b	4.49	1348	8.7	2.7	0.22	
White Pine WETS160201c	3.95	1186	12	3.9	0.25	
Ponderosa Pine WETS160115f	3.86	1159	14.0	4.4	0.002	
California Cedar WETS160128c	4.51	1353	4.2	1.3	0.002	
California Cedar/Gypsum/Wood WETS160129b	3.15	944	16.5	5.2	0.002	
White Pine/Gypsum/Wood/PVC WETS160201d	4.58	1374	16	5.1	0.22	
Gypsum/Wood/PVC WETS160201e	4.58	1374	120	38	2.2	Benzene on Backup Sorbent Section - Possible break through
California Cedar/Gypsum/Wood/PVC WETS160129c	3.88	1164	20	6.2	0.26	
Air Blank	3.79	1136	0.79	0.2	0.002	
Burner Blank	3.87	1162	0.52	0.2	0.002	

With regard to PAH concentrations, most of the samples were below the reportable limits under the analysis, with only instance where Phenantherene was recorded in a sample burn that included white pine, gypsum, pine wood board, and PVC. This suggests that PAH concentrations under these laboratory scenarios is somewhat limited and not able to produce detectable results under the volume burned and time allotted (Appendix C).

6.0 Field Assessment of Smoke Exposure

6.1 Methods

During the fire assessments, the sensor platform was placed at or near where firefighters were actively engaged in training activities, suppression, or other duties related to the incident. Data were typically collected for 4 hours where possible (ensuring that no operational impact from the data collection occurred to the fire operations). Sensors were either placed or carried alongside where the firefighters were actively engaged in their duties, with an emphasis on identifying those individuals or teams that were working in conditions where smoke exposure was likely.

Eighteen fire incidents were analyzed during the study, including six controlled burns, seven wildland fire incidents, and five training academy burns. The controlled burns were conducted in Northern California, Riverside, and San Diego County, in grassland areas and mixed grass/shrubland during fire control training courses conducted by CAL FIRE during the spring/summer of 2014-16. The wildland fire incidents included two "typical" wildland fires in southwest Riverside County in mixed chaparral/coastal sage scrub, two incidents in both Riverside and San Diego county that included mixed scrub, grassland, and some wildland urban interface, and three fires in northern California that were dominated by timber (mostly pine and cedar) that included infrastructure, homes, vehicles, etc. from the wildland urban interface (Table 7). The sensors used to collect data at these burns included the same sensor platform used at the NIST burn laboratory, however the sensors were not encased in the steel cylinder as we were attempting to monitor ambient air constituents.

6.2 Results

In general, controlled burns showed limited levels of exposure, with CO and PM being the most common exposure type. While the firefighters were working in the smoke, the occupational exceedances of both PM and CO were commonplace, however the variability of wind gusts seemed to have an effect on the ability of the sensors to accurately collect data on ambient air quality conditions. It was noticed on these incidents (and others) that even in a heavy inversion, when gusts of wind would pass through the sensors, they typically reached at or near zero levels of key constituents. This may be a limitation of the sensors themselves, and may not accurately reflect actual ambient air conditions outside the laboratory. It was thought that encasing the sensors in the same type of metal cylinder that was used in the NIST laboratory experiments, and allowing small fans to pull in ambient air from outside would help stabilize that ambient air conditions in the field, providing for a more accurate assessment of environmental contamination. We were unable to test this hypothesis during this study, but will continue to evaluate this as an option for future studies on wildland smoke exposure.

In those incidents where manmade materials were included (for both training burns and WUI incidents), key constituents were observed that were otherwise absent or below occupational exposure levels in the other vegetation-only burns. While the laboratory tests provided similar results, the data collected in the field on actual WUI and training fires demonstrated a much more consistent and elevated exposure risk in certain constituents. In general, PM, CO, SO2, VOCs, NO, cyanide, and benzene were commonplace when these combusted materials were included in the smoke exposure, while PAHs, HCN, and HCL were also detected (however these occurrences were typically at lower levels of occurrence and minimal exceedances of occupational levels).

With regard to the use of sorbent tubes on actual wildfire incidents, there were both logistical and technological issues that limited our ability to collect reliable data. To overcome those issues, we have

investigated the use of optical sensors that can detect PAHs and Benzene in real time. Unfortunately, this method does not allow for a similar analysis as a sorbent tube (as was used in the laboratory testing), with total exposure and air volume sampling not immediately comparable to the data collected by a sorbent tube, it is still valuable to be able to detect levels of PAHs and Benzene on a wildland/WUI incident and determine whether these constituents are present.

Table 7. Controlled burns, training burns, and WUI incidents with key exposures/toxicants found at the incidents exceeding established threshold values for NIOSH (REL-ST) and OSHA (IDLH).

.

Fire Type	Main Products Combusted	Atmospheric Conditions	Key Exposures Detected
Controlled Burn			
NorCal1a	Grassland	75F, 48%RH, wind <2mph	CO, PM
GrassV1a	Grassland	72F, 33%RH, wind <1mph	CO, PM
Grassv1b	Grassland/Shrub	71F, 30%RH, wind 4mph	PM
Cleveland	Shrub/Timber	88F, 44%RH, wind 3mph	CO, PM, HCN
Riverside	Grassland/Shrub	68F, 33%RH, wind <2mph	CO, PM, SO2
Training			
Clark1a	Household products, furniture, mattress, carpet, gypsum	84F, 28%RH, wind 3mph	CO, PM, NO2, NO, SO2, VOCs, Cyanide
Clark1b	Plywood, tar shingles, pine	84F, 28%RH, wind 3mph	CO, PM, SO2, HCL
Indio1	Home burn (no furniture or carpet)	79F, 40%RH, wind 5mph	CO, PM, SO2, HCN, HCL, VOCs
Indio2	Home burn (no furniture or carpet)	73F, 44%RH, wind <2mph	CO, PM, SO2, HCN, HCL, VOCs
Riverside1	Home burn (no furniture or carpet)	85F, 34%RH, wind <2mph	CO, PM, SO2, HCN, HCL, VOCs
Riverside2	Home burn (office/home furniture and carpet)	85F, 34%RH, wind <2mph	CO, PM, SO2, HCN, HCL, PAHs, Benzene, VOCs
WUI			
Temecula	Chaparral, Freeway, Utilities	95F, 25%RH, wind 15mph	CO, NO2, Cyanide, PM
Sands	Timber/WUI	75F, 28%RH, wind 7mph	CO, Cyanide, VOCs, Benzene, PM, NO2
Yolo	Grassland/Homes	83F, 35%RH, wind 3mph	CO, PM, NO
Cleveland	Chaparral, Freeway, Utilities, Barn	75F, 34%RH, wind <2mph	CO, PM, Cyanide, VOCs
Calaveras	Timber, Shrubland, homes, vehicles, utilities	80F, 22%RH, wind <2mph	CO, PM, NO, NO2, SO2, Cyanide, HCL, VOCs, Benzene, PAHs
Napa	Timber, Shrubland, homes, vehicles, utilities	71F, 34%RH, wind <2mph	PM, CO, NO, VOCs
Paradise	Timber, shrubland, highway and utility infrastructure	98F, 20%RH, wind 15mph	PM, CO, NO, VOCs

Figure 21. Firefighter exposure at grass fire controlled burns.

Figure 22. Limited respiratory protection provided for wildland and WUI incidents.

Figure 23. Typical timber and shrubland wildfire.

Figure 24. Sensors deployed at WUI incident.

Figure 25. Typical smoke exposure and materials burned at WUI incident.

Figure 26. Typical smoke exposure and materials burned at WUI incident.

Figure 27. Urban materials burn testing conducted at Clark Training Base with CAL FIRE.

Figure 28. WUI training burn smoke exposure sampling.

7.0 Wildland Urban Interface Firefighter Assessment

In conjunction with the FEMA-FPS funded program described herein, our team worked in partnership with the US Forest Service, International Association of Fire Fighters, CAL FIRE, and CAL FIRE Local 2881 to evaluate the physiological conditions of wildland firefighters between through 2014-2015. Wildland firefighters often work for extended periods in intense heat and brutal environmental conditions. It is important to understand how the regular duties and environmental conditions experienced by wildland firefighters influence key physiological conditions including heart rate, respiratory rate, core body temperature, and hydration. Ninety-five wildland firefighters with CAL FIRE volunteered to participate in this study, including personnel at training events (extended hose lays), controlled burns, and actual wildland fires. The results show that wildland firefighters regularly exceeded safe physiological conditions (regardless of the event type). Nearly 65% of the firefighters had sustained peak heart rates above 200 beats per minute (bpm), with nearly 20% exceeding 220bpm (all but three of the volunteers regularly exceeded the recommended maximum hearts rate for work (220bpm minus your age). Likewise, measured core body temperatures exceeded 102F in roughly 70% of the firefighters, with 10% exceeding 103F. Furthermore, nearly two-thirds of the firefighters started their shifts at or near a level of dehydration. Dehydration rates significantly increased across all firefighters at the end of duty, with only 25% of the firefighters that started off at or near dehydration self-correcting and becoming more hydrated by the end of the shift. Finally, the type of personal protective equipment (PPE) worn by wildland firefighters has a significant influence on their physiology. The results suggest that the traditional double-layer PPE produces significantly higher core body temperatures, higher incidence of dehydration, and higher heart rates than single-layer PPE.

A full report on the findings, methods, and recommendations is provided in a separate report.

8.0 Presentations and Workshops

Throughout the research process, we worked closely with partners in the IAFF, CAL FIRE, CAL FIRE Local 2881, NIST, and the US Forest Service. Annual updates were provided at conferences and symposia for both CAL FIRE and the IAFF (Redmond and Alts), as well as presentations given at the NWCG annual conference. In 2014 and through 2015, a symposium was held in Sacramento that included all the major state and federal agencies that deal with wildland and urban interface issues.

The results of that effort are included in a separate report.

9.0 References

1.Mulholland, G. W.; Bryner, N. P., "Light Extinction and Total Scattering Measurements via a Transmission Cell-Reciprocal Nephelometer", Combustion Institute/Eastern States Section. Chemical and Physical Processes in Combustion. 20th Fall Technical Meeting AND National Bureau of Standards/Center for Fire Research. Annual Conference on Fire Research. Combined Technical Meetings. Abstracts. November 2-5, 1987, Gaithersburg, MD, 34/1-4 pp, 1987.

2. Evans, D. D.; Baum, H. R.; Mulholland, G. W.; Bryner, N. P.; Forney, G. P., "Smoke Plumes from Crude Oil Burns", Environment Canada. Arctic and Marine Oil Spill Program Technical Seminar, 12th. June 7-9, 1989, Calgary, Canada, 1-22 pp, 1989.19.

3.Benner, B. A., Jr.; Bryner, N. P.; Wise, S. A.; Mulholland, G. W.; Lao, R. C.; Fingas, M. F., "Polycyclic Aromatic Hydrocarbon Emissions from the Combustion of Crude Oil on Water", Environmental Science and Technology, Vol. 24, No. 9, 1418-1427, 1990.

4.Mulholland, G. W.; Bryner, N. P., "Laboratory Studies of Smoke Properties at NIST Past, Present, and Future", Paper F-08; CRDEC-CR-092; Office of the Project Manager Smoke/Obscurants. Smoke/Obscurants Symposium 14. Volume 2. April 1990, Laurel, MD, Deepak, A.; Klimek, W., Editors, 671-684 pp, 1990.

5.Benner, B.A.; "Polycyclic Aromatic Hydrocarbon Emission from the Combustion of Crude Oil on Water" Environment and Science Technology, Vol. 24, p 1418, 1990.

6.Bryner, N. P.; Mulholland, G. W., "Smoke Emission and Burning Rates for Urban Structures", Atmospheric Environment, Vol. 25A, No. 11, 2553-2562, 1991.

7.Benner, B. A., Jr.; Bryner, N. P.; Wise, S. A.; Mulholland, G. W.; Evans, D. D.; Fingas, M. F.; Li, K., "Emissions of Polycyclic Aromatic Hydrocarbons from the Combustion of Crude Oil on Water", Spill Technology Newsletter, Vol. 16, No. 1, 1-16, March 1991.

8.Pitts, W. M.; Bryner, N. P.; Johnsson, E. L., "Production Mechanisms for Carbon Monoxide in Enclosure Fires", Combustion Institute/Central and Eastern States Section. Combustion Fundamentals and Applications. Joint Technical Meeting, 1993. March 15-17, 1993, New Orleans, LA, 102-106 pp, 1993.

9.Mulholland, G. W.; Bryner, N. P., "Radiometric Model of the Transmission Cell-Reciprocal Nephelometer", Atmospheric Environment, Vol. 28, No. 5, 873-887, 1994.

10. Dobbins, R. A.; Mulholland, G. W.; Bryner, N. P., "Comparison of a Fractal Smoke Optics Model With Light Extinction Measurements", Atmospheric Environment, Vol. 28, No. 5, 889-897, 1994.

11.Bryner, N. P.; Benner, B. A., Jr., "Ground-Based Smoke Sampling Techniques Training Course and Collaborative Local Smoke Sampling in Saudi Arabia", NISTIR 5306; National Institute of Standards and Technology, Gaithersburg, MD, 85 p. Issued January 1994.

12.Pitts, W. M.; Johnsson, E. L.; Bryner, N. P., "Carbon Monoxide Formation in Fires by High-Temperature Anaerobic Wood Pyrolysis", Combustion Institute. Symposium (International) on Combustion, 25th. Proceedings. July 31-August 5, 1994, Irvine, CA, Combustion Institute, Pittsburgh, PA, 1455-1462 pp, 1994.

13.Bryner, N.P.; Walton, W.D.; DeLauter, L.A.; Twilley, W.H.; Mullin, J.V., "Response of Portable Particulate Monitoring Instruments to Combustion Particulates, Road Dust, and Salt Aerosols", Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, 22nd. Volume 2. Proceedings. June 2-4, 1999, Calgary, Alberta, Canada, Environment Canada, Ottawa, Ontario, 519-544 pp, 1999.

14.Bukowski, R. W.; Peacock, R. D.; Averill, J. D.; Cleary, T. G.; Bryner, N. P.; Walton, W. D.; Reneke, P. A.; Kuligowski, E. D., "Performance of Home Smoke Alarms, Analysis of the Response of Several Available Technologies in Residential Fire Settings", NIST TN 1455; National Institute of Standards and Technology, Gaithersburg, MD, 396 p. December 2003

15.Lin, Q.; Mendelssohn, I. A.; Carney, K.; Miles, S.M.; Bryner, N. P.; Walton, W. D., "In-Situ Burning of Oil in Coastal Marshes. 2. Oil Spill Cleanup Efficiency as a Function of Oil Type, Marsh Type, and Water Depth", Environmental Science and Technology, Vol. 39, No. 6, 1855-1860, 2005.

16. Lin, Q.; Mendelssohn, I. A.; Bryner, N. P.; Walton, W. D., "In-Situ Burning of Oil in Coastal Marshes. 1. Vegetation Recovery and Soil Temperature as a Function of Water Depth, Oil Type, and Marsh Type", Environmental Science and Technology, Vol. 39, No. 6, 1848-1854, 2005.

17. *Carbon dioxide* https://www.osha.gov/dts/chemicalsampling/data/CH_225400.html

18. Bostrom, C.-E.; Gerde, P.; Hanberg, A.; Jernstrom, B.; Johansson, C.; Kyrklund, T.; Rannug, A.; Tornqvist, M.; Victorin, K.; Westerholm, R. (2002). "Cancer risk assessment, indicators, and guidelines for polycyclic aromatic hydrocarbons in the ambient air." *Environmental Health Perspectives* ***110*** *(Suppl 3): 451–488.* ISSN 0091-6765. PMC 1241197. PMID 12060843