Firesmoke: A Field Evaluation of Self-Contained Breathing Apparatus

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16. Abstract (Limit: 200 words) The efficacy of positive pressure respirators under field conditions during actual fire fighting activities was evaluated at five major fire departments in the United States. Probes placed into the respirators continuously sampled for contaminants both inside of and outside of the facepiece of the respirator. Fourier Transform Infrared Spectrophotometry was used to subsequently identify the contaminants. Individual measurements were made on 64 firefighters at 25 active fire scenes. Preexposure and post exposure carbon-monoxide (630080) breath samples were collected. Only low levels of contaminants were found in each of the fires sampled, making measurement of protection impractical. An additional problem was the inability to determine the test subjects' prior exposure to carbon-monoxide. The types of fire studied in this research included rubbish outside, building and contents occupied, unoccupied building, passenger vehicle, unoccupied building fought from outside, building and contents unoccupied, and oil from a generator. Removal of the respirator was a significant limiting factor in respirator effectiveness.

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ABSTRACT

Positive-pressure self-contained breathing apparatus are recommended for use in structural fire fighting under both the National Institute for Occupational Safety and Health and National Fire Protection Association standards. However, the efficacy of this respirator against contaminants encountered in actual structural fire fighting activities has not been determined by field trials. Existing studies have been laboratory-based fit-test measurements. This project was the first major study of the efficacy of positive-pressure respirators under field conditions during actual fire fighting activities. Field evaluations were conducted in conjunction with five fire departments in major U.S. cities. Respirators were modified to accept probes which continuously sampled for contaminants both inside and outside the facepiece of the respirator. Subsequent analysis was conducted by Fourier Transform Infrared Spectrophotometry. Low levels of contaminants during the study fires, coupled with problems in collecting samples, resulted in a modification of the study design. Data were collected on in-facepiece respirator air pressure, rather than on actual contaminant levels. However, some limited data were obtained on carbon monoxide exposure. The most notable

finding was that removal of respirators, for communications or other reasons by individual fire fighters, was a significant limiting factor in respirator effectiveness.

PROJECT FIRESMOKE

I. BACKGROUND

Fire fighters are subject to various health hazards in the course of performing their jobs. Increased rates of melanomas and myelomas, ischemic heart disease, pulmonary disease, and other health effects have been associated with fire fighting. Inhalation of toxic gases, mists, fumes, and particulates such as smoke particles, has been indicated as a causative factor in the development of these illnesses, as well as with such direct and immediate health effects as asphyxiation and shock.[1]

Air purifying respirators — respirators which filter contaminants out of the air — can be effective against a wide range of gases, mists, and fumes, but this class of respirator is not effective against high levels of carbon monoxide or oxygen deficiencies. These two respiratory hazards constitute a significant proportion of the overall airborne hazards facing fire fighters. Pressure-demand (PD) (also referred to as positive pressure) self-contained breathing apparatus (SCBA) are recommended for fire fighting.[2] Pressure Demand-SCBA maintain positive air pressure in the facepiece of the respirator at all times during the breathing cycle. This design feature is intended to prevent or minimize contaminant leakage into the facepiece. These PD-SCBA constitute the optimal design for fire fighting and are required equipment under the Occupational Safety and Health Administration (OSHA) Standard 29CFR 1910.156 for fire brigades performing interior structural fire fighting.[3]

The effectiveness of PD-SCBA against environmental contaminants has been tested under controlled laboratory conditions, but field studies have been few and limited in scope.[4] Laboratory studies have also suggested potential problems with these respirators under the heavy workload conditions likely to be encountered in actual work situations.[5-7] Project Firesmoke was conducted by the National Institute for Occupational Safety and Health (NIOSH) to test the effectiveness of PD-SCBA respirators. This was accomplished by collecting in-mask pressure samples and by collecting air samples both inside and outside of the SCBA facepiece. NIOSH also identified a significant variable in the protection afforded fire fighters--interrupted use of the respirator.

In cooperation with five metropolitan fire departments, NIOSH tested two brands of PD-SCBA which the manufacturers had certified as being in compliance with the Code of Federal Regulations, Title 30, Part 11 (30CFR11)[(8)] revised July 1, 1986, and the National Fire Protection Association (NFPA) Standard 1981-1987 for Open-Circuit Self-Contained Breathing Apparatus for Fire Fighters.[(9)] Tests were conducted at 25 active fire scenes, and through 64 individual measurements,[a] to determine the effectiveness of PD-SCBA in maintaining the minimum ratio of contaminants in the facepiece to contaminants found in the ambient atmosphere. This ratio is defined as a workplace protection factor (WPF).[(11)]

This study was jointly funded by the National Institute for Occupational Safety and Health (NIOSH) and the United States Fire Administration (USFA), which is part of the Federal Emergency Management Agency (FEMA). The cooperation of the administration and personnel of the fire departments in Pittsburgh, New York City, Phoenix, Boston, and Cincinnati, and the cooperation of the

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[a]In a companion paper by Campbell et al., 57 individual measurements were reported. It was later determined that 7 additional samples could be used in the subsequent analysis for this report.[(10)]

Pennsylvania Fire Training Academy in Lewistown, Pennsylvania were an integral part of the success of Project Firesmoke.

II. SCBA EFFECTIVENESS

SCBA are available in both pressure-demand and demand configurations. Pressure Demand-SCBA is the type recommended for fire fighting by NFPA,[9] OSHA,[3] and NIOSH.[2] These SCBA maintain a positive pressure by means of a regulator that provides a continual air pressure in the facepiece. This positive pressure is maintained by a spring-loaded exhalation valve. During inhalation, the regulator allows more air to flow to supply the increased demand. In contrast, the negative-pressure or demand SCBA regulator is activated by a valve that responds to the negative pressure exerted by the wearer's inhalation. Each class can be shown to be effective against the expected range of contaminants in fire fighting activities, but the limits of the effective range of each has been called into question by various studies.[12-23]

Pressure Demand-SCBA have been questioned as to their effectiveness in relation to maintaining positive pressure.

These SCBA may develop negative pressure inside the respirator facepiece — i.e., allow negative air pressure inside the facepiece of the respirator relative to the ambient atmospheric pressure. This is possible because of the high instantaneous air flows demanded by fire fighters working at high workrates. Such a negative pressure situation could allow airborne contaminants to enter the facepiece of the respirator and thereby increase the wearer's exposure to potentially toxic substances.

A study designed to evaluate carboxyhemoglobin levels (CoHb) in the blood of fire fighters concluded that demand SCBA were protective, but that the difference in mean CoHb levels (pre- and post-exposure to carbon monoxide) between fire fighters who used SCBAs and those who did not wear any respiratory protection was minimally significant.[24] In addition, a study designed to evaluate CoHb levels in the blood of fire fighters during controlled situations concluded that demand SCBA provided protection from the inhalation of carbon monoxide, if the respirators were properly worn, during work in burning or recently burned structures.[25]

Increased risk of overexposure, presumably created by intermittent SCBA usage, has been suggested by other researchers.[26-30] An important finding of this research [26,28,30] was that the continued use of demand SCBA offered protection from the inhalation of carbon monoxide, but its intermittent use provided as little protection as did non-use. This conclusion was based on the results of CoHb sampling. Measurements of serum thiocyanate made during the same study[26] yielded similar results.[26,28,30]

The authors of a study[29] designed to measure acute changes in the ventilatory capacity of fire fighters observed large decreases in FEV_1 (forced expiratory volume in 1 second) associated with the use of demand SCBA. A mean decrease of 0.21 liter in FEV_1 was reported for five occasions when SCBA were used. The reason for this decrement was postulated to be due to (1) donning of the SCBA after significant exposure to irritant smoke, (2) facepiece penetration, or (3) removal of the SCBA before it was safe to do so.

There have been several investigations which have attempted to quantify the amount of inboard leakage in a pressure-demand SCBA.

Most of these studies, called fit testing, have been laboratory based and consisted of a subject standing in a small transparent flexible plastic cylinder that extended to the waist. The use of this equipment precluded any meaningful attempt at duplicating the physical movements associated with fire fighting. The attenuation of the test gas, or aerosol, was measured by taking the ratio between the values for the "external" environment and the in-facepiece concentration. This ratio of concentration is called the fit factor. This can be differentiated from workplace protection factors (WPFs) in that fit factors are strictly a laboratory based measurement; WPFs are measures of protection afforded by respirators in the actual workplace. Fit factors tended to be very high for PD-SCBA. The fit factors which were measured were primarily based upon limits of detection of the monitoring equipment, rather than reflecting actual protection afforded to the fire fighter.[12-19,31]

III. AIRBORNE CONTAMINANTS

Interior structural fires are complex, multifactorial events involving a wide range of variables, including the combustible materials (manmade or natural), air flow, size of the enclosure, and other factors. Airborne contaminants produced as combustion products of structural fires can be similarly varied; numerous studies examined the substances produced by controlled fires, and several studies examined combustion products encountered by fire fighters during actual structural fire fighting.[32-34]

Hazardous airborne substances commonly found in structural fires include particulates such as asbestos and concrete dust and gases or vapors such as acrolein, nitric acid, and hydrofluoric acid. However, the most significant threat comes from toxic gases. Ammonia, aldehydes, sulfur dioxide, hydrogen chloride, and other toxic gases are commonly released during the pyrolysis or combustion of synthetic and natural substances.

Carbon monoxide is one of the principal gases generated by the combustion of carbon-containing fuels[35] and can be particularly hazardous in structural fires. Carbon monoxide can be present in large quantities in most fires and can be released in massive quantities within the relatively brief time span surrounding "flashover" — the transition from a growing fire to a fully developed fire in which all combustible items in the compartment are involved in fire[36].

Compartment fires produce carbon monoxide (CO) at a rate governed in part by the available oxygen concentration, the rate at which oxygen is supplied, and the mass burning rate. As mentioned previously, the maximum concentration of CO evolves just prior to flashover and for a few minutes post flashover. During this brief period, CO concentrations may exceed 10% or 100,000 ppm.[37,38] This exceeds the NIOSH short term exposure limit (STEL)[39] of 200 ppm by a factor of 500.

Carbon monoxide binds preferentially to the oxygen-carrying hemoglobin in the blood, forming carboxyhemoglobin (COHb), which cannot transport oxygen to the cells of the body. The resulting tissue hypoxia produces a series of symptoms and signs as a toxicological effect of the concentration of COHb. The amount of COHb formed is dependent, in part, upon the concentration of CO and the time of exposure.[24] Chronic inhalation of carbon monoxide has been measured or estimated by several researchers, who have associated it with numerous diseases.[40-52] Levy[53] and others[24,54] measured COHb levels in smoking and non-smoking fire fighters. COHb levels were approximately the same for the smoking fire fighters and their smoking controls. However, non-smoking fire fighters had a significantly increased COHb over their non-smoking controls.

IV. METHODS

The purpose of this project was to investigate the protective capabilities of PD-SCBA during actual fire fighting episodes. This was accomplished by collecting real-time in-mask pressure measurements and by collecting air samples both inside and outside the facepiece of individual fire fighters' SCBAs. Additionally, a pre-shift and post-exposure expired carbon monoxide breath sample was collected from each fire fighter. This was later changed to pre-event and post-event. An event was defined as the period of exposure to fire gases during normal fire fighting activity.

At its inception, the project was intended to evaluate positive-pressure SCBA by measuring the real-time concentration of a contaminant both inside and outside of the facepiece during actual fire fighting operations. Substantial effort was made to locate, develop or modify an instrument that could measure the expected range of contaminants — both the high concentrations of contaminants outside the facepiece and the very low concentration that would be expected inside the facepiece of a device that was worn correctly and functioning properly. Such an instrument would need to function accurately, for the measurement of carbon monoxide, in both the .1 ppm range and in the 1000 ppm range, or four orders of magnitude. It was apparent that this element of the project design — real-time monitoring with a direct reading instrument that was calibrated for these ranges — would present a challenge to develop. Various manufacturers of direct reading instruments were contacted to locate such a device, but no commercially available instruments with the requisite sensitivity could be located. It was necessary to consider modifications to existing instruments.

The manufacturers of a commercially available CO detector were willing to modify their device by detaching the integral sensor from the case; this allowed us to mount the sensor inside the facepiece of the SCBA for the in-mask sample, and outside of the facepiece for the ambient sample. This also allowed us to place the remainder of the device in a protected position on the SCBA and to connect the sensor to it by running a cable along either the high-pressure line or the breathing tube (dependent on the configuration of the brand of SCBA that we used). We mounted the sensors in the appropriate locations and proceeded with testing the devices to verify that we would be able to collect the data. The instrument that we had selected was intended to sound an alarm at a predetermined CO level. The wet-cell sensor generated a voltage that varied depending on the amount of CO present. We intended to measure that voltage after the units were calibrated to the ranges that we expected to measure. The major problem that was encountered in the development of this sampling method was the inability to measure the very low part per million (ppm) range that we expected to detect in the facepiece of the SCBA. The units, as commonly sold, were set to alarm at 50 ppm and could be user-adjusted to a range between 0 ppm and 300 ppm. The units that we had modified were to be accurate down to the tenth of a ppm range for the in-facepiece units and up to 5000 ppm range for the ambient units. After much laboratory testing and many attempts to get the low range units to function properly, we were forced to abandon this method due to the difficulty in collecting reliable data from inside the facepiece.

We then decided that a measurement of the pressure inside the facepiece would allow us to evaluate whether or not the SCBA was remaining positive in relationship to the ambient atmosphere. Again, there were no commercially available devices that we could modify to fit our needs. We contracted with an electrical engineer to develop pressure-sensing systems that would allow us to store up to 45 minutes of pressure data in a small battery-operated computer that he designed for this project. A description of the data logger developed for this project is provided below in the section titled "Data Logger."

We also decided to collect a gas sample from both inside and outside the facepiece to obtain a measure of the protection that the SCBA was providing. We realized that a "time weighted average" sample from inside the facepiece would not be meaningful if the facepiece was removed or dislodged even for a brief period of time.

Our sampling package consisted of two pumps to collect air samples, a miniature computer to log the pressure data, and a pressure transducer. Both of the pumps and the pressure transducer were connected to the facepiece by means of flexible silicon tubing.

The sampling package was to be mounted to the SCBA in a manner such that it would be out of the way of the operating valves and would minimally affect the fire fighters' performance of their duties. The package was also configured to be operable by a single switch that would simultaneously activate both pumps and start the pressure data logger.

A. DATA LOGGER

The data logger and software package designed for NIOSH Project Firesmoke is a portable unit that could be used to sample pressure and temperature in both laboratory and field-study situations. The data logging system consists of the data logger, battery pack, pressure and temperature transducers, and the software which enables the user to retrieve data from the logger unit using an IBM or IBM-compatible personal computer with a serial port.

These loggers have been incorporated into a system which monitors the fire fighter's face-mask pressure and the temperature to which the fire fighter and the breathing apparatus are exposed. The system also collects ambient and in-facemask air samples for later analysis.

Experimentation was needed to determine an in-facepiece pressure sensing probe location. It was noted that the pressure measurement varied with changes in probe location on the facepiece. We determined that an average value should be used rather than either the high or the low value because either extreme was more a function of test subject variability related to individual breathing patterns rather than the performance of the facepiece. On the test respirator with the belt-mounted regulator, we probed the respirator facepiece lens in numerous locations around its periphery and located a position near the eye that gave us reproducible average values. In the other brand of test respirator with a facepiece-mounted regulator we measured the values and found an appropriate location for the probe near the chin. The manufacturer of the respirator machined the facepiece-mounted regulator to accept the sampling probe. This location also provided the most protection for the pressure sampling line.

Operation of the Firesmoke sampling unit containing the pumps, data logger, pressure transducer, and batteries, was kept as simple as possible so that field use would not be unduly complex. The battery pack and data logger are connected to the wiring harness; the STANDBY/LOG switch is moved to the STANDBY position and the RESET switch is pressed to clear the memory. Sampling lines are connected to the SCBA, and the unit is now ready to start logging data. Moving the STANDBY/LOG switch to the LOG position activates the logger and simultaneously starts the sampling pumps. The data logging process can be halted and restarted as many times as the user wishes as long as enough data memory — volatile memory stored in RAM microchips — remains.

The logger is capable of collecting data, without overflowing memory, for approximately 53 minutes with a fresh battery pack installed. The pressure sensor is capable of measuring either differential or gauge pressure. Gauge pressure was selected for this project and in-mask pressure was measured with respect to atmospheric pressure. The pressure transducer outputs a voltage proportional to applied pressure.

B. FOURIER TRANSFORM INFRARED SPECTROPHOTOMETER

Fourier transform infrared spectrophotometry (FTIR) was selected as an appropriate analytic method for the measurement of contaminant gases in Project Firesmoke for a number of reasons. Briefly, FTIR is an analytical method to identify and quantify compounds by infrared spectroscopy, and in this sense is identical to spectrophotometry with grating- or filter-type IR spectrophotometers. The instrument configurations and capabilities are significantly different, however. FTIR instruments have vastly simplified optics, only one moving part (the interferometer), no slits or apertures, no gratings or prisms, and very powerful data processing and storage capabilities. All wavelengths are measured simultaneously, and a wavelength calibration laser is referenced on every scan. All of these factors contribute to very high sensitivity and favorable signal-to-noise ratio, very high spectral resolution (to separate compounds with overlapping spectra), and ease of identification of chemical species. FTIR instrument data, both interferograms and spectra, are easily stored, retrieved, and processed, and the data form is optimal for library searches for component identification in complex environmental mixtures. Identification and quantification are rapid with most samples; this rapid analysis is valuable in determining effective sampling strategies and procedures.

The greatest advantage of FTIR for Project Firesmoke was that many gases and vapors could be measured simultaneously, with minimal delay, by using two sampling pumps and collection bags which were taken to the NIOSH mobile laboratory at the fire stations. Samples were diluted, analyzed, and the data archived for subsequent analysis. Reactive species could be analyzed within a few minutes of collection. No concentration or preparation of the samples was needed for analysis. Sampling time adequacy could be estimated quickly and corrections made for the next sample. Data were stored as time-domain interferograms so that records could be re-transformed into spectra if necessary. Unexpected or unknown compounds could be identified and quantified (if they had IR spectra and interferences were minimal).

C. PROJECT ADMINISTRATION

The cities in which to conduct the project were chosen mutually by the U.S. Fire Administration and NIOSH. Selection criteria included expected number of fires, the willingness of fire department and other city officials to conduct research projects, and the ability of the fire department to provide a convenient and secure location for the NIOSH mobile laboratory. This mobile laboratory held the analytical instruments which were used in the analysis of the collected gas samples, and also contained equipment used for respirator fit testing and equipment used for calibration of the various sampling equipment that was used in the project.

Arrangements for conducting the project were made in each of the cities in advance of the actual project execution by visits to each of the sites by NIOSH personnel. Arrangements were made for electrical connections from the mobile laboratory and the delivery of both liquid and gaseous nitrogen, which was needed for the analytical instrument (FTIR). It was also necessary to meet with the fire department administrative personnel and union officials to define the study goals, to answer any questions that they might have had, and to secure final approval for conducting the project.

The random and unpredictable nature of fire occurrence, especially when considered in light of the limited time in which the Project Firesmoke crew and equipment would be available for taking measurements--generally 12 hours per day, for 2 weeks in each city--meant that there was a likelihood that some fires would occur during times when there was no coverage. There was a further likelihood that there might be no major fires reported during the period altogether; the probability of major fire occurrence during a specific 2-week testing period was small. It was reasonably safe to assume that there would be some fires of limited magnitude, and this was generally what was found.

To maximize the ability of Project Firesmoke personnel to respond to any fires which did occur, an attempt was made to categorize historical fire data by time of day of fire occurrence, with the intention of providing coverage during those times. This proved to be of limited utility in establishing periods of probable heaviest fire occurrence. While general trends could be established, the historical and anecdotal information indicated that "fires could happen at any time." No specific time-allocation of crew and equipment could be predicted to be most effective for the specific, limited periods in which Firesmoke personnel were available. Although, some fires were missed because there was no coverage, this did not prove to be significant. Continuous coverage during the same 2-week periods would not have significantly changed the overall findings.

V. RESULTS

Our investigation produced information which was significant in terms of understanding fire fighter exposures. However, only low levels of contaminants were found in each of the fires sampled, making measurement of protection impractical. Without measurable levels of contaminants it was impossible to make comparisons of concentrations inside and outside the facepiece. It was also impossible to determine if measured concentrations of contaminants were collected over the entire sampling period, or during the period in which the facepiece was removed. The data collected by the pressure-sensing device allowed us to determine for what percent of time the mask was removed or was manipulated in such a manner that faceseal integrity was compromised. Therefore a calculation of workplace protection factors would be valid only for those samples where the facepiece was worn for 100% of the sampling period.

An additional confounding factor in the measurement of the protection afforded by the PD-SCBA against CO was our inability to determine the test subjects' prior exposure to this gas. Smokers were not excluded from our sample population, and exposure to CO from smoking, fires fought prior to the commencement of our sampling, and other sources was impossible for us to control. The physiological process of flushing CO from the lung would be expected to produce higher levels of in-mask CO during some of the sampling periods. The pre-event CO measurement which we attempted to obtain would have allowed us to establish a baseline level. However, this baseline sampling proved to be difficult to control on a routine basis due to the dynamic nature of the emergency response. These questionable baseline samples were not used to correct in-mask CO measurements, and the resulting variability of these measurements precluded the calculation of WPF's for CO.

Project Firesmoke observational data is synopsized in Appendix I. This information is supplemental to the data logged by the automatic recording devices, and is included to characterize the kind of fires encountered, the contaminants measured, and the amount of time respirators were worn. Two general kinds of data were recovered from these field observations: nonquantified or observational data, and quantified data from the data logger. An analysis of each type of data is given in the sections following the synopses. Each is significant for an understanding of the factors contributing to fire fighter exposure to contaminants. The quantified information is amenable to statistical analysis, and a fairly detailed statistical evaluation of these data is provided in the Analysis section. Appendix II contains a data sheet on CO exposures and facepiece usage. Appendix III contains the protocol that was used in conducting Project Firesmoke.

A. OBSERVATIONAL INFORMATION

There are numerous instances of problems encountered while conducting sampling on fire fighters during fire fighting. The fire fighters who agreed to wear the specially modified SCBA had to contend with an additional weight burden of approximately 5.5 pounds, which certainly contributed to their overall thermal stress. There were also occasions when the sampling period was longer than anticipated and the sampling bag could not accommodate the additional volume of air, causing some sample bag failures. We wanted to collect the greatest possible volume of sample; however, the pump flowrate had to be set so that the bag would fill in the average time that we expected a fire to last. This is a problem with collecting a time-weighted average of samples under these circumstances.

It was discovered early in the methods development phase that commonly used laboratory sampling tubing would fail under the heat load in some of the training fires that we attended. We had some rather spectacular failures of sampling lines until we changed to silicon tubing. There were also other failures caused by lines being cut or pulled loose in both training fires and actual fires.

Battery life was another problem. The sampling units contained a number of batteries to power the data logger and the pumps. The pumps drew no current when they were not sampling, and the pump batteries were rechargeable and generally trouble free. The data logger batteries, on the other hand, did draw current and would discharge in the stand-by mode. We lost some of our samples when fires would occur late in the shift, when the batteries were partially discharged. This reduced voltage below the level needed to keep the data logger in calibration; therefore, the data could not be utilized. The problem was solved by changing the batteries midway through the shift.

The sampling pumps were mistakenly assumed to be internally checked, so that when not pumping there would not be a reverse flow from the sample bag back to the atmosphere. Some of our samples were lost in this manner until check valves were installed in the sampling line near the collection bag, to prevent this backflow.

B. ANALYSIS

Appendix II contains the data recorded in each of the 25 fires. One of the most significant of these data recordings was of the overall percentage of time that facepieces were worn (FP); we considered this an important variable in the equation of fire fighter safety, and subjected this variable to careful statistical analysis.

A frequency histogram of this variable is presented in Figure 1. From visual inspection of this histogram we see that the majority of the observations fell in the 80-100% category (44/64 = 68.8%) indicating that more than two-thirds of the time, the facepiece was worn for most of the fire. We can also see that this variable has a distribution which is skewed to the right, which indicates that non-parametric analysis would be appropriate for this variable. Also, in Figure 1 we see FP broken out by type of fire (FT). For this analysis we have separated the fires into different types which are identified as follows:

Fire Types

100	Rubbish - Outside
110	Building and contents-occupied
112	Unoccupied building
130	Passenger vehicle
140	Unoccupied building-fought from outside
150	Building and contents-unoccupied
160	Oil from generator[b]

Again, from visual inspection we can see indications where FT110 and FT160 have a similar distribution to the overall histogram. However, FT112 and FT140 seem to have a distribution centered more towards 0%, while FT100 and FT150 seem to have a distribution centered more towards 100%. Table 1 presents the mean, median, minimum, and maximum FP for all fire types observed.

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[b]Not a standard codable fire type but a category that we added to characterize a fire type that was unusual and where sampling was conducted.

FIGURE 1

Facepiece Use by Fire Type

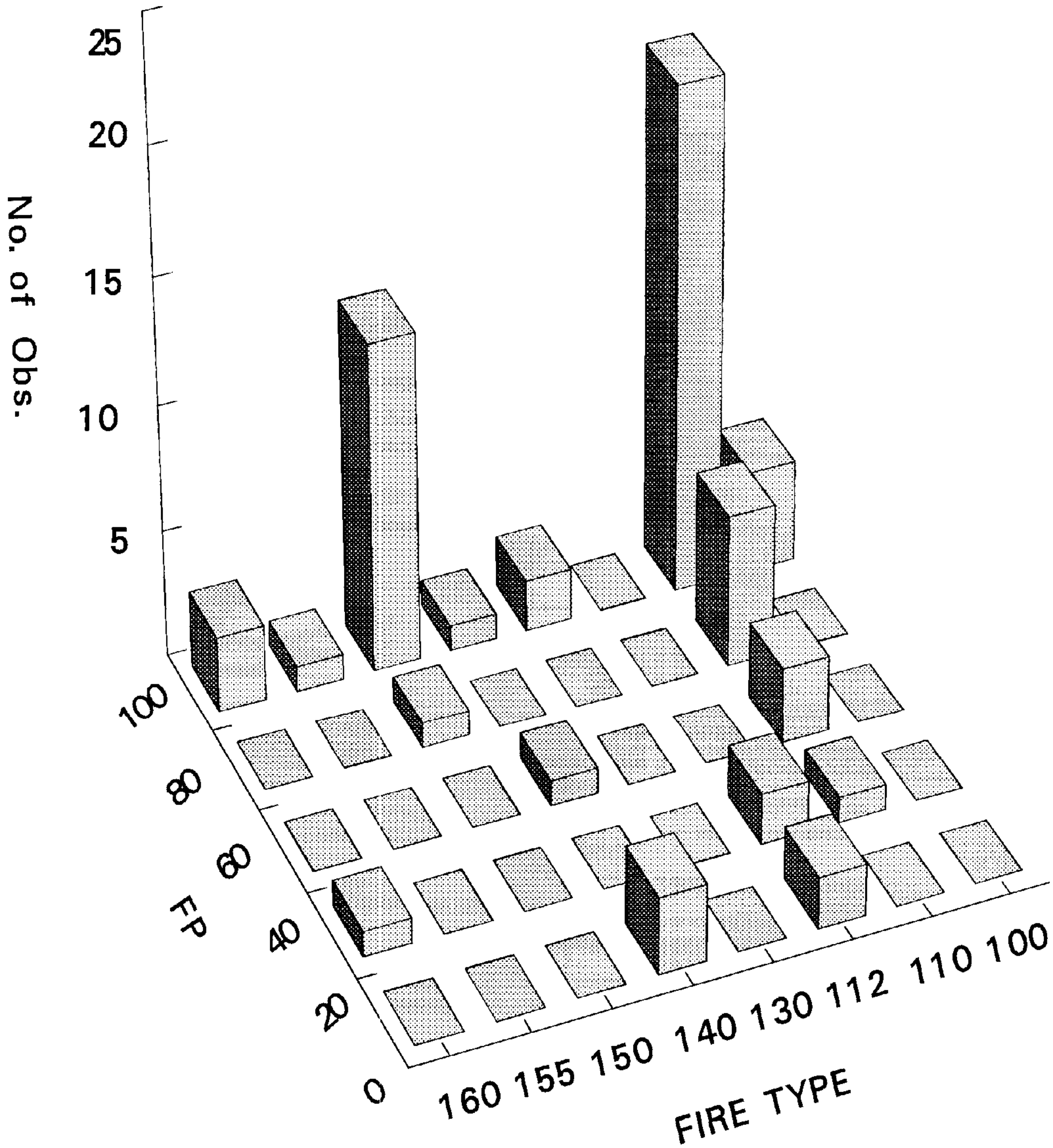

TABLE 1

Percent Facepiece Use by Fire Type

FIRE TYPE	NUMBER OBS.	MEAN FP	MEDIAN FP	MIN	MAX
130	2	100.0%	100.0%	100.0%	100.0%
100	4	99.6%	100.0%	98.3%	100.0%
150	14	96.2%	100.0%	79.5%	100.0%
155	1	93.6%	93.6%	93.6%	93.6%
110	30	83.3%	90.7%	39.6%	100.0%
160	4	82.1%	94.3%	39.8%	100.0%
140	5	30.4%	0.0%	0.0%	100.0%
112	4	14.2%	16.7%	0.0%	23.4%

To test the hypotheses that the Median FP is identical for each FT, a Kruskal-Wallis test for k-samples was used.[55] In a Kruskal-Wallis test, all data is ranked with the smallest value of FP receiving a rank of one, the next smallest a rank of two, etc. Equal values of FP are treated by averaging the ranks of all equal values. A null hypothesis of equivalent medians is

then assumed, and a p-value is calculated assuming the null hypothesis is true. All analyses, including the Kruskal-Wallis test, were performed in SAS with the NPAR1WAY procedure.[56]

Since it is very likely that values of FP are dependent within the same fire, mean values of FP were calculated for each fire and these mean values were used in the analysis. Fire types were then separated into two groups; FT100, FT130, FT155, and FT140 comprised a group of outside-type fires in which reduced exposures and lesser facepiece use would be anticipated; and FT110, FT112, and FT150 comprised a group of interior fires with higher potential for exposure and correspondingly increased expected facepiece use. The chi-square value for the hypothesis that these two groups (outside fires and inside fires) have the same FP or amount of facepiece wear was .09 (p-value = .7639), indicating that facepiece use was not different for these two groups. Facepiece use by fire types which involve buildings (FT110, FT112, FT140, FT150) were compared to each other under the null hypothesis that at least one of these four FTs differs from the other three. We found the chi-square value to be 10.184 (p-value = .0171). Table 2 presents the t-statistics with 17 degrees of freedom for the multiple comparison test between the respective FT and the corresponding p-value in parenthesis.

TABLE 2

T-Statistic for Multiple Comparison of Facepiece Use by Fire Type (p-values in parenthesis)

FT	110	140	112
150	1.516	3.456	3.143
	(0.1479)	(0.0030)	(0.0059)
110		2.620	2.358
		(0.0179)	(0.0306)
140			0.116
			(0.9084)

Under the null hypothesis of equivalent means, these four mean FTs determine which FT has high and low FP. From this table, we can conclude that SCBA were worn more often for FT110 and FT150 than for FT112 and FT140.

The next variable of interest is the ambient amount of carbon monoxide (AMBCO). Figure 2 presents the same analysis as Figure 1 but for AMBCO in place of FP. Again, we see an extremely skewed distribution indicating a more robust procedure, such as Kruskal-Wallis, should be used to determined if there is a significant difference in CO concentration by fire type. Table 3 presents the identical descriptive statistics as Table 1, but for AMBCO in place of FP.

FIGURE 2

Ambient Carbon Monoxide by Fire Type

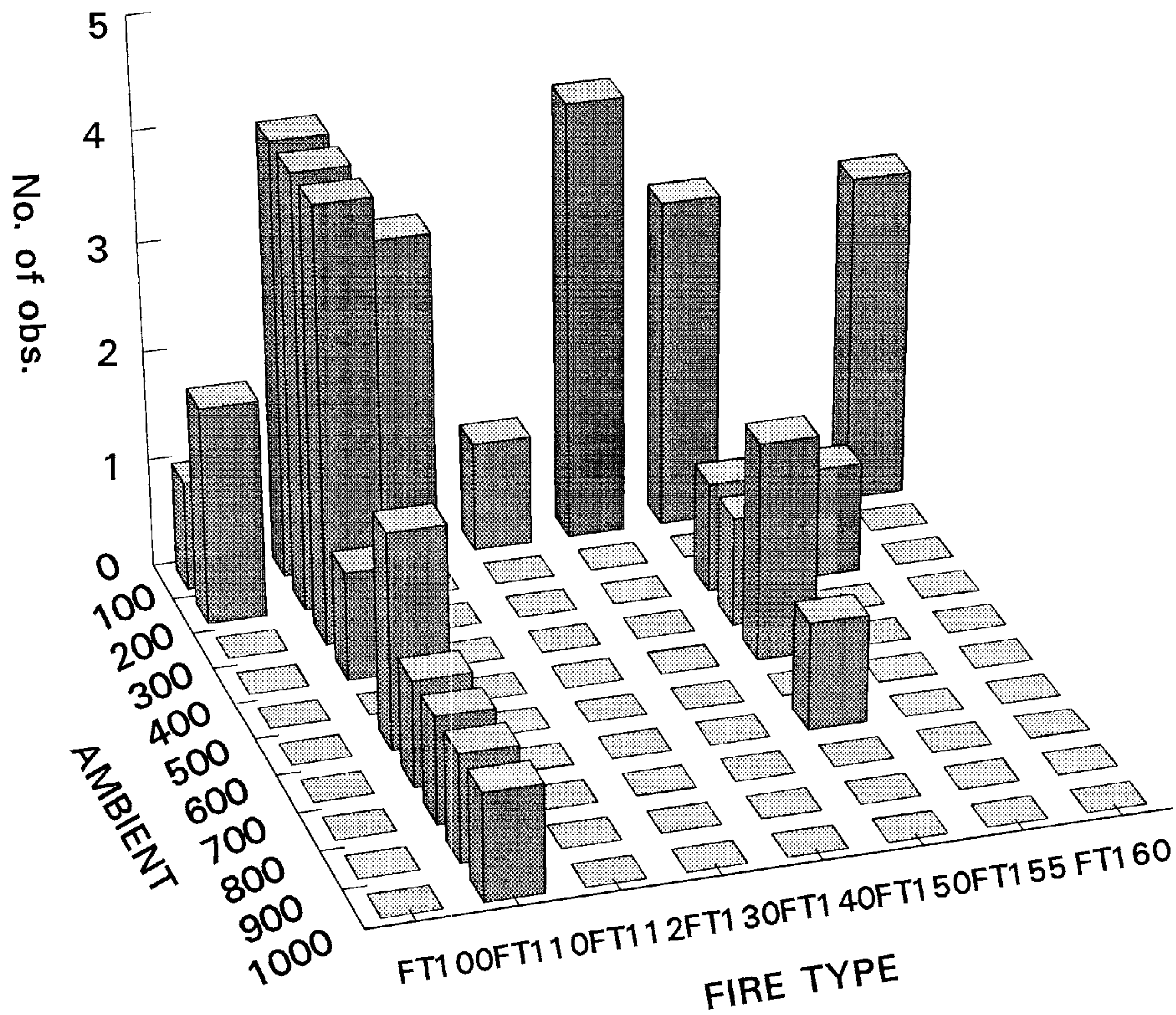

TABLE 3

Ambient Carbon Monoxide (ppm) by Fire Type

FIRE TYPE	NUMBER OBS.	MEAN AMB	MED. AMB	MIN	MAX
130	1	23.8	23.8	23.8	23.8
100	3	105.5	109.0	90.0	90.0
150	8	280.2	294.0	16.4	620.0
110	19	332.3	242.3	30.2	956.0
140	4	24.9	18.0	4.7	59.0
112	3	24.5	33.7	5.8	33.9
160	3	10.9	9.6	5.8	17.2
155	1	268.0	268.0	268.0	268.0

In each case a worse-case scenario was assumed so that the maximum AMBCO for each fire was used in the analysis. When the FTs are grouped, as they were for the FP analysis (FT100, FT130, FT155, and FT140 vs. FT110, FT112, and FT150), we find significant evidence that the fire fighters were exposed to more CO for FTs 110, 112, and 150 than for FTs 100, 130, 140, and 155

(Kruskal-Wallis χ^2 = 4.60, p-value = .0320). Again, all building-related FTs were compared, and we found that at least one of the four FTs differed from the other three in terms of exposure to CO (Kruskal-Wallis χ^2 = 8.2331, p-value = 0.0414). Table 4 presents multiple comparisons again with the t-statistic with 13 degrees of freedom and the corresponding p-values in parenthesis.

TABLE 4

T-Statistic for Multiple Comparison of Ambient CO by Fire Type (p-values in parenthesis)

FT	150	140	112
110	0.470	3.024	2.640
	(0.6464)	(0.0098)	(0.0204)
150		2.092	1.918
		(0.0566)	(0.0774)
140			0.047
			(0.9634)

Probably due to lack of sample size, there is only slim evidence indicating that FT150 had a higher CO exposure than FTs 112 and 140. We can, however, conclude that FT110 had higher CO exposure than FTs 112 and 140.

To address the question of how effective the SCBA are at reducing the exposure to CO and other contaminants, a correlation analysis was performed and factors were evaluated. There are 30 observations that have valid data for both AMBCO and carbon monoxide in the mask (MCO). Once again, due to the extreme skewness of this data, a non-parametric test, specifically Kendall's τ[55] is presented here. Kendall's τ counts the number of concordant and discordant pairs of data and then assumes equal probability of finding a discordant or concordant pair of data to calculate the p-value. Kendall's τ can range from -1 to +1, where -1 implies a perfect negative correlation, 0 implies no correlation, and +1 implies a perfect positive correlation. This procedure assumes a null hypothesis of no correlation to calculate p-values so that a small p-value implies a significant correlation. Results presented here were calculated using PROC CORR in SAS.[56] The value of τ for the variables FP and MCO is -0.2672 (p-value = .0174). This provides further evidence that the SCBA is effective at reducing the amount of carbon monoxide in real fire situations.

The last analysis performed is whether the amount of CO in the air affects the usage of the SCBA. Correlation analysis provides τ = .1051 (p-value = .3657) for the variables FP and AMBCO. This does not provide enough evidence to conclude that AMBCO and FP are correlated. This evidence, when combined with the evidence when the two groups of fires were compared with regard to FP and AMBCO, would indicate that although the different fires cause different exposures to CO, the SCBA are not used more often in instances where exposure levels of CO are high.

VI. DISCUSSION

Project Firesmoke provided new and important data on areas of concern for fire fighter safety and health; these data identified exposures related to contaminants, most notably carbon monoxide, and identified areas for future research. These areas include: instrument design, human factors related to facepiece design, and behavioral matters related to fire fighter activity in various types of fires. Certain data could not be obtained, basically because the fires that provided the test data were of short duration and contained low contaminant concentrations. There were some problems with equipment failure; overfilling of sample collection bags led to some burst bags and resulting sample loss, and premature failure of batteries led to some further sample loss. However, these problems remained a minor component of the project. The problem with the bags was corrected with the incorporation of a check valve into the sampling circuit design, and the problem with the batteries was corrected with the adoption of a more frequent battery replacement schedule.

The inadequate test data on contaminants other than carbon monoxide, however, obviated a major part of the project design; contaminants other than carbon monoxide were generally beneath the limits of detection, which meant that the effectiveness of the respirator could not be determined. Respirator effectiveness is determined as a ratio of the contaminants measured in the ambient air compared to the contaminants measured in the facepiece (WPF).[11] Neither in-mask nor ambient concentrations could be measured reproducibly in this study, because the sampling period did not encompass any major fires, and the fires that were studied did not release significant amounts of contaminants.

Future project designs might eliminate the effects of this element of chance associated with predefined sampling periods, by establishing reactive or "on call" sampling procedures with local fire departments to sample major fires or fires in settings likely to produce large amounts of contaminants. Many fire departments carry data sheets on exposures likely to be encountered in fires within their response area, so it should be a simple matter to predetermine which fire calls would represent appropriate sampling opportunities. Continuous, real-time automatic sampling sensors in every fire would be optimal, of course, but such equipment is not currently available.

A reactive local sampling procedure was not possible with Project Firesmoke, in that the project was national in scope. However, national data for preselected representative cities could be returned by establishing a standard protocol to be followed by state health departments or other researchers in these locations. The protocol contained in Appendix I could serve as the basis for such state-based and local-based data collection efforts.

The most notable information discovered about the protection afforded by respirators during fire fighting activity was that there was a significant human component in the overall equation of fire fighter protection. This human component was so significant as to suggest the general finding that respirator design was not the limiting factor in providing protection to fire fighters in the particular fires measured in this project. Respirators designed for fire fighting applications, in fact, were quite effective in reducing or eliminating contaminants in the air breathed by fire fighters, especially in comparison with the exposures that were recorded. Actual incidents of overbreathing leading to negative pressure excursions and the potential for ambient air to enter the facepieces were only recorded on four occasions, and each of the excursions lasted for such a brief period of time as to be insignificant.

By way of contrast, in 25 fires and 64 observations, 4 observations involved no use of respirators and only 22 involved facepiece use 100% of the time. The exposures in these cases were, for the most part, a function of patterns of respirator use; respirators were frequently removed during the course of fire fighting activity — to communicate or because they were uncomfortable — or were not worn in situations which represented minimal or acceptable levels of perceived risk to the fire fighters or situation commanders.

While some contaminant exposure levels could not be measured, it was possible to measure the level of exposure to carbon monoxide as a time weighted average during some of the fires. Fire fighter ambient atmosphere sampling routinely showed CO exposures which were in excess of the NIOSH STEL, although none were exposed to levels which would have been immediately dangerous to life or health (IDLH).

Direct observation and post-sample interviews indicated that human factors and the decision logic exercised by the fire fighters as to the perception of risk were the decisive factors in intermittent use and nonuse of respirators. It should be noted that a behavioral analysis component had not been built into the protocol of Project Firesmoke, so much of this information was anecdotal and observational. Future studies might focus on more rigorous analysis of this component of the study.

However, given these limitations, the clear indication was given that the most significant findings related to human factors was the inability to communicate effectively during a fire while wearing respirators. Facepieces were commonly removed to give directions or request assistance. Secondary reasons include the fact that facepieces were not comfortable to wear over extended periods, due to the normal range of human factors effects: heat, transpiration, etc.. The inability to see properly through facepieces seemed to be a factor for a small but significant number of fire fighters who wore spectacles. While all facepieces have built-in holders for spectacles, their utility is inferior to that of spectacles worn on the face. A number of fire fighters complained about the reduction in vision caused by scratches on the lens, and by the collection of soot and dust on the exterior of the lens surface. Some fire fighters complained of fogging inside the facepiece. This effect could be reduced by the use of nose cups. The number of objections directed toward existing facepiece design indicates that the human factors inherent in facepiece design will need increased attention if fire fighters are to have comfortable and effective respiratory protection.

Patterns of wear and usage, especially in relation to perceptions of risk, were also significant. Respirators are commonly not worn during the overhaul stage of fire fighting, at which point the fire has been extinguished and continued operations are oriented toward securing the area from further fires. Smoldering objects can continue to produce significant volumes of gas and particulates for some time, during which fire fighters are typically unprotected.

Fire fighters responded to certain classes of fires — exterior structural fires, most notably — without donning respirators, based on an unfounded perception of minimal or negligible risk of exposure. Finally, equipment design and the perception of risk contributed to nonuse of facemasks in a significant fashion — fire fighters felt that the limited amount of air in the tank should be conserved, because severe, immediately life-threatening conditions could develop without warning. At such times an adequate supply of compressed air would be critical for escape and survival. In effect, fire fighters had made the decision to trade off the perceived risk of exposure to substances presumed to be hazardous on continued exposure, against the perceived risk of unprotected exposure to immediately life-threatening conditions.

It appears that this matter — perceived risk — is an important area for further research. There have been extensive system-based studies on the physical and chemical effects of a fire on property and materials. However, there appears to have been no comparable research on risk and decision-based behavior of fire fighters in response to environmental variables during fire fighting activity. This is surprising, in that this appears to be an important variable in predicting exposure to an entire range of hazards.

Decision logic regarding respirator use also appears to be of significance on a departmental and interdepartmental scale. A notable example of this would be the variance in respirator use which was noted among fire departments in different cities. Project Firesmoke recorded completely different responses among fire departments in selected cities on the matter of respirator use. In certain cities respirator use was accepted by fire fighters, and enforcement of policies was strict and mandatory. In other cities respirator use was not as regular and policies were enforced unevenly. Increased education and increased enforcement of use policies would provide users with a better understanding of the need to use their respirator consistently during fire fighting activities which involve exposure to hazardous atmospheres.

Notable achievements of Project Firesmoke include the data previously cited, the development of the protocol as a basis for future studies, and the pioneering use of several pieces of equipment: the pressure data logger and the use of the FTIR as an analysis tool for fire fighting exposures.

The data logger was an essential part of the project design, and was responsible for determining whether facepieces maintained positive pressure during fire fighting activities, as well as for recording duration of use. The detailed description of the instrument provided in this paper could be used for developing similar instruments for future studies. Future instrument designs might incorporate a more advanced central processing unit, very large scale integrated circuits (VLSICs) and various technology developed for digital signal processing.

The initial concept for this project involved real-time, continuous monitoring for contaminants. At the time the instruments were developed for Firesmoke, this was not possible, given the state of readily available electronics. Future project designs should reconsider the goal of real-time continuous monitoring in light of the rapid advances in digital signal processing technology since the project began. Such a goal may be possible in the near future, using modifications of existing equipment.

The selection and use of the FTIR as an instrument for analyzing contaminant samples taken during fires showed great promise for future studies. Insufficient samples prevented the complete testing of the FTIR as a field tool; however the FTIR was successful in identifying, separating and quantifying most compounds in the laboratory; its dynamic range was excellent, and the dilution scheme could easily be changed to the appropriate range for different elements and compounds. This technique would be appropriate for future studies of fire fighters and other users of SCBA.

Another notable achievement of Project Firesmoke was the development of a pressure-based in-facepiece sensor. Similar designs might be incorporated into future respirator designs, providing instantaneous warning of loss of facepiece seal or negative pressure. Sensors for the continuous monitoring of contaminants might also be developed for future respirator designs.

Project Firesmoke also established related areas for further research, especially in human factors relative to respirator use and in the behavioral aspects of fire fighter decision making. The application of the public health model to the issue of respirator use would also seem to be of immediate utility. Selective education efforts in areas where respirator use is not readily accepted, would be of great benefit to fire fighters at risk. The development of passive instrumentation and controls is also an area that needs to be examined. Selective enforcement of existing policies may also need to be strengthened.

Many areas for research still exist. Fire fighters continue to be exposed to harmful concentrations of contaminants, and to suffer the health effects of these exposures. Concerted efforts by protective equipment manufacturers, researchers and associations of fire fighters can produce new equipment, procedures and methods to save the lives and health of these valued public servants.

VII. CONCLUSIONS

Carbon monoxide was present in measurable amounts, in levels which frequently exceeded the NIOSH STEL of 200 ppm, although not the IDLH limit of 1500 ppm. As would be expected, ambient levels of CO were higher in interior fires than in exterior fires; however, the use of facepieces was not significantly different in fighting the two different kinds of fires. This would suggest higher levels of exposure to CO in interior fire fighting than exterior fire fighting, although there were insufficient observations to confirm this.

In cases where respirators were worn 100% of the time during the fire and for which valid data were measured, respirators were generally effective in reducing the carbon monoxide levels measured in the facepiece. However, discontinuities in facepiece use invalidated a significant part of the data. The use of time-weighted average data necessarily excluded data for which there was non-continuous sampling; contaminants found in the facepiece could not be identified as to source — overbreathing of the respirator or removal of the facepiece.

The invalidation of some data sets was significant in itself; however, it indicated that there were discontinuities in the protection afforded by respirators, generally as a function of behavioral aspects in the use of the respirators. This appears to have been a much more significant matter than overbreathing or negative pressure excursions. These negative pressure excursions only occurred on 4 of 64 observations, for insignificant periods of time, while 100% respirator use was observed for only 22 of the 64 observations. This suggests that interrupted or non-use of the respirator was a much more significant matter in determining fire fighter pulmonary exposure than respirator performance in the observations obtained in Project Firesmoke. This is a matter for further study; it suggests that the human factors element in the design of respirators, and the human behavior aspects of wearing respirators, may be of equal or greater importance to the actual mechanical functioning of the respirator itself in providing worker protection. Future studies might be oriented toward the recording and analysis of fire fighter behavior during actual fires; the identification and quantification of periods of respirator removal, and the correlation with observed behaviors during this time. Such studies might yield significant information for identifying high risk situations.

Based on anecdotal and observational information, the most significant matter in regard to behavioral aspects of facepiece use would appear to be the design of the facepiece, specifically in regard to its effect on communication. Fire fighters commonly removed their masks to communicate, whether this meant talking to fire fighters working alongside them, or shouting to fire fighters some distance away. If facepieces prevent normal communication, it is to be expected that they might be removed when communication was necessary. Equipment design research should be conducted to develop or improve acoustically transparent materials, or other engineering modifications which would allow communication by some other means — built in radios, electronic amplification, or some other method.

Facepieces should be developed which would also be lightweight and comfortable to wear for extended periods. Observational and anecdotal information indicated that masks were frequently regarded as too hot or cumbersome for continued use, except under extreme conditions. Fire fighters commonly removed their masks as soon as it was possible to do so; a valuable area for further research would be the design elements which make facepieces comfortable or uncomfortable to wear during a fire.

The use of FTIR analytic methods also holds significant promise for future studies. Data from preliminary laboratory studies, which were conducted in conjunction with the manufacturer's tests, indicated that the FTIR had the requisite sensitivity and functional capacity to perform the kind of testing required for Project Firesmoke. The majority of the compounds which were tested could be readily identified, separated and quantified. Low levels of contaminants precluded the extensive use of the FTIR in the field. However, the proven sensitivity of FTIR, as well as its freedom from noise, its high resolution and its ease of identification of compounds strongly suggests that it would be an appropriate instrument for further studies of airborne contaminants.

The data loggers utility was well established by Project Firesmoke. Continuous pressure monitoring revealed that PD-SCBA respirators were generally quite effective in maintaining facepiece pressure integrity. Negative pressure was recorded for insignificantly brief periods of time, in four observations. The data logger was responsible for identifying a significant finding, that removal of facepieces was a common practice, even under hazardous circumstances. Overall, the data logger worked very well; there were no failures of equipment and no lost data due to its use after battery "life" was accurately determined.

Other matters for further study include the development of real-time sampling units which would record contaminant exposures on a continuous basis, rather than taking the time-weighted average of all exposures during a particular period. The replication of this experiment, using on-call procedures for sampling fires with the potential for substantial release of contaminants, would also be valuable for further research. Instrument design would constitute a third area; the potential for the application of advanced technology to the methods and procedures developed in Project Firesmoke would appear to be very great. Ultimately, advanced sensors which would be capable of detecting all contaminants in a fire, and providing the fire fighter with a warning would be the goal of research based on this program.

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IX. APPENDIX I

The field studies for Project Firesmoke were conducted in five U.S. cities — Pittsburgh, New York, Phoenix, Boston, and Cincinnati — between July 1988 and June 1989. The circumstances and conditions under which observations were taken are noted in the following synopses.

Pittsburgh:

The Pittsburgh study was conducted July 25 - 29, 1988. The survey team was assigned to a four-person manpower squad from Engine Company 33; each member of the manpower squad agreed to wear the modified SCBA during the study. The duties of the manpower squad are similar to those of other fire fighters in the city. In addition, the manpower squad is often used for rescue or to relieve other fire fighters. For the purposes of the study, it was arranged that a four-person manpower squad would be involved in front line fire fighting and their normal response area would be increased to include most of the city. This was done to optimize the likelihood of their being involved in a fire where sampling could take place.

Fire #1

No fires occurred on the first three days of the study. On the last night, a residential structural fire occurred where we were able to collect samples from three of the modified SCBA units.

At the fire scene, the fire fighters donned their SCBA facepieces on the street before entering the fire. The facepieces were worn continuously during the fire fighting episode and were only removed when the fire fighters were clear of the building. Because of these good work practices or respirator use it was unlikely that we would detect contaminants in the in-mask air sample and that, in fact, was what was found.

The in-mask pressure samples confirmed that the SCBA facepieces were worn continuously during the fire fighting episode. The in-mask pressure samples also showed that two of the units experienced a momentary negative pressure excursion. However, the negative pressure excursion did not result in any detectable inward leakage of contaminants from the fire environment.

New York:

The New York City (NYC) field study was conducted November 14 - 22, 1988. The survey team was assigned to a station house in Harlem which housed Engine Company 35 and Ladder Company 14. Fire fighters from both companies participated in the study. Samples were collected for six fires during the New York study.

<u>Fire #2:</u>

The first NYC fire occurred on the first day of the study. It was a structural fire and was fought from the inside of the building. Samples were collected from the SCBA units worn by the nozzleman, the backup man, and two NIOSH personnel. The in-mask pressure data shows that neither fire fighter wore the SCBA facepiece continuously while engaged in fire fighting activities. The NIOSH staff also did not wear the facepiece continuously during the sampling period. The data shows that the nozzleman wore the facepiece 65% of the time and the backup man wore the facepiece 40% of the time. The pressure data shows that the unit worn by the backup man experienced a momentary negative pressure excursion. Contaminants at the fireground evolve at different rates depending on the stage of the fire. A comparison of the ambient and in-mask air samples show that some contaminants evolved while the fire fighters were wearing the facepiece, while others evolved while they were not wearing the facepiece. For example, the ambient air sample for the nozzleman shows a Time Weighted Average (TWA) concentration of 807 ppm of carbon monoxide, while the in-mask sample shows a TWA of 17 ppm. This suggests that the greatest potential for exposure to carbon monoxide occurred while the nozzleman was wearing the facepiece. On the other hand, the ambient TWA for benzene was 22 ppm and the in-mask TWA was 21 ppm. This would suggest that the nozzleman's exposure to benzene during this fire occurred while he was not wearing his facepiece, and that benzene evolved for only the portion of the same sampling period that coincided with the fire fighter's non-use of the SCBA.

<u>Fire #3:</u>

The second NYC fire occurred in a vacant, previously burned building. SCBA units modified by NIOSH were worn by two forcible entry fire fighters. One fire fighter donned his facepiece briefly during the fire. The other fire fighter did not wear his facepiece at any time during the sampling period. No negative pressure excursion was recorded for the unit in which the facepiece was worn. The ambient air samples from both units showed a carbon monoxide concentration of 34 ppm during the sampling period.

Fire #4

The third NYC fire occurred in a vacant seven story tenement building. This building had been previously burned and was abandoned. The fire was fought from the outside of the building and none of the fire fighters wore SCBA facepieces while fighting the fire. An ambient air sample was collected from one SCBA unit. The sample showed a TWA of 17 ppm for carbon monoxide. Small or trace amounts of other fire contaminants were also detected. No in-mask air samples were collected.

Fire #5

The fourth NYC fire occurred in a basement of a tenement building. The basement was used for church meetings and a fire had started in cardboard egg cartons which had been affixed to the walls and ceiling to act as sound suppressors. In-mask pressure data was collected for four units. The units were worn by the backup man, two forcible entry men, and one NIOSH staff person. The fire fighters donned the facepiece before entering the basement; however, they both removed the facepiece before they left the building. The pressure data indicates that the facepieces worn by the fire fighters were worn for about 90% of the sampling period. No negative pressure excursions occurred. Ambient and in-mask air samples were collected from one of the units. The air sample results for one SCBA unit show a TWA for carbon monoxide of 531 ppm for the ambient sample and 105 ppm for the in-mask sample. Measurable amounts of other contaminants also were found in both the ambient and in-mask samples. These results suggest that the fire fighters removed the facepieces prematurely.

Fire #6

The fifth NYC fire occurred in a vacant, previously burned building. The fire was brief in duration. The in-mask pressure data collected for two units shows that the facepieces were worn about 23% of the time. Ambient and in-mask air samples were not collected.

Fire #7

The sixth NYC fire was a vacant multistory building. The fire was fought from the outside. One modified SCBA was worn by a forcible entry fire fighter, but the facepiece was not worn at any time during the sampling period. No contaminants were found in the ambient air sample.

Phoenix:

The Phoenix field study was conducted February 14 - 21, 1989. The survey team chose to work out of two different stations to maximize the number of fires that they could attend. The study participants were assigned to Engine Company 10 and Ladder Company 24. Samples were collected for six fires during the Phoenix study.

Fire #8

The first Phoenix fire occurred in a vacant house. The fire had been extinguished and most of the smoke had been cleared by the time the fire fighters wearing our sampling equipment arrived. The modified SCBA units were worn by two fire fighters and one NIOSH staff person. The fire fighters donned their facepieces and entered the house for a short period of time. The in-mask pressure data shows that the fire fighters wore the facepiece continuously while inside the house with no negative pressure excursions. No ambient air samples were collected. No fire contaminants were detected in the in-mask air samples.

Fire #9

The second Phoenix fire also occurred in a vacant house. There was very little smoke and no need for fire fighting. The modified SCBA units were worn by two fire fighters and two NIOSH staff people. The fire fighters donned their facepieces and entered the house for a short period of time. The facepieces were worn continuously while in the house with no negative pressure excursions. The ambient air samples showed TWAs of 57 ppm, 28 ppm, and 16 ppm carbon monoxide. No fire contaminants were detected in the in-mask air samples.

Fire #10

The third Phoenix fire occurred in a trailer classroom behind a school. In-mask pressure data was collected for one unit. The fire fighter wore the facepiece 85% of the time with no negative pressure excursion. The in-mask air sample showed a TWA of 20 ppm of carbon monoxide and small amounts of other contaminants. No ambient air sample was collected.

Fire #11

The fourth Phoenix fire occurred in an occupied second floor apartment. Samples were collected from one SCBA unit worn by a fire fighter and two units worn by NIOSH personnel. The in-mask pressure data shows the facepieces for all three units were worn 100% of the sampling time with no negative pressure excursions. Ambient air samples collected for two units showed TWAs of 287 ppm and 250 ppm carbon monoxide. No contaminants were detected in the in-mask air sample.

Fire #12

The fifth Phoenix fire occurred in a vacant condominium complex and involved four apartments. Pressure data was collected from two SCBA units worn by the fire fighters and two units worn by NIOSH personnel. The in-mask pressure data indicates two facepieces worn by the NIOSH personnel were worn 100% of the sampling period with no negative pressure excursions. The facepieces of the other two units were worn by the fire fighters 99% and 80% of the sampling period. One unit experienced a momentary negative pressure excursion. The ambient air sample for the units with the facepieces worn 100% of the time showed TWAs of 498 ppm and 620 ppm carbon monoxide. No fire contaminants were detected in the in-mask air samples. No air samples were collected for the other two units.

Fire #13

The sixth Phoenix fire was in a wooden shed. Pressure data was collected from one modified SCBA. The facepiece was worn 83% of the sampling period. No negative pressure excursions were recorded. No air samples were collected.

Boston:

The Boston field study was conducted April 25 - May 2, 1989. The city of Boston has two rescue units; each responds to approximately one-half of the city. The rescue units respond to all types of emergencies, including fires. To optimize the number of fires where we could collect samples, the survey team worked with both rescue units and Engine Company 10 which shares quarters with Rescue 1. Samples were collected from 12 fires during the Boston study.

Fire# 14

The first Boston fire was an automobile fire. Data was collected from two SCBA units. The fire fighters donned the facepieces before approaching the fire. The in-mask pressure data show that the facepieces were worn continuously with no negative pressure excursions. One ambient air sample showed a TWA of 24 ppm carbon monoxide. No fire contaminants were detected in the in-mask air samples.

Fire #15

The second Boston fire occurred in a partially vacant four-story tenement building. The fire was located on the first three floors. Three samples were collected — one from one unit and two from another unit. The in-mask pressure data shows that the facepiece was worn 100% of the sampling period for one sample and 56% and 65% of the sampling period for the other two samples. No negative pressure excursions were recorded. The air samples collected from the unit where the facepiece was worn 56% of the sampling period showed a TWA of 129 ppm of carbon monoxide for the in-mask sample and 538 ppm for the ambient air sample. The ambient air sample for the unit where the facepiece was worn 100% of the sampling period showed a TWA of 767 ppm carbon monoxide. No in-mask air sample was collected for this unit. No air samples were collected for the unit where the facepiece was worn for 65% of the sampling period.

Fire #16

The third Boston fire occurred in a single family home that was being remodelled. The home was unoccupied. Samples were collected for two SCBA units. The in-mask pressure data shows that the facepieces were worn 91% and 95% of the sampling period. No negative pressure excursions were recorded. The air samples collected for the unit where the facepiece was worn 91% of the sampling period showed a TWA for carbon monoxide of 435 ppm in the ambient sample and 92 ppm in the in-mask air sample. This fire fighter is a cigarette smoker and showed a pre-fire exhaled breath concentration of 42 ppm carbon monoxide. Part of his exposure to carbon monoxide is believed to have occurred from the fire when he was not wearing his mask, while most of the remaining exposure can probably be attributed to his cigarette smoking. Small amounts of other fire contaminants were also detected in the in-mask and ambient air samples.

Fire #17

The fourth Boston fire occurred in a power plant when oil that was leaking from a generator caught fire. Pressure data was collected from four SCBA units. For two units, the facepiece was worn continuously during the sampling period. The facepieces on the other units were worn 40% and 89% of the sampling period. No negative pressure excursions were recorded. No contaminants were detected in the air samples.

Fire #18

The fifth Boston fire occurred when a fire in an oil furnace spread to the first floor of a two-story single family dwelling. Pressure data were collected from two SCBA units. For one unit, the facepiece was worn continuously during the sampling period. The facepiece of the other unit was worn about 52% of the sampling period. No negative pressure excursions were recorded. The ambient air samples showed a TWA of 140 ppm and 182 ppm carbon monoxide. No fire contaminants were detected in the in-mask samples of either unit.

Fire #19

The sixth Boston fire occurred on the top floor of a rooming house. Samples were collected from four SCBA units. The in-mask pressure data shows that the facepiece of one unit was worn 100% of the sampling period, while the other three were worn 89%, 99%, and 97% of the time. No negative pressure excursions were recorded. Two ambient air samples were collected and showed TWAs of 312 ppm and 50 ppm carbon monoxide. No fire contaminants were detected in the in-mask air samples of any unit.

Fire #20

The seventh Boston fire occurred in a fifth story apartment. The structure was not involved in the fire, only the contents. Pressure data were collected from two SCBA units. For one unit the facepiece was worn continuously during the sampling period. The other facepiece was worn 91% of the sampling period. No air samples were collected for this fire.

Fire #21

The eighth Boston fire was a grass fire. Pressure data was collected from one SCBA unit. The facepiece was worn 94% of the sampling period. No negative pressure excursions were detected. The ambient air sample showed a TWA of 268 ppm carbon monoxide. No in-mask air sample was collected.

Fire #22

The ninth Boston fire occurred on the third floor of a brick tenement building. Samples were collected from two SCBA units. The in-mask pressure data shows that the facepiece of one unit was worn 84% of the time and the other was worn 52% of the time. No negative pressure excursions were recorded. One ambient air sample showed a TWA of 168 ppm carbon monoxide. No fire contaminants were found in the in-mask air samples of either unit.

Fire #23

The tenth Boston fire occurred in a three-story brick tenement building. Samples were collected from two SCBA units. The in-mask pressure data shows the facepieces were worn 70% and 86% of the sampling period. No negative pressure excursions were recorded. One ambient air sample showed a TWA of 30 ppm carbon monoxide. No fire contaminants were detected in the in-mask air samples.

Fire #24

The eleventh Boston fire occurred in an abandoned building. This three alarm fire was fought from outside the building. Samples were collected from two SCBA units. The in-mask pressure data shows that one unit was worn 100% of the sampling period and the other was worn 52% of the sampling period. No negative pressure excursions were recorded for either unit. The ambient air samples showed TWAs of 60 ppm and 17 ppm carbon monoxide. No fire contaminants were detected in the in-mask sample of either unit.

Fire #25

The twelfth Boston fire was rubbish burning between two buildings. Pressure data were collected from four SCBA units. Three of the facepieces were worn continuously during the sampling period. The other facepiece was worn 98% of the sampling period. Ambient air samples collected from three of the units showed TWAs of 118 ppm, 109 ppm, and 90 ppm carbon monoxide. No contaminants were detected in the in-mask air samples of any unit.

Cincinnati:

The fifth city selected for the Project Firesmoke field studies was Cincinnati; the survey was conducted June 15 -

23, 1989. As was done in Boston and Phoenix, the survey team elected to work from two stations to maximize the number of fires they could attend. During this time, no fires occurred in the city for which we could obtain samples.

X. APPENDIX II

Percent Facepiece Use and CO Exposure

	FIRE TYPE	TIME (sec)	FP %	AMBIENT (ppm)	IN-MASK* (ppm)
Pittsburgh					
Fire #1					
Sample 1	110	738	93.5	243	N/D
Sample 2	110	984	99.2	N/A	N/D
Sample 3	110	1122	91.6	956	N/D
New York					
Fire #2					
Sample 4	110	1140	73.9	111	N/A
Sample 5	110	1116	69.8	241	1
Sample 6	110	1362	64.7	807	17
Sample 7	110	1656	39.6	N/A	53
Fire #3					
Sample 8	112	1680	0	34	27
Sample 9	112	642	11.2	34	17
Fire #4					
Sample 10	140	612	0	N/A	N/A
Sample 11	140	1206	0	19	N/A
Fire #5					
Sample 12	110	720	65.1	614	N/A
Sample 13	110	936	90.7	N/A	N/A
Sample 14	110	924	91.3	531	105
Sample 15	110	272	95.6	44	N/A
Fire #6					
Sample 16	112	624	23.4	N/A	N/A
Sample 17	112	612	22.2	6	4
Fire #7					
Sample 18	140	498	0	5	2

***In-mask sampling results were not corrected for smoking or for prior exposure**

Phoenix

	FIRE TYPE	TIME (sec)	FP %	AMBIENT (ppm)	IN-MASK* (ppm)
Fire #8					
Sample 19	150	306	100	N/A	N/D
Sample 20	150	462	100	N/A	N/A
Sample 21	150	282	98.9	N/A	N/D
Fire #9					
Sample 22	150	630	100	28	N/D
Sample 23	150	252	100	N/A	3
Sample 24	150	618	100	17	N/A
Sample 25	150	420	100	57	N/D
Fire #10					
Sample 26	110	654	85.5	N/A	20
Fire #11					
Sample 27	110	720	100	287	N/D
Sample 28	110	426	100	N/A	N/D
Sample 29	110	720	100	250	N/A
Fire #12					
Sample 30	150	768	98.9	N/A	N/A
Sample 31	150	918	100	620	4
Sample 32	150	1380	79.5	N/A	N/A
Sample 33	150	918	100	498	9
Fire #13					
Sample 34	150	384	83.1	N/A	N/D

Boston

	FIRE TYPE	TIME (sec)	FP %	AMBIENT (ppm)	IN-MASK* (ppm)
Fire #14					
Sample 35	130	588	100	N/A	N/A
Sample 36	130	708	100	24	2
Fire #15					
Sample 37	110	1356	56.2	538	129
Sample 38	110	438	100	767	N/A
Sample 39	110	1992	65.4	N/A	N/A
Fire #16					
Sample 40	150	756	91.1	435	92
Sample 41	150	459	95	276	N/A

	FIRE TYPE	TIME (sec)	FP %	AMBIENT (ppm)	IN-MASK* (ppm)
Fire #17					
Sample 42	160	246	88.6	N/A	8
Sample 43	160	1086	39.8	6	13
Sample 44	160	744	100	18	6
Sample 45	160	786	100	10	10
Fire #18					
Sample 46	110	168	100	140	20
Sample 47	110	360	51.7	182	6
Fire #19					
Sample 48	110	612	98.5	N/A	4
Sample 49	110	690	88.3	312	9
Sample 50	110	1152	100	50	9
Sample 51	110	936	96.8	N/A	17
Fire #20					
Sample 52	110	330	90.6	N/A	N/A
Sample 53	110	180	100	N/A	15
Fire #21					
Sample 54	155	390	93.6	268	N/A
Fire #22					
Sample 55	110	816	51.6	46	7
Sample 56	110	510	83.1	168	11
Fire #23					
Sample 57	110	654	85.8	N/A	N/A
Sample 58	110	642	69.9	31	4
Fire #24					
Sample 59	140	342	100	59	1
Sample 60	140	684	52.1	18	6
Fire #25					
Sample 61	100	474	98.3	118	N/A
Sample 62	100	462	100	N/A	1
Sample 63	100	276	100	90	N/D
Sample 64	100	300	100	109	N/A

XI. APPENDIX III

This protocol was used in conducting Project Firesmoke and is included for information on how we attempted to conduct the project. It was not possible in some instances to adhere completely to all aspects of the protocol. The appendices to this protocol are not included.

PROTOCOL

This section contains a detailed description of 1) the sampling strategy, 2) laboratory testing of SCBA, 3) sampling methods, and 4) field activities involved in Project Firesmoke. The project will be conducted in the following order:

1. SCBA units received from manufacturers.
2. SCBA units modified with pressure sampling and air sampling facepiece probes by FIS/IPRB/DSR/NIOSH.
3. Laboratory testing of SCBA units by Certification Branch, DSR, NIOSH.
4. Field Study
    a. Project described to fire fighters
    b. Signing of consent document
    c. Quantitative fit testing

d. Pre-shift exhaled breath sample collection and questionnaire

e. Measurement of CO in SCBA breathing air

f. Fire episode — pressure measurement, air sampling

g. Post fire episode exhaled breath sample collection

h. Post fire episode questionnaire

SAMPLING STRATEGY

Field Study Site Selection/Sample Size

Field studies will be conducted in five major cities which have large fire departments. These cities are Pittsburgh, New York City, Phoenix, Cincinnati, and Boston. One of the considerations in selecting these cities is that in the two-week period of the study there should be enough fire fighting activity to gather a required number of samples. To have statistically significant data, a minimum of 275 samples of each of the different types of data (environmental data, facepiece pressure data, temperature data, etc.) will be collected. The sample size is based on a 95% confidence interval of the assigned protection factor value of a pressure-demand SCBA, 10,000. After the collection of 30 sample sets the protection factors and standard deviation will be calculated. If these values differ greatly from the estimated values used to compute the sample size then recalculation of sample size will be performed using these revised estimates. The sample size equation derivations and calculations are contained in Appendix II.

NIOSH will stay at a survey site until 30 samples are collected. A lower limit will be set at 0 samples in three days and an upper limit of 100 samples in ten to twelve days.

SCBA Selection

Participants will wear SCBA that has been modified by DSR/NIOSH to accommodate the sampling devices. The SCBA will be identical to that the fire fighter normally wears, except for the modifications. Using SCBA the fire fighter is already familiar with and has confidence in will minimize training needs.

Fire Fighter Selection

All fire fighters on the unit to which NIOSH is assigned, (who have granted consent) and who wear SCBA while performing their job, will be sampled. In New York City (NYC) for example, there are four people, including the driver, on a ladder truck and there are three people including the driver on the pumper truck. We would expect to sample three to four SCBA-wearing fire fighters at each fire episode in the above example. In other cities this may differ. The maximum number of personal samples to be collected at one time at a fire episode will be five. This number is based on the number of fire fighters who will typically be wearing SCBA, the complexity of taking this type of sample at a fireground, the number of industrial hygienists available to monitor the fire fighter, and the availability/cost of the equipment and analysis.

Shift Sampling

An attempt will be made to optimize the number of people that NIOSH has on a shift by working at a time when fires are more likely to occur. For example, in NYC most fires occur between the hours of 4 p.m. and 2 a.m. Therefore, we will try to work those hours. These times may differ at the other study sites.

Laboratory Testing of SCBA

Prior to field testing, all SCBA that will be used by fire fighters will be inspected by personnel from the Certification Branch, Division of Safety Research (DSR), NIOSH. Laboratory performance testing will be performed as specified in 30 CFR Part 11. Only SCBA units which pass these tests will be used in the field study. Records of the laboratory testing will be maintained by the DSR Project Officer.

Sampling Methods

Sampling Apparatus Requirements and Design

Fire fighters have indicated that the sampling apparatus should be lightweight, of minimum bulk, and self-contained. The sampler must also be rugged and insensitive to the extreme environmental conditions to which it may be exposed. Sampling apparatus location was also an important consideration. The most appropriate location was determined to be the SCBA harness or backframe. The sampling apparatus would need to be mounted in such a way as to be of minimum hindrance to the fire fighter when he was (1) putting on the SCBA and (2) changing SCBA bottles. An operating time of 45 minutes for the sampling device was required. This is based on an over-estimation of the time a 30-minute SCBA could be continuously used and on the estimated duration of most fires.

Respirator In-facepiece Pressure Monitoring

To measure and collect SCBA in-facepiece respirator pressures, a dynamic pressure sensor and portable data logging unit were devised. The pressure sensor will be located in a lightweight metal case mounted to the harness. The sensor measures pressures in the range of ±5 inches of water. One pressure port is left open to ambient atmosphere while the other port is connected by silicone tubing to the inside of the respirator facepiece. The pressure sensor connected in this manner measures a differential pressure or the pressure inside the respirator facepiece. The case containing the pressure sensor will be insulated to insure that the temperatures inside the case do not exceed the operating range of the sensor. Pressure data will be collected real-time by a portable data logging unit which was constructed for this specific application. The unit is a self-contained unit which is powered by a 12 volt battery supply. Negative-pressure excursions inside the SCBA facepiece have been measured, in the laboratory, to last as short as 50 milliseconds[1]. Therefore, the data logging unit was designed to record pressure samples every 50 milliseconds. The accuracy of the pressure sensor is ±.02 inches of water.

The data from the data logging unit is transferred to an IBM PC compatible lap top computer. The lap top computer is uniquely suited for field applications since it is extremely mobile.

Software specifically designed for the project converts the binary data transferred from the logger via a 15 pin serial connection into readable form. The software allows the data to be stored on a 3-1/2" disk in file format for later analysis and also to be sent to a printer so that a hard copy of the data can be obtained. The data is output in line format which presents a pressure measurement every 50 milliseconds and also in a graph which presents pressure inside the respirator facepiece versus time.

Temperature Monitoring

Temperature exposure data will also be measured during each fire fighting episode. This data will be collected by a Type J thermocouple assembly and recorded by the data logger once every 30 seconds. The thermocouple probe, which has a measurement range of +32 to 1382°F, will be mounted on the outside of the case containing the pressure sensor.

Air Sampling for WPF Determination

To measure the fire fighter's exposures, two 3-liter "bag" samples will be collected for each SCBA wearer on the fire fighting team. One sample will be an in-facepiece sample. This sample will be collected through a probe in the SCBA facepiece. Where practical, the sampling probe location will be based on latest NIOSH research to minimize the amount of sampling bias(2). The tubing will be connected to the inlet port of a low flow air sampling pump which will draw air at a rate of 100 cc/min. Another piece of tubing attached to the exhaust port of the pump will be connected to an 3-liter tedlar air sample bag.

The lapel, or outside facepiece sample, will be collected in the same way except that the tubing attached to the inlet port of the air sampling pump will be in the breathing zone of the fire fighter. A particulate filter will be attached to the open end of the tubing to ensure that particulates do not interfere with sample collection.

Bag samples will be analyzed utilizing a series of analytical devices including a real-time carbon monoxide analyzer, direct reading length-of-stain color indicating tubes, and a Fourier Transform Infrared Spectrophotometer (FT-IR). Sampled gases will be systematically quantified utilizing a combination of the above methods. Additional components of the air samples may be qualitatively identified.

By collecting air samples inside the facepiece and in the breathing zone of the fire fighter, a "workplace protection factor"[3] for the SCBA used during the study can be calculated.

Sampler Assembly and Operation

The pressure data logging unit and both low flow pumps will be contained in a metal case mounted to the backframe of the SCBA. The case, with sampling apparatus inside, weighs less than 5 pounds and will minimally interfere with the fire fighters' activities, but also protect the sampling equipment. The two pumps and pressure data logging unit will be connected to one switch which will be mounted on the exterior of the case. This explosion proof switch will be mounted on the exterior of the case. This explosion proof switch will be mounted to allow the fire fighter to activate the entire package himself with minimal effort.

The two sampling bags will be attached to the SCBA backframe harness. The bags will be placed inside a heat reflective fire resistant bag to ensure sample bag survivability in the harsh fire fighting environment.

Fire Fighter Instruction

Each subject will receive a full explanation of the study protocol, including purpose, expected duration of subject involvement, procedures to be followed, reasonable foreseeable risks or discomforts and benefits to the subjects and others, confidentiality of records, voluntary nature of the study, and whom to contact concerning questions related to the research.

Following this, an opportunity will be made available for both group and individual question and answer periods with the investigator. Finally, the participant and project officer will sign the informed consent form. The project officer will retain the signature page and the subject will retain the information portion of the form. The consent document is contained in this report as Appendix III.

Measurement of Carbon Monoxide Concentration in SCBA Breathing Air

Prior to the field survey a sample of air will be collected from each SCBA air tank on which respirator sampling will be performed. This will be done to quantify the carbon monoxide concentration in the breathing air tank. A two-liter "bag" sample will be collected from the tank. Analysis for carbon monoxide concentration will be performed by a variety of methods including an Ecolyzer 2000 CO analyzer.

Quantitative Facepiece Fit Testing

Preshift fit factors will be measured using standard quantitative fit testing equipment and methodology. This will be done to document the "quantitative" respirator fit the SCBA wearer had on the day of field testing.

The test device will be a Dynatech Frontier model 2000 Respirator Fit Test Instrument. The test device will generate a polydispersed aerosol from reagent grade corn oil. The size distribution of aerosol will be approximately .6 μm with a geometric standard deviation of 2.0-2.2. Quantitative facepiece fit test procedures are given in Appendix IV.

Exhaled Air Samples

An exhaled carbon monoxide (ECO) sample will also be collected from each fire fighter who has granted consent. This will be done both pre- and post-fire episode and will require the fire fighter to provide information concerning his smoking habits. The sampling procedure involves the fire fighter taking a full inspiration, holding his breath for 20 seconds at total lung capacity, exhaling the initial 500 cubic centimeters (dead space and early alveolar air) into a discard bag, and then exhaling expired alveolar air into a 2-liter, 5-layer polyvinyl collection bag. The sample will be analyzed using Fourier transform infrared (FT-IR) spectroscopy (Appendix VII). The carbon monoxide level in the expired air will be measured in ppm. The data will be used to estimate carboxyhemoglobin levels from known regression equations[4].

Fire Fighter Monitoring

Each fire fighter sampled will be monitored by an assigned industrial hygienist. The fire fighter will activate his own sampling apparatus after donning his SCBA. The industrial hygienist will activate the apparatus if a request is made by the fire fighter and if time permits. The industrial hygienist will stay in close proximity of the fire fighter, when possible, and thus, be able to document any noticed equipment malfunction. When the fire fighter is changing air tanks the industrial hygienist, if possible, would be able to deactivate the sampling apparatus. If the sampling apparatus is not deactivated and the fire fighter works longer than anticipated, the sampling apparatus will simply "shut off" and the information can be retrieved later.

Data Recording

At the initial training period an ID number will be assigned to each participating fire fighter. The same ID number will be marked on all sampling performed on that fire fighter. For pressure data files, the ID number plus a 1-digit number corresponding to the fire episode (starting with 1) will be entered into the computer system. For example, a fire fighter with ID number 0001 would have the data file tag 0001-1 assigned for the first pressure measurement on the first fire fighting episode. Air sample bags will be marked similarly. An "I" will designate an inside facepiece sample, with an "A" designating an ambient sample.

For example, an in-facepiece air sample taken on a fire fighter with ID number 0001 on the first fire fighting episode would be labeled 0001-I-1. The sample ID will be recorded on the "Respirator Air Sample Data Form" which is presented in Appendix VI. Quantitative fit test results and ECO results will also be recorded by fire fighter ID number on the data sheet presented in Appendix VI.

Data Analysis

Each in-facepiece sample of carbon monoxide which exceeds the individual's baseline measurement of CO (pre-shift ECO) will be considered indicative of facepiece leakage. Samples that are greater than the baseline measurement will be indicative that inward leakage occurred. In addition, a workplace protection factor[5] will be calculated for each of the sample sets. This factor will be determined by dividing each ambient time-weighted average concentration of carbon monoxide by its corresponding in-facepiece time-weighted average concentration. A log-normal probability plot will be prepared using the workplace protection factors. The fifth percentile value will be determined by the method of Natrella described previously by Lenhart and Campbell[5]. This value will represent the assigned protection factor for the pressure-demand SCBA used during this research study.

Pressure data will be analyzed to determine the percentage of time that the pressure in the facepiece remains positive. Any negative pressure excursions will be quantified, and an attempt will be made to correlate those events to physical phenomenon such as breaking facepiece seal (e.g., to talk), high work rate, etc.

PROTOCOL REFERENCES

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