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# QUANTITATIVE DETERMINATION OF TRUCKING INDUSTRY WORKERS' EXPOSURES TO DIESEL EXHAUST PARTICLES\*

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As part of a case-control mortality study of trucking industry workers, exposures to diesel aerosol were measured among the four major presumably exposed job groups (road drivers, local drivers, dock workers, and mechanics) in the industry. Eight industrial hygiene surveys were conducted during both warm and cold weather at eight U.S. terminals and truck repair shops. A single-stage personal impactor was used to sample submicrometer-sized diesel particles on quartz fiber filters. Laboratory and field studies demonstrated that the elemental carbon content of the particles is a useful and practical marker of exposure to vehicular diesel exhaust. A thermal-optical analysis technique was used to determine the concentration of elemental carbon in the filter samples. Overall geometric mean exposures to submicrometer-sized elemental carbon ranged from 3.8  $\mu\text{g}/\text{m}^3$  in road (long distance) drivers ( $N = 72$ ) to 13.8  $\mu\text{g}/\text{m}^3$  in dock workers ( $N = 75$ ). Geometric mean background area concentrations, measured in the same cities where workers were sampled, were 2.5  $\mu\text{g}/\text{m}^3$  on major highways ( $N = 21$ ) and 1.1  $\mu\text{g}/\text{m}^3$  in residential areas ( $N = 23$ ). A factorial analysis of variance indicated that exposures in two job groups, dock workers (particularly those exposed primarily via diesel forklift trucks, introduced relatively recently) and mechanics (working in poorly ventilated shops during cold weather), were significantly higher than background concentrations and were significantly higher than the exposures in the local and road drivers. The expo-

sure of the truck drivers could not be distinguished from background highway concentrations but were significantly higher than background concentrations in residential areas.

**N**umerous studies have been undertaken to measure emissions from diesel engines, to estimate their concentrations in ambient air, and to assess the levels of possible human exposure.<sup>(1)</sup> It is difficult to selectively measure diesel exhaust emissions because of their complex composition and because many of the components present may be derived from many other sources, such as tobacco smoke, manufacturing emissions, and wood smoke.

Most studies of diesel emissions have focused on the particles, partly because the organic extracts of diesel particles have been determined to be mutagenic in vitro<sup>(2)</sup> and partly because diesel particles are small, readily inhalable, and can easily reach the lower respiratory system.<sup>(3)</sup> Heavy-duty diesel particulates are primarily composed of aggregates of elemental carbon core particles (60–70% by weight), which are surrounded by a layer of adsorbed organic carbon species (30–40%).<sup>(3)</sup> At least several thousand organic compounds can be adsorbed on the surface of the carbon particle aggregates, many of which are cytotoxic, carcinogenic, or mutagenic.<sup>(2,4)</sup> These adsorbed compounds can include polynuclear aromatic hydrocarbons (PAHs), oxy-substituted PAHs, and nitro-substituted PAHs such as 1-nitropyrene and 2-nitrofluorene. Carbonaceous diesel particles are relatively stable in biological media such as lung fluid. Thus, inhaled diesel particles tend to be retained for long periods in the lower respiratory tract and can accumulate, favoring

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induction of chronic pulmonary effects such as respiratory impairment and, potentially, carcinogenesis.<sup>(5)</sup>

Whole (i.e., unfiltered) diesel exhaust also includes a number of toxic gases or vapors (e.g., various oxides of nitrogen and sulfur, and aldehydes), which appear to play a major role in effects such as acute respiratory irritation. However, it is conceivable that these gases or the organic material adsorbed on deposited particles may reduce ciliary clearance as well, perhaps through direct chemical cell toxicity.<sup>(5)</sup>

A major chronic inhalation study conducted by the Lovelace Institute exposed rats to whole diesel exhaust at a concentration of 350  $\mu\text{g}/\text{m}^3$  for 7 hr/day, 5 days/week for up to 2 yr. These rats did not have clearance rates that were significantly different from controls.<sup>(5)</sup> However, rats similarly exposed at a concentration of 7000  $\mu\text{g}/\text{m}^3$  did show clear evidence of pulmonary accumulation after only 12 months, indicating impaired particle clearance. Rats exposed at concentrations of 3500  $\mu\text{g}/\text{m}^3$  did not demonstrate impaired clearance until after 18 months of exposure. These data suggest that (at least in rats) impairment of pulmonary clearance is a function of both concentration and duration of exposure and that significant impairment of pulmonary clearance and subsequent accumulation of diesel exhaust particulates begins somewhere between a concentration of 350 and 7000  $\mu\text{g}/\text{m}^3$  (0.35 and 7  $\text{mg}/\text{m}^3$ ). However, accurate risk assessment must account for many factors, and these data are difficult to interpret in terms of human risk assessment.<sup>(6)</sup>

The National Institute for Occupational Safety and Health (NIOSH) recently published a Current Intelligence Bulletin,<sup>(7)</sup> which concluded that “. . . whole diesel exhaust be regarded as a potential occupational carcinogen in conformance with the OSHA Cancer Policy (29 CFR 1990).” This conclusion was based on the results of recent animal and human epidemiology studies.

The studies in rats and mice confirmed the association between induction of lung tumors and exposure to whole diesel exhaust, especially the particulate phase.<sup>(5,8-11)</sup> Several recent human epidemiology studies also consistently suggested an association between occupational exposure to whole diesel exhaust and lung cancer.<sup>(12-16)</sup>

The most recent and thorough epidemiologic studies were done by Garshick et al.<sup>(14,15)</sup> in railroad workers. In a case control study,<sup>(14)</sup> significant excesses of lung cancer were identified in certain age groups of exposed railroad workers, after controlling for tobacco smoking and asbestos exposures. Classification of the workers into exposed and unexposed groups was confirmed by using adjusted respirable particulate (ARP) exposure measurements in 39 representative jobs from four U.S. railroads over a 3-yr period. The measurements were adjusted for smoking by analyses for nicotine from composited filters obtained from each job group.<sup>(17)</sup> Geometric mean exposures to ARP ranged from 17  $\mu\text{g}/\text{m}^3$  for clerks to 134  $\mu\text{g}/\text{m}^3$  for locomotive shop workers. Differences in climate, facilities, equipment, and work practices were found to affect exposures to diesel exhaust.<sup>(18)</sup>

Because of the uncertainty about which specific agent or agents might be responsible for the mutagenic or carcinogenic properties of diesel aerosol and the environmental pervasiveness of many diesel exhaust components, choosing a practical air

sampling method to measure exposures to diesel exhaust is difficult. At present, the role of individual diesel components in the etiology of human lung cancer is unknown. However, it has been established that 90% of the mutagenic potency of whole diesel exhaust appears to be associated with the particulate phase.<sup>(19)</sup> In addition, although a few animal studies indicate that filtered diesel exhaust (i.e., the gaseous phase) may also be carcinogenic, lung tumor induction in animals has been primarily associated with exposure to the particulate fraction.<sup>(7)</sup> Therefore, it is reasonable to use an index directly related to the particulate, and not gaseous phase, of diesel aerosol.

Several gravimetric methods have been used previously to measure worker exposures to diesel exhaust. Measurement of ARP (respirable particulate adjusted for the contribution of tobacco smoke by quantitation of nicotine extracted from the same filters) was used in a recently completed exposure study in railroad workers.<sup>(18)</sup> The Mine Safety and Health Administration (MSHA), the Bureau of Mines (BOM), and NIOSH have measured exposures to diesel aerosol in coal mines by gravimetric determination of submicrometer-sized particulates with a custom-designed “dichotomous” sampling cassette<sup>(20)</sup> designed to accept and collect airborne particles with a mass median aerodynamic diameter of less than 1  $\mu\text{m}$ .

The major difficulties associated with the use of these methods in the trucking industry include (1) the relative insensitivity of the gravimetric method (with a limit of detection as high as 200  $\mu\text{g}/\text{filter}$ ) and (2) lack of specificity, because tobacco smoke and particles from other combustion processes, airborne soil and other naturally occurring particulates, and other chemical contaminants may produce a variable and potentially large positive bias.

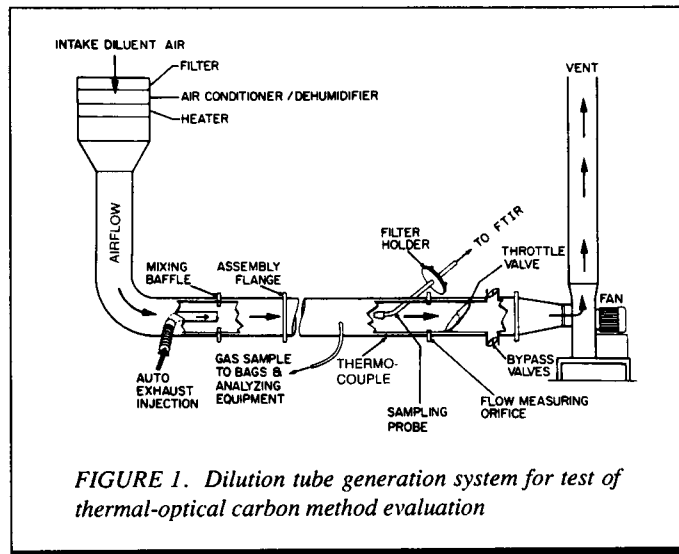
In this study, exposure to submicrometer-sized elemental carbon ( $\text{C}_c$ ), by using thermal-optical analysis,<sup>(21,22)</sup> was chosen as the principal marker of exposure to whole diesel exhaust. This method separately quantitates elemental carbon and organic (i.e., volatile and semi-volatile) carbon species in particulate matter collected on the filter. The four major reasons for this choice were (1) it has 100-fold greater sensitivity over the gravimetric method (the limit of detection is on the order of 2  $\mu\text{g}/\text{filter}$ ), which is important in measuring exposures to workers in the trucking industry; (2) diesel particulate carbon is typically 60–80% elemental carbon<sup>(23-25)</sup> (thus, the major component of diesel exhaust is measured); (3) tobacco smoke, pervasive in the trucking environment, was thought to be almost entirely organic carbon,<sup>(26)</sup> and should not produce a significant positive bias; and (4) almost all of the particulate carbon associated with vehicular traffic has been attributed to diesel exhaust, although the contribution of many other potential sources, such as gasoline engine exhaust and tire debris, appears to be minimal.<sup>(27)</sup>

Because the issue of potential confounding by tobacco smoke was considered to be very important in this study, a separate laboratory evaluation was conducted to determine the elemental carbon-to-organic carbon ratio generated in tobacco smoke. In addition, to ensure that the thermal-optical analytical results were reproducible, a laboratory experiment was conducted by generating controlled atmospheres of diesel exhaust with a diesel-powered vehicle running on an electric dynamometer and a dilution tube.

## EXPERIMENTAL MATERIALS AND METHODS

### Diesel Emissions Studies

In order to investigate the precision and reproducibility of the thermal-optical method, a dilution tube technique was used to generate controlled atmospheres of diesel exhaust at four different concentrations. The experiment was conducted by using a dynamometer and dilution tube apparatus (Figure 1) located



at Ford Motor Co.'s Research and Engineering Center in Dearborn, Michigan. The exhaust was injected into the dilution tube from a subcompact automobile equipped with a light-duty diesel engine, cruising on the dynamometer at about 30 mph. Diluent air (filtered with high-efficiency particulate filters and tempered to approximately room temperature) was injected co-current with the exhaust stream, and co-planar with a mixing baffle to ensure rapid and complete mixing. The concentration of diesel exhaust was varied by changing the amount of air mixed with the diesel exhaust. A total of four concentration levels were set by varying the quantity of air injected into the tube: 1200, 900, 600, and 300 cfm (indicating in each case the volumetric flow rate of air plus injected exhaust moving through the dilution tube).

During each of eight runs (two at each concentration level), simultaneous sampling for total weight of particulate matter, elemental carbon, and organic carbon was conducted. The total particulate samples were obtained by drawing air at a flow rate of approximately 100 Lpm through Pallflex (Putnam, Conn.) TX40 142-mm Teflon<sup>®</sup>-backed glass fiber filters. The filter holders were connected by vacuum tubing to a flowmeter, a bellows-type pump, and a dry gas meter. The elemental and organic carbon samples (for thermal-optical analyses) were obtained by drawing air at approximately 4 Lpm through 47-mm Pallflex QAOT quartz fiber filters and a stainless steel support screen, both of which were held in aluminum 47-mm in-line filter holders. The holders were again connected by vacuum tubing to a bellows-type pump, a flowmeter, and a dry gas meter. Isokinetic sampling was not considered necessary because diesel particulates, mainly submicrometer in size, behave much like a gas under dilution tube conditions.<sup>(28)</sup>

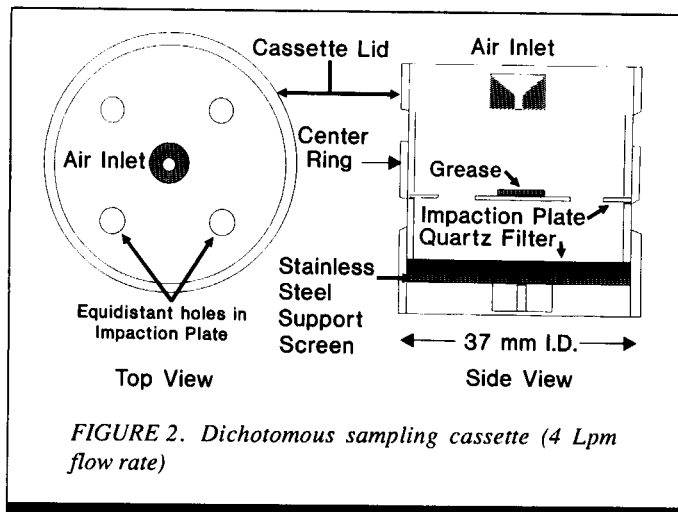
### Tobacco Smoke Studies

An experiment was also conducted in an environmentally controlled chamber to investigate the extent of possible tobacco smoke interference in the measurement of elemental carbon on quartz filters. (This experiment was conducted by NIOSH investigators during an existing study administered concurrently by the John B. Pierce Foundation in New Haven, Connecticut.) During the 8-hr experiment, three men smoked a total of eight cigarettes per hour on a rotating basis. The chamber was approximately 800 ft<sup>3</sup> in volume and was ventilated at a rate of 2.5 air changes/hr (recirculation rate 20 ACH). The respirable particulate concentrations were on the order of 1100 µg/m<sup>3</sup>. After a 2-hr equilibration period, nine area air samples for analysis of elemental and organic carbon were started. Three of the samples were stopped after 4 hr, as were three each at 6 and 8 hr. Three additional control samples were obtained in clean chamber air (in the absence of tobacco smoke). All samples were obtained by drawing air at a flow rate of 2 Lpm through Pallflex QAOT 37-mm quartz fiber filters, supported by stainless steel screens and held in polystyrene cassettes with the caps removed (open-faced). The samples were obtained at a flow rate of 2 Lpm (not 4 Lpm as were the field samples) because no flow-sensitive size-selective device was used and because concentrations of particulates in the chamber were predictably high.

### Field Studies

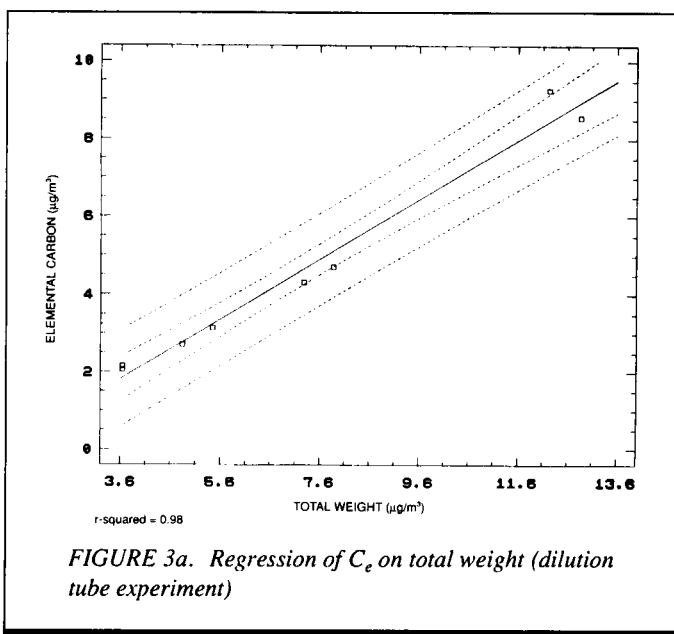
Exposures to diesel aerosol were measured among the four major presumably exposed job groups identifiable from Teamsters Union records (road drivers, local drivers, dock workers, and mechanics) at each of six large, breakbulk (hub) truck terminals. Three of these surveys were conducted during cold weather, arbitrarily defined as daytime highs of less than 10°C (50°F). Three other surveys were conducted during warm weather, during which daytime highs were greater than or equal to 10°C. Limited sampling was also conducted among dock workers at one additional breakbulk terminal and among mechanics at a small, independent truck repair shop. At the breakbulk terminals, approximately eight personal samples, each of which was analyzed for both submicrometer-sized C<sub>c</sub> and organic carbon (C<sub>o</sub>), were obtained on each of the two shifts sampled each day. Generally, four personal samples were obtained from each of two of the four jobs (e.g., four samples in dock workers and four in local truck drivers) on one of the two shifts, and an equivalent number of personal samples were obtained from each of the other two jobs (e.g., mechanics and road drivers) during the other shift sampled. At each site the sampling was conducted for three days (six shifts total, three shifts in each of the four jobs). For logistical reasons, personal sampling in road drivers and area sampling in road tractor cabs were limited to "short-turnaround" drivers; i.e., those drivers who delivered their freight to another city and returned 10–12 hr later to the originating terminal.

Except for the small repair shop, all of the sites were breakbulk (i.e., large, hub) terminals incorporating both line-haul and city freight operations as well as dock and repair shop operations. Typically, these terminals consist of a dock building, adjacent



offices, and separate buildings housing repair shops, service/safety inspection bays, and a truck wash.

The function of the dock is to receive large, long-distance loads (inbound freight) and break them down into smaller loads (outbound) for distribution to regional or local destinations. The terminal is thus referred to as a "breakbulk" terminal. The dock is a long (typically 300–400 ft by about 100 ft), open-sided steel structure situated on an elevated concrete slab. Most of the wall space in the dock area (except for the office areas) consists of open bay doors nearly the same size as the rear doors of truck trailers. "Switcher drivers" (not the truck drivers), using special switching vehicles, back truck trailers up to these doors to load and unload freight. Dock workers use forklift trucks to move freight around on the dock and into and out of truck trailers. Typically, there is no mechanically assisted ventilation on the dock, and this was the case at all seven of the facilities visited. Ventilation is mainly natural or by means of passive, dilution-type ventilators. Air from outdoors enters the building through open doors and openings between the trailer and door.



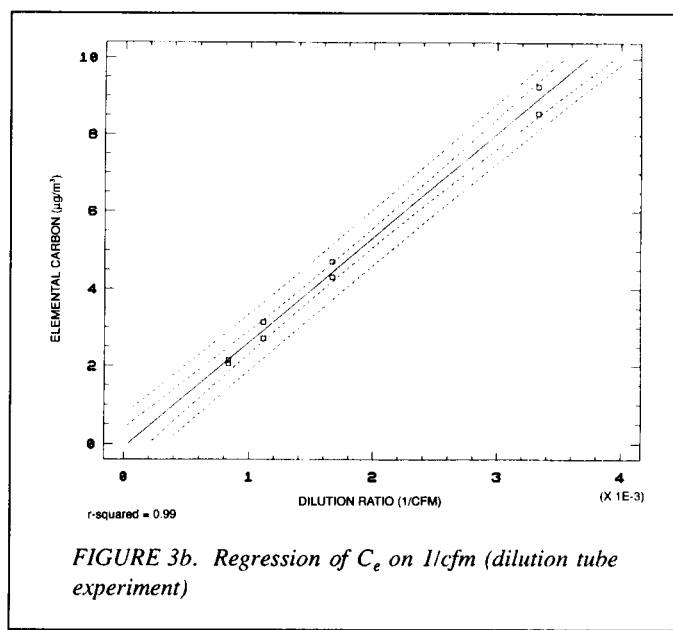
Repair shops and service areas are usually located in one or more separate buildings on the terminal site. Each area typically consists of a single large room with overhead bay doors at one or both ends. In tractor repair shops, there is at least one center driving lane and a series of repair bays on each side. All of the tractor repair shops visited had some type of mechanical ventilation equipment in place to remove diesel exhaust emissions from the exhaust pipes of the trucks. These consisted of either flexible ducts connected to a central duct system and exhaust fan or drive-under canopy exhaust hoods located at each repair bay.

Trailer repair shops and service/safety check lanes usually consisted of a series of long side-by-side (parallel) bays with overhead bay doors at each end. Many of these shops had no mechanically assisted ventilation systems in place, relying instead on natural ventilation and infiltration of air from the outside.

Four of the six breakbulk terminals used diesel-powered forklift trucks on the dock. One dock used propane-powered forklift trucks exclusively, and one used gasoline-powered forklift trucks exclusively. One of the sites exclusively used line-haul tractors fitted with horizontal (undercarriage) exhaust systems. The remainder of the sites used line-haul tractors fitted with vertical (stack) exhaust systems.

Worker exposures to submicrometer-sized  $C_e$  and  $C_o$  were determined by obtaining full-shift personal samples with a modified dichotomous sampling cassette developed by researchers at NIOSH's Division of Respiratory Disease Studies (DRDS),<sup>(20)</sup> but containing prefired, 37-mm Pallflex QAOT quartz fiber filters. Programmable, battery-operated personal sampling pumps were used to draw air through these cassettes at a flow rate of 4 Lpm. The modifications to the DRDS design entailed resizing the inlet diameter to approximately 0.052 in. in order to accommodate a flow rate of 4 Lpm and using quartz fiber filters (supported by stainless steel pads) instead of PVC filters.

The dichotomous cassette (Figure 2) is essentially a single-stage personal impactor, designed to collect submicrometer-sized particles and to reject supermicrometer-sized (those larger than 1  $\mu\text{m}$ ) particles. The dichotomous cassette was used in order



to exclude, to the extent possible, nondiesel particulate matter, because almost all diesel particles (about 95%) are smaller than 1  $\mu\text{m}$ .<sup>(29-32)</sup> An important characteristic of this device is that the particulate matter is uniformly deposited on the quartz filter, which is not necessarily true of commercially available personal cascade impactors. Uniform deposition on the filter is important because only a portion of the filter is removed for analysis by the thermal-optical method.

All of these samples were obtained for a full shift (approximately 8 hr) to maximize sensitivity. The limit of detection is about 2  $\mu\text{g}/\text{filter}$ , which translates to a concentration of about 1  $\mu\text{g}/\text{m}^3$ , assuming a 2  $\text{m}^3$  air volume. Prefired quartz fiber filters were loaded in the dichotomous sampling cassettes just prior to each survey. Shortly after each sampling device was removed from the worker, the filter was removed from the cassette, placed in a small petri dish lined with aluminum foil, sealed in an airtight plastic pouch, and stored in a refrigerator until shipment to the laboratory. The filters were also kept cool during shipment to the laboratory by using cold packs in an insulated container, and they were kept refrigerated in the laboratory until analysis. The filters were kept cool primarily to prevent potential losses of some volatile organic carbon compounds.

Subsequent to the survey, the sample filters were submitted to a laboratory for thermal-optical quantitation of both elemental and organic carbon.<sup>(21,22)</sup> The analysis used was a modification of one previously described<sup>(22)</sup> and employs thermal programming and optical measurements for analysis of carbonaceous aerosols.<sup>(33)</sup> This method overcomes limitations associated with many of the existing combustion-based methods by optically correcting for pyrolytically generated elemental carbon ("char") generated during the first phase of the analysis. This is accomplished by continuously measuring transmittance of a helium-neon laser light through the filter punch in the furnace and determination of the amount of elemental carbon oxidation required to return the instrument to its initial transmittance value.

In the thermal-optical analysis, a 1-  $\times$  1.54-cm rectangular portion of the filter (i.e., a "punch") is removed and placed in a furnace. During the first two of the three major phases of the analysis, the furnace temperature is increased (stepped) one or more times to drive off the various carbon species in stages, resulting in a carbon species profile or thermogram (plot of detector response versus time). The first phase is done in a 100% helium atmosphere, during which time the organic and inorganic (carbonate) carbon are volatilized. The oven temperature begins at room temperature and progresses through four temperature steps (250, 385, 580, and 680°C). The temperature steps are chosen such that the carbonate peak is clearly identifiable and is not confused with organic carbon species. The volatile carbon is oxidized to  $\text{CO}_2$  (in a bed of granular  $\text{MnO}_2$  at 950°C) and subsequently reduced to  $\text{CH}_4$  (in a Ni/firebrick [450°C] metha-

**TABLE I.  $C_e^A$  and  $C_t^B$  as Proportions of Particulate Loading at each of Four Dilution Levels (Dilution Tube Experiment, May 1987)**

Dilution <sup>C</sup> (cfm)	Run	$C_e$ /Total Weight	$C_t$ /Total Weight
1200	1	0.58	0.92
1200	2	0.56	0.89
900	1	0.61	0.90
900	2	0.53	0.80
600	1	0.60	0.89
600	2	0.62	0.85
300	1	0.68	0.99
300	2	0.74	1.01
All samples		0.62	0.91

<sup>A</sup> $C_e$  = Elemental carbon.

<sup>B</sup> $C_t$  = Total carbon (elemental + organic carbon).

<sup>C</sup>Dilution level refers to the flow rate of gas through the dilution tube in cubic feet per minute; 1200 cfm is the most dilute concentration of diesel exhaust and 300 cfm is the most concentrated.

**TABLE II. Results of Controlled Smoking Experiment**

Sample Description	N	$C_e^A$ Conc. ( $\mu\text{g}/\text{m}^3$ )	Loading ( $\mu\text{g}$ )		$C_e/C_t^B$ (%)
			$C_e$	$C_o^C$	
Chamber (2 hr)	3	15.0	3.5	168	2.04
Chamber (4 hr)	3	12.4	5.8	306	1.84
Chamber (6 hr)	3	9.1	6.4	406	1.55
All samples	9	12.2	—	—	1.81
Chamber (control)	3	<2.7	<2.0	17.7	<11.5

<sup>A</sup> $C_e$  = Elemental carbon.

<sup>B</sup> $C_t$  = Total carbon (elemental + organic carbon).

<sup>C</sup> $C_o$  = Organic carbon.

nator), which is then quantitated with a flame ionization detector. The second stage of the analysis begins with a reduction in temperature to 525°C and the introduction of a 2%  $\text{O}_2$  atmosphere into the furnace and proceeds with two additional temperature steps (to 600°C and 750°C). The  $\text{CO}_2$  formed is again reduced to  $\text{CH}_4$  and quantitated with a flame ionization detector. The peaks observed during the second stage are reported and quantitated as elemental carbon ( $C_e$ ). In the third and final stage of analysis, a known amount of methane is injected for calibration and quality control.

Additional area sampling was conducted during the survey to measure concentrations of (1) respirable particulates by gravimetry with a 10-mm nylon cyclone and a 37-mm, 5- $\mu\text{m}$  pore size PVC filter (NIOSH method No. 0600<sup>(34)</sup>) and (2) submicrometer-sized elemental and organic carbon. This was done in order to allow comparisons of the elemental carbon data collected in this study with another recently completed study of exposures in railroad workers.<sup>(18)</sup> Area sampling was conducted on the dock platform, in road and local truck cabs driven by nonsmokers, and in various areas of the maintenance shops. Finally, for purposes of comparison, area samples were obtained to measure background concentrations of submicrometer-sized elemental and organic carbon on a major

state or interstate highway located in or near each city in which exposure evaluations were done (hereafter referred to as highway samples). Additional background area samples were obtained in a residential area of each city (*residential* defined as located at least 1 mile from any major highway—hereafter referred to as residential samples).

## RESULTS

The main purpose of the study was to estimate current exposures of the four a priori job categories to diesel exhaust aerosol by using an appropriate surrogate marker of exposure. Descriptive statistics (means, standard deviations, and confidence limits) were first compiled by the categories being examined for both elemental and organic carbon concentrations. Both arithmetic and geometric means were calculated and reported. The statistical analyses consisted of a preliminary analysis that investigated assumptions for the analysis of variance (ANOVA), a factorial analysis of variance that investigated the presence or absence of differences between group means (job type and weather), and a posteriori multiple range tests (by using 95% Scheffé intervals) to test the presence or absence of differences between group means two at a time. Weather was treated as a dichotomous variable (cold, defined as less than 10°C [50°F] and warm, greater than or equal to 10°C). Several specific aspects of the data (e.g., methods comparisons) were explored by using linear regression techniques. A small number of the sample results (approximately 1%) were below the limit of detection. These results were included in the overall statistical analysis by substituting a value of one-half of the limit of detection for each "less-than" value.<sup>(35)</sup>

### Dilution Tube Studies

The results of the dilution tube experiments demonstrated strong linear relationships between measurements of elemental carbon (dependent variable) and the independent variables—total weight of particulates ( $r^2$  of 0.98, Figure 3a) and the inverse of the volumetric flow rate in the dilution tube ( $1/\text{cfm} \times C_e$ ,  $r^2 = 0.99$ , Figure 3b). The mean coefficient of variation (expressed as a percent of the arithmetic mean) of the elemental carbon method was 7.3%, indicating a relatively high level of precision, because this value includes both sampling and analytical errors. Elemental carbon constituted an average of 62% of the total

particulate loading (by weight) on the filters (Table I) and 64% of the total carbon loading. Similarly, total carbon (elemental plus organic carbon) constituted an average of 91% of the total particulate loading on the filters (Table I).

### Cigarette Smoke Studies

The results of the controlled smoking chamber study (Table II) indicated that elemental carbon comprised an average of 1.8% of the total carbon (from tobacco smoke) collected on the filter (i.e., 98.2% of the total carbon was organic carbon). Even in the presence of extremely high concentrations of tobacco smoke, the measured concentrations of elemental carbon were extremely low, thus confirming that tobacco smoke should not seriously interfere in the measurement of elemental carbon from diesel exhaust. Assuming a respirable dust concentration of 1100  $\mu\text{g}/\text{m}^3$ , as measured in the chamber during the experiment, elemental carbon would comprise approximately 1% or less of the airborne respirable dust from pure tobacco smoke.

### Field Studies

Statistical analyses of the field data distributions in general indicated that the exposures to elemental carbon in submicrometer-sized particulates were lognormally distributed. For example,

**TABLE III. Submicrometer-Sized Elemental Carbon Means by Job, Weather, and Job  $\times$  Weather<sup>A</sup>**

Exposure Group	N	Arithmetic Mean	SE	Geometric Mean	SD	95% Confidence for Mean	
<i>Job</i>							
Dock workers	75	23.5	2.3	13.8	3.59	11.3	16.8
Highway background	21	3.4	0.5	2.5	2.36	1.7	3.6
Local drivers	56	5.4	0.9	4.0	2.01	3.2	5.0
Mechanics	80	26.6	4.1	12.1	3.67	10.0	14.7
Residential bkgd.	23	1.4	0.2	1.1	2.03	0.7	1.5
Road drivers	72	5.1	0.4	3.8	2.31	3.1	4.7
<i>Weather</i>							
Cold (< 50°F)	163	16.4	2.3	5.3	4.51	4.6	6.0
Warm (> 50°F)	164	12.2	1.2	7.0	2.88	6.2	8.0
<i>Job and Weather</i>							
Dock workers (cold)	32	18.5	2.7	8.7	4.79	6.4	11.7
Dock workers (warm)	43	27.3	3.4	19.5	2.42	15.0	25.2
Highway bkgd. (cold)	12	1.9	0.5	1.5	2.09	0.9	2.4
Highway bkgd. (warm)	9	5.3	0.7	4.9	1.52	2.8	8.7
Local drivers (cold)	31	3.1	0.2	2.8	1.63	2.0	3.7
Local drivers (warm)	25	8.3	1.8	6.3	1.93	4.5	8.8
Mechanics (cold)	42	44.4	6.7	28.0	2.79	21.5	36.5
Mechanics (warm)	38	7.1	1.3	4.8	2.39	3.6	6.3
Residential bkgd. (cold)	12	1.7	0.4	1.3	2.14	0.8	2.1
Residential bkgd. (warm)	11	1.1	0.2	0.9	1.85	0.5	1.5
Road drivers (cold)	34	2.4	0.3	2.0	1.94	1.5	2.6
Road drivers (warm)	38	7.6	0.5	7.0	1.51	5.3	9.2
Overall total	327	14.3	1.0	6.1	2.38	5.6	6.7

<sup>A</sup>Values in  $\mu\text{g}/\text{m}^3$ .

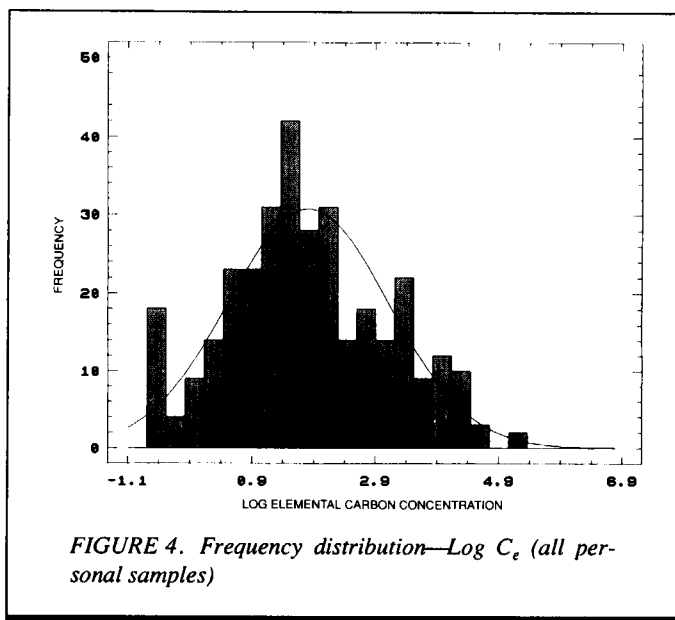


FIGURE 4. Frequency distribution—Log  $C_e$  (all personal samples)

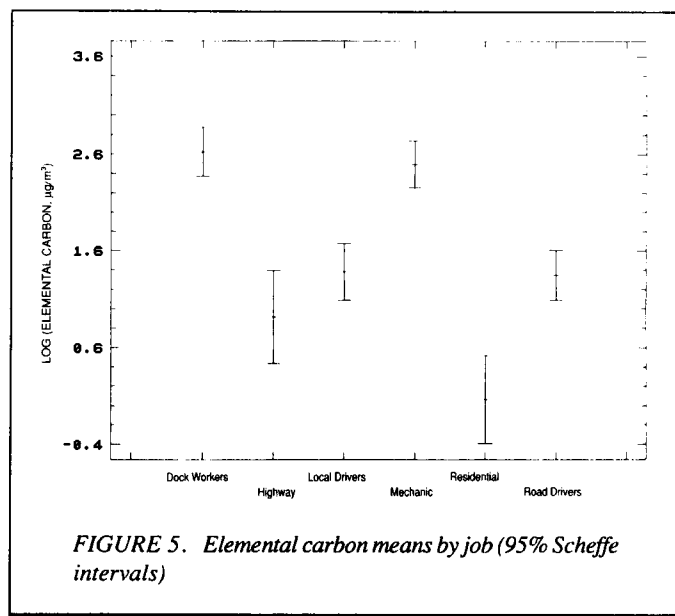


FIGURE 5. Elemental carbon means by job (95% Scheffe intervals)

Figure 4 is a frequency histogram for the log-transformed elemental carbon concentration obtained in all personal samples ( $N = 327$ ), upon which is superimposed the theoretical normal distribution with that data set's mean and standard deviation. A Kolmogorov-Smirnov (K-S) test for the data set illustrated indicated that the distribution was not significantly different ( $p = 0.27$ )

than the theoretical normal distribution. In addition, the residuals, based on the analysis of variance of the log-transformed data, followed a normal distribution. Thus, all subsequent statistical analyses were done with the log-transformed data.

TABLE IV. Submicrometer-Sized Organic Carbon Means by Job, Weather, and Job + Weather<sup>A</sup>

Exposure Group	N	Arithmetic		Geometric		95% Confidence	
		Mean	SE	Mean	SD	for Mean	
<i>Job</i>							
Dock workers	46	45.2	5.3	35.1	2.0	27.6	44.6
Highway background	21	7.4	1.8	3.4	4.2	2.4	4.8
Local drivers	43	30.2	2.1	25.3	2.2	19.7	32.3
Mechanics	51	55.9	6.3	44.5	1.9	35.5	55.9
Residential bkgd.	22	5.2	1.5	2.0	4.2	1.4	2.8
Road drivers	59	28.3	3.0	21.8	2.3	17.6	26.9
<i>Weather</i>							
Cold (<50°F)	121	33.8	3.4	16.2	4.8	14.0	18.8
Warm (>50°F)	121	33.7	2.6	23.4	2.8	20.2	27.2
<i>Job and Weather</i>							
Dock workers (cold)	24	43.9	8.1	32.8	2.1	23.6	45.7
Dock workers (warm)	22	46.7	7.0	37.7	2.0	26.7	53.3
Highway bkgd. (cold)	12	2.7	0.9	1.6	2.9	1.0	2.6
Highway bkgd. (warm)	9	13.7	2.8	9.3	3.4	5.4	16.0
Local drivers (cold)	23	31.0	2.9	24.6	2.7	17.5	34.5
Local drivers (warm)	20	29.2	3.1	26.1	1.7	18.1	37.5
Mechanics (cold)	24	70.4	10.3	59.1	1.8	42.4	82.3
Mechanics (warm)	27	43.2	6.8	34.6	1.9	25.3	47.3
Residential bkgd. (cold)	11	1.2	0.4	0.9	2.2	0.5	1.5
Residential bkgd. (warm)	11	9.1	2.4	4.5	4.4	2.8	7.4
Road drivers (cold)	27	21.9	2.2	17.7	2.3	12.9	24.2
Road drivers (warm)	32	33.8	5.0	26.0	2.1	19.5	34.7
Overall total	242	33.8	1.8	19.5	2.3	17.6	21.7

<sup>A</sup>Non-smoking samples only; values in  $\mu\text{g}/\text{m}^3$ .

Tables III and IV summarize the overall descriptive statistics for submicrometer-sized elemental and organic carbon, respectively. The data were grouped by job (or sampling location in the case of area and background samples) and ambient weather conditions (warm or cold). These statistics include data from all eight study sites. For the organic carbon results (Table IV), the descriptive statistics were computed (and the statistical analyses were carried out) with only nonsmoking samples because tobacco smoke would have provided an unknown and potentially large positive bias.

Figure 5 compares the means of the log-transformed submicrometer-sized elemental carbon concentrations for each of four major job categories (dock workers, city drivers, mechanics, and line-haul drivers), together with the means of background concentrations on the highway and in residential areas within each city. The error bars surrounding each mean are the 95% Scheffe intervals. On the basis of this comparison and the results of the ANOVA and follow-up multiple range tests, all job means were

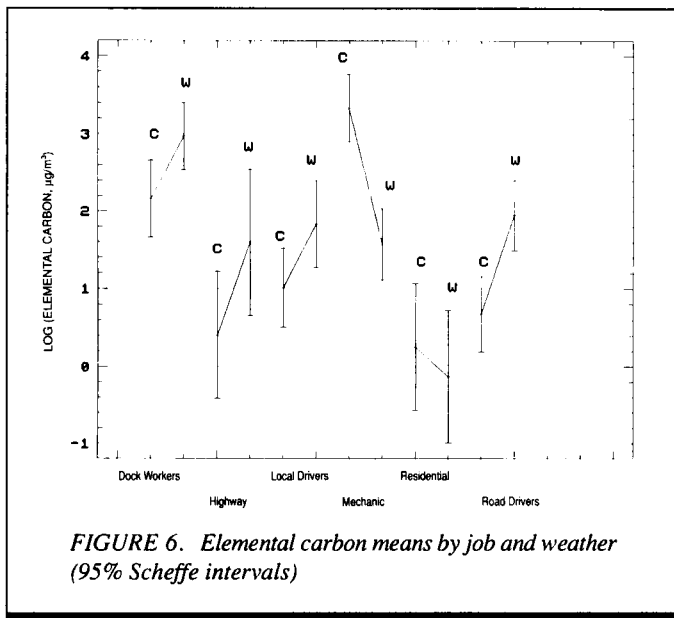


FIGURE 6. Elemental carbon means by job and weather (95% Scheffe intervals)

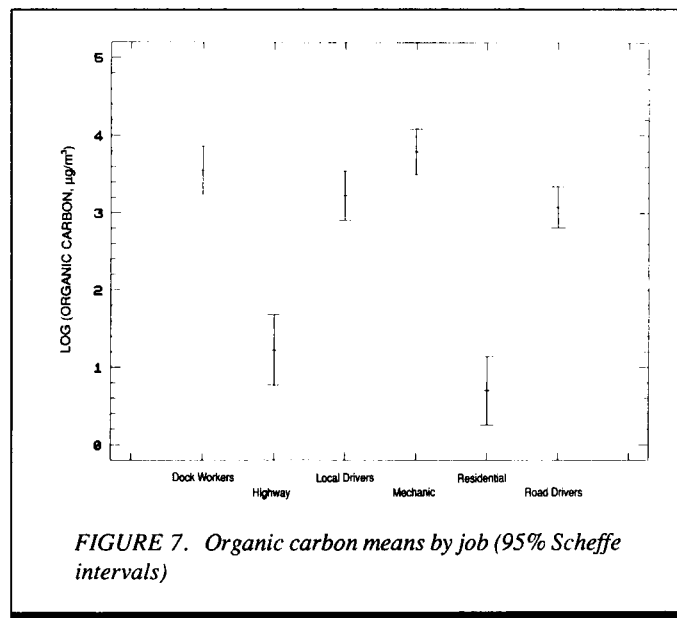


FIGURE 7. Organic carbon means by job (95% Scheffe intervals)

greater than the mean residential concentration ( $1.1 \mu\text{g}/\text{m}^3$ ), but only dock workers' ( $13.8 \mu\text{g}/\text{m}^3$ ) and mechanics' ( $12.1 \mu\text{g}/\text{m}^3$ ) mean exposures were greater than highway background concentrations ( $2.5 \mu\text{g}/\text{m}^3$ ). Road and local drivers' exposures ( $3.8$  and  $4.0 \mu\text{g}/\text{m}^3$ , respectively) were not discernible from background highway concentrations measured, and dock workers' exposures were not different than mechanics' exposures. Both job type and climate factors were significant in the ANOVA ( $p < 0.0001$  and  $p = 0.023$ , respectively). In addition, the interaction term between job and climate was highly significant ( $p < 0.0001$ ).

Figure 6 shows the same data broken down further by samples obtained in cold weather (leftmost bar in each pair) versus those obtained in warm weather (rightmost bar). In mechanics, exposures were clearly higher in cold weather ( $28 \mu\text{g}/\text{m}^3$ ) than they were in warm weather ( $4.8 \mu\text{g}/\text{m}^3$ ). In road drivers, exposures were significantly higher in warm or moderate weather ( $7.0 \mu\text{g}/\text{m}^3$  versus  $2.0 \mu\text{g}/\text{m}^3$  in cold weather). In dock workers and local drivers, a trend appeared to be toward higher exposures in warm weather, but no significant differences were observable. The changes in mean exposures in the mechanics and road drivers by weather were undoubtedly responsible for the significant interaction term in the ANOVA.

Two of the breakbulk terminals studied used nondiesel forklift trucks on the dock. One terminal used propane-fueled forklift trucks, and the other used gasoline-fueled forklift trucks. Because the type of forklift trucks used should have been the primary determinant of the level of dock workers' elemental carbon exposures, a second analysis of variance was performed comparing dock workers' exposures by forklift truck engine type: diesel, gasoline, and propane.

Dock workers' mean exposures to submicrometer-sized elemental carbon by engine type are shown in Table V. The ANOVA

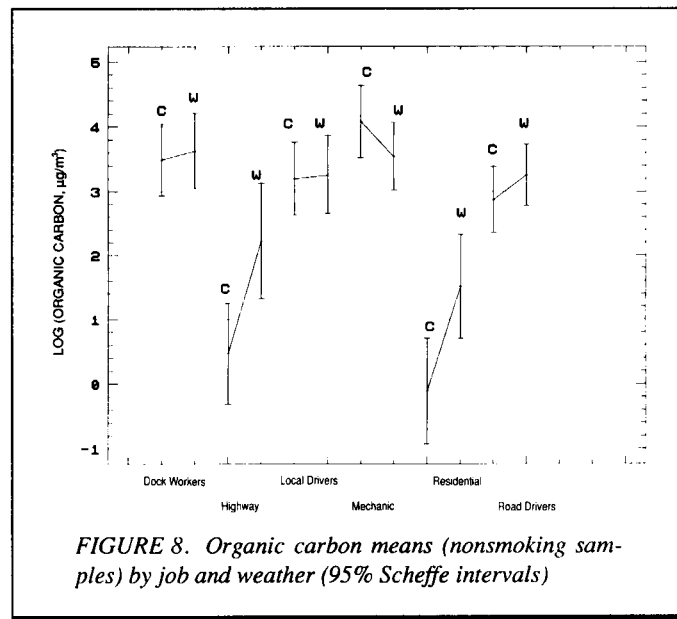


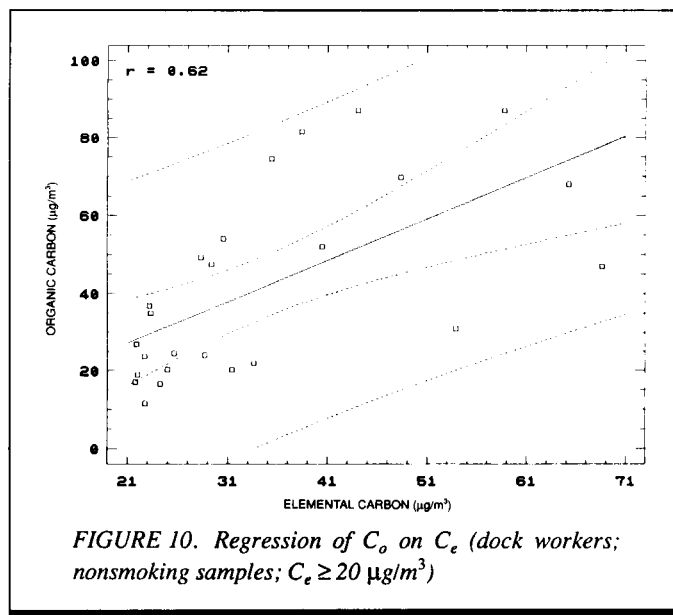
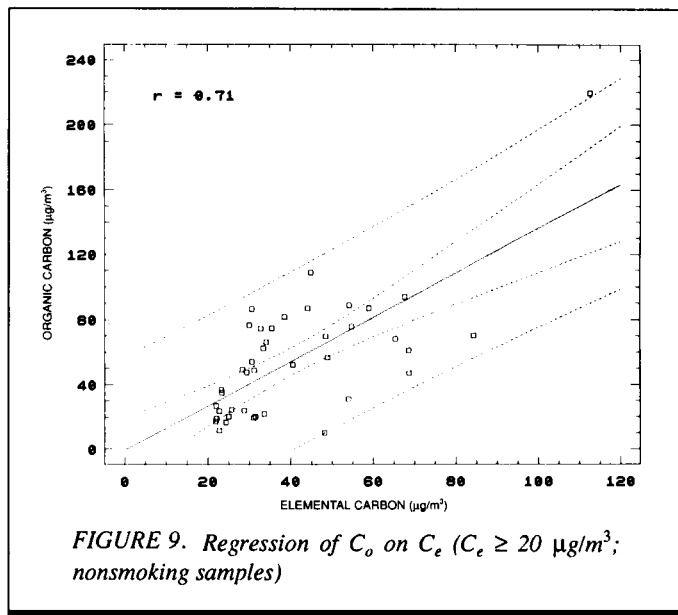
FIGURE 8. Organic carbon means (nonsmoking samples) by job and weather (95% Scheffe intervals)

and the a posteriori multiple range test indicated that all three group means were significantly different ( $p < 0.0001$ ) from each other. Geometric mean exposures to submicrometer-sized elemental carbon were by far the highest where diesel engines were used ( $27.2 \mu\text{g}/\text{m}^3$ ), followed in order by gasoline ( $5.46 \mu\text{g}/\text{m}^3$ ) and propane

TABLE V. Dock Workers' Mean Exposures to Elemental Carbon by Towmotor Engine Type<sup>A</sup>

Towmotor Engine Type	N	Arithmetic Mean	SE	Geometric Mean	SD	95% Confidence for Mean	
Diesel	54	31.3	2.45	27.2	1.70	23.8	31.0
Gasoline	9	5.93	0.79	5.46	1.56	3.95	7.53
Propane	12	1.61	0.35	1.30	1.97	0.99	1.72
Total	75	23.5	1.79	13.8	1.73	12.3	15.4

<sup>A</sup>Values in  $\mu\text{g}/\text{m}^3$ .

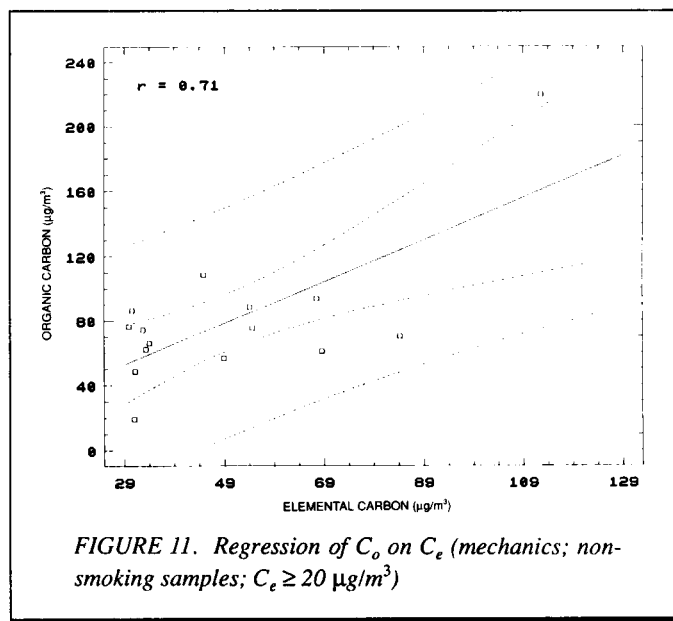


( $1.30 \mu\text{g}/\text{m}^3$ ). The latter two exposure means were of the same order of magnitude as the residential and highway background sample means ( $2.0$  and  $3.4 \mu\text{g}/\text{m}^3$ , respectively).

Table IV and Figures 7 and 8 summarize and compare exposures to submicrometer-sized organic carbon by job and weather, excluding personal samples obtained on workers who smoked. The ANOVA for this dependent variable ( $C_o$ ) again indicated that job ( $p < 0.0001$ ), weather ( $p = 0.003$ ), and interaction (job \* weather) terms ( $p < 0.0001$ ) were all highly significant.

Figure 7 indicates that all  $C_o$  job means were significantly higher than either highway ( $3.4 \mu\text{g}/\text{m}^3$ ) or residential ( $2.0 \mu\text{g}/\text{m}^3$ ) background area samples. Figure 8 indicates that both highway and residential background levels were significantly higher in warmer weather. This change could have been caused by either or both the location (city) effects, or the temperatures, because surveys were not done during both warm and cold weather at each terminal (resources were not sufficient to do this). These trends may have been caused by a number of factors, such as increased levels of ambient pollutant levels during the summer months or decreased suspension of soil particles (which contain a high proportion of organic carbon) in winter because of the frozen ground. However, it appears that all job means were significantly higher than both highway and residential background samples during cold weather and were also higher than residential background samples during warm weather. However, none of the  $C_o$  job means were significantly higher than highway samples during warm weather.

Because both organic and elemental carbon fractions were quantitated from the same filters, the data were examined for the possibility of a significant relationship between submicrometer-sized elemental and organic carbon sampling results. This was done because the focus of most toxicity studies has been the organic carbon species adsorbed onto diesel particulate matter. It is known that the proportion of organic to total carbon typically varies from about 10% to 30% in diesel particulates,<sup>(23-25)</sup> although in at least one study of diesel engine exhaust from passenger cars<sup>(36)</sup> extractable (organic) fractions were as high as 90%.



Figures 9, 10, and 11 are plots of elemental versus organic carbon for (respectively) all nonsmoking personal samples, nonsmoking dock workers only, and nonsmoking mechanics only. The comparisons excluded samples in which the  $C_e$  concentrations were less than  $20 \mu\text{g}/\text{m}^3$ . This was done in order to make it more likely that a substantial proportion of diesel exhaust particles was present on the sample filter and not a large proportion of ambient particles. As indicated, calculated correlations were 0.71 for all nonsmoking samples ( $p < 0.00001$ ), 0.62 for nonsmoking dock workers ( $p = 0.00086$ ), and 0.71 for nonsmoking mechanics ( $p = 0.0030$ ).

Although these relationships are highly significant, the degree of association appears to be only moderate. The reasons for lack of better relationships are many, including other sources of organic carbon such as sidestream tobacco smoke, diesel fuel, degreasing solvents, and grease and oil, all of which are strongly

**TABLE VI. Means for Ratio  $C_e/C_t^A$  by Job<sup>B</sup>**

Level	N	Average (%)	SE	95% Scheffe intervals	
Dock workers	29	47.3	1.89	42.5	52.0
Local drivers	4	42.2	13.8	29.3	55.0
Mechanics	23	34.2	2.62	28.9	39.6
Road drivers	7	33.4	4.25	23.7	43.1
All samples	63	40.6	1.59	37.4	43.9

<sup>A</sup> $C_e$  = Elemental carbon;  $C_t$  = total carbon (elemental + organic carbon).

<sup>B</sup>Nonsmoking samples,  $C_e \geq 10 \mu\text{g}/\text{m}^3$ .

adsorbed by the quartz fiber filters. Even where a personal sample was recorded as having been obtained from a nonsmoking employee, those employees invariably spent part of each shift in a smoke-filled break room.

Table VI contains the mean percentages of elemental to total carbon ( $C_e/C_t \times 100$ ) in nonsmoking personal samples obtained in each of the four jobs. In each case, the statistics exclude samples in which the concentration of elemental carbon was less than  $10 \mu\text{g}/\text{m}^3$  (using a cutoff value of  $20 \mu\text{g}/\text{m}^3$  as above excluded too many samples from the analysis). In this sample subset, the overall mean was about 41%. Within the four jobs, the mean percentage ranged from a low of 33% in road drivers to a high of 47% in dock workers. A one-factor ANOVA indicated a highly significant difference ( $p = 0.0024$ ) between these percentages. A multiple-range analysis of the data indicated differences only between dock workers (higher) and mechanics (lower) but no differences between any other two of the jobs. These percentages are somewhat lower than are typically reported for diesel particles and indicate the probable presence of sources of nondiesel particles. In dock workers, there were no obvious external sources of nondiesel organic carbon exposure other than sidestream tobacco smoke. However, in the mechanics, sources included frequent exposure to diesel fuel, oils, greases, and degreasing solvents (the quartz filters also adsorb organic vapors to a variable extent, particularly if a layer of diesel exhaust-derived carbon soot is present on the filter), as well as sidestream tobacco smoke.

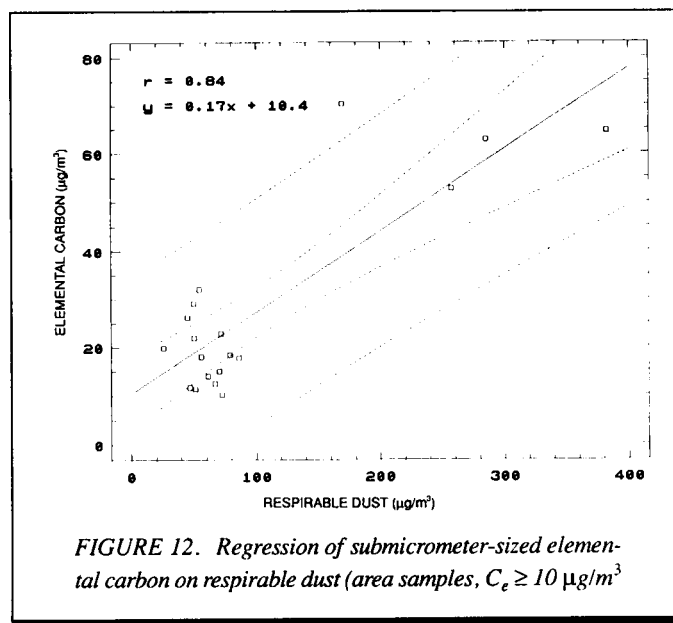
Fifty paired area samples consisting of one of each pair for respirable dust and the other for submicrometer-sized elemental carbon were obtained in various areas (on the docks, in road and city driver cabs, and in repair shops) to determine whether a usable relationship could be demonstrated between gravimetric measurements for respirable dust and submicrometer-sized  $C_e$  by thermal-optical analysis. This relationship is important because a major exposure evaluation of diesel exhaust was recently conducted by using ARP as the principal surrogate index.<sup>(18)</sup> Because the sample pairs were area samples or were obtained in nonsmoking cabs, the influence of tobacco smoke on the results should have been minimized.

Figure 12 is a scatter diagram of a subset of 18 pairs (pairs were excluded if the elemental carbon concentration was less than  $10 \mu\text{g}/\text{m}^3$ ) and the results of a linear regression analysis. As shown, the strength of the relationship was moderate with a correlation of 0.84 and a coefficient of determination of about 71%. On the basis of the regression coefficients, the  $C_e$  results averaged slightly less than 20% of the respirable dust concentrations.

## DISCUSSION AND CONCLUSIONS

An important problem with many past epidemiologic studies related to diesel exhaust and its health effects has been either the lack of any exposure characterization or an inadequate exposure characterization with relatively insensitive and nonspecific methods: e.g., total or respirable dust measurements by gravimetry or surrogates such as measurement of nitrogen dioxide or carbon monoxide, each of which has its own problems. Many of the compounds that could be measured, such as solvent extractable matter from particulates, PAHs or substituted PAHs, or common combustion gases, are also frequently ubiquitously present in the occupational environment at levels far above normal background pollution concentrations from sources such as tobacco smoking and work with solvents, fuels, oils, and greases. In this study, the problem was addressed by using the elemental carbon content of submicrometer-sized particulates as the primary index of exposure to diesel exhaust. Because elemental carbon is present only at very low levels in general ambient particulate matter from sources such as tobacco smoke, sand, dirt, and fibers, it is much more likely that measured elemental carbon results from exposure to diesel exhaust.

On the basis of the dilution tube study, it appears that elemental carbon is a very sensitive and precise indicator of particulate diesel exhaust concentrations. In the dilution tube study, where only diesel exhaust was present, elemental carbon comprised approximately 62% of the total weight of particulate matter. Correlations with two independent measures of diesel exhaust (the dilution ratio and the total weight of the particulate matter) were very high; 99% and 98%, respectively, of the total variability in the elemental carbon concentration was explained by these two independent variables. In addition, the controlled smoking study indicates that airborne tobacco particulates contribute proportionally minor quantities of elemental carbon to the sample filters. The percentage of elemental carbon found in tobacco smoke, expressed as a proportion of total carbon, was on the order of 2% or less. Thus, the presence of tobacco smoke in the sampling environment should not provide a serious interference.



**FIGURE 12. Regression of submicrometer-sized elemental carbon on respirable dust (area samples,  $C_e \geq 10 \mu\text{g}/\text{m}^3$ )**

Other researchers within NIOSH are currently working on specification of one or more methods to measure exposure to whole diesel exhaust. Currently, the surrogate method used in this study, submicrometer-sized elemental carbon, is being evaluated along with several potential alternate methods for this purpose. However, the elemental carbon method worked very well for the purpose of this study, which was to estimate relative exposures to diesel aerosol among the four major exposed Teamsters job categories.

The results of the field sampling at the eight sites included in this study indicated that dock workers' exposures to  $C_e$ , where diesel-powered forklift trucks were used on the dock, were significantly above background concentrations measured in the same cities during either warm or cold weather. On docks where either gasoline- or propane-powered forklift trucks were used, however, exposures to  $C_e$  were essentially indistinguishable from either residential or highway background concentrations.

In addition, mechanics' exposures to  $C_e$  were significantly above background highway concentrations in cold weather but not during warm weather. Exposures appeared to be a function of relative rates of natural ventilation within the shop areas; i.e., doors and windows open in warm weather and closed in cold weather. None of the shops examined had general dilution ventilation equipment installed, although all had essentially the same type of mechanical local exhaust systems in place in the tractor repair shops, consisting of flexible ducts attachable to the exhaust stacks of the tractors or drive-under canopy hoods situated at each repair bay.

Road drivers experienced exposures to  $C_e$  above residential background concentrations in warm weather but not in cold weather, and their exposures to  $C_e$  were significantly higher in warm weather. Road drivers' exposures were never distinguishable from background highway exposures. Local drivers' exposures followed the same trend. In fact, both local and road drivers' exposures corresponded closely with background highway concentrations measured in each city. This suggests that truck drivers' exposures result (at least currently) not so much from the truck they are driving but from the environment in which they spend the majority of their time (the highway).

Thus, if truck drivers have experienced an excess rate of disease because of exposure to diesel exhaust compared to nonexposed Teamsters, it may be because they spend more time on the highway and not because the truck they are driving is exposing them to diesel exhaust. This idea also makes sense from a common sense viewpoint, because almost all of the exhaust in a moving truck should be removed rather quickly from the vicinity of the cab by the airstream surrounding the cab. Road and local truck drivers historically may have also experienced higher exposures from using truck cabs or engines with older designs.

Because there are so many possible sources for airborne organic carbon species in the occupational environment (which would confound measurements of organic carbon species such as  $C_o$ , benzene solubles, or PAHs), and because of other factors discussed in this paper,  $C_e$  appears to be a superior surrogate index to diesel exhaust exposures. However,  $C_o$  concentrations were also reported and statistically summarized for the sake of completeness and because the adsorbed organics (of which  $C_o$  is a measurement) may be partly responsible for the mutagenic and

carcinogenic activity of diesel particulates.<sup>(7)</sup> The  $C_o$  concentrations measured in these jobs (in personal samples obtained from nonsmokers) indicated trends in exposures similar to the elemental carbon results, although road and local drivers' exposures appeared to be significantly higher than background highway concentrations in cold weather (although they were not in the case of the  $C_e$  results). This may be caused by the presence of a nondiesel source of organic carbon in the atmosphere, especially during warm weather. This is supported by the fact that organic carbon means in both residential and highway background samples were significantly higher during warm weather and by the relatively low proportion of elemental to organic carbon in the field samples (41%) compared to the 62% seen in the dilution tube study.

Highly significant (but only moderate in strength) relationships were computed between the elemental and organic carbon fractions of the collected particulates. Correlations ranged from 0.62 in dock workers to 0.71 in mechanics and 0.71 in all nonsmoking personal samples. Because both analytes were determined from the same filters, a near-perfect correspondence (barring analytical errors) should have resulted if all samples collected exactly the same particulate species. Because some scatter (and therefore some unexplained variation) is apparent in the empirical data, it is obvious either that some variable amount of nondiesel particulate matter was also collected on the filters or the proportion of elemental-to-organic carbon in collected diesel particulates varies to some degree between samples, or both. With the exception of a statistically significant difference between dock workers and mechanics, the calculated proportions of  $C_o/C_e$  within each of the four jobs were not statistically distinguishable in this study, and roughly the same amount of scatter was observed within two of the jobs as was observed when using samples from all jobs. Thus, it may be that a significant amount of nondiesel particulate matter (possibly tobacco smoke) is being collected on the filters, probably with a high proportion of organic carbon compared with diesel exhaust, particularly in road drivers (33%) and mechanics (34%). This again suggests that the measurement of organic carbon species (such as  $C_o$ ), as a surrogate to measure exposure to diesel exhaust, is problematic.

Dock workers using diesel-powered forklift trucks had the highest geometric mean exposures to  $C_e$  among the four jobs, followed by mechanics (particularly during cold weather when doors and windows were kept closed). Geometric mean  $C_e$  exposures of local drivers and road drivers were well below those of dock workers and mechanics and were indistinguishable from background highway concentrations.

The mechanics' exposures may have more significance than those of dock workers in terms of long-term chronic exposures to diesel exhaust, particularly those mechanics working in the northern half of the country. Prior to approximately 1980, almost all forklift trucks used on truck docks in the United States were propane or gasoline powered. Thus, exposures of dock workers prior to this time would have been essentially at background levels (as indicated by the comparisons in Table V). However, there is every reason to believe that mechanics' exposures have been as high, or higher, than those documented in this report over a much longer time period (since at least 1960).

Diesel-powered truck tractors were used in the U.S. as early as 1950 and were in widespread use for road tractors by the mid-1950s. In addition, other changes in tractor designs, such as the introduction of vertical, "stack" exhaust systems (which have for the most part replaced horizontal, undercarriage systems) in both road and city tractor cabs, and the introduction of road tractor cab air-conditioning systems, may have influenced (probably lowered) the level of road driver exposures to diesel exhaust. Thus, historical exposures of road and local drivers may have been higher, by an unknown factor, than current exposures. Unfortunately, no historical data exist which would allow an estimate of historical exposures in these job groups. The data developed in this study, which describe current exposures in these job groups, are only suggestive of relative exposures in the past and should be used with caution in interpreting epidemiologic findings.

Overall, the current exposures to diesel exhaust in the trucking industry are generally low compared to some occupational exposures (e.g., miners in enclosed spaces) but are still measurably higher than background levels in the general population. In the railroad industry, average exposure to respirable particulates, adjusted for tobacco smoke, ranged from 17 to 134  $\mu\text{g}/\text{m}^3$ .<sup>(18)</sup> Truck drivers averaged about 4  $\mu\text{g}/\text{m}^3$ , which represents about 20  $\mu\text{g}/\text{m}^3$  of respirable particulates, assuming that  $C_e$  is about 20% of respirable dust by gravimetry. Measurements of diesel exhaust in mines, to date, have been in terms of submicrometer-sized dust, which is not directly comparable to either respirable particulates or elemental carbon. However, available measurements<sup>(20)</sup> indicate that levels of exposure are likely to be substantially higher in mines than in either the trucking or railroad industries.

### RECOMMENDATIONS

Exposures to diesel exhaust significantly higher than background (as measured using  $C_e$ ) were demonstrated in dock workers where diesel-powered forklift trucks are used and in mechanics during colder weather. Because NIOSH, in its Current Intelligence Bulletin No. 50,<sup>(7)</sup> has recommended that exposures to diesel exhaust be reduced to the lowest feasible limits, research is needed to assist in improving and developing techniques to reduce exposures, particularly in these job groups. Improvements are needed in the efficiency and utility of known engineering controls, and additional techniques should be developed. Substitution (replacing a known hazard with an alternative considered less hazardous) is a useful control technique; e.g., substitution of diesel-powered forklift trucks with gasoline or propane vehicles. However, careful evaluations of the health and safety implications of any proposed alternatives should be conducted prior to their implementation.

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