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# Project Summary

# Studies of Particulate Removal from Diesel Exhaust

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**Tests have been conducted to characterize the collection of particulate emissions from diesel exhaust by several different methods. The sources of particulate emissions were 5.7 liter General Motors (GM) diesel engines. The control devices that are discussed include fiber filters, gravel bed filters, trap/cyclones, and electrostatic precipitators (ESPs). The overall mass collection efficiencies, fractional mass collection efficiencies, and operating characteristics of these devices were determined by measuring inlet and outlet total mass loadings and particle size distributions.**

**A device containing a fiber filter was investigated with three different filter materials: long-fiber glass wool, batts derived from fiberglass insulation, and stainless steel fiber mats. Collection efficiencies as high as 90% were achieved, coupled with a quick pressure rise culminating in gas sneakage. A device containing a gravel bed of 45.7 cm diameter and 10.2 cm depth was investigated with 2 mm steel shot. Efficiencies ranged from 45 to 70% and increased with increasing system backpressure.**

**A two-stage ESP was used to agglomerate the primary particulate matter, resulting in an order-of-magnitude increase in mass median diameter. The agglomerated particulate is characterized. Aerosol sampling data are presented for the variation in particle size distribution and the efficiency of trapping the agglomerated particulate in cyclones, fiber filters, and a granular bed filter. The ESP/cyclone combination can provide a collection efficiency of at least 50%. Overall mass removal efficiencies greater than 80% have been achieved with an ESP/granular bed filter system for a duty distance greater than 800 km (500 mi) at a constant highway speed of 88 km/hr (55 mph). Methods of cleaning the devices and removing collected particulate are discussed.**

***This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).***

## Introduction

The superiority in fuel economy of the diesel engine compared to a gasoline engine of the same horsepower has created a widespread market for diesel powered light duty vehicles due to the increasing cost of fuel. In addition, automobile manufacturers view the diesel engine as a possible solution to the Federal regulation requiring that the average fuel mileage for each auto manufacturer be at least 11.6 km/liter (27.5 mi/gal.) by the year 1985. Unfortunately, one characteristic of the diesel engine is a high level of combustion by-products, the most obvious of which is particulate matter (defined by EPA as "everything collected on a filter at 52°C (125°F) after dilution with ambient air in a dilution tunnel").

The particulate effluent of the diesel engine consists largely of agglomerates of very small particles of carbon which have condensed hydrocarbons adsorbed onto them. The mass median diameter (mmd) of the particles ranges from 0.3 to 0.5 $\mu m$, with about 70% occurring at diameters less than 1.0 $\mu m$. The small size of the particulate places it in a range where the collection efficiencies of both filtration and electrostatic devices are reduced. The problem of particle collection is magnified by the large quantities of particulate produced, ranging from 0.14 g/km for the Volkswagon Rabbit to 0.53 g/km for the 5.7 liter GM engine. The ultimate goal for particulate emissions set by EPA is 0.125 g/km, which would require that 76% of the particulate matter from the GM 5.7 liter engine be removed from the exhaust stream. Over a 8000 km (5000 mi) service interval, this would amount to about 3.2 kg of particles. Using 120 kg/m$^3$ for the value of the bulk density of this collected material, this corresponds to about 27 liters (~1 ft$^3$).

Southern Research Institute (SoRI) has been studying nonregenerative aftertreatment devices for collection of diesel particulate. These devices include both those specifically developed for light duty vehicles and stationary-source devices which have been adapted to vehicular sources. The devices tested in this study can be classified as either electrostatic or purely mechanical. The mechanical devices include a deep bed filter which can accommodate up to a 15 cm depth of fibrous filter material, a granular bed filter, and a barrier filter. Also in this category are condensation traps which depend on gas stream cooling to condense particles on a relatively coarse wire mesh. Electrostatic devices include an electrified filter, a moving-belt ESP, and a two-stage ESP used as a primary collection device and as an agglomerator followed by a mechanical collector. Data on these devices are presented following a brief description of the test layout and particle sampling techniques used.

## Test Conditions

The diesel exhaust used in the control device tests was furnished by 5.7 liter GM diesel engines. At the SoRI facility in Birmingham, AL, a 1979 Chevrolet diesel pickup truck mounted on a chasis dynamometer provided the exhaust. For tests at the Department of Transportation's (DOT's) Transportation Systems Center, Cambridge, MA, an engine mounted in one of the engine dynamometer tests cells was used.

Most of the tests were run with the truck operating at a steady road speed of 88 km/hr (55 mph) to provide a high load for the control device. At DOT the engine was operated at 1700 rpm to achieve this same condition. This provided a gas flow rate of about 7.6 actual m$^3$/min (270 acfm). For lower speed runs, the truck was operated at 24 or 32 km/hr (15 or 20 mph). These speeds corresponded to flow rates of 2.4 and 3.2 m$^3$/min, respectively. The other engine speed used at DOT was 900 rpm, corresponding to 48 km/hr (30 mph). Total mass and particle size distribution were measured before and after each control device to characterize the particle collection of the device. The total mass loading information was obtained by using Gelman 47 mm stainless steel filter holders with glass fiber filters.

The particle size distribution data were obtained using modified University of Washington Mark V cascade impactors having seven stages with stainless steel inserts coated with Apiezon H grease to prevent particle bounce. These instruments were used to obtain particle size distributions on a mass basis over the size range from about 0.2 to 4 μm. The impactors were either mounted in ovens close-coupled to the exhaust pipe or wrapped in heating jackets which allowed them to be operated at the same temperature as the exhaust gas.

In addition to the cascade impactors, a Thermo Systems Model 3030 Electrical Aerosol Size Analyzer (EASA) were used to determine concentrations and electrical mobility derived size distributions of particles in the 0.01 to 0.3 μm size range. A Climet Model 208 optical particle counter was used to monitor concentrations in the fine particle size range. The SoRI SEDS III sample extraction, conditioning, and dilution system was used as an interface between these instruments and the exhaust stream. The system removes condensable vapors from the sample gas at elevated temperatures followed by controlled dilution to particle concentrations within the operating ranges of the measurement instruments.

Optical data were not used for detailed sizing information but gave quick indications of efficiency in several size bands.

## Deep Bed Filter

The first device to be tested was the deep bed filter shown schematically in Figure 1. Device dimensions are based on a theoretical study which predicts 82% collection of diesel particulate when used with a 10 cm thick fiber mat of 10 μm fiber diameter and a porosity of 0.99. The filter box was fabricated at SoRI for use in a joint testing program with the Automotive Research Laboratory of DOT's Transportation Systems Center in Cambridge, MA. Fiberglass batts derived from roll insulation and long-fiber spun glass (angel hair), which had demonstrated efficiencies in the 80-90% range, were used in the DOT test. The fiberglass batts had a fiber diameter of about 15 μm and, for the sample tested, a porosity on the order of 0.99. However, since the material was very compressible, the porosity was highly variable. The angel hair had a 20 μm fiber diameter and an undefinable porosity since it came compressed in 0.45 kg (1 lb) bags and could easily be pulled apart with the fingers.

The tests were run at engine speeds equivalent to 48 and 88 km/hr which imply

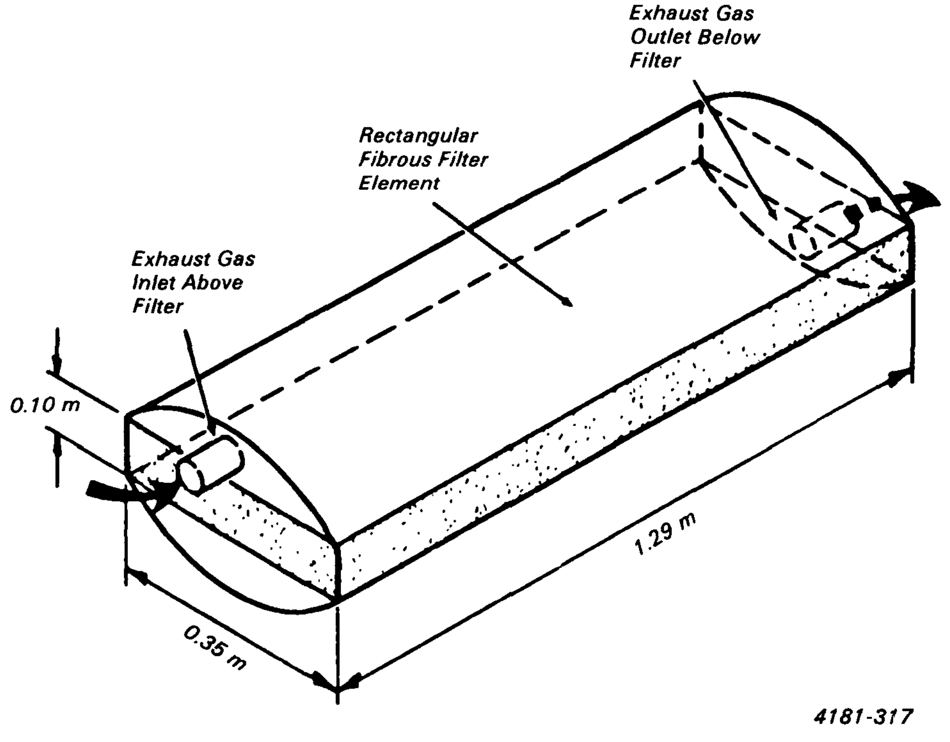

*Figure 1.* *Deep bed filter.*

linear velocities through the filter of 0.17 and 0.27 m/sec. The pressure drop across the control device was monitored and the testing was discontinued if the pressure became too high or rose quickly and then leveled out or dropped, an indication that the gas was finding an alternate path through or around the filter material.

Initially, the deep bed filter demonstrated about 90% collection efficiency at 88 km/hr (55 mph) and 95% efficiency at 48 km/hr (30 mph) using 15 cm of fiberglass batts for the filter material. These values are degraded, however, as the pressure drop across the filter rose and gas sneakage was induced. Figure 2 shows the pressure drop across the filter for one of the tests. In this example the pressure curve starts low, rises quickly as the cake builds up, and then levels off. This pressure behavior proved to be typical of every run in the series. The front surface of the filter material was very black and showed signs of building a cake of particulate. The edges were also very black, which implies the presence of gas sneakage, an effect that would explain the leveling out of the pressure curve of Figure 2. Collection efficiencies measured after the pressure drop curve had leveled off were quite low. Figure 3 shows the collection efficiencies calculated from data taken early and late in the same test shown in Figure 2. The overall efficiency for the early data is 89%. The data taken late in the test, after the backpressure had leveled off, showed a 6% efficiency.

The behavior of the spun glass in the deep bed filter was very similar to that of the fiberglass batts. Initial efficiencies using about 15 cm of the material were in the 80-90% range for the 88 km/hr equivalent engine speed. This material appeared to be less susceptible to sneakage than the fiberglass batts. This is probably due to the less rigid form of the spun glass which should allow the material to flow to fit the container. Two runs were made with this material: in the first, the pressure curve started to break over, an indication of the onset of sneakage; and in the second, with spun glass, no break in pressure rise was evident. This run was terminated due to high backpressure (23 kPa or 92 in. $H_2O$).

During a second series of tests at DOT, the deep bed filter was run using a stainless steel fiber mat which has been fabricated specifically for the test. This material was composed of 12 μm diameter stainless steel fibers which were spun into a 0.64 cm (0.25 in.) thick mat which was then sintered on both sides to give it some rigidity. A 2.5 cm thick bed (four layers) was used in the test. The test was run at 88 km/hr (55 mph) equivalent speed with an upward gas flow to determine if the soot could be dislodged

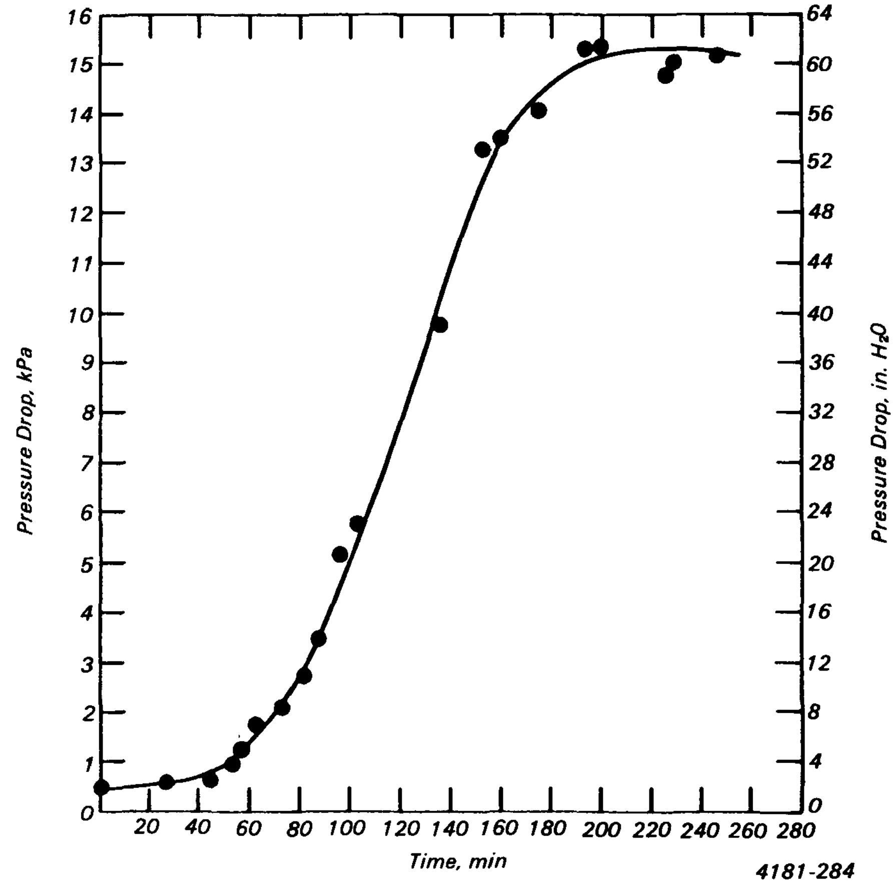

*Figure 2.* *Pressure drop across fiberglass batt.*

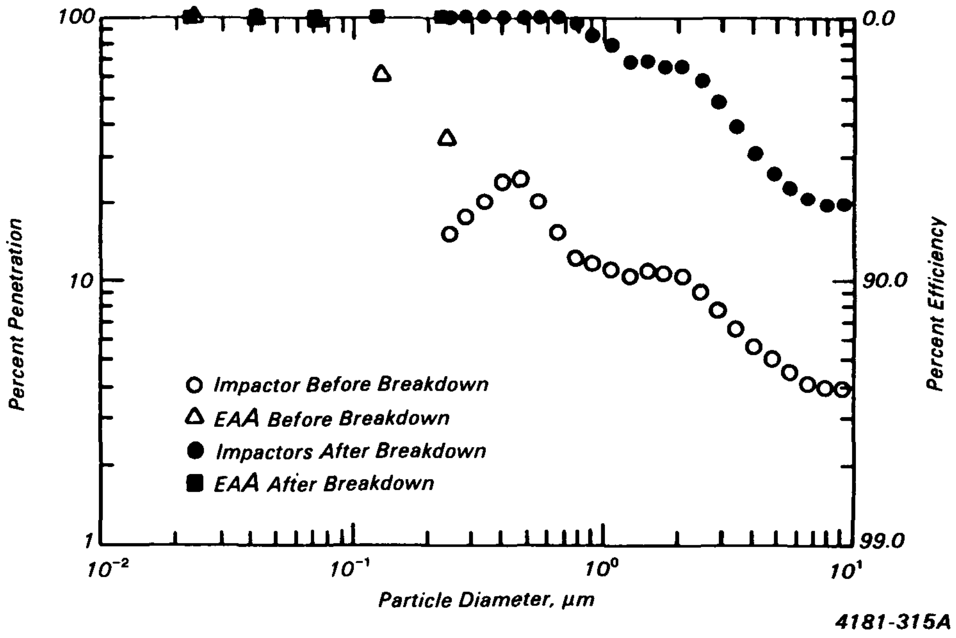

*Figure 3.* *Efficiencies before and after onset of sneakage for deep bed filter using fiberglass batts.*

from the face of the filter mat by rapping the filter box. However, the test was cut short when the backpressure rose to 1.4 kPa (5.6 in. $H_2O$) in 25 minutes and then leveled out. After the test, the filter box was opened and the filter material was examined: obvious soot trails on the sides of the fiber bed indicated severe sneakage. There was no evidence of soot between the layers. The soot cake on the first surface of the fiber mat was very dense and tenacious: it could not be shaken from the surface. Attempts to remove the cake by using a backflow of compressed air were only slightly successful, but the compressed air permanently compressed the filter material. The cake could be removed only by scaping the face of the filter. The cake appeared denser here than it did with the fiberglass batts used in the previous test, probably due to the smooth surface of the stainless steel.

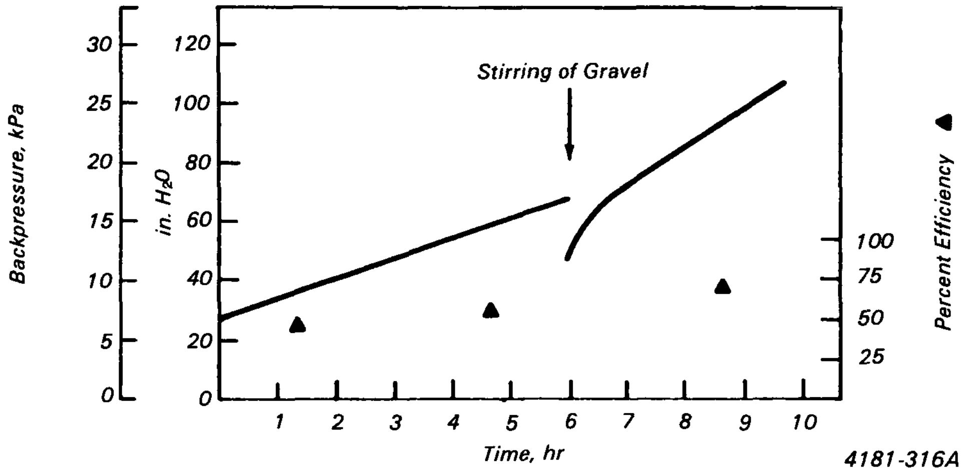

*Figure 4.* *Gravel bed filter efficiency and backpressure.*

## Gravel Bed Filter

The next device examined was a gravel bed filter. It was anticipated that the gravel bed would agglomerate the particulate matter so that it could be collected in a large particle separator such as a cyclone. A gravel bed offers the advantages of elimination of gas sneakage, limited dust capacity (which should promote fast filling and subsequent reentrainment), higher linear velocities for compactness, and rugged filter material (which will allow stirring or other agitation of the filter bed to break up clogging and induce loss of collected particles). The device was built from a 114 liter (30 gal.) drum — 45 cm (18 in.) inside diameter — with a removable lid. A platform covered with a steel screen supported the bed, which consisted of industrial grade steel shot. A stirrer, a rake whose teeth extended 3-4 cm into the shot bed, was added later in the test.

Initial tests were conducted at the SoRI laboratories with an upward gas flow to allow observation of the bed while the truck was running. The truck was run at 88 km/hr (55 mph) to supply 7.6 $m^3$/min of exhaust resulting in a linear velocity of 0.78 m/sec. The initial collection efficiency using 5 cm of 2 mm shot was 22%. After 6 hours of operation, the backpressure dropped and localized boiling of the shot was observed. The efficiency was then 5%.

At this point the system was replumbed to a downdraft. The bed was changed to 10 cm of 2 mm shot and was covered by a screen. The results of this test are shown in Figure 4. After 6 hours of operation, the unit was opened and inspected: some of the shot had been rearranged due to the direct blast from the inlet air. Consequently, the screen was removed, the shot bed was smoothed out, and the screen was recut and replaced. At this point, although the particulate had dispersed itself through the shot bed fairly evenly, it was also piling up on the top surface. This surface deposit was easily broken up when the bed was smoothed out and releveled. This mild stirring of the shot caused the break in the $\Delta P$ curve in Figure 4. However, the pressure quickly resumed its upward trend and reached 27 kPa (108 in. $H_2O$) after 10 hours of operation. Inspection again showed a thick surface layer of particulate. The collection efficiency at the end of the test was 72%.

At this point the system was modified to remove the screen on top of the bed, install a baffle so the gas stream would not dig holes, and install a rake so the top 3 cm of the shot could be stirred to break up the top layer. Stirring at 1 hour intervals constrained the pressure drop to 10-12 kPa (40-50 in. $H_2O$) with efficiencies of about 40%. Emissions increased briefly each time the bed was stirred. Although the ratio of large to small particles increased considerably during the stirring puff, no appreciable agglomeration effects were observed during the non-stirring portion of the operation cycle. Therefore the gravel bed filter must be considered a particle collector rather than an agglomerator.

## Condensation Trap

A condensation trap (the Aut-Ainer) is being developed specifically as a diesel exhaust control device by Eikosha Co. in Japan. Figure 5 is a sketch of one version of the Aut-Ainer with three bands of stainless steel mesh followed by a cyclone for soot collection. This mesh is a coarsely woven belt of 0.2 x 0.4 mm flat wire which has been rolled around the central tube and sandwiched between perforated plates. The device depends on cooling condensation for agglomeration and collection of particulate. The cooling is supplied by the central tube which acts as a ram air tube. Heat transfer is augmented by several perforated plates across the gas flow and connected to the cooling tube. The exhaust gas flow is expected to tear agglomerates from the wire mesh and swirl them through the cyclone to a catch bag on the side of the device, resulting in an effectively self-cleaning device. The only maintenance required would be periodic changing of the soot collection bag.

Two models of the Aut-Ainer were tested. The first was the one shown in Figure 5. The first two bands of steel mesh are 5 cm thick and the third is 2.5 cm thick. The mixing of the cooling air with the exhaust at the end of the Aut-Ainer initially caused some concern because the effects on the condensable hydrocarbons in the exhaust stream were unknown. This difficulty was overcome by extending the cooling air tube down the center of the sampling port tube so that undiluted exhaust could be sampled. After this section, a baffle was placed in the exhaust pipe to promote mixing and another sampling tube was placed downstream to allow sampling of the diluted exhaust. The amount of dilution present was determined by examining the concentrations of CO, $CO_2$, and $NO_x$ present before and after dilution and deriving a correction factor based on the assumption that the quantities of these gases were invariant.

The first Aut-Ainer was examined at DOT. According to the manufacturer, the Aut-Ainer requires about 12 hours of running-in time to obtain maximum efficiency. After 20 hours of running at 1700 rpm (88 km/hr), which corresponds to a linear velocity through the filter of 2.9 m/sec, an efficiency of 12% was obtained with a pressure drop of 5 kPa (20 in. $H_2O$). The manufacturer also pointed out that the device was designed for an engine in the 2-3 liter displacement range rather than the 5.7 liter GM engine being used. By scaling speeds and displacements, 48 km/hr (900 rpm) on the 5.7 liter engine can be considered the equivalent of the desired test speed of 88 km/hr for a 3 liter engine. Therefore a test was run at 900 rpm which yielded an efficiency of 32%. The efficiencies quoted are overall figures derived from filter and impactor data. Figure 6 shows size dependent efficiencies for both engine speeds. Ultrafine data indicate that the device was condensing but not collecting large quantities of small particles.

The second Aut-Ainer tested was designed after the DOT test by Eikosha Co., which believed that a larger design would be more suitable for an engine of 5.7 liter displacement. This device is essentially the same as the one shown in Figure 5 except that (1) the three sections of mesh are 18 cm long for a total of 54 cm, and (2) a bleed-off pipe is connected to the back of the cyclone. The outlet used a double pipe which carried the cooling air past the sampling ports before allowing mixing. At the suggestion of the manufacturer the catch bags were enclosed so that the exhaust through the bags could be examined. The flow rates at the inlet and regular outlet were close to 7.6 actual $m^3$/min (270 acfm) which gives a velocity through the primary filter of 2.1 m/sec. The flow through the bags barely registered on the water manometer used with the pitot tube. Based on an estimated 0.18 cm (0.05 in.) deflection, a flow rate of 0.9 actual $m^3$/min (31 acfm) was obtained. This is only 14% of the total flow.

The large capacity Aut-Ainer was tested at SoRI using the conditions for which it was designed; i.e., a 5.7 liter vehicle operating at 88 km/hr. Filter data at the regular gas outlet indicated that the device was collecting 35% of the particulate after 40 hours of operation. Electrical aerosol analyzer (EAA) data taken at this point showed a negative efficiency for particles of less than 0.7 µm diameter, which suggests that this device, like its smaller counterpart, was condensing vapors to form small particles.

The filter samples taken from the exhaust through the catch bags were pale yellow which implies that only negligible quantities of soot passed the bags. However, these filters showed a larger weight gain than the very black filters from the regular exhaust. The collection efficiency through the bags was 22%, with negative efficiency again occurring for the small particles. The temperature of the gas at this outlet was 84°C (184°F) compared to 132°C (271°F) at the regular outlet. Gas chromatography data from the residue collected on the filters suggest that the weight gain was due to condensed hydrocarbons by showing a distinct shift toward lighter, lower condensation temperature, organic compounds in the sample from the catch bag exhaust filter compared to a sample from the regular outlet filter.

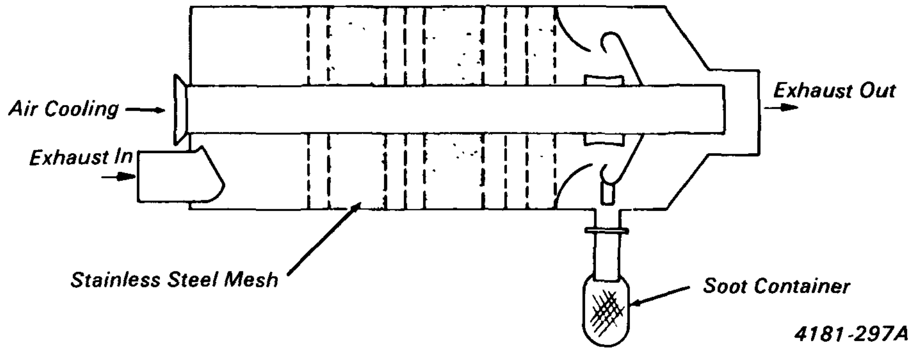

*Figure 5.* *Aut-Ainer.*

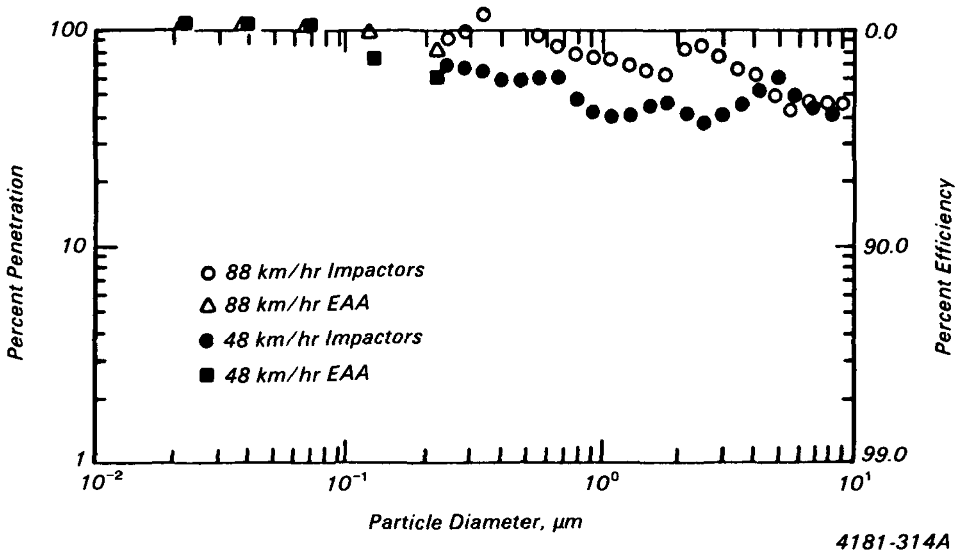

*Figure 6.* *Aut-Ainer efficiency for 88 and 48 km/hr speeds.*

A different condensation trap, designed by the University of Tokyo, was also tested. This device has no air pipe but is designed to maximize its surface area for cooling. The device is 5 cm thick by 40 cm wide and contains three 27 cm long sections of the same steel mesh. There is no cyclone in this device; therefore, any agglomerates which are reentrained should be discharged through the exhaust outlet. The device was built for a 1 liter engine having a maximum gas flow rate of 3.5 $m^3$/min. Consequently, the truck was run at 32 km/hr, giving a gas flow of about 3.2 $m^3$/min. and a filtration velocity of 2.7 m/sec. After 20 hours of operation the efficiency was 36% with a backpressure of less than 3 kPa (12 in. $H_2O$). EAA data indicate that the device is not agglomerating at all but is producing a condensation fog of very small particles.

## Barrier Filter

The barrier filter tested was a ceramic monolith made by Corning. The device was run at an engine speed equivalent to 48 km/hr (30 mph) and showed efficiencies of 92% using impactors, and 97% using the electrical aerosol analyzer. However, its lifetime is very limited due to the rapidly rising pressure drop which reached 35 kPa (140 in. $H_2O$) in 7 hours.

## Electrostatic Precipitator

An electrostatic precipitator (ESP) was developed by SoRI and tested at the SoRI laboratories. The ESP is a cylindrical, two-stage device that obtains maximum collecting plate area in a small volume (Figure 7). It is designed to be wet-flushed periodically in a vertical orientation. The internal diameter (ID) of the cylinder is 20 cm (8 in.). A volume gas flow of 6.2 $m^3$/min (220 acfm) at 88 km/hr (55 mph) gives an average linear gas flow down through the ESP of 3.2 m/sec. For the charging section, five star-shaped corona electrodes are mounted on a vertical high-voltage rod chosen for mechanical strength. The corona electrodes were typically operated at 40 kV (negative) and about 250 μA. The product of negative ion density and gas treatment time in the corona section is

$$N_{o}t \simeq 0.6 \times 10^{13}\ \mathrm{sec/m^3},$$

at an electric field of approximately $4 \times 10^5$ volt/m. The electric field for particle charging could be increased by using improved high voltage insulation.

The collector section is a set of concentric cylinders (overlapping length 28 cm), alternately grounded and biased negative. The total collecting area is 1.18 $m^2$ (12.7 $ft^2$). For a volume flow of 6.2 $m^3$/min (220 acfm), the specific collection area is about 11.3 $m^2/(m^3/sec)$ (58 $ft^2$/1000 acfm). The collector cylinders have a nominal spacing of 0.6 cm. After wet-flushing loose particulate, the cylinders will hold about 6 kV without arcing. To increase the collecting electric field, the voltage is increased typically to 15 kV, with steady arcing carrying about 1.5 mA. Then the collecting electric field is about $24 \times 10^5$ volt/m.

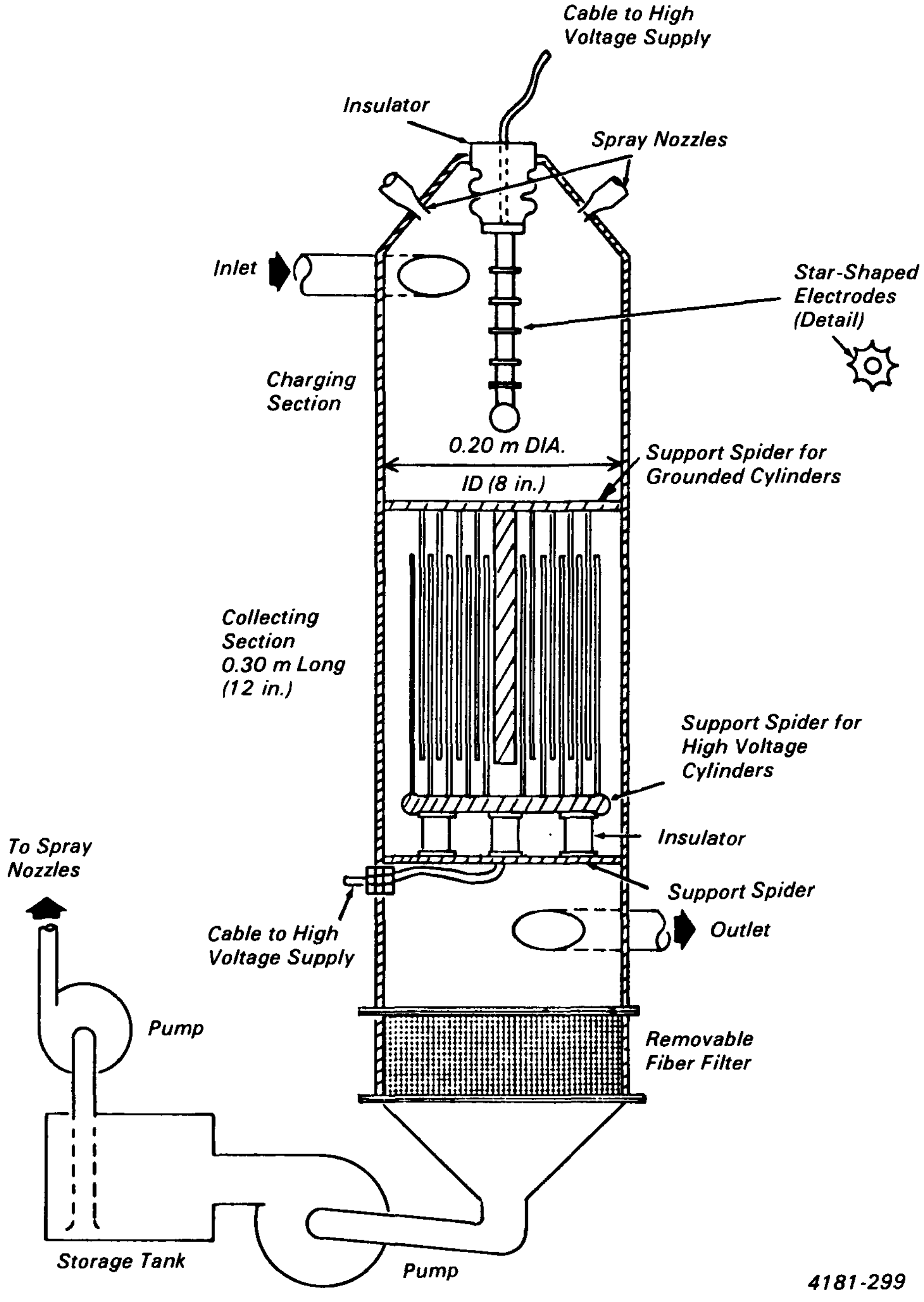

*Figure 7. Schematic diagram of the precipitator.*

Early tests of the ESP produced little permanent collection of diesel particulate because of reentrainment. Preliminary mass train sampling (non-isokinetic) indicated an overall mass removal efficiency of about 30-40%. Later measurements (with cascade impactors and a backup filter) of the mass removal efficiency of the ESP gave values of about 26%. While the ESP achieved only low collection of diesel soot, there was substantial agglomeration of the particles. Electrical aerosol size analyzer data showed roughly 50-70% removal of particles of aerodynamic diameter on the order of 0.1 μm. Moreover, the mmd was raised by an order of magnitude. This phenomenon was easily confirmed by visual observation of some microscopic agglomerates. Microscopic examination of particles at the ESP outlet showed a prepondrance of very loose and fluffy agglomerates on the order of 25 μm in actual size. Settling velocity experiments with large agglomerates indicated that the aerodynamic diameter was roughly 10% of the physical particle diameter. This was consistent with later cascade impactor measurements of the mmd at the ESP outlet. Subsequent testing of the ESP emphasized its role as an agglomerator, with the ESP followed by some other device for trapping the agglomerated diesel soot.

The electrical resistivity of the diesel soot is of concern in regard to surface conduction through sooty deposits on insulating standoffs in the ESP. The resistivity of a bulk sample of diesel soot collected at the ESP outlet was measured in moist air using an ASME PTC-28 test cell. The soot was compacted as little as possible. With temperature and moisture content comparable to those of the diesel exhaust gas, the resistivity of the fluffy agglomerated soot was about $10^7$ ohm-cm.

Several common cleaning fluids were bench-tested for effectiveness in cleaning the ESP. They were tested both on bulk samples of diesel soot and on soot layers impacted on metal parts. Perchloroethylene, a common dry cleaning fluid, was chosen for cleaning the ESP because it is effective, nonflammable, and of relatively high boiling point and low toxicity.

The ESP was occasionally flushed after the device had cooled down overnight. About 4 liters (1 gal.) of perchloroethylene was pumped directly from a supply container through four spray nozzles in the top of the ESP. The dirty fluid flowed directly from an outlet in the bottom of the ESP into a take-up container. Teflon insulators were thoroughly cleaned, but there always remained a thin film of soot on metal surfaces which could not be removed by any cleaning fluid (without rubbing).

One problem in the aftertreatment of diesel exhaust is the collection and handling of the large volume of low bulk density soot (roughly 120 kg/m³). An advantage of wet-flushing with perchloroethylene is that the collected soot is left in a highly compacted state when the dirty cleaning fluid is evaporated (to be followed by condensation in a closed system). The measured bulk density of dry residue from the wet-flushing procedure was 1300 kg/m³. Consequently, the collected particulate storage volume required for an 8000 km service interval would be reduced to 3 liters (~0.1 ft³).

## ESP/Cyclone

Three series of tests were conducted on three different ESP/cyclone combinations, with the diesel truck running at 88 km/hr (55 mph). First, a Fisher-Klosterman XQ-4 industrial cyclone was connected in the exhaust line after the ESP. The cyclone was calibrated by the manufacturer under ambient conditions to have a $D_{50}$ cutpoint of 2.0 µm for a volume gas flow of 5 m³/min (180 acfm). By Lapple's law, the $D_{50}$ cutpoint extrapolates to 1.6 µm under actual operating conditions: 175°C, 2.5 x $10^{-5}$ Pa·sec, 6.2 m³/min, 36.5 m/sec, and 108 kPa positive pressure (27 in. $H_2O$). There was a pressure drop of 44 kPa (11 in. $H_2O$) across the ESP, and a temperature drop of 5°C. Across the cyclone, there was a temperature drop of 10°C, but no measurable pressure drop on a mercury manometer. Performance of the ESP/cyclone combination was tested by extracting samples of the exhaust gas through cascade impactors. Three test stations were used to accumulate data simultaneously at the outlets of the diesel truck, the ESP, and the cyclone. Average results of several tests are shown in Figure 8 where the agglomeration of carbon soot by the ESP is demonstrated: the aerodynamic mmd at the ESP outlet is increased by roughly an order of magnitude to about 3.5 µm.

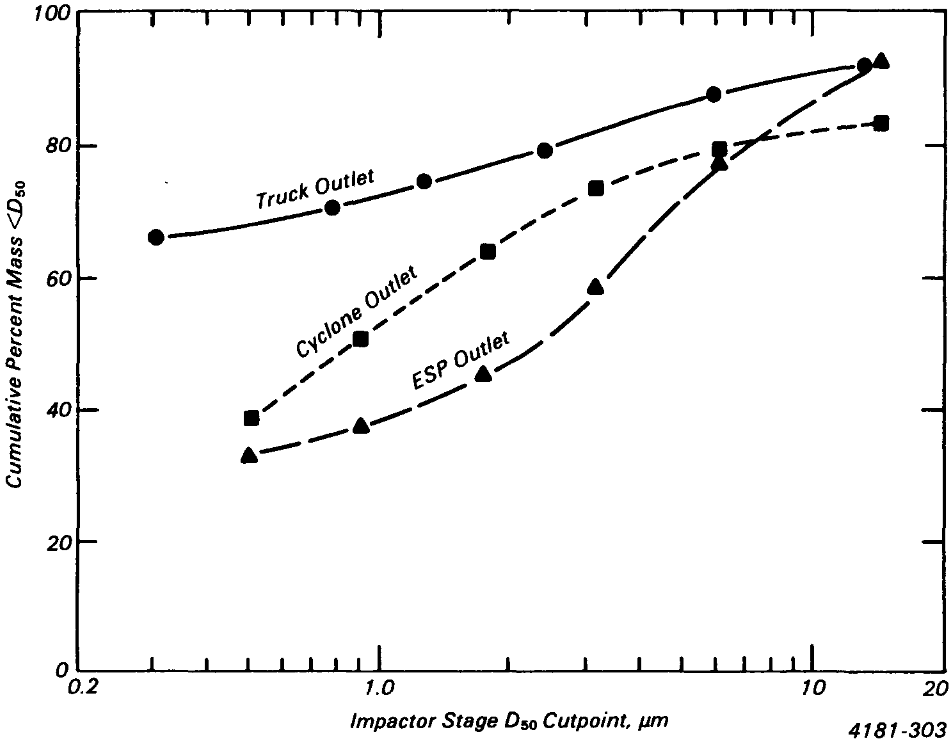

*Figure 8.* *Impactor testing of ESP/cyclone combination. Cumulative percent particulate mass of aerodynamic diameter less than the impactor stage $D_{50}$ cutpoints.*

Figure 8 shows that about 56% of the diesel particulate at the ESP outlet had an aerodynamic diameter greater than the extrapolated $D_{50}$ cutpoint of the cyclone. However, the total mass loading at the cyclone outlet was 28% greater than at the ESP outlet. There was evidently substantial hydrocarbon condensation in the gas stream passing through the cyclone. Figure 8 shows also that the mmd of the diesel particulate was greatly reduced (to about 0.9 µm) in passing through the cyclone. This was not due to collection of large particles in the cyclone because only a very small amount of diesel soot was retained in the cyclone catchpot. The decrease in mmd could have resulted both from hydrocarbon condensation and from breakup of the fluffy, agglomerated soot particles in the vortex of the cyclone, in reentrainment from the cyclone catchpot, or in the impactor jets.

The ESP/cyclone combination was tested further with a small five-stage cyclone system designed and calibrated for *in-situ* stack sampling. In this case, a gas sample at the ESP outlet was extracted through the five-stage cyclone at 170°C and 0.03 m³/min (1 acfm). The corresponding calibrated $D_{50}$ cutpoints are 8.3, 3.9, and 2.5 µm for the first three cyclones, and an estimated 1.1 and 0.5 µm for the last two cyclones. A total of 136 mg of diesel particulate was collected in the cyclones (57%) and on the backup filter (43%). The measured mass distribution is shown in Table 1. The five-stage cyclone data are compared with the cascade impactor data, where the cumulative percent mass of aerodynamic diameter greater than the $D_{50}$ cutpoint is extracted from the ESP OUTLET curve of Figure 8. The five-stage sampling cyclone collects roughly the expected amount of agglomerated diesel particulate.

Finally, tests were conducted on various combinations of sampling cyclones, with diesel exhaust gas samples (at the ESP outlet) pulled through the cyclones at much higher flow rates than those for which they were designed. The concept under investigation was that if such a cyclone could collect agglomerated diesel particulate efficiently at a flow rate of 0.55-0.85 m³/min (20-30 acfm), the total exhaust gas flow from an ESP agglomerator could be passed through a parallel array of perhaps 10 such cyclones.

The tests were conducted with the diesel truck running at 88 km/hr (55 mph) and cyclone sampling gas temperatures approximately 170°C (340°F). The cyclone combinations were tested at flow rates of 0.55 and 0.80 m³/min (20 and 28 acfm). Particulate masses collected in the cyclone catchpot and in a backup filter were measured. The three cyclones used were designated 9, 3, and 4, with specifications as follows:

Cyclone 9 — Large Cyclone
$D_{50}$ = 15 μm at 0.015 $m^3$/min, 22°C
$D_{50} \cong$ 17 μm at 0.015 $m^3$/min, 170°C
Cyclone 3 — Small Cyclone (mounted inside Cyclone 9)
$D_{50}$ = 2.5 μm at 0.015 $m^3$/min, 22°C
$D_{50} \cong$ 2.9 μm at 0.015 $m^3$/min, 170°C
Cyclone 4 — Cyclone 4 of the Five-Stage Sampling Train
$D_{50}$ = 0.6 μm at 0.03 $m^3$/min, 22°C
$D_{50} \cong$ 1.1 μm at 0.03 $m^3$/min, 170°C

Results of testing the cyclones at high flow rates are given in Table 2. These tests indicate that an ESP agglomerator followed by cyclonic trapping of agglomerated particulate is a viable concept for aftertreatment of diesel exhaust. The mass removal efficiency of such a device is at least 50%. The mass removal efficiency can be improved by extensive engineering and testing to match the cyclone performance to the characteristics of the agglomerated diesel particulate. Methods of disposal of the trapped diesel particulate require further investigation. An ESP will require cleaning sooner or later, by wet flushing or air jet scouring. Soot collected in the cyclone catchpot will have to be removed and/or compacted. During the tests of the ESP in combination with other devices, it was necessary to clean the collector cylinders by wet flushing with perchloroethylene after 16 to 20 hours of operation with the diesel truck running at 88 km/hr.

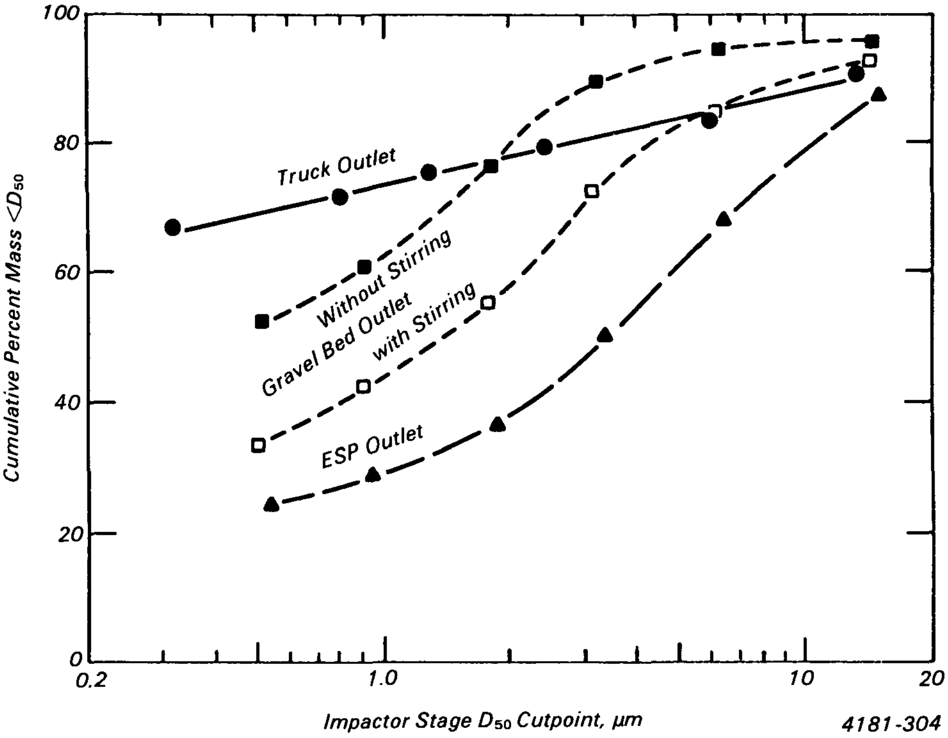

*Figure 9. Impactor testing of ESP/gravel bed combination. Cumulative percent particulate mass of aerodynamic diameter less than the impactor stage $D_{50}$ cutpoints.*

## ESP/Gravel Bed Filter

The gravel bed filter was connected in the exhaust line after the ESP to test the concept of using a granular filter to trap diesel particulate that had been agglomerated in the ESP. The ESP/gravel bed filter was tested at a diesel truck speed of 88 km/hr (55 mph). The gravel bed consisted of a 10 cm depth of 2 mm steel shot. Cascade impactor data for the ESP/gravel bed combination are shown in Figure 9. The combination was tested with and without stirring of the surface of the gravel with a rake to break up the cake of carbon soot that forms on the surface. Stirring resulted in a large puff of collected carbon soot passing through the exhaust line. The curve labeled WITH STIRRING represents average data for impactor runs which included one stir in the middle of each 30 minute data collection run. The curve labeled WITHOUT STIRRING represents average data for runs taken over 3 days, with the gravel bed stirred once each day before the beginning of testing. This daily stirring reduced the engine backpressure from a maximum value of 17 kPa (68 in. $H_2O$) to about 12 kPa (48 in. $H_2O$). Comparison of data from afternoon impactor runs and runs the next morning, after stirring, indicated that mass removal efficiency did not vary measurably with the change in engine backpressure.

The total mass loading of the impactor stages plus backup filter is summarized in Table 3. The overall mass removal efficiency, without stirring the gravel bed, was 86%. The data in Figure 9 show that the mmd of the agglomerated diesel soot (about 3.5 μm) greatly decreases when the gas stream passes through the gravel bed. This is the result of larger particulate being trapped in the gravel bed. Figure 10 shows electrical aerosol size analyzer data for the ESP/gravel bed combination, with the diesel truck running at 88 km/hr. In the aerodynamic size range around 0.1 μm, the ESP alone achieved 60-70% removal of particulate mass. The addition of the gravel bed resulted in only a small improvement in mass removal in this small size range. The main function of the gravel bed is to trap the particulate mass which has been shifted to a larger size range by the ESP.

*Table 1. Cumulative Percent Mass > $D_{50}$ of Diesel Soot Agglomerated by the ESP*

| | 8.3 μm | 3.9 μm | 2.5 μm | 1.1 μm | 0.5 μm |
|---|---|---|---|---|---|
| Cascade Impactors | 17% | 35% | 49% | 61% | 67% |
| Five-Stage Cyclone | 24% | 35% | 44% | 50% | 57% |

*Table 2. Summary of Testing Cyclones at High Gas Flow Rates*

| Cyclone | Flow Rate $m^3$/min | Pressure Drop kPa (in. $H_2O$) | Mass in Catchpot % |
|---|---|---|---|
| 9 | 0.55 | 1 (4) | 23 |
| 9 and 3 | 0.55 | 56 (14) | 52 |
| 9 and 3 | 0.80 | 96 (24) | 52 |
| 4 | 0.80 | 96 (24) | 37 |

Because the ESP/gravel bed combination had demonstrated high-efficiency cleaning of diesel exhaust gas for a practical operating time, the gravel bed was reduced to a more practical size. A gravel bed diameter of 20 cm was chosen, to correspond to the ID of the ESP and to achieve a reduction in filter area by a factor of 5. Operating the diesel truck at 88 km/hr results in a filtration velocity of 3.2 m/sec. The mass removal efficiency was tested by mass train sampling at the diesel truck outlet and at the gravel bed outlet. Test results for gravel beds 5 and 10 cm deep are summarized in Table 4.

These tests indicate that a compact gravel bed filter can be contained in the ESP housing, directly below the collecting cylinders, and can achieve mass removal efficiency of 70% or better, at acceptable levels of engine backpressure. The gravel bed filter can be cleaned simultaneously with the ESP by wet flushing with perchloroethylene. The mass removal efficiency of the ESP/gravel bed combination is largely independent of the running speed of the diesel truck. The higher mass loadings at lower exhaust gas flow rates are compensated by collection of greater particulate mass per unit volume gas flow by both the ESP and the granular filter. However, lower exhaust gas flow rates reduce the scouring of the insulating standoffs in the ESP and lead to more frequent cleaning.

## ESP/Fiber Filter

Two types of ESP/fiber filter combinations were tested: (1) the deep bed filter, previously tested on primary diesel exhaust, was loaded with fiberglass batts and connected in the exhaust line after the ESP; and (2) the concept of agglomerating and trapping diesel particulate in a single compact device, with a removable cartridge filter, was tested with an electrified filter. This two-stage device transforms high axial gas flow past a disk electrode in the corona charging section into a much lower radial gas flow in the collector section. The inner and outer sections of the collector assembly were loaded with various types of fiberglass filter media. The device had both electrical and mechanical forces acting to collect diesel soot.

The performance of these devices exhibited the behavior typical of all fiber filters tested: high mass removal efficiency (60-70%) but a lifetime of at most a few hours due to rising engine backpressure. The electrified filter also experienced deterioration of electrification because of diesel soot buildup in the electrified fiberglass filter. Two general conclusions derive from a variety of laboratory tests involving the aftertreatment of diesel exhaust with fiber filters: (1) high collection efficiencies and short operating

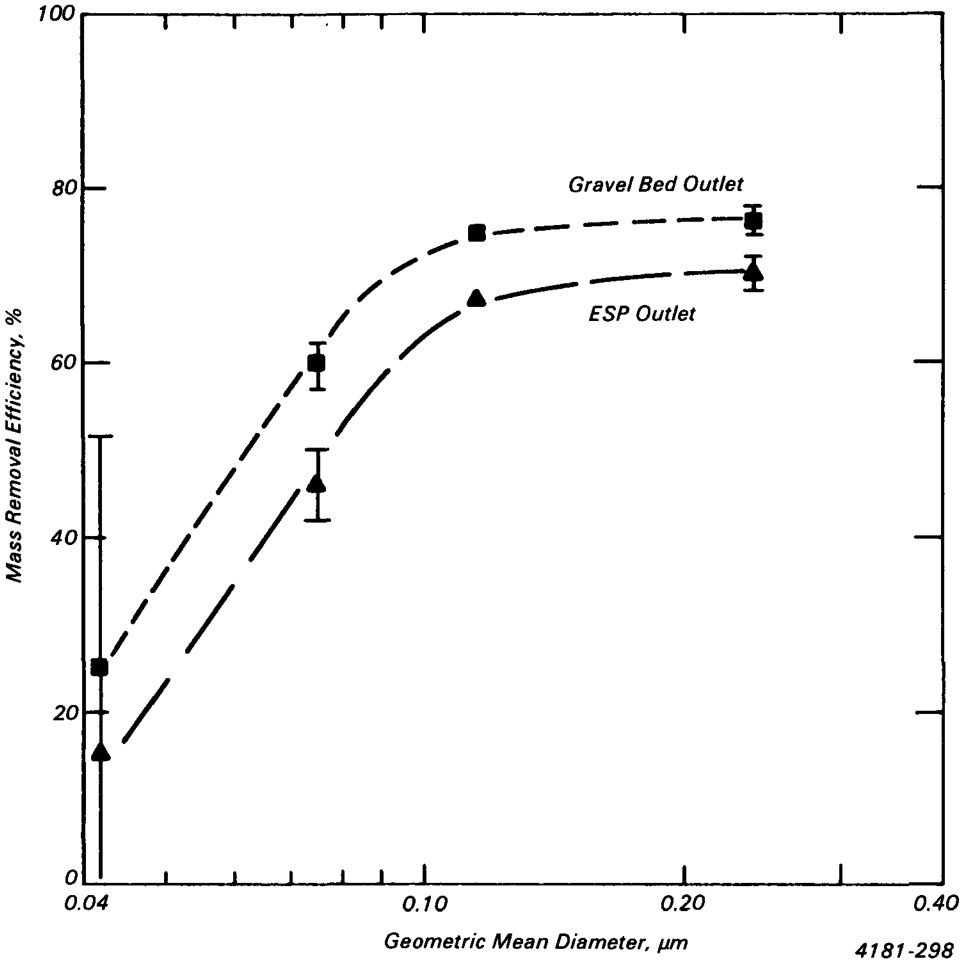

*Figure 10.* *Mass removal efficiency in small size ranges of diesel particulate.*

*Table 3.* *Total Mass Loadings Measured for the ESP/Gravel Bed Combination*

| *Sampling Point* | *Total Mass Loading mg/scm* | *Total Removal Efficiency %* |
|---|---|---|
| *Truck Outlet* | 37.7 | — |
| *ESP Outlet* | 27.7 | 26 |
| *Gravel Bed Outlet:* | | |
| *With stirring during impactor runs* | 20.7 | 45 |
| *Without stirring* | 5.4 | 86 |

*Table 4.* *Mass Removal Efficiency of the ESP in Combination with a 20-cm Diameter Gravel Bed Filter*

| *Gravel Bed Depth cm* | *Backpressure kPa (in. $H_2O$)* | *Outlet Mass Loading* | | *Efficiency %* |
|---|---|---|---|---|
| | | *Truck mg/scm* | *Gravel Bed mg/scm* | |
| 5 | 10 (40) rising to 15 (60) in 3 hours | 34.9 | 15.3 | 56 |
| 10 | 12 (48) rising to 16 (64) in 3 hours | 37.9 | 11.6 | 69 |

periods will result from a dense cake of carbon soot forming on the surface of the filter material and causing a rapidly increasing pressure drop; and (2) exhaust gas leakage around the edges of the filter material, resulting from high pressure drop, will be a problem in using any replaceable cartridge filter.

## Moving Belt ESP

A moving belt ESP designed for automotive use was also tested. In this device, the collection surface is a thin steel belt which slowly moves so that the collected material is removed from the area of high gas flow to reduce reentrainment. The device was tested in Japan using a 0.9 μm mmd soot produced by burning natural gas with excess air. For a 2.7 $m^3$/min gas flow rate at 40°C, collection efficiencies of 60% with a stationary belt and 82% with a moving belt were measured. At the SoRI laboratory, the moving belt ESP was tested on diesel exhaust which differed from the soot used in the Japanese test in that the particulate mmd was 0.3 μm at a flow rate of 3.2 $m^3$/min. The gas temperature was 113°C, resulting in a drier, more easily reentrained soot. In addition, current leakage problems necessitated reducing the operating voltage of the ESP from 18 to 15 kV. Consequently, the collection efficiency was reduced to 9% with a stationary belt and 21% with a moving belt. The latter was unreliable: it repeatedly "walked" off the end of the rollers and jammed the mechanism. Tests at a lower flow rate (2.0 $am^3$/min) were inconclusive due to conductive contamination of the insulators.

## Conclusion

Use of a fine fiber filter to capture diesel soot does not appear to be practical due to its tendency to form a cake on the face of the filter. This cake of particles reduces gas flow through the filter which rapidly increases the pressure drop across the device. The pressure continues to increase until it either impedes the operation of the engine or establishes a lower pressure route around the filter mat. Once a route for gas sneakage is established, the collection efficiency of the device drops sharply.

The three condensation traps tested were unable to achieve acceptable collection efficiencies. In addition, there was no evidence that these devices were agglomerating particulate. Instead, they produced a fog of small particles as hydrocarbon vapors in the diesel exhaust were condensed in the control device.

The granular bed filter may be applicable to the diesel exhaust problem. Although its collection efficiency was not as high as that of a fiber filter, the gravel bed has the important advantage of being cleanable, whether by mechanical agitation or wet flushing. The ceramic monolith filter showed a high collection efficiency but has a limited lifetime without *in situ* regeneration. This device is being developed by EPA at Ann Arbor, MI, and by several automobile manufacturers to extend its usable lifetime by direct or catalytic combustion of cakes of collected particles.

Conventional ESP is effective in agglomerating diesel particulate matter. An ESP can be used with either cyclones or a granular filter to obtain mass removal efficiencies of 50-85% at moderate engine backpressure and for a practical operating time between maintenance periods. Such a combination device can be made sufficiently compact to be used on stationary diesel engines or on large, heavy duty diesel vehicles engaged in fleet operation where periodic maintenance can be performed at a central garage. However, an ESP will demonstrate too low a collection efficiency to be used alone.

## Recommendations

Fiber filters do not appear suitable for the capture of diesel soot. Fine fiber filters exhibit high collection efficiency but have short lifetimes due to filter blinding. The coarse fiber filters tested, the traps, had inadequate collection efficiency. The granular bed filter proved to be usable, but needs to be redesigned for adaptation to a vehicle and for easy disposal of collected particles. The ESPs tested had poor collection efficiencies but were successful particle agglomerators. An ESP in combination with a mechanical collector, such as a cyclone or gravel bed, may be usable, but further development is needed to provide a device of practical safety, size, and durability as well as to develop the total system for electrode and bed cleaning.

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***Dennis C. Drehmel** is the EPA Project Officer (see below).*

*The complete report, entitled "Studies of Particulate Removal from Diesel Exhaust," (Order No. PB 84-168 913; Cost: $13.00, subject to change) will be available only from:*
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