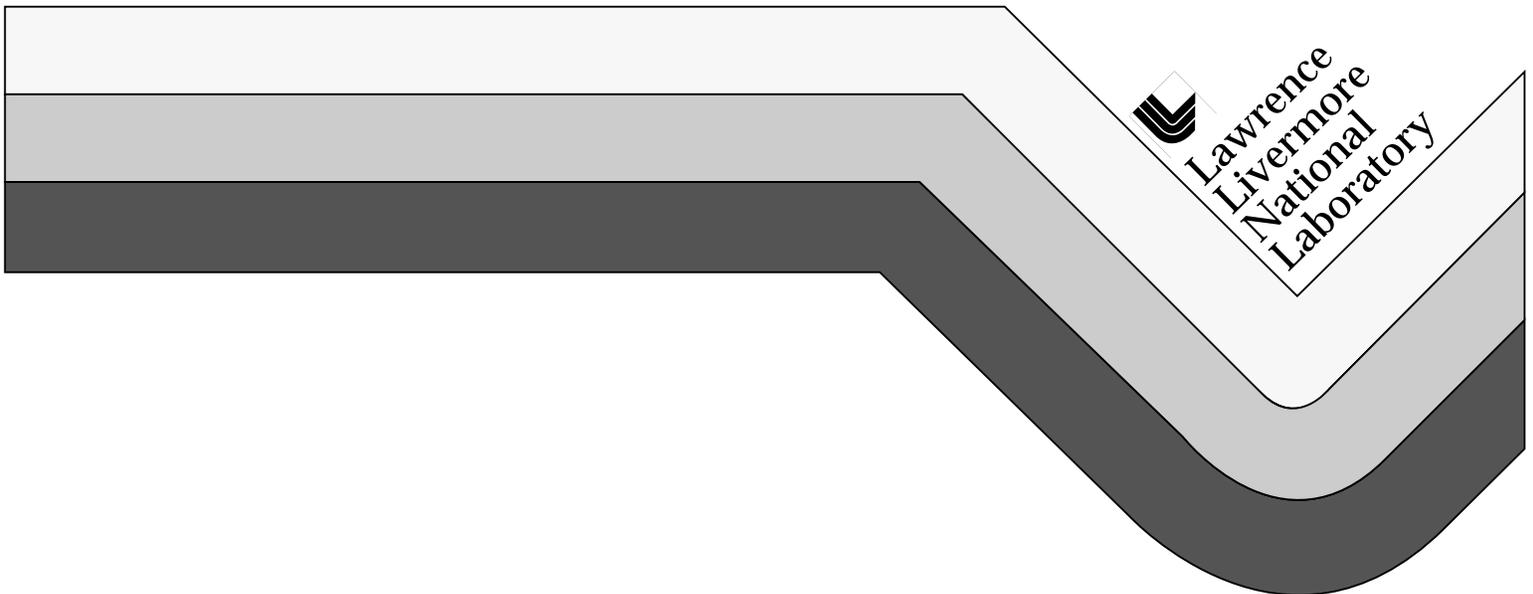


# Determination of Toxic Material Penetrations for Wildland Respirator Filters

**Kenneth Lawrence Foote**

**M.S. Thesis**

**May 1994**



#### DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This report has been reproduced  
directly from the best available copy.

Available to DOE and DOE contractors from the  
Office of Scientific and Technical Information  
P.O. Box 62, Oak Ridge, TN 37831  
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the  
National Technical Information Service  
U.S. Department of Commerce  
5285 Port Royal Rd.,  
Springfield, VA 22161

# **Determination of Toxic Material Penetrations for Wildland Respirator Filters**

**Kenneth Lawrence Foote**

**A Thesis Presented to  
The Faculty of the Department of Chemical Engineering  
San Jose State University**

**In Partial Fulfillment  
of the Requirements for the Degree  
Master of Science**

**Manuscript date: May 1994**





Thesis approved for the Department of Chemical Engineering

\_\_\_\_\_ Date \_\_\_\_\_  
Dr. M. A. McNeil, Thesis Advisor and Chairperson  
SJSU, Department of Chemical Engineering

\_\_\_\_\_ Date \_\_\_\_\_  
Dr. M. B. Jennings, Reading Committee Member  
SJSU, Department of Chemical Engineering

\_\_\_\_\_ Date \_\_\_\_\_  
Dr. J. S. Johnson, Reading Committee Member  
LLNL, Special Projects Division

APPROVED FOR THE UNIVERSITY

\_\_\_\_\_ Date \_\_\_\_\_

## **ABSTRACT**

### **DETERMINATION OF TOXIC MATERIAL PENETRATIONS FOR WILDLAND RESPIRATOR FILTERS**

by Kenneth L. Foote

Thousands of wildland firefighters are exposed to high levels of toxic materials every year. Carbon monoxide, formaldehyde and acrolein gases, along with high particulate concentrations, are the major toxics encountered. Currently, the only respiratory protection wildland firefighters use is a bandanna over the mouth and nose. In this study, a modern activated carbon cartridge with an electrostatic prefilter was compared to a typical bandanna for its ability to filter wildland smoke toxics such as formaldehyde and particulates. The results of the tests were disappointing; neither filter performed very well. The activated carbon cartridge and prefilter efficiently collected formaldehyde gas for up to 60 minutes; however, it only collected 85 percent of the challenge particulate. The bandanna, as expected, was only partially effective at collecting smoke particulate and filtered no toxic gases.

## **Acknowledgments**

I wish to thank Dr. M. A. McNeil and Dr. J. S. Johnson for their guidance and advice. Without the technical assistance of Don Beason and Scott Doughty this project could not have been completed. I would also like to thank Jeanine Cheng, Amalia Neidhardt and Steve Priante for their assistance during the chemical analysis.

## Table of Contents

	Page
List of Figures	vii
List of Tables	viii
Chapter 1. Introduction	1
Chapter 2. Literature Review	6
Chapter 3. Hypothesis	13
Chapter 4. Materials and Methods	14
Chapter 5. Experimental Results	24
5.1 Reproducibility Data	24
5.2 Particle Size Data	29
5.3 Penetration Data	30
5.4 Breakthrough Data	33
5.5 Preliminary HEPA Filter Data	36
Chapter 6. Discussion	37
Chapter 7. Conclusions	43
References	45
Appendix A. Discussion of Other Test Geometries	48
Appendix B. Tables of Experimental Data	49
Appendix C. Plots of Experimental Data	65

## List of Figures

	Page
Figure 1. Bar chart of acres burned in U.S. wildland fires for 1983-88.	2
Figure 2. A schematic of the test chamber showing the sampling system.	15
Figure 3. Picture of the burner smoke production from a typical loading.	16
Figure 4. A typical gas chromatogram plot of an upstream smoke sample.	18
Figure 5. Plots of the burner mass loss for three identical activated carbon cartridge with prefilter tests.	26
Figure 6. Plots of the carbon monoxide concentration for three identical activated carbon cartridge tests.	27
Figure 7. Plots of the chamber exhaust gas temperature for three identical activated carbon cartridge tests.	28
Figure 8. Plots of the pressure differential across the test filter for the breakthrough test 10.	34
Figure 9. Plot of the pressure across filter for the breakthrough test 9e showing the plugging of the filter.	35
Figure 10. Plot of the pressure differential across the filter for the HEPA test.	36

## **List of Tables**

	Page
Table 1. Table of chemical information and threshold limit values.	8
Table 2. Matrix of experimental parameters and the tests performed.	22
Table 3. A listing of the instrumentation used in this investigation.	23
Table 4. Impactor particulate size data upstream of the test filter.	31
Table 5. Impactor particulate size data downstream of the test filter.	31
Table 6. Particulate and formaldehyde penetration data.	32
Table 7. Formaldehyde breakthrough times.	32

## **Chapter 1.**

## **Introduction**

Every summer the United States employs over 80,000 seasonal wildland firefighters <sup>1</sup>. These firefighters respond to approximately 70,000 fires per year. Even with this large force of personnel, an average of nearly 2,000,000 acres of land are burned every year. Figure 1 shows the total acres burned for the six years from 1983 through 1988, as recorded by the National Interagency Fire Coordination Center. As can be seen, in 1988 the United States experienced its worst fire season in 50 years. Over 5,000,000 acres were burned, about 2.5 times the average. This was due to several large fires in Yellowstone National Park <sup>2</sup>.

Wildland firefighters respond to a variety of fire types, not just forest fires. Wildlands consist of grasslands, forests, open range or a mixture of all three types. Wildland firefighters also conduct control burns over these types of terrain. Because of this variety of fires, wildland firefighters use different methods to attack fires than structural firefighters. Their job is very physically demanding. They are frequently required to hike several miles over steep terrain. They normally work on the fire line 8 to 12 hours, sometimes longer, enduring many hazards. In 1988, eleven wildland firefighters died on the job <sup>3</sup>. Heat and flames are obvious hazards. Falling trees and rocks also cause injury and death. A less obvious hazard is the inhalation of toxic gases created by the fire.

The health effects from breathing wildland smoke can be significant. Headaches are common complaints of wildland firefighters. Firefighters are more subject to bronchitis and pneumonia than the population as a whole. The antigenic effects of poison oak and

poison ivy are not destroyed by fire. Breathing the smoke from one of these plants can kill someone who is sensitive to them. Rothman <sup>4</sup> reports that a 3 percent drop in lung capacity can occur after one week of wildland fire fighting and there is evidence of permanent lung damage in wildland firefighters.

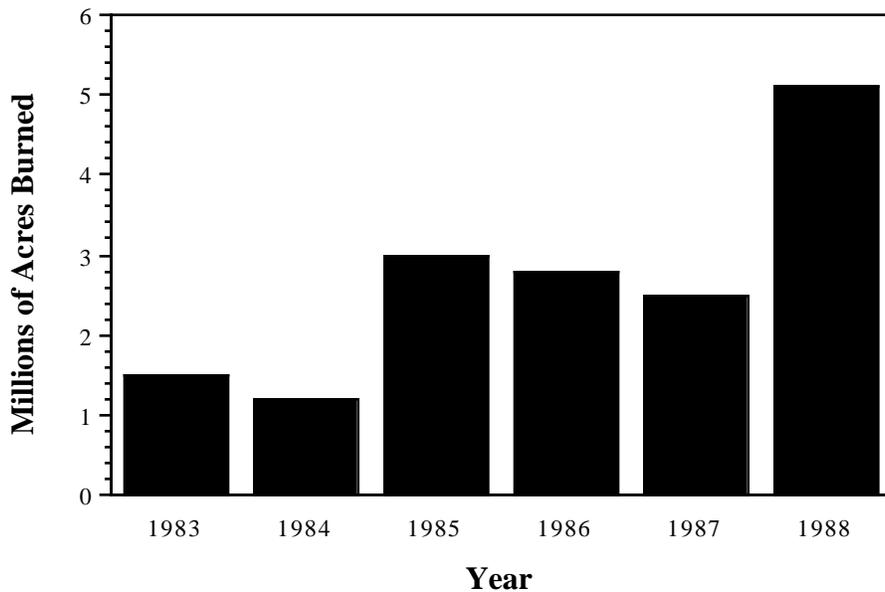


Figure 1. Bar chart of acres burned in U.S. wildland fires for 1983-88.

Incidents of debilitating wildland fire smoke exposure are increasing <sup>3,5</sup> as is awareness of the occupational health hazards. The continual lowering of toxic material Threshold Limits Values (TLV) is an example of this general increased awareness. TLV is the recommended average toxic chemical exposure concentration that is considered safe to be exposed to during an eight hour day. In 1993, the TLV of formaldehyde was

lowered from 1.0 ppm to 0.3 ppm. Table 1 lists the current TLV of several wildland smoke toxics. The yearly addition of new compounds to toxic lists is another example of the increased interest in occupational safety and health. In order to meet many of these reduced exposure limits, worker respiratory protection needs to improve.

Respiratory protection for wildland firefighters is unsophisticated. There is no respiratory equipment required by any current standard. Most wildland firefighters use a bandanna tied over their mouth and nose as the only protection against toxic materials. By standard respiratory practice, a bandanna is not adequate protection. Nevertheless, this has been the typical practice for the last 50 years. The solution, however, is not as simple as putting a respirator on every wildland firefighter.

Developing a wildland firefighter respirator is a difficult task. There are several factors to consider when attempting to provide respiratory protection for wildland firefighters. The wildland firefighters' effectiveness can not be compromised. They can not have significantly more physical burdens placed on them that might add to their direct risk from fire. Thus, heavy canisters of air or restrictive helmets are not viable solutions. The protection must be rugged and durable, due to the environment it will be exposed to in a wildland fire. Because of these constraints, it may be impossible to provide complete respiratory protection for wildland firefighters. However, there may be a more effective means of respiratory protection which does meet these physical constraints, other than a bandanna.

It may not be necessary to completely remove all the toxins in wildland smoke. A filter which removes the major toxic components can be a significant improvement.

Furthermore, it may not be necessary to totally remove the toxic components. One criterion for an adequate wildland respirator would be to reduce the major toxic materials to below their TLV. Another criterion, which may be more applicable to wildland firefighters, would be to reduce the concentration of a toxic material to below the Short Term Exposure Limit (STEL) of the substance. The STEL is the recommended maximum 15 minute average exposure concentration that is considered safe.

In order to evaluate different wildland respirators, actual wildland fire smoke exposure concentrations need to be defined. Unfortunately, not much wildland smoke exposure data is currently available. Being at the right place at the right time to collect data can be very difficult. Predicting the occurrence of fires is nearly impossible. Wildland fires are a fast moving and variable phenomena. Because of the altitude and remoteness (e.g. mountain ranges) of the sampling locations, data collection is difficult.

Sampling smoke alone is not a simple thing to do. Smoke is a very complex and variable aerosol. Incomplete combustion produces hundreds of products. In the wildland environment, the fuel source (grass, brush, timber) is constantly changing as are the ambient conditions (wind, temperature and humidity). Wildland smoke has a large dust and soot component that can damage sampling equipment. Factors such as the long shifts firefighters work and whether or not they smoke cigarettes complicates gathering and analysis of exposure data. Also, wildland firefighters are frequently exposed to smoke during off-shift hours when they are not totally removed from the area of the fire. This additional off-shift exposure increases exposure values when data is collected long after the work shift.

Because of these problems, much of the wildland smoke exposure data that has been previously collected is highly questionable. However, it still has some value quantitatively for trend analysis on wildland smoke exposure. Fortunately, new data is more thorough and reliable. The following section reviews the past and current literature on smoke toxins and smoke exposures.

## Chapter 2.

## Literature Review

Until the 1980's, very little attention had been paid to the dangers of wildland smoke. Because of this, relatively little information has been gathered on the composition of wildland smoke and firefighter exposure. Wildland smoke contains many toxic materials. Several reports have identified the major components of wildland smoke in laboratory experiments <sup>6-9</sup>. Carbon monoxide is the most common toxic component in smoke. Several aldehydes such as formaldehyde, acetaldehyde and acrolein are also found in significant concentrations. Formaldehyde is a common by-product of combustion. It is a colorless gas with a strong odor. Concentrations below 1 ppm are detectable by humans. It is known to cause irritation of the eyes, respiratory tract and skin <sup>10</sup>. Formaldehyde is a suspected carcinogen. Acrolein, also called 2-propenal, has respiratory effects that are more severe than formaldehyde's effects <sup>11</sup>. Ten ppm concentrations of acrolein have been shown lethal in rats. Particulate is a generic name for all the aerosols found in wildland fire smoke including dust and soot particles. Particulate is of highly variable composition, particularly in wildland smoke. Benzene, a known carcinogen, as well as other complex aromatic hydrocarbons and Polycyclic Aromatic Hydrocarbons (PAHs) are found in smoke <sup>7</sup>.

Table 1 lists the TLV and toxic effects for several common wildland smoke components <sup>12, 13</sup>. The TLV is the recommended average toxic exposure concentration that is considered safe to work around. A TLV is usually defined as an eight-hour Time Weighted Average (TWA). The TWA is the average airborne exposure concentration in any 8-hour work shift of a 40-hour work week which shall not be exceeded. There are also ceiling concentrations that should never be exceeded.

There is no recommended TLV concentration for wildland smoke particulate. The TLV for particulate is defined in mg/m<sup>3</sup>. Dust particulate exposure limits <sup>12</sup> vary depending on the material, from 1 mg/m<sup>3</sup> for wood dust to 10 mg/m<sup>3</sup> for diatomaceous earth. Carbon black has a TLV of 3.5 mg/m<sup>3</sup>. Wildland smoke particulate is more toxic than any of these, since other toxic smoke constituents can be absorbed on its surface <sup>25</sup>.

Before 1980, most of the data on smoke exposure was for structural fires. More research was done on structural fires because they are more common than wildland fires <sup>16, 17</sup> and present a greater threat to human life <sup>3,5</sup>. Burgess <sup>18</sup> reports carbon monoxide concentrations up to 27,000 ppm in structural fires. Treitman <sup>19</sup> reports peak acrolein concentrations of 100 ppm. He also observed particulate concentrations of 10,000 mg/m<sup>3</sup>. Gold <sup>20</sup> measured particulate concentrations with the Boston fire department and observed average particulate concentrations of only 22 mg/m<sup>3</sup>. These concentrations are higher than we would expect of wildland fires because of the increased oxygen starvation and the lack of dilution in structural fires. However, they do serve as a guideline and a possible upper bound on the expected species concentrations. The range of the reported particulate concentrations also demonstrates the difficulty in characterizing smoke composition.

The toxicity of the products of cellulose-based combustion is well established in laboratory experiments <sup>6-9</sup>. One source of fuel often used in these small-scale tests is douglas fir <sup>14</sup>. In the laboratory, douglas fir smoke is a good approximation for the toxic products to which a wildland firefighter might be exposed. Hartzell <sup>11</sup> used douglas fir as the baseline material for comparative toxicity (i.e., more toxic than douglas fir or less

Table 1. Table of chemical information and threshold limit values.

	Molecular Weight	Threshold Limit Value	Short Term Exposure Limit	Health Effect
Carbon dioxide	44.00	5,000 ppm	30,000 ppm	headaches, mild narcotic
Carbon monoxide	28.01	25 ppm	Ceiling	odorless asphyxiant gas
Formaldehyde	30.03	0.3 ppm	Ceiling	irritates eyes and respiratory tract, suspected carcinogen
Acetaldehyde	44.05	25 ppm	Ceiling	headaches, mild narcotic, animal carcinogen
Acrolein	56.06	0.1 ppm	0.3 ppm	irritates eyes and respiratory tract, carcinogen
Benzene	78.12	0.1 ppm	0.3 ppm	carcinogen
Particulate (Diatomaceous earth)	variable	10 mg/m <sup>3</sup>		irritates respiratory tract

toxic than douglas fir). Farrar <sup>14</sup> defined two mechanisms of toxic component action by douglas fir smoke on rats. High carbon monoxide concentrations incapacitated the majority of a test population. The remainder of the population was incapacitated by another mechanism called anoxic anoxia which is a lack of oxygen in the blood. This condition is caused by sensory irritants such as acrolein and formaldehyde which inhibit respiration.

Wildland fire research has increased since 1980. Reinhardt <sup>25</sup> has reported several hundred toxic compounds in actual wildland smoke, among them carbon dioxide, carbon monoxide, formaldehyde, acetaldehyde, acrolein, furfural and benzene. Several PAHs such as acridine, anthracene and pyrene were also found. Reinhardt also reports that PAHs are often found associated with smoke particulate matter.

The Equipment Development Center of Montana found carbon monoxide exposure levels of over 50 ppm in 10 percent of 1661 personnel tested <sup>21</sup>. The U.S. Forest Service <sup>22</sup> reported carbon monoxide exposure levels of 26 ppm and formaldehyde exposure levels of 0.2 ppm. The National Institute for Occupational Safety and Health (NIOSH) <sup>23</sup> measured carbon monoxide exposure levels of 23 ppm at the 1988 Yellowstone fire. Unfortunately, this data is clouded in controversy as sampling methods and accuracy are questioned. Tobacco smoke from cigarettes interferes with the measurement of the carbon monoxide exposures, and many of those tested were smokers. For all of these tests, carboxyhemoglobin levels were measured long after the fire exposure. Thus, only TWA values are reported. No short term exposure data was collected. Few conclusions can be drawn from these data.

In the last few years, more reliable data has been collected. Brotherhood et al.<sup>24</sup> reports low concentrations of carbon monoxide in controlled experimental Australian bush fires. The highest eight-hour average carbon monoxide concentration they observed was 50 ppm. The average of all the 8 hour exposures was 25 ppm. Careful attention was paid to correct for ambient carboxyhemoglobin from cigarette smoking. Unfortunately, in these tests alveolar air samples were taken at the end of an eight hour work shift. Thus, these tests also measured average exposure data and didn't measure transient exposure concentrations.

Matera et al.<sup>26</sup> has collected the most reliable wildland smoke exposure data to date. They collected time history data for carbon monoxide. This data reports several short term carbon monoxide exposures in excess of 300 ppm. Many of these exposures were from the exhaust of fire trucks used to transport wildland firefighters around the fire scene. In addition to time history carbon monoxide data, average exposure data for particulate and some toxic gases was collected. The average particulate exposure reported in this study was 40 mg/m<sup>3</sup>. Formaldehyde exposure data was collected and an average value of 0.3 ppm was reported. Acrolein sampling was very limited and unreliable; however, the value reported was 0.05 ppm.

Reinhardt et al.<sup>25</sup> has done a thorough exposure study of wildland combustion products. They studied 16 actual wildland fire exposures over a one year period in California, Oregon and Washington. The data collected was for carbon dioxide, carbon monoxide, acrolein, formaldehyde, benzene, furfural, PAHs and particulate concentrations. Typical particulate concentrations were 10 mg/m<sup>3</sup>. Mean concentrations of formaldehyde of up to 2 ppm were observed during direct fire attack activities.

Acrolein concentrations of 0.3 ppm were recorded. Bag samples of air showed carbon monoxide concentrations as high as 200 ppm. Carbon dioxide concentrations of 2000 ppm were observed.

From the available literature, it can be concluded that at current TLV's and STEL's, some type of respiratory protection is needed for wildland firefighters to insure a safe work environment. Acceptable levels and types of respiratory protection need to be determined. In addition, the effectiveness of traditional bandannas in filtering out toxic smoke products need to be established. It is generally accepted that bandannas aren't very efficient filters. However, no research has determined the effectiveness of cotton bandannas to filter out the toxic materials of wildland smoke. Since the amount of toxic materials in wildland smoke doesn't appear to be that much over the accepted level, in many cases even an inefficient bandanna may provide adequate protection. A sophisticated wildland respirator may not be worth the added cost or the increased firefighter encumbrance of added weight and reduced visibility.

Filter efficiency can be evaluated by determining toxic material penetration. Filters are rarely 100 percent efficient in removing a substance. Penetration is the ratio of the toxic concentration after the filter to the toxic concentration before the filter. Penetration is dependent on the environmental toxic concentration and the efficiency of the filter. To date no penetration data for wildland smoke filters has been reported. Recommended penetration values for firefighter applications are below 0.01, or 99 percent efficient.

Another important characterization parameter for filters, such as activated carbon cartridges, is breakthrough time. These types of filters eventually become ineffective,

because all the adsorption sites become filled, allowing additional chemicals to pass through without being absorbed. This phenomenon is called breakthrough.

Breakthrough time is an important activated carbon cartridge parameter. If this type of filter has a breakthrough time significantly less than eight hours it will not be effective for a complete wildland firefighter work shift. An adequate wildland filter will need to be effective for at least eight hours, since wildland firefighters work long shifts and can not carry extra filters.

Filter plugging is similar to toxic gas breakthrough time. If the particle concentration in the smoke is high enough, a test filter can plug with particulate and be difficult to use. A filter is considered plugged at a pressure differential across the filter of 3" of water (747 Pascals), the nominal value of comfortable human inhalation. Filter plugging is considered the particulate equivalent of chemical breakthrough.

In this study, an activated carbon cartridge with and without an electrostatic prefilter was compared to a typical bandanna for its ability to filter three wildland smoke toxics, formaldehyde, acrolein and particulate. The parameters of interest were toxic material penetration and toxic gas breakthrough time.

## **Chapter 3.**

## **Hypothesis**

The experimental hypothesis was that an activated carbon cartridge with an electrostatic prefilter will provide significant improvement in respiratory protection over a cotton bandanna by reducing inhaled particulate and toxic gases, such as acrolein and formaldehyde, to acceptable levels for wildland firefighters. A series of tests in a small-scale test chamber was conducted to determine the effectiveness of two wildland respirator filters. The measurements of interest were toxic material penetration and toxic gas breakthrough time.

## Chapter 4.

## Materials and Methods

The determination of the penetration and breakthrough time of the toxic materials of actual smoke was done in a small-scale test chamber as shown in Figure 2. The dimensions of the chamber are 28 x 32 x 36 inches. Two Hundred grams of Japanese Black Pine needles (*Pinus thunbergii*) were placed in a burner on a load cell in the chamber at the start of each test. These pine needles were gathered from the ground outside the test building in Livermore, CA. The pine needles were dry and brown in color. The needles were ignited with a 10 second blast of a small propane torch. Within 2 minutes, a thick white smoke was produced. It should be noted that much less smoke was produced by these same pine needles during flaming combustion in other configurations. See Appendix A for discussion on alternative fuels and geometries. Figure 3 is a picture of the burner used and the resulting smoke from a typical pine needle loading. During testing, the burner inside the test chamber became obscured from view as the smoke filled the chamber. 200 grams of needles produced smoke for up to 60 minutes.

Room air was pulled into the test chamber by an exhaust fan controlled by a butterfly valve. Thus, the chamber ventilation rate could be set at several levels to generate different combustion product concentrations. The chamber ventilation rate was varied from 425 lpm to 325 lpm. The chamber exhaust flow was measured with a sharp-edged orifice. As shown in Figure 2, a small portion of the chamber exhaust flow, designated the sample stream, was pulled through the test filter. The remainder of the chamber exhaust flow was exhausted to the building ventilation system.



Figure 3. Picture of the burner smoke production from a typical loading.

Two minutes after the pine needles were ignited by the propane torch, the sample stream was pulled through the test filter at either 20 or 50 lpm. This simulated either moderate or fast respiration. Silverman determined the respiration rate for moderate work was 40 lpm<sup>27</sup>. A flow rate of 20 lpm through a single activated carbon cartridge represents the average human respiration rate during moderate work, since two activated carbon cartridges are used per respirator. A flow rate of 50 lpm represents the human respiration rate during vigorous work such as fighting a wildland fire.

Particulate and aldehyde sampling was also initiated 2 minutes after ignition. Particulate and aldehyde sampling was performed before (upstream) and after (downstream) the test filter. The sampling period was 20 minutes long. Since the majority of the burner mass loss and smoke production occurred during this 20 minutes, it was chosen as the sample period. The burner continued to produce toxic material and smoke for up to 60 minutes, but at a reduced rate.

The concentrations of formaldehyde and acrolein in the sample stream were analyzed both upstream and downstream from the test filter. These concentrations were determined by pulling the sample stream through an ORBO-24 adsorbent tube. This tube contained 150 grams of XAD-2 media coated with 2-hydroxymethylpiperidine (2-HMP) which reacts selectively with aldehydes to form a stable oxazolidine derivative. The formaldehyde-oxazolidine and acrolein-oxazolidine derivatives were desorbed with toluene and analyzed on a Varian 3700 gas chromatograph (GC). The concentration in the sample stream was determined by calibration of the GC with known standards. Figure 4 is a typical gas chromatogram plot of a sample. The first set of peaks on the left are from the toluene solvent, with formaldehyde-oxazolidine appearing at 9.11 minutes

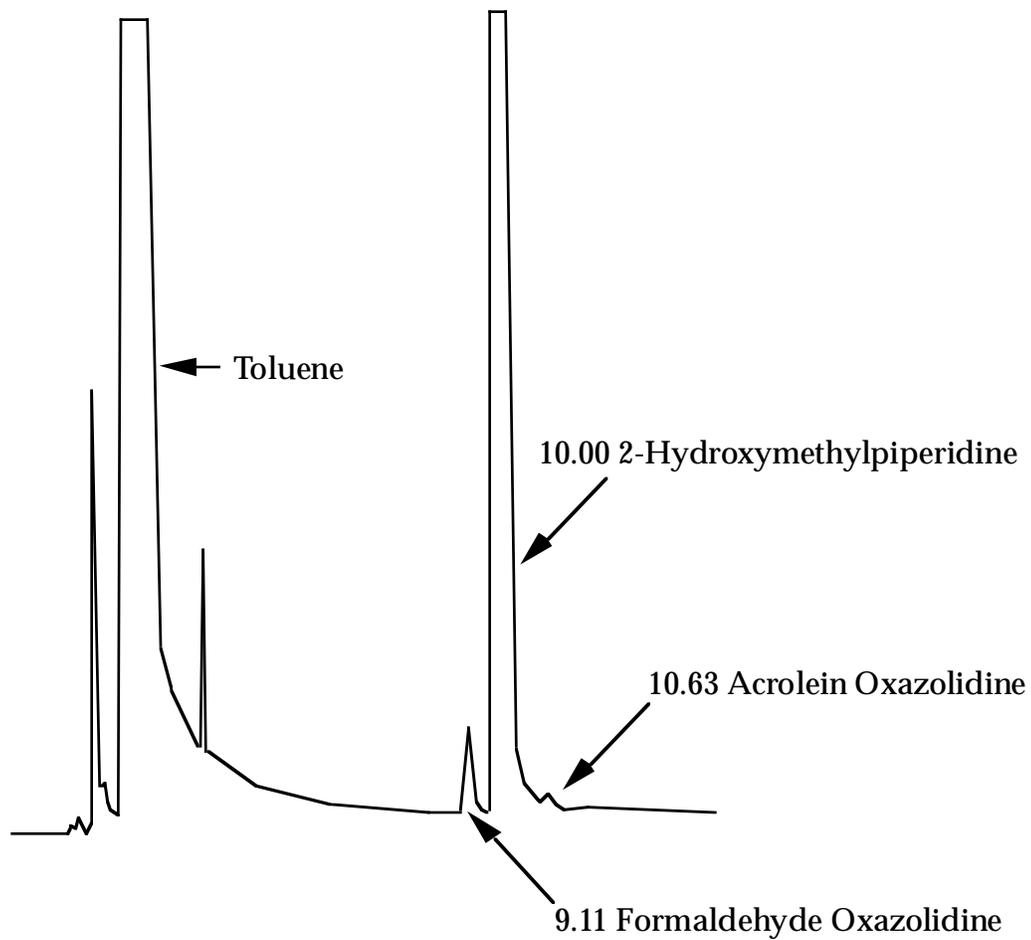


Figure 4. A typical gas chromatogram plot of an upstream smoke sample.

followed by the large 2-HMP peak at 10.00 minutes. The last small peak on the right is acrolein-oxazolidine at 10.63 minutes. The detection limit of formaldehyde and acrolein was 1 ppm as determined by internal standards. The calibration curves for the acrolein and formaldehyde analysis are in Appendix C.

Particle density measurements were obtained using glass fiber filters upstream and downstream of the test filter. Gelman type E 47 mm filters were used. Average mass densities were determined by weighing the absolute filters on a Mettler PM200 microbalance to  $\pm 0.001$  grams. These filters were weighed immediately after sampling ended.

An Anderson impactor was used to determine the aerodynamic particle size of the smoke generated in the chamber. The smoke particles were sized by pulling them through successively smaller orifices and impacting them on stainless steel plates. Large particles were impacted on the first plates and smaller particles on later plates. A High Efficiency Particulate Airfilter (HEPA) filter was the final particle collection stage. The plates and the filter were weighed before and after to determine the amount of particulate collected. The Anderson impactor has eight stages and can size particles from 11 microns to 0.4 microns. Starting at 240 seconds after ignition, during the greatest mass loss of a test, a 60 second sample of smoke was taken from the chamber and drawn through the impactor.

An eight test fractional factorial test matrix was used to design experiments to determine toxic material penetration. Five parameters were investigated. Two types of filters were tested, bandanna and activated carbon filter with prefilter. The activated

carbon cartridge was also tested in two configurations, with and without a prefilter. The cotton bandanna was tested in two geometries. A double or single thickness of cotton was mounted in an empty activated carbon cartridge. Two sample flow rates were tested, 20 lpm and 50 lpm. Two chamber ventilation rates were tested, 325 lpm and 45 lpm.

Two tests were done to evaluate formaldehyde breakthrough time and filter plugging for the activated carbon cartridges. For this evaluation repeated fires were necessary to provide exposure times longer than 20 minutes used in the penetration tests. For the formaldehyde breakthrough analysis over 4 hours of exposure was required. For these breakthrough tests, the sample flow through the test filter was stopped, the test chamber was opened, the burner removed and a new burner with fresh pine needles was installed and ignited. The sample flow through the test filter was restarted two minutes after the new burner was ignited. The test was to be terminated if no breakthrough of toxic materials occurred after eight hours of testing. However, all configurations tested resulted in breakthrough prior to eight hours of exposure.

In addition to the eight planned penetration tests using bandannas and activated carbon cartridges with electrostatic prefilters, a single preliminary penetration test was performed using an activated carbon cartridge in combination with a HEPA filter. Table 2 lists the experimental matrix for all the tests performed for this analysis: the eight penetration tests, the two breakthrough tests and the single preliminary HEPA penetration test.

Much of the data collected for the evaluation was gathered by a Hewlett-Packard 3497A data acquisition unit and recorded by a Hewlett-Packard model 200 computer.

The scanner monitored 13 channels of type K thermocouples located in various locations around the test chamber as shown in Figure 2. Two Validyne P24 pressure transducers measured pressure across the test filter as well as the test chamber ventilation rate. A Transducers Inc. load cell model C462-10-10P1 measured the mass loss of the pine needles in the burner during the test. An Automated Custom Systems Model 3300 infrared carbon monoxide analyzer was used to measure carbon monoxide concentrations in the test chamber exhaust gas. The carbon monoxide monitor was calibrated with a known standard containing a carbon monoxide concentration of 1054 ppm. The carbon monoxide monitor has a rated accuracy of  $\pm 10$  ppm at 1000 ppm. The measured full scale response time of the instrument was 10 seconds. Since the burner continued to produce smoke after the 20 minute sampling period, temperature, pressure, mass loss and carbon monoxide data were collected until carbon monoxide concentrations returned to baseline levels and no mass loss was observed. Approximately 40 minutes after sampling ended, the test was ended. Temperature, pressure, mass loss and carbon monoxide data were collected every 10 seconds throughout the 60 minute tests. Table 3 lists specific information on the instrumentation used for these experiments.

Table 2. Matrix of experimental parameters and the tests performed.

The filter geometries tested:  
a cotton bandanna (single and double layer thickness)  
an activated carbon cartridge with and without prefilter

The test parameters varied:  
fire ventilation rate (low and high, 325 and 425 lpm)  
simulated respiration rate (low and high, 20 and 50 lpm )

A  $2^{4-1}$  fractional factorial matrix yields eight tests.

Test 1: Single bandanna, high fire ventilation, low respiration rate

Test 2: Single bandanna, low fire ventilation, low respiration rate

Test 3: Double bandanna, high fire ventilation, low respiration rate

Test 4: Double bandanna, high fire ventilation, high respiration rate

Test 5: Cartridge without prefilter, high fire ventilation, low respiration rate

Test 6: Cartridge without prefilter, low fire ventilation, low respiration rate

Test 7: Cartridge with prefilter, high fire ventilation, low respiration rate

Test 8: Cartridge with prefilter, high fire ventilation, high respiration rate

Test 9: Cartridge with prefilter, low fire ventilation, high respiration rate,  
1 hour exposure

Test 10: Cartridge with prefilter, low fire ventilation, high respiration rate,  
20 minute exposure

Test 11: Cartridge with HEPA filter, low fire ventilation, high respiration rate

Table 3. A listing of the instrumentation used in this investigation.

Data Collection	HP 200 computer HP 3497A Data Acquisition Unit
Carbon Monoxide Sampling	Automated Custom Systems Model 3300 Infrared Analyzer (0-500 ppm CO)
Aldehyde Sampling	Supelco ORBO-24 Tube
Gas Chromatograph	Varian Model 3700 (30 m X 0.53 I.D. DB17 nonpolar column) Splitless Injection Initial Temperature = 75°C for 5 minutes Range = 75-140°C Rate = 10° C/min.
Pressure Measurements	Validyne Model P24
Sample Flow Rate	Fischer Porter 1/2-17-6-10/55 Flowmeter
Sample Weighing	Transducers Inc. Load Cell Model C462-10-10P1  Doric Transducer Indicator Model 420  Mettler Micro Balance Model PM200

## Chapter 5.

## Experimental Results

The presentation of experimental results is divided into five sections. First, data validating the reproducibility of the tests is presented. This consists of mass loss data, temperature data and upstream toxic gas and particulate concentrations. Second, Anderson impactor particle size data is presented. Third, filter penetration data is presented. The penetration data consists of particulate penetration and formaldehyde penetration values. Next, the formaldehyde breakthrough time and filter plugging data are reported. Finally, some data from the preliminary HEPA test is presented.

### 5.1 Reproducibility Data

A blank test was performed where the pine needles were not ignited. No formaldehyde or carbon monoxide was detected in the chamber exhaust. No mass loss was observed during this blank test and the particulate filters did not collect any observable mass. This test was used to determine the accuracy of some of the instrumentation used for the experiments. The pressure measurements had a standard deviation of 5.7 Pascals. The standard deviation of a mass loss measurement was 1.4 g.

Figure 5 shows the burner mass loss with time for three identical activated carbon cartridge with prefilter tests. These mass loss curves are remarkably consistent, given that a random combustion process is occurring. Mass loss is a good indicator of the consistency of combustion data. The mass loss is a measure of the pyrolysis rate which drives the other parameters of interest such as the carbon monoxide, formaldehyde and particulate concentrations. The average rate of mass loss during the 20 minute sampling

period for these tests was 6.5 grams/minute. Over 70 percent of the total mass loss for these tests occurred in the twenty minute sampling period. Appendix B-1 lists mass loss data for all the experiments done in this series.

The amount of carbon monoxide produced during the tests was consistent from test to test. Figure 6 shows the carbon monoxide concentration in the chamber exhaust gas during three similar tests. The maximum carbon monoxide concentration observed for these three tests was 2147, 2043 and 2172 ppm, respectively. The average carbon monoxide concentration for these three tests during the 20 minute sampling period was 1392 ppm. Appendix B-2 lists carbon monoxide data collected showing the highest or peak concentration of carbon monoxide observed during a test and average carbon monoxide concentrations during sampling.

The amount of formaldehyde detected upstream of the filter varied significantly. The upstream formaldehyde concentration for test 7a, test 7b and test 7c was 35 ppm. The formaldehyde concentration standard deviation of these three tests was 10 ppm. Appendix B-3 lists the formaldehyde data upstream and downstream of the test filter for each test. GC area counts are listed. Each GC sample was injected three times and the averaged area count was used for comparison. No acrolein data is presented here since little or none was detected.

Gas temperatures during these tests were low due to the high chamber ventilation rate and the slow combustion rate of the pine needles. The highest temperature observed was 57 °C. Figure 7 shows the chamber exhaust gas temperature for three identical activated carbon cartridge tests. Again, the reproducibility of the apparatus is observed.

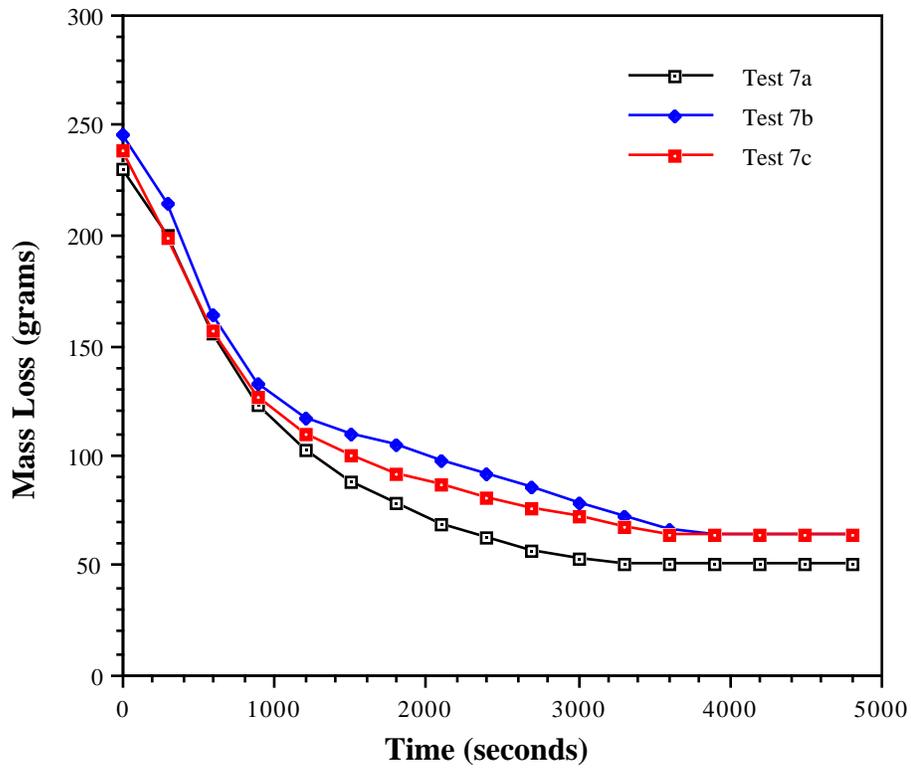


Figure 5. Plots of the burner mass loss for three identical activated carbon cartridge with prefilter tests.

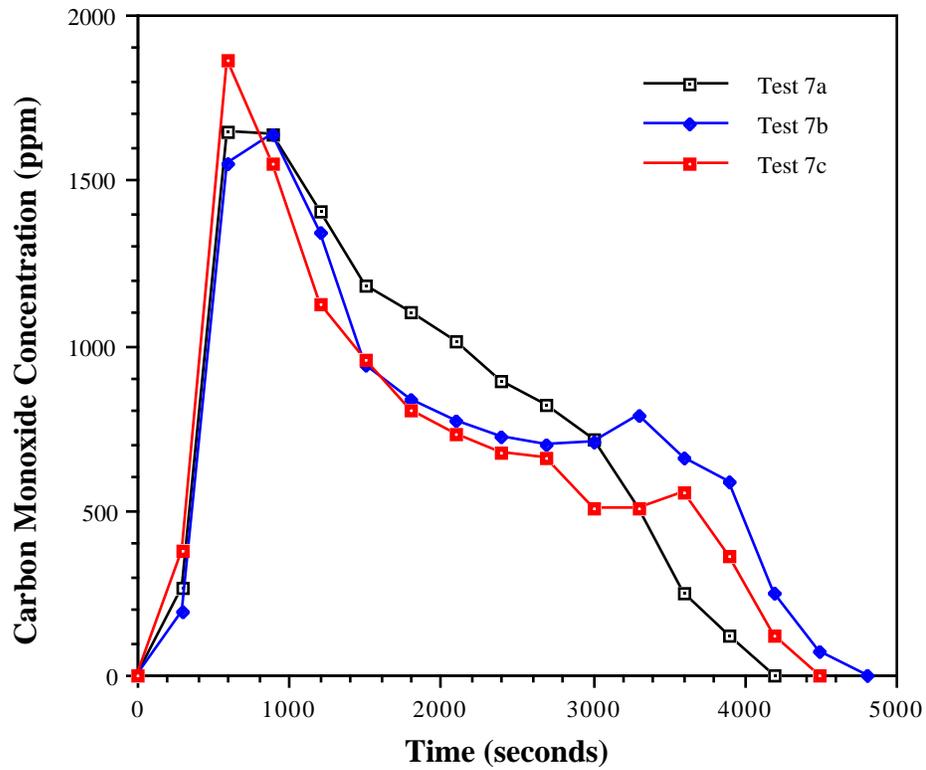


Figure 6. Plots of the carbon monoxide concentration for three identical activated carbon cartridge tests.

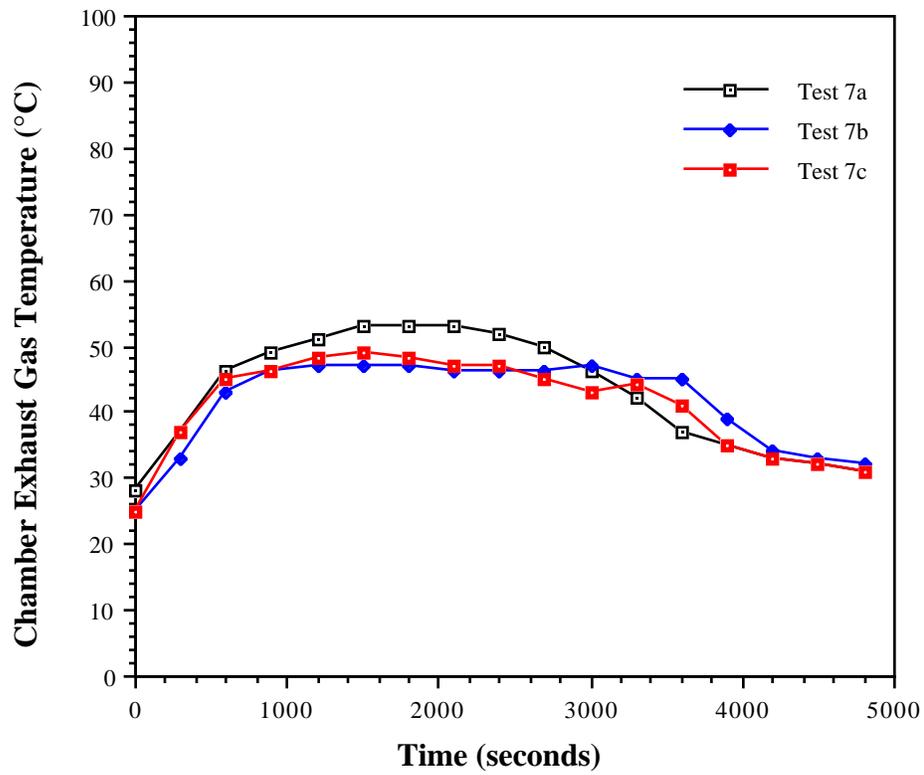


Figure 7. Plots of the chamber exhaust gas temperature for three identical activated carbon cartridge tests.

Appendix B-4 lists the thermocouple data collected. The observed temperature in the exhaust stream of the test chamber is presented in two forms, average temperatures during the sampling period and the peak or highest temperature observed during the entire test.

The average upstream particulate concentrations for tests 7a,b,c was  $2.16 \text{ g/m}^3$  with a standard deviation of  $0.03 \text{ g/m}^3$ . The average downstream particulate concentrations for tests 7a,b,c was  $0.33 \text{ g/m}^3$  with a standard deviation of  $0.03 \text{ g/m}^3$ . Appendix B-5 lists the particulate concentration data for all the tests. Appendix B-6 lists the pressure data across the test filter and across the exhaust flow orifice for each test.

## 5.2 Particle Size Data

Table 4 lists the Anderson impactor particle size data from a 60 second sample collected upstream of an activated carbon cartridge with prefilter. Due to the high concentration of particulate upstream of the test filter, Anderson impactor sampling times longer than 60 seconds were not practical, since the impactor would clog up with particulate. For this test, the average mass density of the upstream smoke was  $3.14 \text{ g/m}^3$ . Approximately 45 percent of the particulate was from 1.1 to 2.1 micron in aerodynamic diameter. Over 90 percent of the particles were from 0.7 to 3.3 microns in size. Table 5 lists the particle size data from a 20 minute sample collected downstream of an activated carbon cartridge with prefilter. The most abundant size of particles ranges from 0.7 to 1.1 micron. The average mass density of the downstream smoke was  $0.33 \text{ g/m}^3$ . Appendix C contains log-normal probability plots of the data in Tables 4 and 5.

### 5.3 Penetration Data

Table 6 contains the particulate and formaldehyde data for the eight tests done to investigate penetration. The formaldehyde penetration data was difficult to analyze. For the activated carbon cartridge tests no formaldehyde was detected downstream of the filter and thus penetration values are impossible to calculate. The penetration values for the bandanna are questionable because the error in measuring the formaldehyde concentration is too large for this detailed a comparison. The formaldehyde measurement standard deviation of 10 ppm is too large. For example, at a concentration of 40 ppm, this represents a possible error of 50 percent. This large error makes it possible to calculate formaldehyde penetrations greater than 1.00 which are invalid. The calculated penetration for test 4 is 1.16. No conclusions can be drawn from the formaldehyde penetration data.

The particulate penetration data is more informative. The average particulate penetration for the single layer bandanna was 0.89 and for the double layered bandanna it was 0.87. This is an apparent improvement between the single and double layered bandanna. Unfortunately, it is not a statistically significant difference, given the error of the measurement.

The particulate penetration through the activated carbon cartridge by itself was 0.45 and with the prefilter it was 0.15. The activated carbon cartridge traps more particles than the bandanna. The addition of the prefilter reduces the penetration of smoke particles even more. However, this is a small improvement. Acceptable penetration values are an order of magnitude lower, approximately 0.01.

Table 4. Impactor particulate size data upstream of the test filter.

Stage	Initial Mass (g)	Final Mass (g)	Net Mass (g)	Percent Mass	Lower Limit (micron)	Upper Limit (micron)
0	22.2088	22.2089	0.0001	0.10%	>11	
1	19.2965	19.2966	0.0001	0.10%	7	11
2	22.2654	22.2655	0.0001	0.10%	4.7	7
3	28.1147	28.1148	0.0001	0.10%	3.3	4.7
4	22.1018	22.1134	0.0116	11.42%	2.1	3.3
5	21.9353	21.9963	0.0610	60.04%	1.1	2.1
6	20.4735	20.4967	0.0232	22.83%	0.7	1.1
7	28.1629	28.1670	0.0041	4.04%	0.4	0.7
HEPA	0.1245	0.1258	0.0013	1.28%		<0.4
	total mass collected =		0.1016	100.00%		

Table 5. Impactor particulate size data downstream of the test filter.

Stage	Initial Mass (g)	Final Mass (g)	Net Mass (g)	Percent Weight	Lower Limit (micron)	Upper Limit (micron)
0	19.2963	19.2963	0.0000	0.00%	>11	
1	22.2088	22.2088	0.0000	0.00%	7	11
2	22.2661	22.2663	0.0002	0.11%	4.7	7
3	28.1132	28.1134	0.0002	0.11%	3.3	4.7
4	22.1014	22.1055	0.0041	2.22%	2.1	3.3
5	21.9351	21.9839	0.0488	26.39%	1.1	2.1
6	20.4733	20.5680	0.0947	51.22%	0.7	1.1
7	28.1622	28.1948	0.0326	17.63%	0.4	0.7
HEPA	0.1236	0.1279	0.0043	2.33%		<0.4
	total mass collected =		0.1849	100.00%		

Table 6. Particulate and formaldehyde penetration data.

Test	Media	Particulate Penetration	Formaldehyde Penetration
Test 1	Single Layered Bandanna	0.88	0.87
Test 2a	Single Layered Bandanna	0.93	0.75
Test 2b	Single Layered Bandanna	0.86	0.71
Test 3a	Double Layered Bandanna	0.89	0.77
Test 3b	Double Layered Bandanna	0.86	0.80
Test 4	Double Layered Bandanna	0.85	1.16
Test 5	Activated Carbon Cartridge	0.42	Not Detected
Test 6	Activated Carbon Cartridge	0.47	Not Detected
Test 7a	Activated Carbon Cartridge with Prefilter	0.14	Not Detected
Test 7b	Activated Carbon Cartridge with Prefilter	0.16	Not Detected
Test 7c	Activated Carbon Cartridge with Prefilter	0.15	Not Detected
Test 8	Activated Carbon Cartridge with Prefilter	0.18	Not Detected

Table 7. Formaldehyde breakthrough times.

Test 9	180 minutes
Test 10a	60 minutes
Test 10b	50 minutes
Test 10c	50 minutes

## 5.4 Breakthrough Data

Four breakthrough experiments were performed. Table 7 lists the formaldehyde breakthrough times of the activated carbon cartridges tested. Three replicates (test 10a,b,c) were performed using repeated twenty minute exposures. One breakthrough experiment was performed using a 1 hour exposure. The 1 hour exposure experiment started with the normal 20 minute exposure, however, sampling continued for forty minutes longer. Breakthrough time was determined to the nearest 10 minutes by changing the downstream ORBO-24 tube every 10 minutes. The sample stream was pulled through the test filter at 50 lpm for these experiments to reduce the required exposure time. Figure 8 is a plot of the pressure increase across the test filter for successive fires (test 10a-a,b,c,d,e). The pressure across the filter increases with each successive smoke exposure.

Tests 9a,b,c,d,e were done using 1 hour sampling times. This experiment had a longer observed breakthrough time than the shorter exposure experiments due to the reduced average exposure concentrations as a result of the longer sample times. During test 9e the test filter was observed to plug. Figure 9 shows the pressure increase across the test filter for test 9e.

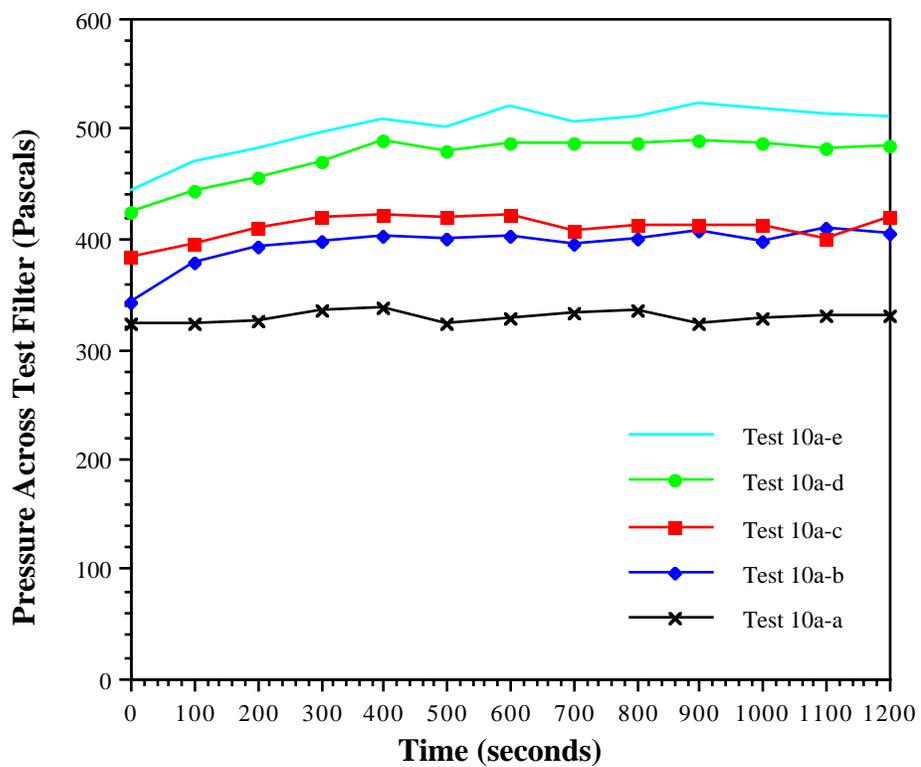


Figure 8. Plots of the pressure differential across the test filter for the breakthrough test 10.

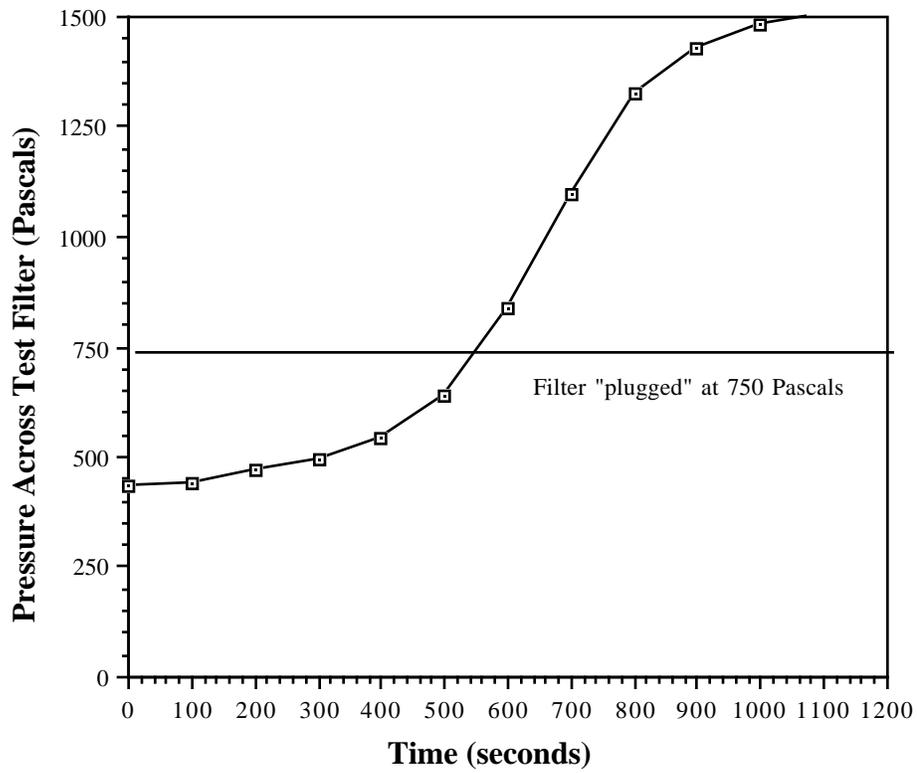


Figure 9. Plot of the pressure across filter for the breakthrough test 9e showing the plugging of the filter.

## 5.5 Preliminary HEPA Filter Data

A single preliminary test was run with a HEPA filter in combination with an activated carbon cartridge. No detectable mass increase was measured on the downstream side of the test filter. No formaldehyde or acrolein was detected downstream of the filter during the twenty minute exposure test. Figure 10 shows a plot of the pressure difference across the test filter during sampling. The pressure across the HEPA filter/activated carbon cartridge was relatively constant throughout the test at 350 Pascals.

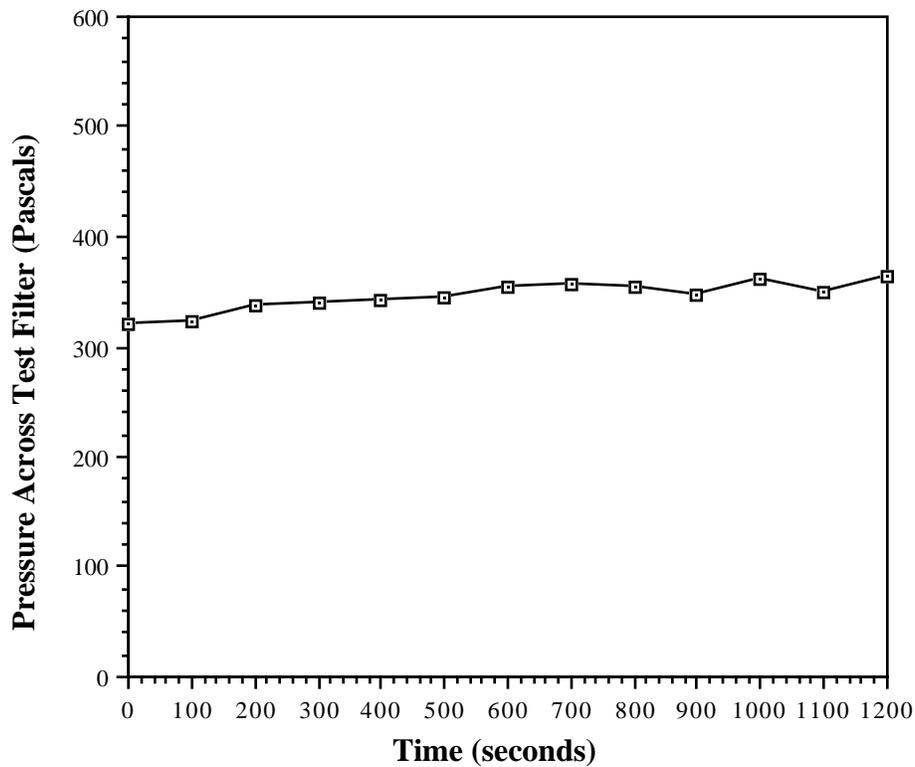


Figure 10. Plot of the pressure differential across the filter for the HEPA test.

## Chapter 6.

## Discussion

The experimental set up provided substantial amounts of smoke exposure. Exposure experiments were performed in a relatively short period of time and with greater reproducibility compared to previous methods. Other experiments, discussed in Appendix A, showed that methods producing lower particulate and toxic gas concentrations were less reproducible. The experimental test method used in this study is also versatile; a variety of fuel sources can be used. Preliminary tests using dry grass or hay also produced viable particulate and formaldehyde concentrations.

The concentration of particulate observed in these tests is higher than would be expected in normal wildland exposures due to the confined nature of the experiment. These concentrations represent "worst case" particulate concentrations. The accumulation of particulate on the test filters was easily observed. Even the bandannas would discolor, turning yellow across the filtration area. The bright orange electrostatic prefilters would turn brown from a single twenty minute exposure.

The Anderson impactor data shows that most of the particulate generated is 1.0-2.0 microns in diameter. This is slightly larger than the size reported by others for wildland smoke. MacArthur<sup>28</sup> reported particle sizes from 0.1 to 1.0 micron. The high density of the smoke and confined space of the test chamber may contribute to agglomeration of particles and raise the mean diameter of the particles. The average mass density of the challenge smoke, 2.51 g/m<sup>3</sup>, is also higher than observed by others in real fire environments. This can be attributed to more dilution in the actual wildland

environment measurements. It is difficult to consistently keep sampling probes directly in a wildland fire smoke plume. Thus, smoke density measurements are usually taken at large distances from the smoke source which allows more dilution to occur.

The formaldehyde and carbon monoxide concentrations are also higher than would be expected in actual wildland fire exposure situations. This is also due to the small amount of dilution of the smoke generated. The low temperatures observed in this study are realistic. Gas temperatures above 70°C cause discomfort during breathing and wildland firefighters do not work in these environments.

Any proposed wildland firefighter respiratory protection needs to be evaluated experimentally in realistic "worst case" wildland smoke conditions. Unfortunately, these conditions are difficult to quantify and reproduce. This small-scale fire may not exactly simulate a real wildland fire or wildland smoke exposure; however, it is a good approximation. Pine needles are a realistic wildland fire smoke source, and as observed in actual wildland fires <sup>25,26</sup>, formaldehyde, acrolein, carbon monoxide and particulate were present in the smoke produced in the test chamber. For the purposes of comparison of respiratory protection devices, it is equally important for the method to be consistent as well as realistic. The general conclusions from this study on the effectiveness of an activated carbon cartridge with prefilter compared to a bandanna with respect to penetration and breakthrough times can be directly used to evaluate performance under estimate wildland fire fighting conditions.

Comparison of the data in Table 4 and Table 5 shows that the activated carbon cartridge with prefilter is not efficient in filtering particles in the 0.7 to 1.1 micron range.

Upstream of the activated carbon cartridge with prefilter these particles make up only 22 percent of the challenge particulate, whereas downstream of the filter, they comprise over 50 percent of the particulate. The particles in the range of 0.7 to 1.1 micron are not efficiently filtered by the human respiratory system; most of these size particles are exhaled after inhalation. Yu <sup>29</sup> lists several references that show only 10 percent of the inhaled particles of this size are absorbed during respiration. Thus, it could be argued that these particles would not represent a respiratory threat. However, these particles have the highest probability to deposit in the sensitive alveoli of the lungs where they can do the most damage.

Particulate sampling was complicated by the presence of volatile gases in the smoke condensing on the filter paper. Freshly used filters gave off a very strong odor. Weight loss would occur well after sampling ended. This mass loss was not observed on the particulate samples downstream of the activated carbon cartridges. The error associated with weighing the volatile materials is small. Upstream samples would lose 0.009 grams after 1 week. This represents a reduction of the upstream particulate densities by only 9 percent. Correction for the additional upstream mass loss would increase the already high penetration values calculated.

In wildland smoke <sup>25,26</sup>, acrolein is typically found in concentrations below 1 ppm. For these tests the detection limit for acrolein was 1 ppm as determined by calibrated standards. The flame ionization detector on the GC used for this analysis could not detect smaller concentrations of acrolein. Typically, a different type of detector is used for acrolein analysis. Little or no acrolein was detected in these tests and no acrolein data is discussed here. The method of determining formaldehyde concentration was

inconsistent. This may be due to the problems with the GC used. During the GC analysis, large solvent shoulders frequently invalidated GC injections. After these tests, the valve controlling the flow to the column was found to be malfunctioning. It is not known if this valve is responsible for the inconsistency of the measurement.

Three of the five parameters investigated in the penetration tests appear to have no influence on the data. Comparing the penetration data of test 1 and 3, in Table 6, shows no effect of bandanna thickness on particulate penetration. The particulate penetration is the same, approximately 0.88, for both tests. Comparison of test 1 with test 2 and test 5 with test 6 shows no influence of chamber ventilation rate. The results of test 3 and test 4 indicate that simulated respiration rate (i.e. sample rate) did not significantly effect the penetration values observed.

The other parameters investigated, type of filter and prefilter addition, did have a significant effect on particulate penetration. Comparison of the bandanna tests with the activated carbon cartridge test shows the cartridge collects particulate better than the bandanna. Comparison of test 5 and test 7 shows that the activated carbon cartridge with the electrostatic prefilter collected particulate better than the cartridge by itself. Without the prefilter, the cartridge had a particulate penetration of 45 percent. With the electrostatic prefilter, the cartridge had a particulate penetration of only 15 percent. Nevertheless, these results were disappointing. The electrostatic prefilter doesn't provide substantial particulate removal protection. A 100-fold reduction in exposure concentration is typically expected for even the simplest respirator systems. This is the minimum protection factor for firefighters recommended by Burgess<sup>18</sup>. Unfortunately, neither the bandanna nor the activated carbon cartridge could reduce the particulate

exposure concentration by a factor of 100. Because of this inefficiency, the formaldehyde sampling tubes downstream of the prefilter would visibly discolor with particulate, with the glass wool packing turning a brownish tan color. The particulate density downstream of the activated carbon cartridges with prefilter was still an order of magnitude above the TLV of diatomaceous earth.

The activated carbon cartridge formaldehyde breakthrough time of 60 minutes is adequate considering the high concentration and sampling rate used for the test. At the lower respiration rates and lower exposure concentrations expected during actual wildland fire fighting, this cartridge could provide protection for over eight hours.

Additional bandanna geometries could be evaluated that might be more realistic to actual wildland firefighter use conditions. In actual wildland fire fighting conditions, bandannas are typically wet and have been washed. The bandannas evaluated in this study were new and dry. Several test bandannas were moistened with water to evaluate the effect of water on the filtering properties. Unfortunately, the bandanna would dry out during the 20 minute sampling time. It was determined that testing wet bandannas was beyond the scope of the evaluation due to the difficulty of quantifying the drying rate. Washing the bandanna may increase its efficiency since the unwashed fibers would shrink. Thus, new bandannas may be less efficient filters than used ones. Used and wet bandannas may filter a little more particulate than the ones tested here.

A single preliminary test was run with a HEPA filter in combination with an activated carbon cartridge. This combination performed remarkably well. The HEPA filter appeared to collect all of the challenge particulate, since no detectable particulate

mass was collected downstream. The experimental method needs to be changed in order to accurately measure the efficiency of the HEPA filter to this challenge stream.

Typically, HEPA filters are 99.97 percent efficient at removing 0.3 micron particulate from airstreams. This represents a 3000 fold reduction in particulate concentration. If the HEPA filter proved to be 99.97 percent efficient in filtering this smoke particulate, this would be a 500 fold improvement in particle filtration over the electrostatic prefilter.

Because of their high efficiency, filter plugging is a problem with HEPA filters. However, Figure 10 shows there was no significant pressure build up across this HEPA filter to indicate filter plugging during the single preliminary test performed for this analysis. Repeated experiments to determine the time it takes to plug the HEPA filter should be done. The HEPA filter/activated carbon cartridge performed as well as the other activated carbon cartridges in removing formaldehyde gas from the sample stream.

Based on a single preliminary test, the HEPA filter/activated carbon cartridge may be an attractive alternative to the electrostatic prefilter combination. However, further studies are necessary in order to determine if the HEPA filter/activated carbon cartridge combination can provide adequate wildland respiratory protection.

This thesis has described a reliable method for evaluating filter media effectiveness during exposure to wildland smoke. The test method produced a consistent and reproducible challenge smoke for 20 minutes. The challenge smoke contained high concentrations of formaldehyde, carbon monoxide and particulate. Two types of filters were thoroughly evaluated in this study: an activated carbon cartridge and a cotton bandanna. As might be expected, the cotton bandanna did not collect much formaldehyde in any of the tests. The activated carbon cartridges, on the other hand, collected all the detectable aldehydes until the cartridge became saturated. At high concentrations of smoke, the activated carbon cartridge had a breakthrough time for formaldehyde of approximately 1 hour. At slightly lower concentrations, the cartridge lasted 3 hours. Considering the high concentration and high flow rate to which the cartridge was exposed in these "worst case" tests, this is an acceptable breakthrough time. At low concentrations and flow rates, the activated carbon cartridge would be expected to last over eight hours. The activated carbon cartridge demonstrated an adequate ability to remove the chemicals of interest in this study.

Substantial amounts of particulate material penetrated and passed through both filters. The activated carbon cartridge with the prefilter collected more particulate than the cotton bandanna. Nevertheless, the prefilter did not do a very efficient job of filtering this particulate. The activated carbon cartridge with prefilter filtered out only 85 percent of the challenge particulate. Thus, 15 percent of the particulate was passing through the filter and potentially into the lungs of a respirator user.

From these tests, it is unclear that this activated carbon cartridge and prefilter is a significant improvement over the bandanna. If the elimination or reduction of chemical exposure is a high priority, then activated carbon cartridges represent a significant improvement in respiratory protection. If, however, the elimination of particulate exposure is the highest priority, then it is an improvement but not a significant one. Considering the added restriction associated with cartridge use during fire fighting, it probably is not a practical particulate respiratory protection solution.

The HEPA type filter warrants further testing based on the excellent initial results observed. The combination of HEPA filter and activated carbon cartridge could provide superior wildland firefighter respiratory protection. The activated carbon cartridge has already demonstrated in these tests that it effectively removes formaldehyde from a typical challenge stream and the HEPA filter has the ability to filter high concentrations of particulate very efficiently. However, the longevity of the HEPA filter/activated carbon cartridge combination still needs to be evaluated. Breakthrough tests need to be done with the HEPA filter to evaluate whether filter plugging will occur with longer exposures to wildland smoke.

## References

1. "The Effects of Forest Fire Smoke on Fire Fighters: A Comprehensive Study Plan.", D. Ward et al., John Hopkins University (1989).
2. "The Most Difficult Season in History.", Wilson J.F., *Fire Command*, 56:14-18 (1989).
3. "U.S. Fire Fighters Injuries - 1988.", Karter M.J. et al., *Fire Command*, 56:20-29 (1989).
4. "Pulmonary Function and Respiratory Symptoms in Wildland Firefighters.", Rothman, N., et al., *J. Occup. Med.*, 33(11):1163-1167 (1991).
5. "U.S. Fire Fighter Injuries - 1990.", Karter M.J. et al., *NFPA Journal*, Nov/Dec, 43-53 (1991).
6. "Analysis of Condensates from Wood Smoke: Components Derived from Polysaccharides and Lignins.", Edye, L.A. and Richards, G.N., *Environmental Science and Technology*, 25:1133-1137 (1991).
7. "Polynuclear Aromatic Hydrocarbons in Forest Fire Smoke.", McMahan, C.K. et al., *Carcinogenesis*, 3:140-145 (1978).
8. "Toxic Gases from Fires.", Terrill J.B., et al., *Science*, 200:1343-1347 (1978).
9. "Sensory Irritation and Incapacitation Evoked by Thermal Decomposition Products of Polymers and Comparisons with Known Sensory Irritants.", Barrow, C.S. et al., *Arch. Environ. Health*, 33:79-88 (1978).
10. "Documentation of the Threshold Limit Values and Biological Exposure Indices.", American Conference of Governmental Industrial Hygienists Inc., 5th Edition (1986).
11. "Toxic Products from Fires.", Hartzell, G.E., et al., *Am. Ind. Hyg. Assoc. J.*, 44(4):248-255 (1983).
12. "Air Contaminants - Permissible Exposure Limits.", Title 29 Code of Federal Regulations Part 1910.1000, U.S. Department of Labor, Occupational Safety and Health Administration, OSHA 3112, (1989).
13. "1993-1994 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices.", American Conference of Governmental Industrial Hygienists Inc., ISBN 1-88247-03-8 (1993).
14. "The Effect of the Sensory Irritant Component of a Combustion Atmosphere Derived from Douglas Fir on the Leg-flexion Avoidance Response of the Rat.", Farrar D. G., *J. Combustion Toxicology*, 7(1):3-22 (1980).

### References (cont.)

15. "Advances in the Characterization and Control of Emissions from Prescribed Broadcast Fires of Coniferous Species Logging Slash on Clear-cut Units.", Ward, D.E. and C.C. Hardy, Pacific Northwest Research Station USDA Forest Service, (1986).
16. "Large-loss Fires in the United States during 1988 - A year of historical losses.", Taylor K.T. and Tremblay K., *Fire J.*, 83:58-63 (1989).
17. "A Year for the Books: Large-loss Fires in the United States during 1989.", Taylor, K.T. and Tremblay, K., *Fire J.*, 84:44-49 (1990).
18. "Minimum Protection Factors for Respiratory Protective Devices for Firefighters.", Burgess, W.A. et al., *Am. Ind. Hyg. Assoc. J.*, 38(1):18-23 (1977).
19. "Air Contaminates Encountered by Firefighters.", Treitman, R.D. et al., *Am. Ind. Hyg. Assoc. J.*, 41(11):796-802 (1980).
20. "Exposure of Firefighters to Toxic Air Contaminants.", Gold, A. et al., *Am. Ind. Hyg. Assoc. J.*, 39(7):534-539 (1978).
21. "Consideration of Acute Toxicological Responses to Components of Vegetation Smoke.", Dost, F., Draft Report Bureau of Land Management, November (1986).
22. "A Preliminary Analysis of Employee Exposure to Carbon Monoxide on Wildfires and Prescribed Burns.", Jackson G., et al., USDA Forest Service, EDT 2424 (1979).
23. "Yellowstone National Park Fire Exposures 1988.", NIOSH PB-20895 (1990).
24. "Fire Fighters' Exposure to Carbon Monoxide During Australian Bushfires.", Brotherhood et al., *Am. Ind. Hyg. Assoc. J.*, 51(4):234-240 (1990).
25. "Fire Fighter Smoke Exposure at Prescribed Burns: A study and action recommendation.", Reinhardt, T.E., USDA Forest Service (1990).
26. "Occupational Exposures in California Wildland Fire Fighting.", Matera, B.L., et al., *Am. Ind. Hyg. Assoc. J.*, 53(1):69-76 (1992).
27. "Fundamental Factors in the Design of Protective Respiratory Equipment.", Silverman, L. et al., Dept. of Physiology and Industrial Hygiene, Harvard School of Public Health, PB-28613, (1943).
28. "Particle Sizes in Bushfire Smoke.", MacArthur, D.A., *Aust. For.*, 30:274-278 (1966).
29. "A Comparative Study of Aerosol Deposition in Different Lung Models.", Yu, C.P. and Diu, C.K., *Am. Ind. Hyg. Assoc. J.*, 43(1):54-85 (1982).

## **Appendix**

## **Appendix A.**

### **Discussion of Other Test Geometries**

The test method presented in the body of the report was developed after several attempts to use douglas fir sticks as a fuel source. Eventually, douglas fir sticks were abandoned for pine needles which produced a thick and consistent smoke during slow combustion. Many problems occurred with douglas fir. Either the fire burned too fast or it extinguished completely. In most cases, very little smoke was produced from douglas fir sticks. In none of the douglas fir tests was it possible to measure any significant particulate mass. Douglas fir simply burned too efficiently. Additionally, very little aldehyde was detected in the ORBO-24 sampling tubes. A variety of douglas fir stick configurations were tried from tightly packed to thinly packed cribs of wood. A few unsuccessful tests were attempted where the sticks were moistened to inhibit combustion. Radiant heat sources were used to help maintain combustion at a slow rate to produce a smoldering fire. Several other geometries of burning hay and pine needles were also attempted. Wrapping the hay and pine needles into small or large bundles did not produce usable smoke. Whether the bundles were vertically or horizontally oriented didn't improve the combustion properties of the bundled fuel.

**Appendix B**  
**Tables of Experimental Data**

**Appendix B-1.  
Mass Loss Data.**

	Average Mass from 0-300 sec (grams)	Average Mass from 300-600 sec (grams)	Average Mass from 600-900 sec (grams)	Average Mass from 900-1200 sec (grams)	Maximum Observed Mass (grams)
Test 1	220	183	141	124	239
Test 2a	227	194	154	126	243
Test 2b	236	200	175	162	261
Test 3a	205	166	129	104	411
Test 3b	257	226	180	151	265
Test 4	196	149	122	103	247
Test 5	203	149	106	93	229
Test 6	193	145	115	98	240
Test 7a	208	163	128	105	237
Test 7b	225	171	137	120	250
Test 7c	208	164	132	113	250
Test 8	217	165	124	104	239
Test 9-a	224	177	141	126	249
Test 9-b	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost
Test 9-e	204	162	131	112	243
Test 10a-a	212	170	147	124	283
Test 10a-b	215	178	155	124	282
Test 10a-c	227	193	160	134	300
Test 10a-d	229	183	156	133	265
Test 10a-e	231	188	153	138	281
Test 10b-a	221	198	184	170	253
Test 10b-b	189	130	96	85	238
Test 10b-c	207	170	137	108	258
Test 10c-a	219	162	123	101	292
Test 10c-b	214	161	123	105	251
Test 10c-c	224	184	154	121	293
Test 11	210	161	123	103	236

**Appendix B-1 (cont.).  
Mass Loss Data.**

	Initial Mass	Final Mass	Total Mass Loss during Test	Mass at start of Sampling	Mass at end of Sampling	Total Mass Loss during Sampling	Average Rate of Mass Loss during Sampling	Percent Mass Loss during Sampling
	(grams)	(grams)	(grams)	(grams)	(grams)	(grams)	(grams/min.)	
Test 1	237	51	186	231	113	118	5.9	63%
Test 2a	240	49	191	236	116	120	6.0	63%
Test 2b	259	79	180	253	154	98	4.9	54%
Test 3a	237	53	185	223	88	135	6.7	73%
Test 3b	263	79	184	260	142	118	5.9	64%
Test 4	242	57	185	220	91	129	6.4	70%
Test 5	226	40	186	220	87	133	6.6	71%
Test 6	230	43	187	218	100	118	5.9	63%
Test 7a	235	51	185	227	97	130	6.5	70%
Test 7b	249	64	185	245	114	131	6.5	71%
Test 7c	248	63	185	234	106	128	6.4	70%
Test 8	222	45	177	216	101	115	5.8	65%
Test 9a	246	61	185	239	110	130	6.5	70%
Test 9b	data lost	data lost	data lost	data lost	data lost	data lost	data lost	data lost
Test 9c	data lost	data lost	data lost	data lost	data lost	data lost	data lost	data lost
Test 9d	data lost	data lost	data lost	data lost	data lost	data lost	data lost	data lost
Test 9e	236	57	179	223	106	118	5.9	66%
Test 10a-a*	245	95	150	233	112	120	6.0	80%
Test 10a-b*	247	98	149	235	111	124	6.2	83%
Test 10a-c*	247	116	132	243	127	116	5.8	88%
Test 10a-d*	250	105	146	247	119	128	6.4	88%
Test 10a-e*	252	123	130	248	134	114	5.7	88%
Test 10b-a*	252	116	137	237	161	76	3.8	56%
Test 10b-b*	232	78	154	217	82	135	6.7	87%
Test 10b-c*	237	101	137	227	102	125	6.2	91%
Test 10c-a*	243	59	184	239	94	145	7.2	79%
Test 10c-b*	246	89	157	237	99	137	6.9	87%
Test 10c-c*	248	60	189	242	108	134	6.7	71%
Test 11	235	53	182	229	96	132	6.6	72%
* Test interrupted						Average =	6.2	73%
						Std. Dev. =	0.7	11%

**Appendix B-2.  
Carbon Monoxide Data.**

	Average Carbon Monoxide concentration from 0-300 sec (ppm)	Average Carbon Monoxide concentration from 300-600 sec (ppm)	Average Carbon Monoxide concentration from 600-900 sec (ppm)	Average Carbon Monoxide concentration from 900-1200 sec (ppm)	Maximum Observed Carbon Monoxide concentration (ppm)
Test 1	858	1470	1544	932	1971
Test 2a	847	1725	1892	1805	2122
Test 2b	1319	1372	1155	912	1677
Test 3a	1379	1453	1693	1466	1947
Test 3b	242	1368	1452	1040	1805
Test 4	1959	1804	1310	1283	2175
Test 5	1218	1928	1543	943	2128
Test 6	2208	2327	1832	1506	2543
Test 7a	1436	1735	1445	1190	2147
Test 7b	1279	1748	1377	981	2043
Test 7c	1727	1633	1169	985	2172
Test 8	1116	1946	1717	1125	2040
Test 9-a	1514	2142	1823	1080	2285
Test 9-b	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost
Test 9-e	2197	2306	2247	1808	2467
Test 10a-a	1984	1797	1509	1611	2264
Test 10a-b	1753	1514	1418	2213	2371
Test 10a-c	1205	1442	1692	1336	1856
Test 10a-d	1329	1666	1246	1538	2039
Test 10a-e	1339	1929	1622	962	2103
Test 10b-a	1328	875	766	895	1689
Test 10b-b	2428	2637	2144	1337	2757
Test 10b-c	1768	1588	1994	1854	2477
Test 10c-a	1449	2363	2192	1581	2523
Test 10c-b	1602	2050	1968	1300	2236
Test 10c-c	1205	1296	1257	1788	1942
Test 11	1591	2226	2096	1566	2370
			Overall Average =	1531	
			Std. Dev. =	267	

**Appendix B-3. Formaldehyde Oxazolidine Sampling Data.**

	Retention time (min)	Upstream area counts	Average area counts	Retention time	Downstream area counts	Average area counts
Test 1	9.15	33,561	40,020	9.12	37,389	34,958
	9.13	39,728		9.12	34,394	
	9.12	46,772		9.13	33,092	
Test 2a	9.12	35,023	46,120	9.17	33,381	34,469
	9.11	48,086		9.16	39,484	
	9.12	55,250		9.15	49,755	
Test2b	9.10	38,421	34,023	9.10	19,649	24,023
	9.11	28,830		9.10	30,075	
	9.11	34,819		9.13	24,330	
Test 3a	9.11	34,484	39,329	9.13	27,069	30,108
	9.12	47,046		9.11	34,422	
	9.11	36,457		9.13	28,834	
Test 3b	9.11	31,115	32,612	9.10	30,248	26,058
	9.10	33,215		9.10	26,255	
	9.10	33,510		9.10	21,670	
Test 4	9.14	19,899	23,037	9.15	25,787	26,776
	9.28	16,303		9.16	37,420	
	9.14	32,908		9.15	17,120	
Test 5	9.14	23,310	26,839		Not Detected	
	9.13	28,770			Not Detected	
	9.15	28,436			Not Detected	
Test 6	9.12	33,576	38,930		Not Detected	
	9.12	38,076			Not Detected	
	9.13	45,137			Not Detected	
Test 7a	9.17	28,510	35,397		Not Detected	
	9.15	36,134			Not Detected	
	9.16	41,546			Not Detected	
Test 7b	9.16	13,902	17,211		Not Detected	
	9.17	15,531			Not Detected	
	9.16	20,519			Not Detected	
Test 7c	9.15	44,265	40,565		Not Detected	
	9.16	42,869			Not Detected	
	9.17	34,561			Not Detected	

**Appendix B-3 (cont.). Formaldehyde Oxazolidine Sampling Data.**

	Retention time (min)	Upstream area counts	Average area counts	Retention time	Downstream area counts	Average area counts	
Test 8	9.12	23,828	31,004		Not Detected		
	9.13	33,410			Not Detected		
	9.13	35,773			Not Detected		
Test 9-a	9.15	30,273	40,196		Not Detected		
Test 9-b	9.14	33,408			Not Detected		
Test 9-c	9.14	45,087			Not Detected		
Test 9-d	9.14	58,412			Not Detected		
Test 9-e	9.15	33,802			9.12	13,377	15,670
				9.11	14,987		
				9.10	18,645		
Test 10a-a	9.16	32,551	39,841		Not Detected		
Test 10a-b	9.16	42,939			Not Detected		
Test 10a-c	9.16	37,734			Not Detected		
Test 10a-d	9.16	46,140			9.12	16,179	16,886
				9.11	17,593		
Test 10a-e	9.15	39,750		9.12	26,456	33,296	
				9.12	40,135		
Test 10b-a	9.11	43,653	37,899		Not Detected		
Test 10b-b	9.12	33,595			Not Detected		
Test 10b-c	9.15	36,450			9.12	5,882	5,404
					9.12	2,448	
					9.12	2,519	
					9.12	9,288	
				9.12	6,882		
Test 10c-a	9.10	34,294	35,992		Not Detected		
Test 10c-b	9.10	39,403			Not Detected		
Test 10c-c	9.10	34,278			9.11	17,779	21,869
				9.11	27,816		
				9.11	20,011		
Test 11		No sampling done			Not Detected		
		No sampling done			Not Detected		
		No sampling done			Not Detected		

**Appendix B-4.**  
**Gas temperature data collected at the bottom of the test chamber.**

	Initial Temperature (°C)	Average Temperature from 0-300 sec (°C)	Average Temperature from 300-600 sec (°C)	Average Temperature from 600-900 sec (°C)	Average Temperature from 900-1200 sec (°C)	Maximum Observed Temperature (°C)
Test 1	25.3	28.7	28.5	29.2	29.7	32.7
Test 2a	25.8	29.3	29.6	30.0	30.7	32.2
Test 2b	25.5	27.2	27.4	28.0	28.3	33.1
Test 3a	24.2	26.4	26.8	27.4	28.1	31.5
Test 3b	27.7	30.9	31.9	31.9	32.5	34.0
Test 4	27.2	30.5	31.7	32.0	32.5	34.2
Test 5	24.6	27.1	27.3	28.0	28.6	31.9
Test 6	25.0	27.8	28.5	29.2	29.7	31.3
Test 7a	27.1	30.0	30.1	30.6	31.1	33.5
Test 7b	24.7	27.2	27.5	28.3	28.9	31.5
Test 7c	23.7	26.3	27.5	27.5	28.2	30.8
Test 8	20.7	24.2	24.3	25.0	25.6	27.9
Test 9-a	26.6	28.7	29.4	30.2	30.4	33.2
Test 9-b	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-e	21.3	22.6	23.3	23.6	24.5	29.6
Test 10a-a	23.6	25.0	25.4	25.8	26.9	29.4
Test 10a-b	26.0	28.4	28.7	29.0	30.2	31.6
Test 10a-c	26.6	29.8	30.0	30.6	31.3	32.3
Test 10a-d	28.0	31.4	31.4	31.7	32.2	34.1
Test 10a-e	28.5	32.0	32.4	33.1	33.3	34.3
Test 10b-a	20.0	21.3	21.6	21.9	22.3	24.4
Test 10b-b	20.2	23.8	24.5	26.1	26.4	27.6
Test 10b-c	23.2	26.3	26.4	27.0	28.0	29.0
Test 10c-a	24.2	26.7	27.3	28.1	29.3	31.5
Test 10c-b	26.9	30.3	31.4	31.9	32.5	33.5
Test 10c-c	26.7	30.6	31.1	31.3	32.0	34.0
Test 11	24.7	26.4	27.2	27.8	28.9	32.4

**Appendix B-4 (cont.).**  
**Gas temperature data collected in the middle of the test chamber.**

	Initial Temperature (°C)	Average Temperature from 0-300 sec (°C)	Average Temperature from 300-600 sec (°C)	Average Temperature from 600-900 sec (°C)	Average Temperature from 900-1200 sec (°C)	Maximum Observed Temperature (°C)
Test 1	25.7	31.8	36.3	40.2	41.4	46.2
Test 2a	26.9	32.2	35.8	38.6	41.7	46.9
Test 2b	25.7	32.2	35.2	37.6	38.2	44.2
Test 3a	24.3	33.7	36.3	39.2	42.0	45.5
Test 3b	28.2	31.1	38.8	45.3	46.3	47.9
Test 4	27.3	39.9	47.5	47.0	47.9	49.6
Test 5	24.7	31.9	38.1	42.9	44.1	48.5
Test 6	25.4	33.8	39.6	43.6	45.4	48.2
Test 7a	27.2	35.4	43.6	44.7	45.8	48.2
Test 7b	24.9	31.1	39.5	42.4	43.2	44.4
Test 7c	23.8	34.4	42.9	42.0	43.1	44.4
Test 8	27.0	33.0	39.0	43.7	45.9	47.5
Test 9-a	26.9	33.2	38.7	42.9	43.1	45.9
Test 9-b	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-e	22.1	29.4	33.5	37.1	39.7	43.2
Test 10a-a	23.8	30.6	34.2	36.4	40.2	43.3
Test 10a-b	26.5	34.2	36.0	37.6	44.5	46.8
Test 10a-c	27.4	33.9	37.1	40.9	43.4	44.7
Test 10a-d	28.9	35.5	40.0	41.4	43.9	47.5
Test 10a-e	29.2	37.0	42.1	45.7	45.6	46.5
Test 10b-a	20.0	27.2	28.4	28.9	30.2	36.8
Test 10b-b	21.1	31.4	38.0	44.9	44.2	46.1
Test 10b-c	24.1	33.0	35.9	39.2	43.7	44.7
Test 10c-a	24.6	30.6	37.0	42.2	45.6	48.0
Test 10c-b	27.6	36.6	43.3	47.5	48.9	51.4
Test 10c-c	27.8	35.5	39.6	42.0	46.0	51.0
Test 11	24.9	31.3	36.9	41.3	44.7	45.8

**Appendix B-4 (cont.).**  
**Gas temperature data collected at the top of the test chamber.**

	Initial Temperature (°C)	Average Temperature from 0-300 sec (°C)	Average Temperature from 300-600 sec (°C)	Average Temperature from 600-900 sec (°C)	Average Temperature from 900-1200 sec (°C)	Maximum Observed Temperature (°C)
Test 1	26.3	32.2	39.4	46.9	47.5	53.1
Test 2a	29.3	33.6	40.6	47.0	49.8	54.7
Test 2b	26.2	33.8	40.4	45.6	46.1	50.4
Test 3a	24.7	35.4	42.6	47.0	51.2	54.4
Test 3b	29.8	30.6	38.8	47.8	49.7	52.8
Test 4	29.4	41.4	50.6	53.2	54.9	60.3
Test 5	25.3	33.0	42.9	51.0	51.0	59.9
Test 6	26.8	37.9	46.0	51.3	53.7	58.2
Test 7a	27.5	35.7	46.1	51.2	53.8	57.3
Test 7b	25.5	31.7	42.1	46.9	48.1	51.3
Test 7c	24.2	35.2	44.8	47.4	49.2	51.5
Test 8	28.7	34.4	44.9	52.8	54.7	57.1
Test 9-a	27.5	34.6	44.5	50.7	50.1	53.5
Test 9-b	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-e	22.6	32.4	40.1	46.0	48.3	50.4
Test 10a-a	23.8	33.9	42.1	44.7	47.9	53.7
Test 10a-b	29.0	37.1	44.3	46.3	52.2	56.2
Test 10a-c	30.2	35.4	41.5	46.8	50.4	52.7
Test 10a-d	31.9	36.7	45.2	49.2	51.7	57.1
Test 10a-e	32.3	38.5	46.5	52.2	51.8	54.3
Test 10b-a	20.2	30.8	33.0	34.3	34.9	44.1
Test 10b-b	24.4	35.9	46.6	54.6	53.0	57.5
Test 10b-c	27.3	37.4	43.6	47.0	53.2	56.0
Test 10c-a	26.6	32.5	44.8	50.9	54.1	57.3
Test 10c-b	31.8	39.5	51.0	54.9	57.2	60.1
Test 10c-c	32.6	39.0	48.5	49.1	55.6	60.3
Test 11	25.4	33.1	43.7	50.3	54.1	55.9

**Appendix B-4 (cont.).**  
**Gas temperature data collected at the exit to the test chamber.**

	Initial Temperature (°C)	Average Temperature from 0-300 sec (°C)	Average Temperature from 300-600 sec (°C)	Average Temperature from 600-900 sec (°C)	Average Temperature from 900-1200 sec (°C)	Maximum Observed Temperature (°C)
Test 1	25.5	32.1	38.9	45.0	46.4	51.8
Test 2a	26.8	33.0	40.1	44.5	48.4	52.9
Test 2b	25.6	33.7	39.5	42.7	43.4	48.9
Test 3a	24.3	34.8	41.1	45.9	50.3	51.5
Test 3b	28.0	30.8	38.8	47.3	49.2	51.3
Test 4	27.3	40.8	49.8	51.9	53.4	57.2
Test 5	24.8	31.9	41.5	48.1	48.8	54.7
Test 6	25.4	36.7	45.1	49.8	51.7	54.9
Test 7a	27.2	35.3	45.5	49.3	51.6	54.1
Test 7b	24.9	31.3	42.1	46.4	47.5	49.0
Test 7c	23.8	34.7	44.8	46.5	48.6	50.0
Test 8	27.0	33.4	43.8	50.5	52.7	53.7
Test 9-a	26.9	34.9	43.9	49.7	49.4	51.9
Test 9-b	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-e	22.7	32.1	39.0	43.6	46.8	48.3
Test 10a-a	23.8	33.4	40.4	43.1	46.7	50.4
Test 10a-b	26.4	36.4	41.8	43.8	50.9	53.5
Test 10a-c	27.3	35.0	41.3	46.1	49.5	50.5
Test 10a-d	28.6	36.3	45.1	48.0	50.0	54.2
Test 10a-e	29.0	38.4	46.2	51.1	50.9	52.1
Test 10b-a	19.9	30.5	33.0	34.3	35.1	42.6
Test 10b-b	21.1	35.5	44.7	52.9	51.5	54.9
Test 10b-c	24.0	36.7	43.1	45.5	51.6	52.4
Test 10c-a	24.6	32.0	42.9	49.4	52.2	54.5
Test 10c-b	27.6	38.5	48.9	54.3	56.8	58.2
Test 10c-c	27.8	37.2	45.2	47.8	53.3	57.8
Test 11	25.0	32.8	42.3	48.5	52.2	53.2

**Appendix B-4 (cont.).**  
**Ambient gas temperature data collected outside the test chamber.**

	Initial Temperature (°C)	Average Temperature from 0-300 sec (°C)	Average Temperature from 300-600 sec (°C)	Average Temperature from 600-900 sec (°C)	Average Temperature from 900-1200 sec (°C)	Maximum Observed Temperature (°C)
Test 1	26.1	25.9	26.2	26.5	26.6	28.4
Test 2a	25.7	25.6	25.7	25.9	25.8	27.0
Test 2b	26.1	26.5	26.8	27.2	27.5	31.6
Test 3a	24.8	25.2	25.2	25.6	26.4	28.2
Test 3b	28.2	27.9	28.0	28.2	28.5	29.4
Test 4	27.0	27.2	27.4	27.6	27.7	26.0
Test 5	25.7	25.6	26.0	26.5	27.2	28.7
Test 6	25.5	25.6	26.0	26.1	26.5	27.9
Test 7a	27.5	27.5	27.6	28.0	28.3	29.8
Test 7b	25.6	25.6	25.9	26.5	26.9	28.1
Test 7c	24.4	24.6	24.9	25.5	26.1	27.1
Test 8	26.2	26.0	26.1	26.3	26.9	28.0
Test 9-a	27.4	27.5	28.0	28.4	28.7	30.1
Test 9-b	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-e	22.2	22.6	23.0	23.7	24.1	26.8
Test 10a-a	24.2	24.2	24.5	25.0	25.3	26.2
Test 10a-b	25.2	25.7	25.9	26.2	26.6	27.9
Test 10a-c	27.0	26.8	27.3	27.7	27.8	28.8
Test 10a-d	27.8	28.1	28.4	28.7	29.1	30.2
Test 10a-e	28.9	29.0	29.1	29.4	29.5	30.8
Test 10b-a	20.4	20.6	21.2	21.6	22.0	22.9
Test 10b-b	20.6	21.8	22.7	23.3	24.4	25.1
Test 10b-c	23.4	23.5	24.2	24.6	24.8	26.3
Test 10c-a	24.7	24.8	25.2	25.7	26.2	28.7
Test 10c-b	27.2	26.8	27.0	28.0	28.6	29.2
Test 10c-c	27.3	27.1	27.3	28.0	28.2	29.8
Test 11	25.7	25.9	26.3	26.7	27.1	28.9

**Appendix B-4 (cont.).  
Gas temperature data collected at the test filter holder.**

	Initial Temperature (°C)	Average Temperature from 0-300 sec (°C)	Average Temperature from 300-600 sec (°C)	Average Temperature from 600-900 sec (°C)	Average Temperature from 900-1200 sec (°C)	Maximum Observed Temperature (°C)
Test 1	25.8	26.0	26.5	27.2	28.0	28.2
Test 2a	26.1	26.3	27.0	27.8	28.5	28.9
Test 2b	25.7	26.0	26.8	27.6	28.2	28.4
Test 3a	24.3	24.7	25.4	26.2	27.0	27.4
Test 3b	27.6	27.7	28.0	28.8	29.5	29.8
Test 4	26.5	27.7	29.3	30.1	30.6	30.9
Test 5	24.8	25.0	26.0	26.8	27.5	27.8
Test 6	25.5	26.0	27.0	27.7	28.2	28.5
Test 7a	26.9	27.2	27.9	28.4	29.2	29.7
Test 7b	25.0	25.3	26.3	27.3	28.1	28.4
Test 7c	24.0	24.6	25.8	26.9	27.7	28.0
Test 8	26.1	26.4	27.8	29.3	30.5	31.1
Test 9-a	26.8	27.5	29.3	31.0	32.0	33.4
Test 9-b	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-e	21.0	22.4	24.0	25.2	26.3	29.6
Test 10a-a	23.4	24.6	26.4	27.7	28.8	29.2
Test 10a-b	25.8	26.8	28.5	29.6	30.9	31.6
Test 10a-c	27.4	27.8	29.2	30.4	31.5	31.9
Test 10a-d	28.3	28.8	30.5	31.9	32.8	33.3
Test 10a-e	29.0	29.6	31.3	32.8	33.7	34.0
Test 10b-a	20.2	21.3	22.6	23.4	24.0	24.3
Test 10b-b	20.7	22.5	25.0	26.7	28.0	28.5
Test 10b-c	23.4	24.4	25.8	26.9	28.1	28.4
Test 10c-a	24.0	24.8	26.7	28.4	29.8	30.3
Test 10c-b	25.9	27.0	29.2	30.9	32.4	32.7
Test 10c-c	27.7	27.8	29.3	30.4	31.5	32.1
Test 11	24.8	25.6	27.5	29.3	30.7	32.4

**Appendix B-4 (cont.).**  
**Gas temperature data collected at the exhaust flow orifice.**

	Initial Temperature (°C)	Average Temperature from 0-300 sec (°C)	Average Temperature from 300-600 sec (°C)	Average Temperature from 600-900 sec (°C)	Average Temperature from 900-1200 sec (°C)	Maximum Observed Temperature (°C)
Test 1	25.9	28.2	32.0	35.5	37.3	40.0
Test 2a	27.1	28.7	31.8	34.5	36.2	39.1
Test 2b	25.8	28.2	31.3	33.5	34.6	37.9
Test 3a	24.6	28.8	33.1	35.8	38.4	39.7
Test 3b	28.2	29.2	32.0	37.0	38.8	40.0
Test 4	27.3	32.4	37.8	40.2	41.4	43.2
Test 5	24.8	27.5	32.8	36.8	38.6	41.6
Test 6	25.6	29.4	33.9	36.5	38.2	40.2
Test 7a	27.3	30.0	35.4	38.4	40.5	42.3
Test 7b	25.1	27.3	32.8	36.1	37.7	38.1
Test 7c	24.1	28.1	34.2	36.6	38.1	38.9
Test 8	26.7	28.9	34.4	38.5	40.8	41.4
Test 9-a	26.9	29.3	33.6	36.7	37.9	39.6
Test 9-b	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-e	22.0	25.1	28.7	31.0	32.8	35.9
Test 10a-a	24.2	27.1	31.1	33.3	34.8	36.7
Test 10a-b	26.7	29.6	32.9	34.5	36.8	38.6
Test 10a-c	27.6	29.6	32.9	35.2	37.1	38.2
Test 10a-d	29.0	30.7	34.7	37.1	38.2	40.1
Test 10a-e	29.4	31.8	35.5	38.4	39.4	39.6
Test 10b-a	20.5	24.0	26.0	27.0	27.6	30.4
Test 10b-b	21.4	25.7	30.2	33.5	34.7	35.0
Test 10b-c	24.3	27.3	30.7	32.2	34.6	35.3
Test 10c-a	24.6	26.5	31.0	34.0	36.1	38.8
Test 10c-b	27.4	30.1	34.8	37.8	40.0	40.5
Test 10c-c	27.7	30.0	34.2	35.9	37.9	41.4
Test 11	25.3	27.6	32.1	35.5	37.9	39.1

**Appendix B-5.  
Particulate Data.**

	Upstream Initial Filter Mass (grams)	Downstream Initial Filter Mass (grams)	Upstream Final Filter Mass (grams)	Downstream Final Filter Mass (grams)	Upstream Air Particulate Density (g/m <sup>3</sup> )	Downstream Air Particulate Density (g/m <sup>3</sup> )
Test 1	0.124	0.128	0.196	0.192	1.80	1.60
Test 2a	0.125	0.124	0.221	0.214	2.40	2.25
Test 2b	0.127	0.123	0.219	0.203	2.30	2.00
Test 3a	0.124	0.124	0.225	0.214	2.53	2.25
Test 3b	0.123	0.127	0.201	0.195	1.96	1.70
Test 4	0.128	0.125	0.229	0.211	2.53	2.15
Test 5	0.125	0.127	0.219	0.167	2.35	1.00
Test 6	0.126	0.126	0.242	0.181	2.90	1.38
Test 7a	0.127	0.124	0.212	0.136	2.13	0.30
Test 7b	0.124	0.126	0.211	0.141	2.19	0.36
Test 7c	0.122	0.124	0.209	0.137	2.16	0.33
Test 8	0.127	0.125	0.202	0.139	1.88	0.35
Test 9-a	0.124	0.129	0.221	0.147	2.43	0.45
Test 10a-a	0.127	0.124	0.230	0.147	2.58	0.58
Test 10a-b	0.128	0.126	0.244	0.155	2.90	0.73
Test 10a-c	0.124	0.125	0.222	0.146	2.45	0.53
Test 10a-d	0.126	0.124	0.237	0.149	2.78	0.63
Test 10a-e	0.128	0.124	0.205	0.142	1.93	0.45
Test 10b-a	0.124	0.125	0.190	0.138	1.65	0.32
Test 10b-b	0.123	0.128	0.256	0.168	3.34	1.01
Test 10b-c	0.125	0.125	0.258	0.165	3.34	1.02
Test 10c-a	0.124	0.124	0.270	0.156	3.65	0.81
Test 10c-b	0.124	0.123	0.247	0.153	3.07	0.74
Test 10c-c	0.124	0.123	0.247	0.153	3.07	0.74
Test 11	0.127	0.125	0.235	0.125	2.70	0.00

**Appendix B-6.**  
**Pressure differential across the test filter data.**

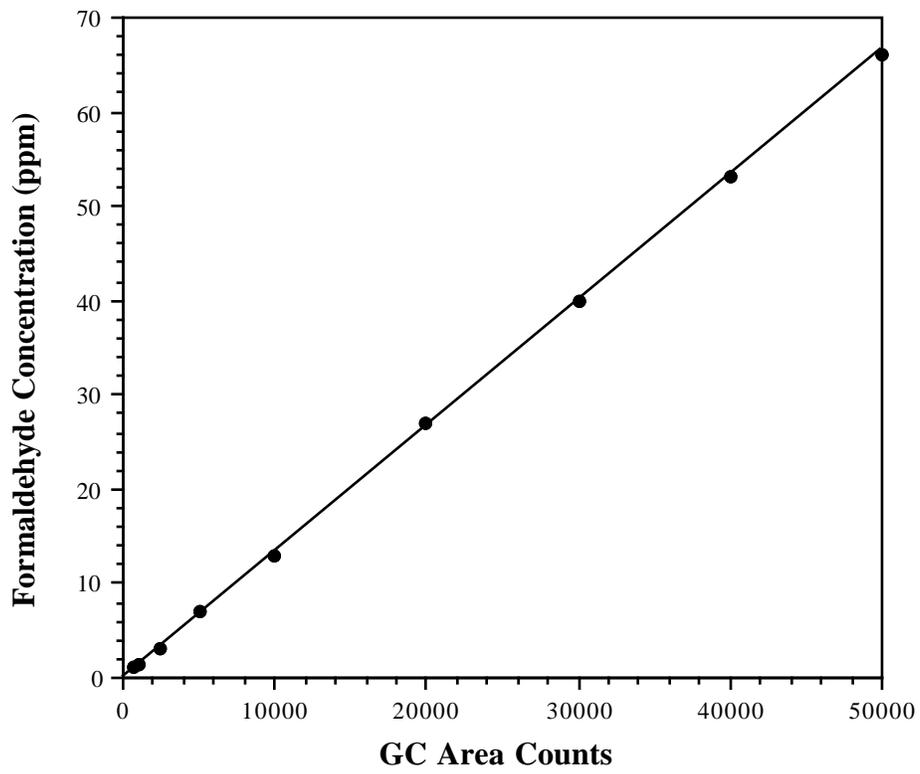
	Initial Delta Pressure  (Pascals)	Average Delta Pressure from 0-300 sec (Pascals)	Average Delta Pressure from 300-600 sec (Pascals)	Average Delta Pressure from 600-900 sec (Pascals)	Average Delta Pressure from 900-1200 sec (Pascals)	Maximum Delta Pressure Observed  (Pascals)
Test 1	0	1	2	1	1	7
Test 2a	0	1	1	1	2	5
Test 2b	1	5	6	5	5	9
Test 3a	-2	2	1	1	1	8
Test 3b	0	3	3	4	4	8
Test 4	-2	5	4	3	2	9
Test 5	-1	95	99	98	85	111
Test 6	-1	92	94	90	72	12
Test 7a	1	98	115	110	110	136
Test 7b	2	145	147	150	147	161
Test 7c	3	145	147	150	149	159
Test 8	-2	194	220	213	207	245
Test 9-a	-2	344	363	374	375	385
Test 9-b	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost	data lost
Test 9-e	0	506	873	1413	1501	1535
Test 10a-a	2	323	330	327	322	339
Test 10a-b	0	368	401	401	405	418
Test 10a-c	0	401	415	413	408	422
Test 10a-d	2	447	483	485	485	494
Test 10a-e	-2	473	505	513	511	523
Test 10b-a	2	336	345	348	350	359
Test 10b-b	0	370	393	388	382	399
Test 10b-c	3	388	391	383	368	402
Test 10c-a	1	320	352	361	364	370
Test 10c-b	1	380	407	414	414	423
Test 10c-c	1	406	439	432	439	448
Test 11	-1	329	344	352	359	367

**Appendix B-6 (cont.).**  
**Pressure differential across the chamber exhaust orifice data.**

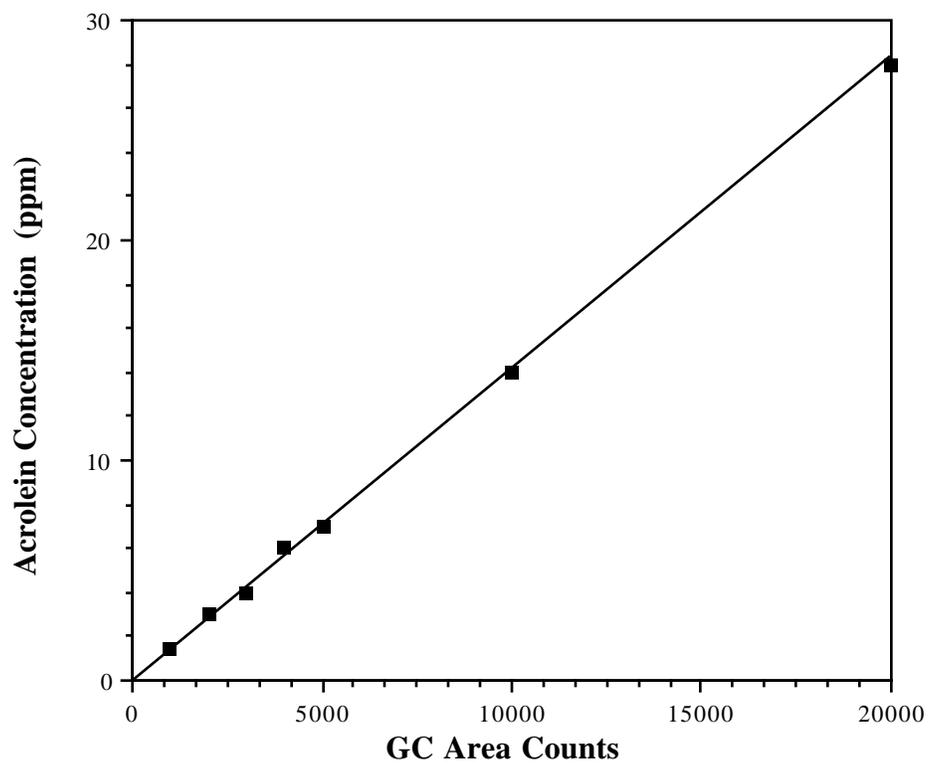
	Average Delta Pressure from 0-300 sec (Pascals)	Average Delta Pressure from 300-600 sec (Pascals)	Average Delta Pressure from 600-900 sec (Pascals)	Average Delta Pressure from 900-1200 sec (Pascals)	Maximum Delta Pressure Observed  (Pascals)
Test 1	0.131	0.131	0.132	0.118	0.137
Test 2a	0.080	0.079	0.078	0.078	0.084
Test 2b	0.055	0.057	0.057	0.057	0.066
Test 3a	0.132	0.132	0.132	0.131	0.139
Test 3b	0.130	0.130	0.131	0.131	0.139
Test 4	0.130	0.129	0.120	0.124	0.138
Test 5	0.130	0.130	0.130	0.130	0.139
Test 6	0.081	0.081	0.081	0.081	0.086
Test 7a	0.131	0.130	0.130	0.130	0.138
Test 7b	0.132	0.132	0.132	0.132	0.141
Test 7c	0.133	0.133	0.133	0.132	0.142
Test 8	0.130	0.131	0.131	0.131	0.140
Test 9-a	0.073	0.072	0.072	0.072	0.078
Test 9-b	data lost	data lost	data lost	data lost	data lost
Test 9-c	data lost	data lost	data lost	data lost	data lost
Test 9-d	data lost	data lost	data lost	data lost	data lost
Test 9-e	0.046	0.044	0.044	0.044	0.068
Test 10a-a	0.066	0.066	0.066	0.066	0.140
Test 10a-b	0.064	0.064	0.065	0.065	0.137
Test 10a-c	0.068	0.068	0.069	0.070	0.140
Test 10a-d	0.070	0.070	0.070	0.071	0.136
Test 10a-e	0.072	0.073	0.073	0.075	0.134
Test 10b-a	0.052	0.049	0.048	0.048	0.059
Test 10b-b	0.043	0.043	0.045	0.044	0.132
Test 10b-c	0.044	0.042	0.044	0.045	0.135
Test 10c-a	0.046	0.046	0.050	0.051	0.061
Test 10c-b	0.057	0.059	0.060	0.061	0.138
Test 10c-c	0.058	0.060	0.061	0.063	0.073
Test 11	0.071	0.071	0.072	0.072	0.076

**Appendix C**  
**Plots of Experimental Data**

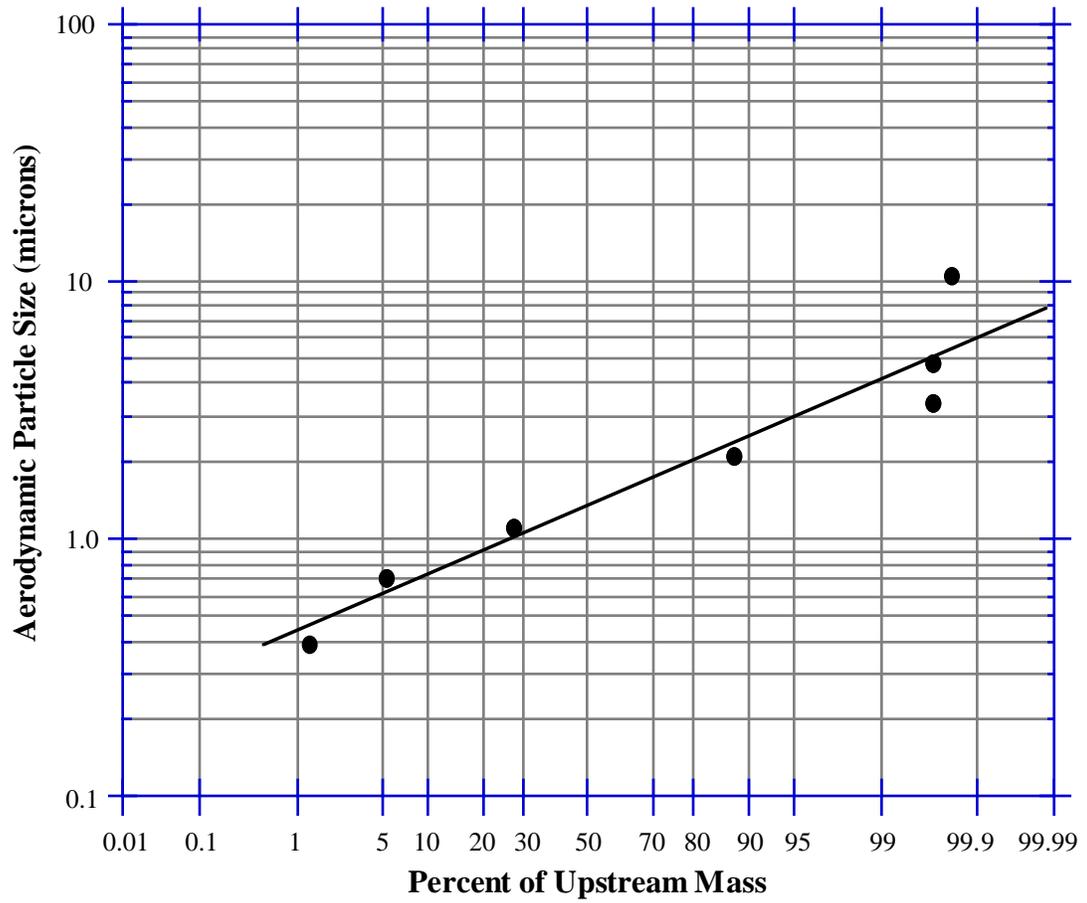
**Appendix C-1.**  
**Gas chromatograph calibration curve for formaldehyde.**



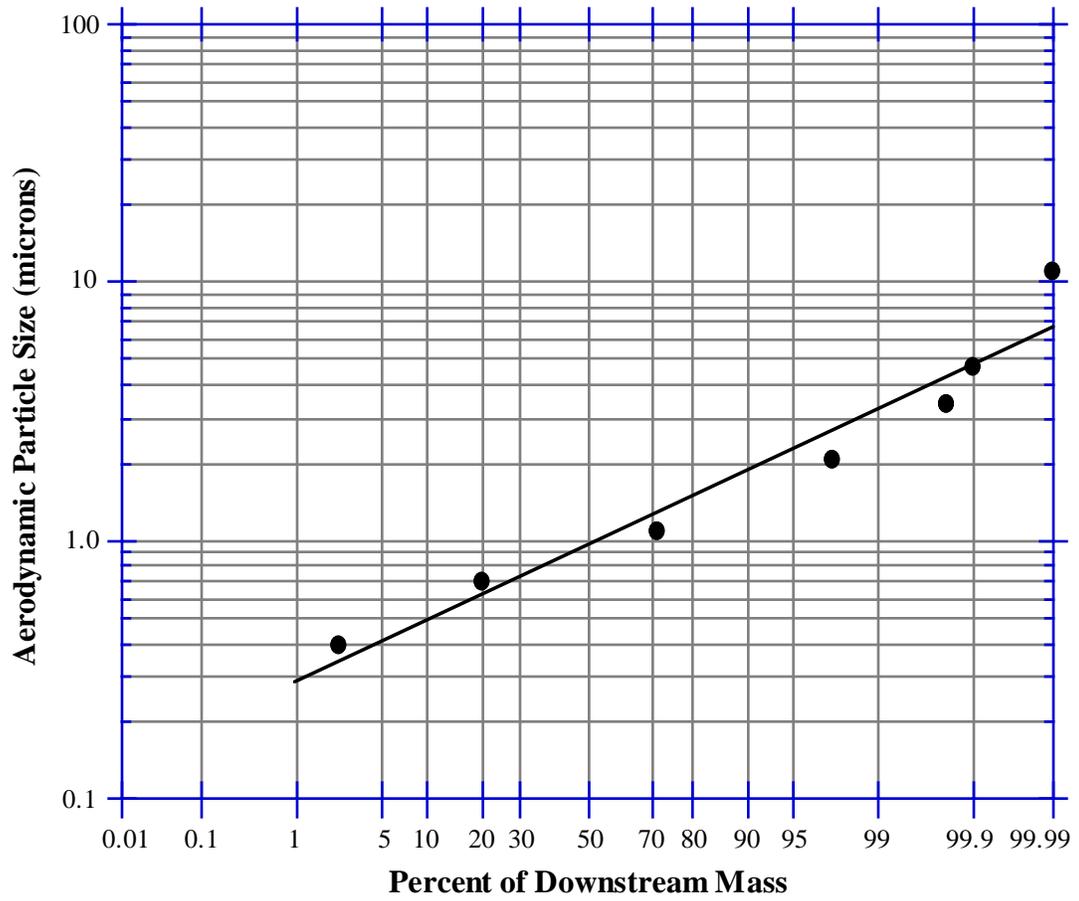
**Appendix C-2.**  
**Gas chromatograph calibration curve for acrolein.**



**Appendix C-3.**  
**Log-Normal probability plot of the upstream particle size data.**



**Appendix C-4.**  
**Log-Normal probability plot of the downstream particle size data.**







*Technical Information Department • Lawrence Livermore National Laboratory*  
*University of California • Livermore, California 94551*

