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Case Studies

Exposure to Diesel Exhaust Emissions at Three Fire Stations: Evaluation and Recommended Controls

Dawn Tharr, Column Editor

Reported by Alan Echt, John Sheehy, and Leo Blade

Introduction

The National Institute for Occupational Safety and Health (NIOSH) conducted a health hazard evaluation (HHE) at three engine houses of a municipal fire department. This HHE was performed in response to a joint request from the fire department and the International Association of Fire fighters Local to evaluate exposure to diesel exhaust emissions in the engine houses. At the time of the survey, the fire department included 77 uniformed employees and two secretaries working in three engine houses. Fire fighters worked a 24-hour shift, followed by 48 hours off duty. The fire department responds within the city limits of a municipality with a population of approximately 36,000. During the opening conference, Thursday evening through Friday morning and Friday evening through Saturday morning were identified as busy periods.

The NIOSH investigators visited the engine houses on three occasions. During the first visit, investigators performed a walk-through survey of the three engine houses to formulate a sampling strategy. During the second visit, air samples for components of diesel exhaust emissions were collected on the evening through early morning of Thursday and Friday and again on the evening through early morning of Friday and Saturday to evaluate exposures during a typically busy shift. During the third site visit, the investigators visited the engine houses to obtain data used to formulate the recommendations regarding engineering controls contained in this report.

Background

Engine house 1 was built in 1897. An addition, with an additional apparatus floor, was built in 1969. Three diesel-powered vehicles were housed in the old apparatus bay, including two fire engines and a medic vehicle. Two reserve trucks, one of which was diesel powered, were housed on the new apparatus floor. Engine house 2, built in 1954, housed a diesel-powered medic unit, a diesel-powered fire engine, and a gasoline-powered brush truck. Engine house 3, built in 1966, housed two diesel-powered vehicles (a medic unit and a fire engine) in addition to a reserve aerial unit with a gasoline engine. None of the three engine houses had any mechanical ventilation system designed to remove vehicle emissions. Tailpipes for all of the diesel-powered vehicles are under the vehicle on the right side. On medic units the tailpipe is behind the rear wheels, and on fire engines it is between the back of the cab and the rear wheels. Figures 1 through 4 are floor plans of the three engine houses. These figures illustrate the relationship between the apparatus floors and the living quarters in each engine house.

Evaluation Methods

Personal breathing zone and general area air samples for elemental carbon were collected at all three engine houses. In addition, a general area air sample for elemental carbon was collected outside each engine house and away from sources of diesel emissions to measure the concentration of ambient elemental carbon.

At each engine house, samples were collected in the breathing zones of an officer and two other employees (either fire fighters, medic/fire fighters, medics, or medic trainees). To evaluate the exposures that occurred in the engine houses, and exclude those that occurred while riding the emergency vehicles, employees were asked to turn off the sampling pumps when their vehicle cleared the engine house doors, and turn the pumps on when the vehicle began backing into the engine house upon their return. In this way, potential exposures were evaluated when the emergency vehicles' engines were started, and when the vehicles reentered the garage. Investigators permitted employees to place the sampling devices near their bunks when they slept. Sampling times represent approximately half of each 24-hour shift. Samples were collected with the engine houses' garage doors closed unless a vehicle was departing or returning. Sampling locations are presented in Figures 1 through 4.

Elemental carbon samples were collected and analyzed using the thermal–optical method (TOM). The TOM is an evolved gas technique wherein speciation of organic, carbonate, and elemental carbon is accomplished through temperature/atmosphere control and optical measurements.[1] Samples were collected on 37-mm-diameter quartz-fiber filters supported on stainless steel screens in open-faced cassettes. The filters were prefired in a plasma furnace before sampling to remove any carbonaceous contaminants. Each cassette used to collect a sample was connected via Tygon tubing to a battery-powered personal sampling pump, calibrated before sampling to a flow rate of 2 L/min. The flow rate was checked at intervals throughout the shift and at the end of the sampling period. The final flow rate was averaged with the initial flow rate and multiplied by the sampling time to derive the volume of air sampled. At the contract laboratory, 1-cm^2 punches were taken from the filters for analysis.

The TOM analysis involves three operational stages. First, organic and carbonate carbon are volatilized from the quartz filter punch in a helium atmosphere as the sample oven's temperature is stepped to 680°C. Evolved carbon is catalytically oxidized to carbon dioxide and subsequently reduced to methane,

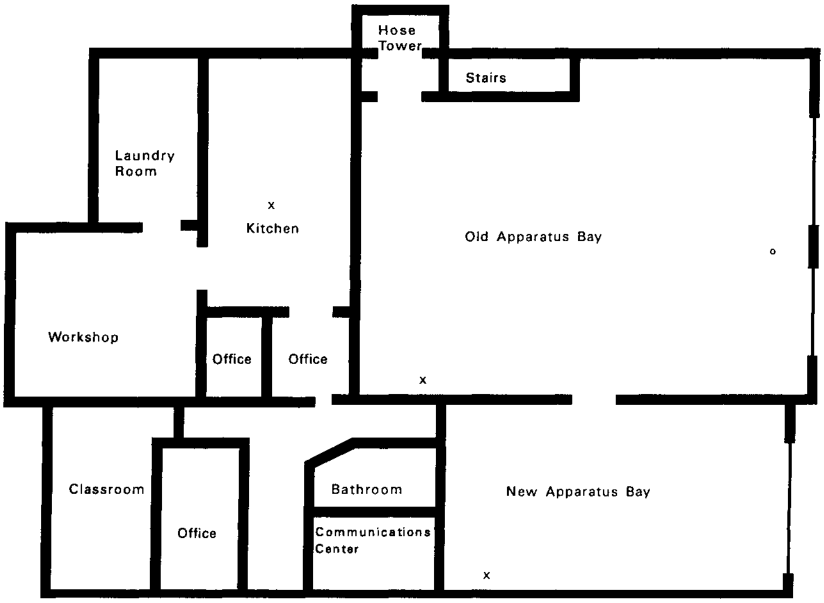

FIGURE 1. First floor, engine house 1. Sampling locations are marked with an X.

which is quantified by a flame ionization detector. Temperature steps were chosen such that carbonate carbon appears as the fourth of four peaks typically observed in the thermogram (a plot of detector response versus temperature). The second stage of the analysis begins after reducing the oven temperature to 525°C. At this point, an oxygen–helium mix is introduced and the oven temperature is raised to 750°C. It is during this stage that pyrolysis correction and elemental carbon measurements are made. An optical feature corrects for pyrolytically generated elemental carbon, or "char," formed during the analysis. In the final stage of the analysis, calibration is achieved by injecting a known quantity of methane into the oven.[1]

Evaluation Criteria

Diesel Exhaust Emissions

Diesel engines function by facilitating the combustion of liquid fuel without spark ignition. Air is compressed in the combustion chamber, fuel is introduced, and ignition is accomplished by the heat of compression.

The emissions from diesel engines consist of a complex mixture, including gaseous and particulate fractions. The composition of the mixture varies greatly with fuel and engine type, load cycle, maintenance, tuning, and exhaust gas treatment. The gaseous constituents include carbon dioxide, carbon monoxide, nitric oxide, nitrogen dioxide, oxides of sulfur, and hydrocarbons (e.g., ethylene, formaldehyde, methane, benzene, phenol, 1,3-butadiene, acrolein, and polynuclear aromatic hydrocarbons).[2–5] The particulate fraction (soot) is composed of solid carbon cores, produced during the combustion process, which tend to combine to form chains of particles or aggregates, the largest of which are in the respirable range (more than 95% are less than 1 μm in size).[6] Estimates indicate that as many as 18,000 different substances resulting from the combustion process may be adsorbed onto these particulates.[7] The adsorbed material contains 15 to 65 percent of the total particulate mass and includes such compounds as polynuclear aromatic hydrocarbons, a number of which are known mutagens and carcinogens.[5,6,8]

Many of the individual components of diesel exhaust are known to have toxic effects. The following health effects have been associated with some of the components of diesel exhaust emissions: pulmonary irritation from oxides of nitrogen; irritation of the eyes and mucous membranes from sulfur dioxide, phenol, sulfuric acid, sulfate aerosols, and acrolein; and cancer in animals from polynuclear aromatic hydrocarbons.

Several recent studies confirm an association between exposure to whole diesel exhaust and cancer in rats and mice.[9] The lung has been identified as the primary site of carcinogenic or tumorigenic responses following inhalation exposure. Limited epidemiological evidence suggests an association between occupational exposure to diesel exhaust emissions and lung cancer.[9] The agreement of current

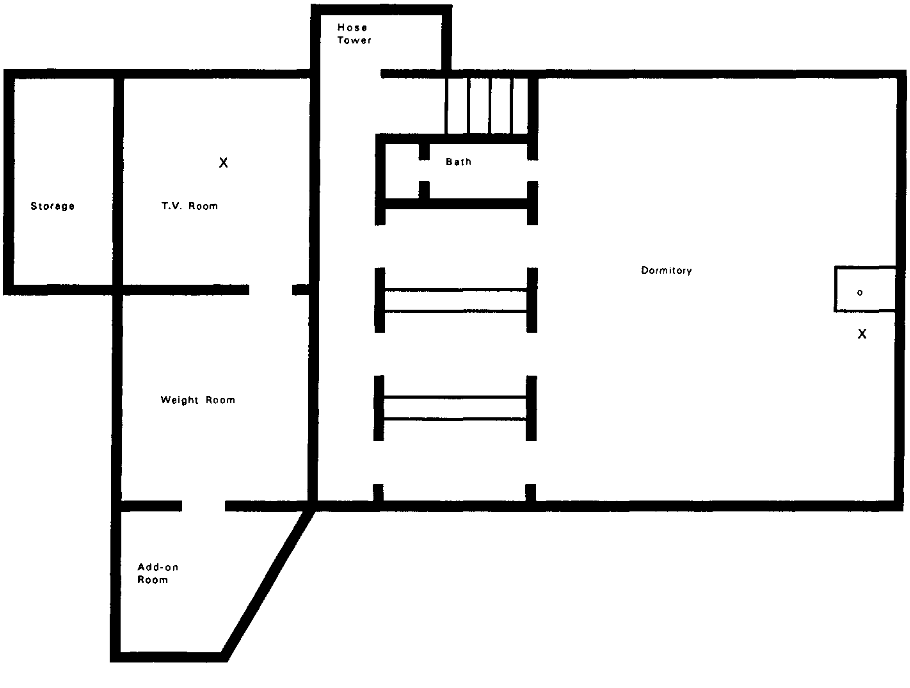

FIGURE 2. Second floor, engine house 1. Sampling locations are marked with an X.

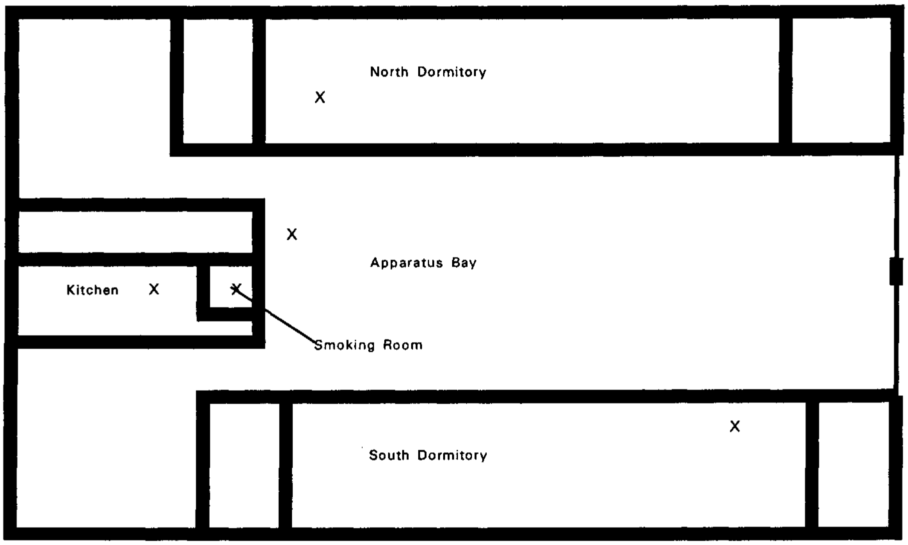

FIGURE 3. Engine house 2. Sampling locations are marked with an X.

toxicological and epidemiological evidence suggests that occupational exposure to diesel exhaust is a potential carcinogen.[6] Tumor induction is associated with diesel exhaust particulates, and limited evidence suggests that the gaseous fraction of diesel exhaust may be carcinogenic as well.[6]

NIOSH recommends that whole diesel exhaust be regarded as a "potential occupational carcinogen," as defined in the cancer policy of the Occupational Safety and Health Administration.[10] This recommendation is based on findings of carcinogenic and tumorigenic responses in rats and mice exposed to whole diesel exhaust. Though the excess risk of cancer in diesel exhaust-exposed workers has not been quantitatively estimated, it is logical to assume that reductions in exposure to diesel exhaust in the workplace would reduce the excess risk.[6]

Elemental Carbon

NIOSH researchers have selected the use of elemental carbon as a surrogate measure of exposure to particulate diesel exhaust because it is more sensitive than the gravimetric approach. Selection of elemental carbon as a marker for diesel exhaust exposure was based upon research which evaluated a number of species as indices of overall diesel exposure. Included in that evaluation were carbon dioxide, carbon monoxide, nitric oxide, nitrogen dioxide, total and fine particulate material (determined gravimetrically), volatilizable carbon (organic), and elemental carbon. Of these constituents of diesel exhaust emissions, elemental carbon was the most reliable measure of "diesel exhaust as an entity." That is, it reflected exposures to the largest number of exhaust components studied. Elemental carbon constitutes a large portion of the diesel particulate mass, serves as a carrier of polycyclic aromatic compounds, and can be quantified at low levels. In addition, the diesel engine is its only significant source in many workplaces.

Results and Discussion

Engine House 1

The diesel-powered aerial platform truck was moved in and out of the engine house one time on the first night of sampling. No other vehicle starts were recorded. None of the vehicles in engine house 1 were moved on the second night of sampling. Elemental carbon results are presented in Tables 1 through 4. Personal samples ranged from 52 to 71 $\mu g/m^3$ on the first night. This is well above the average background elemental carbon concentration of 12 $\mu g/m^3$ measured on the first night of sampling. On the second night of sampling, when no vehicle starts were noted by the NIOSH investigators, the results of personal samples for elemental carbon ranged from 14 to 21 $\mu g/m^3$. The average background elemental carbon concentration measured on the second night of sampling was 8.4 $\mu g/m^3$.

Area samples for elemental carbon on the first night of sampling ranged from 10

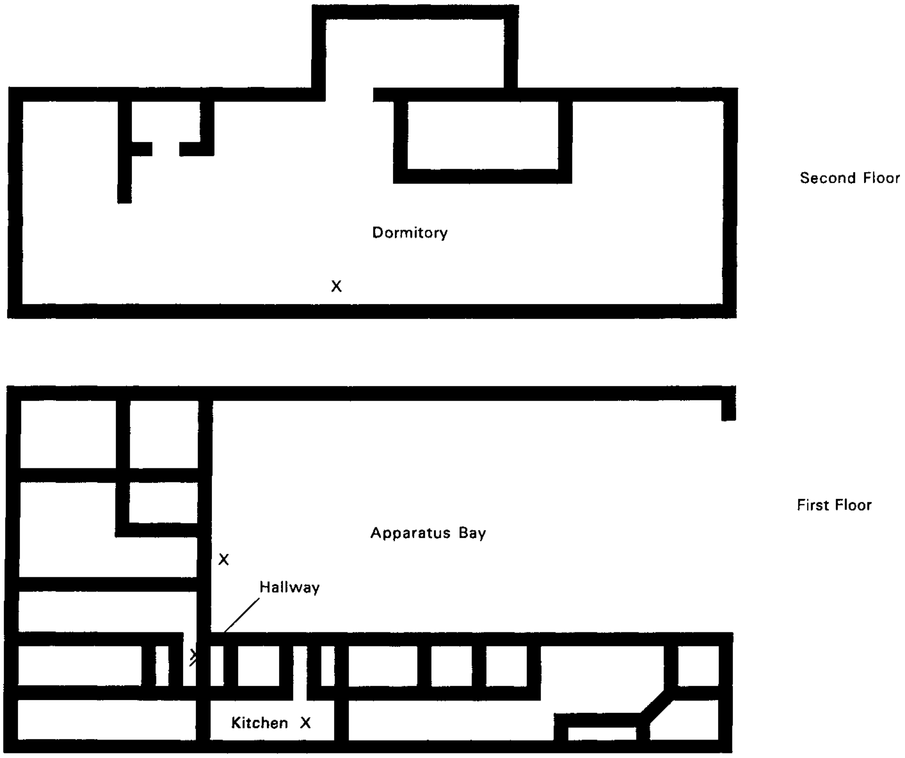

FIGURE 4. Engine house 3. Sampling locations are marked with an X.

TABLE 1. Results of Personal Breathing Zone Air Samples for Elemental Carbon: Day 1

Job Title	Sample Duration (minutes)	Sample Volume (liters)	Concentration (micrograms/ cubic meter)
Engine house 1			
Fire fighter	663	1227	71
Fire fighter	661	1256	52
Captain	662	1225	71
Engine house 2			
Fire fighter	583	1166	38
Medic/fire fighter	582	1135	30
Lieutenant	581	1133	26
Engine house 3			
Fire fighter	818	1636	24
Medic/fire fighter	700	1330	27
Lieutenant	814	1628	35

The average elemental carbon concentration measured outside of the three engine houses on June 25–26, 1992, was 12 $\mu g/m^3$.

$\mu g/m^3$ in the kitchen to 167 $\mu g/m^3$ in the large apparatus bay. Area samples on the second night of sampling ranged from 2.2 $\mu g/m^3$ in the large apparatus bay to 19 $\mu g/m^3$ in the kitchen.

Engine House 2

On the first night of sampling, both the diesel-powered fire truck and the diesel-powered ambulance made one emergency run. On the second night of sampling, the fire truck made two emergency runs, while the ambulance responded at least five times during the sampling period. Elemental carbon results are presented in Tables 1 through 4. Personal samples, which ranged from 26 to 38 $\mu g/m^3$ on the first night of sampling, were well above the average (of three samples) background elemental carbon concentration of 12 $\mu g/m^3$. On the second night, the results of personal samples for elemental carbon ranged from 20 to 79 $\mu g/m^3$, and the average background elemental carbon concentration was 8.4 $\mu g/m^3$.

Area samples for elemental carbon on the first night of sampling ranged from 128 $\mu g/m^3$ in the kitchen to 823 $\mu g/m^3$ in the smoking room, which is located at the rear of the apparatus bay. Area samples on the second night of sampling ranged from 8.5 $\mu g/m^3$ in the north dormitory to 355 $\mu g/m^3$ in the smoking room.

Engine House 3

On the first night, the fire fighters pulled the trucks out of the station to wash them, and drove them back into the station. No other responses were recorded that night. On the second night of sampling, two ambulance runs were recorded, and the fire fighters drove the trucks out of the station once. Elemental carbon results are presented in Tables 1 through 4. On the first night, the results of personal samples ranged from 24 to 35 $\mu g/m^3$. This was greater than the average background elemental carbon concentration of 12 $\mu g/m^3$. On the second night, the results of personal samples collected for elemental carbon ranged from 48 to 61 $\mu g/m^3$. The average background elemental carbon concentration was 8.4 $\mu g/m^3$.

Area samples for elemental carbon on the first night of sampling ranged from 18 $\mu g/m^3$ in the dormitory to 86 $\mu g/m^3$ in the apparatus bay. Area samples on the second night ranged from 19 $\mu g/m^3$ in the kitchen to 204 $\mu g/m^3$ in the apparatus bay.

Conclusions

When diesel-powered equipment leaves or returns to an engine house, exhaust emissions containing diesel particulate are produced inside the apparatus bay. The diesel exhaust can then enter the living quarters. Limited epidemiological evidence suggests an association between occupational exposure to diesel exhaust emissions and lung cancer.[9] The agreement of current toxicological and epidemiological evidence suggests that occupational exposure to diesel exhaust is a potential carcinogen.[6]

Engineering controls and work practices are needed to reduce the potential risk to fire fighters from diesel exhaust emission exposures. Several control options are available for the control of diesel exhaust emissions from these vehicles. Three potentially effective engineering control options are presented below, but other control solutions may be effective. The three options are engine exhaust filters, tailpipe local exhaust ventilation, and dilution ventilation. Work practices can also be implemented to curtail the amount of diesel fumes emitted into the fire station.

The engineering controls and work practices provided in this report represent prudent practice for the reduction of diesel particulate emissions and diesel partic-

TABLE 2. Results of Personal Breathing Zone Air Samples for Elemental Carbon: Day 2

Job Title	Sample Duration (minutes)	Sample Volume (liters)	Concentration (micrograms/ cubic meter)
Engine house 1			
Fire fighter	716	1289	18
Fire fighter	715	1287	14
Lieutenant	722	1300	21
Engine house 2			
Fire fighter	583	1108	32
Medic	295	546	79
Lieutenant	629	1227	20
Engine house 3			
Medic trainee	741	1445	61
Medic trainee	735	1397	53
Officer	779	1519	48

The average elemental carbon concentration measured outside of the three engine houses on June 26–27, 1992, was 8.4 $\mu g/m^3$.

ulate exposures to fire fighters. With a few exceptions, the efficacy of control options discussed here has not been documented. Therefore, no recommendation can be made as to which control option is best, nor can conclusions be made as to the percentage reduction or the ultimate exposure level that may be achieved by using a particular control or combination of controls.

TABLE 3. Results of General Area Air Samples for Elemental Carbon: Day 1

Location	Sample Duration (minutes)	Sample Volume (liters)	Concentration (micrograms/ cubic meter)
Engine house 1			
Kitchen	633	1171	10
Large apparatus bay	490	931	167
Small apparatus bay	626	1158	144
TV room	621	1211	52
Dormitory	618	1174	34
Engine house 2			
Kitchen	582	1106	128
Apparatus bay	605	1180	683
North dormitory	610	1190	435
South dormitory	607	1184	131
Smoking room	588	1117	823
Engine house 3			
Kitchen	792	1584	24
Apparatus bay	787	1574	86
Dormitory	794	1548	18
Hallway	776	1552	67

The average elemental carbon concentration measured outside of the three engine houses on June 25–26, 1992, was 12 $\mu g/m^3$.

In 1988, the Environmental Protection Agency (EPA) began issuing diesel particulate emission standards for heavy-duty diesel-powered equipment such as buses and fire trucks. Reductions in emissions levels were ordered in 1991 and a final level for 1994. The 1994 standard requires that heavy-duty diesel vehicles emit no more than 0.1 g per brake horsepower per hour of diesel particulate.[11] This represents about a 90 percent reduction from uncontrolled diesel exhaust particulate levels. In the long run, implementation of this EPA standard will achieve a major reduction in diesel particulate levels for fire fighting vehicles. However, since diesel equipment typically lasts 15 to 20 years, control options such as those discussed below need to be applied in the interim.

Recommendations

Engineering Controls

ENGINE EXHAUST FILTERS. Engine exhaust filters are designed to remove particulate from the exhaust stream. The

TABLE 4. Results of General Area Air Samples for Elemental Carbon: Day 2

Location	Sample Duration (minutes)	Sample Volume (liters)	Concentration (micrograms/ cubic meter)
Engine house 1			
Kitchen	694	1215	19
Large apparatus bay	686	1269	2.2
Small apparatus bay	681	1260	12
TV room	698	1361	5.8
Dormitory	703	1265	11
Engine house 2			
Kitchen	697	1290	26
Apparatus bay	693	1317	327
North dormitory	702	1334	8.5
South dormitory	690	1344	28
Smoking room	688	1342	35
Engine house 3			
Kitchen	821	1601	19
Apparatus bay	818	1554	204
Dormitory	814	1547	42
Hallway	820	1517	177

The average elemental carbon concentration measured outside of the three engine houses on June 26–27, 1992, was 8.4 $\mu g/m^3$.

filters are installed in the exhaust system or at the tailpipe. One commercially available filter system consists of a porous ceramic filter, a diverter valve, and an electronic control module. The diverter valve is installed in the exhaust pipe and directs the exhaust through the ceramic filter when the engine is started. After a preset time, usually between 20 seconds and 3 minutes, the electronic control vents the exhaust to the exhaust pipe, bypassing the ceramic filter. The timer should be set to allow enough time for the truck to exit the fire station. When the truck is shifted into reverse to back into the garage, the electronic control again routes the exhaust fumes through the filter. The ceramic filter weighs between 20 and 30 pounds and collects about 2 pounds of particulate before requiring servicing. The approximate cost for one filter system is $10,000 (1993).[12]

A report by researchers at the U.S. Bureau of Mines showed that the ceramic filter reduced diesel particulate concentrations by at least 90 percent on a load-haul-dump vehicle in a mine.[13] No documentation on the performance of the ceramic filter specifically for diesel-powered fire trucks was found in the literature. However, a number of local fire chiefs have written letters to the manufacturer of the filter system testifying to the good performance of the ceramic filter in reducing the diesel emissions from fire trucks. Another version of the particulate filter, a filter trap, reduces diesel particulate levels by more than 80 percent. The current cost of this filter trap is about $15,000.[11]

While engine exhaust filters have the advantage of removing particulate from the exhaust stream, and Bureau of Mines research showed a 90 percent reduction in particulate emissions, the filters only remove particulate, and come at a relatively high per-vehicle cost.

LOCAL TAILPIPE EXHAUST VENTILATION. A local exhaust ventilation control for diesel particulate emissions from fire trucks in the fire station is the tailpipe exhaust hose (also called an exhaust extractor). A hose attaches to the tailpipe and connects to a fan which discharges the diesel exhaust to the outside. One manufacturer of these controls recommends an exhaust rate of 600 ft^3/min for each vehicle. The hoses can be purchased with several options. One is an automatic disconnect feature which automatically disconnects the hose from the vehicle exhaust pipe as the vehicle pulls out of the garage. Another option is to install an overhead rail to keep hoses off of the floor. The hoses are suspended from the rail by a balancer that automatically retracts the hose when it is not in use. Various hose diameters are available for different size exhaust pipes. Costs will vary with length of hose, type of overhead mounting, and number of options purchased.

An advantage of the tailpipe exhaust hose is that it also removes gaseous emissions in the diesel exhaust, such as nitrous oxides and sulfur oxides. Tailpipe exhaust also captures emissions at their source. However, the tailpipe exhaust hose captures the exhaust emissions when the vehicle exits the fire station, but affords no control when the vehicle reenters the station unless the exhaust hose is reattached to the fire truck in the driveway. Several configurations of tailpipe exhaust ventilation are available, costing up to $6000 per vehicle, installed.

DILUTION VENTILATION. With dilution ventilation, the air contaminated with diesel fumes is exhausted to the outside while fresh outside make-up air flows into the garage through open doors or supply air openings. Air is exhausted using a roof or wall fan. The exhaust air flow rate and the time required to remove 85 percent of the contaminated air can be calculated from standard ventilation equations.[14] At engine house 1, a fan delivering 5000 ft^3/min can remove 85 percent of the contaminated air in 20 minutes, assuming good mixing of the fresh air with the air in the garage (Table 5). The times needed to remove 85 percent of the air in the garages using a 5000 ft^3/min fan at engine houses 2 and 3 are also shown in Table 5. Keeping the garage doors open during this period should allow for good mixing. The fan can be integrated into the fire alarm system so that it turns on before the fire trucks are started. Fan controls could also be integrated with the operation of the door. It may also be worthwhile to turn the fan on for a few minutes after the fire

TABLE 5. Amount of Time Needed to Exhaust 85 Percent of the Air in an Engine House Garage

Engine House	Garage Volume (cubic feet)	Exhaust Fan Capacity (cubic feet/ minute)	Time (minutes)
1	35,900	5000	20
2	23,000	5000	13
3	33,600	5000	19

trucks have returned to the garage. The fan could be controlled by a timer for this purpose. The major drawback to using dilution ventilation is the cost of heating the make-up air during the cold weather months. Also, dilution ventilation does not remove emissions at their source. The fan, motor, and drive are available for less than $400.

The exhaust fan should be located toward the rear of the fire station garage, opposite the garage doors, so that outside air flows through the open garage doors, sweeping the entire length of the building, before being exhausted. At engine house 1, two fans may be best: a larger fan for the older building and the other for the garage annex. At engine houses 2 and 3, exhaust fans may be located in the roof or in one of the high windows in the wall. The exhaust fans should be located high in the wall (or in the ceiling) and at the opposite end of the garage from the garage doors. If the garage doors cannot be kept open while the exhaust fan is running, a supply air fan located at the opposite side of the building from the exhaust fan can be installed to bring fresh air into the garage.

OTHER. Important information on controlling diesel exhaust emissions in fire stations is found in a bulletin prepared by the New Jersey Public Employees Occupational Safety and Health Program (PEOSH).[15] The brochure entitled "Diesel Exhaust in Fire Stations" includes engineering control options such as modifying the weatherstripping on all doors leading from the garage to the offices and living quarters to prevent infiltration of diesel fumes. Another recommendation is to keep the living quarters under positive pressure to prevent entry of fumes.[15]

Work Practices

In addition to engineering controls, improved work practices may help reduce diesel emissions and subsequent personal exposures to diesel particulate. Some examples that are mentioned in the PEOSH brochure include: (1) always open the garage doors before vehicles are started; (2) keep fire engine operation inside the garage to an absolute minimum; and (3) keep doors between the garage and other areas of the firehouse closed. Other work practices include regular engine maintenance to minimize diesel particulate emissions.

Another approach that may accelerate the trend toward lower diesel particulate emissions is a retrofit program that is being tried by one diesel engine manufacturer. When diesel engines require major overhauls, they are rebuilt so that considerably less diesel particulate is generated.

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