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Technical Report

Summary & Analysis of Comments to the Draft Recommended Practice for Measurement of Gaseous and Particulate Emissions from Heavy-Duty Diesel Engines Under Transient Conditions

by

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NOTICE

Standards Development and Support Branch
Emission Control Technology Division
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Office of Air, Noise and Radiation
U.S. Environmental Protection Agency

EPA will soon publish a Notice of Proposed Rulemaking (NPRM) for the control of heavy-duty diesel particulate emissions for 1985 and later model year engines. Because the early establishment of a test procedure is essential for obtaining test data in response to the proposal, a draft particulate test procedure, entitled "Draft Recommended Practice for Measurement of Gaseous and Particulate Emissions from Heavy-Duty Diesel Engines Under Transient Conditions" was distributed to interested parties in May 1979. The document was accompanied by a request for comments and suggested modifications. Two heavy-duty diesel manufacturers, Cummins and Caterpillar, submitted comments addressing the draft particulate test procedure. A review of these comments and recommendations for changes to the draft test procedure follows.* The comments have been grouped into five general categories which are shown below. In each category, quotations of the comments are presented followed by analyses and recommendations.

I. Single vs. Double Dilution.

II. Equipment Specifications.

III. Temperature and Residence Time Requirements.

IV. Engine-Related Requirements.

V. Filter Weighing Procedure.

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* Only those comments addressing particulate measurement will be considered here. Comments addressing gaseous emission testing have been analyzed elsewhere.

NOTE: All references referred to in this report are shown as _/.

I. Single vs. Double Dilution

A. Cummins

1. Comment (§86.1310-83(b)(2)(a)(i) and (ii))

"It is inconsistent to require 125°F maximum at the sampling zone for single dilution while allowing 125°F maximum immediately ahead of the filter for double dilution. This allows considerably more cooling by heat transfer for the double dilution technique with the result that a lower overall dilution is required."

2. Analysis

Both the single-dilution system and the double-dilution system are designed to cool diesel exhaust by adding dilution air so that the sampling zone temperature never exceeds 125°F. By cooling the exhaust with dilution air, both the single- and double-dilution processes better simulate actual environmental conditions than a system which cooled the exhaust via convection (e.g., with a heat exchanger). The two processes differ in that the single dilution system cools the diesel exhaust with a one-step dilution process while the double dilution system cools the diesel exhaust through a two-step dilution process. Along with this cooling by dilution air, both systems inevitably allow some cooling by convection through the walls of the sampling system.

In reality, the double dilution system can allow more cooling by convection than the single-dilution system due to the low flow rates occurring in the particulate transfer tube and the secondary dilution tunnel. It is generally believed that the equilibrium between the gaseous hydrocarbons and those on the particulate is affected by the method of cooling (specifically cooling by dilution versus cooling via convective heat transfer), as well as by the final absolute temperature of the diluted exhaust. Directionally speaking, cooling the exhaust by convective heat transfer should increase the amount of hydrocarbons associated with the particulate compared to cooling by dilution. This would cause an increase in the mass of particulate formed and measured.

The "Draft Recommended Practice" did attempt to limit the degree of heat loss from the particulate transfer tube by restricting its length to 35 inches. However, manufacturers can design the length of the particulate transfer tube to be much shorter than 35 inches to reduce the convective heat loss even further. Convective heat loss can also be reduced by insulating both the transfer tube and the secondary dilution tunnel. The use of insulation is allowed under the existing requirements of the "Draft Recommended Practice."

Tests of Mercedes-Benz and Peugeot light-duty diesels using the heavy-duty measurement system have shown only very small differences in particulate measurements between single and double dilution systems, when the sample temperature is 125°F or less in both cases.1/ This shows at least in this case that the extra convective cooling for the double dilution system is not important and that use of the two-stage dilution process does not affect results. This also appears to confirm that the maximum sample zone temperature of 125°F is the controlling factor for accurately measuring particulate emissions and that this temperature should remain as a requirement in the proposed test procedure.

In a related development discussed in Section II below, it is recommended that the 2 second residence time requirement for the secondary dilution tunnel be reduced to 0.25 second. This change should allow a further reduction in the amount of convective cooling occuring with double dilution and reduce even further any differences seen between double and single dilution. Thus, the 125°F temperature requirement should remain as the primary dilution controlling specification for both systems.

B. Caterpillar

1. Comments (§86.1310-83(b)(1)(A))

> "Has accurate measurement of gaseous emissions been demonstrated with a diesel engine for the high-dilution ratios necessary for the "single-dilution method" of measurement? Because of this concern and to minimize equipment size, we intend to use the "double-dilution method" of measurement."

2. Analysis

At the present time no test data are available on the measurement of gaseous emissions using the single-dilution method for heavy-duty diesel engines. However, concentrations of gaseous emissions have been measured in the primary dilution tunnel of a double dilution system.2/ If these primary dilution tunnel concentrations are simply divided by the dilution factor from primary to secondary tunnel, then the resulting concentrations should be those that would occur in a single dilution system for the same test, as the overall dilution ratio should be the same in both cases. Thus, the ability to measure gaseous emissions using the single dilution method can be estimated from test results obtained using the double dilution system.

The concentration of gaseous emissions in the primary dilution tunnel of a double dilution system can be estimated from heavy-duty diesel test data taken at Southwest Research. One example of such test results is shown below for a hot start of a Cummins NTC-350 diesel engine.

Bag	HC (ppm)	CO (ppm)	CO_2 (percent)	NOx (ppm)	Cycle
1	16	30	0.30	27.1	New York Non-Freeway
2	19	23	0.45	41.3	Los Angeles Non-Freeway
3	22	23	1.23	174.9	Los Angeles Freeway
4	17	18	0.29	24.9	New York Non-Freeway

The dilution ratio (dilution air/exhaust) in the secondary tunnel is about 4:1. If the above test were performed under a single dilution system, the resulting concentrations should then be about one-fourth of these values. Thus, most of the above values for HC, CO, and NOx would be in the 0-10 ppm range, and some values may even be in the 0-5 ppm range for HC and CO. The CO_2 concentrations would also be very low, on the order of about 0.10 percent (except for Bag #3, which would be about 0.30 percent). These HC, CO_2, and NOx levels should not be a problem to measure accurately with analyzers presently used for measuring these emissions.3/ These analyzers have the ability to measure several different ranges of emission concentrations, with a few range selections covering the low concentrations shown above. Also, background levels, which are presently measured for these three pollutants, are on the order of 0-5 ppm for HC and NOx, and 0-1.0 percent for CO_2.

However, the CO concentrations discribed above would be difficult to measure accurately with the instruments normally used to measure CO concentrations. For example, background CO levels are usually assumed to be zero because most analyzers presently used cannot measure CO concentrations as low as ambient levels. However, these low concentrations can be measured with instruments of higher sensitivity. For example, commercially available nondispersive infrared (NDIR) analyzers can detect CO concentrations down to about 0.5 to 1.0 ppm.4/ The degree of this sensitivity is directly proportional to the length of the cells, the electronic amplification, and operating pressures.4/ The cost of a system that measures CO concentrations as low as 0.5 to 1.0 ppm would be about $3000 more than a system used to measure minimum CO concentrations of 10 ppm.3/ This extra cost is not large in comparison to the overall cost of equipment needed for particulate measurement.

Thus, low concentrations of HC, CO_2, and NOx emissions can be measured accurately in a single dilution system with analyzers currently used while low CO emissions can be measured accurately if high sensitivity analyzers are used. Given this, the single dilution method should still be considered an acceptable method for measuring gaseous as well as particulate emissions.

II. Equipment Specifications

Tunnel Diameter

A. Cummins

1. Comments (§86.1310-83(b)(6)(ii))

"It is our understanding that the 18" primary tunnel diameter is not a requirement. Cummins plans to use tunnels of 12 to 14 inches in diameter."

B. Caterpillar

1. Comments (§86.1310-83(b)(6)(ii))

"Why must the tunnel be 'at least 18.0 inches in diameter?' What is wrong with 12, 13, 14, etc. as long as turbulent flow and complete mixing are achieved? We are using a 12 inch diameter tunnel with our PDP-CVS with no apparent problem."

2. Analysis

A minimum primary dilution tunnel diameter of 18 inches is specified in the "Draft Recommended Practice" and is a requirement. The use of a tunnel diameter smaller than 18 inches would be violating this requirement as it currently exists.

A minimum tunnel diameter and a distance from exhaust inlet to particulate probe has been prescribed to insure that adequate residence times and mixing occur for both the single and double dilution tunnel systems. The question of a minimum tunnel diameter will be examined here, while the question of tunnel length will be examined in the discussion of the following comment.

In general, the dilution tunnel diameter should be specified to insure that differences in tunnel diameter do not produce differences in measured particulate emissions. Since the effective tunnel diameter in-use is quite large, EPA's policy has been to rely on the data taken using relatively large tunnel diameters. Smaller tunnel diameters have only been allowed after their equivalency with larger diameter tunnels has been demonstrated. To date, no such work has been done on heavy-duty diesel testing systems. Only the work performed on light-duty diesels is available.5/ There, the minimum tunnel diameter with demonstrated equivalency was 8 inches.5/ Since the tunnel length specification is being relied upon to provide adequate mixing, the residence time is the parameter of interest here and should be used to scale this 8 inch diameter up to a heavy-duty diesel system. For the light-duty diesel tests in question, the CVS flow would have been around 600 cubic feet per minute. Assuming that the recommended tunnel length of ten tunnel diameters was used, the residence time would then be at least 0.23 seconds, or roughly a quarter of a second.

The residence time required for measuring particulate emissions from heavy-duty diesel (HDD) engines should then also be at least 0.25 seconds. From this residence time, the minimum tunnel diameter can be determined if the tunnel length and the flow rate are known. Looking first at a HDD single dilution system, it is again assumed that the tunnel length will be 10 tunnel diameters, the same as that recommended in the LDD test procedure and the "Draft Recommended Practice." The tunnel flow rate is assumed to be 6000 CFM. The minimum tunnel diameter, then, must at least be 17.7 inches for a residence time of 0.25 seconds. A diameter of 18 inches would assure this proper residence time. This agrees with the minimum tunnel diameter of 18 inches stated in the "Draft Recommended Practice." Thus, this specification should remain for the single dilution system.

For the double dilution system, the residence time has been specified to be at least 2 seconds in the secondary dilution tunnel alone. However, the need for this residence time should be reexamined in light of the conclusion on residence time shown above. Also, Cummins has expressed concern that a residence time of 2 seconds or more in the second tunnel may lead to proportionality problems due to time delays in the secondary tunnel. On the basis of the light-duty data mentioned above, a residence time of 0.25 seconds should be adequate for interaction between particulate matter and hydrocarbons. However, this residence time should occur after the final dilution step to assure enough time for particulate and hydrocarbon interaction at exhaust sampling concentrations. For this reason, a residence time providing adequate particle-gas interaction is not a concern in the primary tunnel of the double dilution system.

As it turns out, the residence time for particle-gas interaction is the only consideration in the secondary tunnel. Mixing is not important in the secondary tunnel since the filter covers the whole area of the tunnel, collecting all particulate matter flowing through this tunnel. Thus, a residence time of 0.25 seconds minimum in the secondary dilution tunnel should be recommended for the proposed test procedure.

As we have seen, the tunnel diameter (and length) of the primary tunnel does not depend on a time necessary for particulate and hydrocarbon interaction. However, the primary dilution tunnel diameter must be large enough to allow for good mixing and to accomodate both the incoming exhaust and dilution air flow rates, so that high pressure drops do not occur along the tunnel. High pressure drops may result in air leaks into the transfer tube and unrepresentative conditions at the particulate sampling zone. Also, the tunnel diameter should be large enough to provide adequate space for the orifice plate and other equipment associated with the primary dilution tunnel (such as sampling probes, transfer tube, etc.). For accommodating raw exhaust only, the diameter of the primary dilution tunnel should be at least the same as the diameter of the tubing from the engine exhaust system to the entrance of the primary dilution tunnel. This diameter is usually 5-6 inches. The primary dilution tunnel diameter should then be at least 8 inches to prevent high pressure drops and to provide space for the orifice plate and other equipment. More importantly, a primary dilution tunnel of 8 inches has been the smallest diameter used for testing light-duty diesels,5/ where accurate measurements have been demonstrated. A smaller absolute diameter should not be allowed until equivalency has been demonstrated with smaller diameters.

An initial attempt has been made to look closer into the necessary tunnel diameter (and length) for good-mixing between particulate emissions and surrounding dilution air. A model was developed to describe the radial diffusion of particulate matter in a tunnel with constant turbulent bulk flow in the axial direction. The model consists of the following equation:

$$Ed\,\frac{\partial^2 C}{\partial r^2} + \frac{Ed}{r}\frac{\partial C}{\partial r} = \frac{\partial C}{\partial t} \qquad (1)$$

where:

Ed = eddy diffusivity
C = concentration of particulate in dilution air
r = radius at any point in the tunnel
t = space time, or Al/v
A = area of tunnel, πr_2^2, l= tunnel length, v= average gas velocity in tunnel

Initial conditions and boundary conditions must be specified so that the above equation can be solved. The following initial condition was assumed:

$$C(r,\ t = 0) = C(r) \text{ for } 0 \leq r \leq r_2 \qquad (2)$$

C(r) is further described by:
$C = Co$ at $0 \leq r \leq r_1,\ t = 0$
$C = 0$ at $r_1 \leq r \leq r_2,\ t = 0$

where:
r_1 = exhaust pipe radius
r_2 = tunnel radius

The following boundary condition was specified:

$$\frac{dC}{dr} = 0 \text{ for all } t \text{ at } r = r_2$$

The rigorous details needed to obtain the final solution will not be given here. The final solution was obtained by using the separation of variables technique along with a Bessel function solution.6/ The formal solution to this boundary value problem is:

$$C(r, t) = \frac{2}{r_2^2} \sum_{j=1}^{\infty} \frac{Jo\ (\alpha(j)r)}{[J_1(\alpha(j)r_2)]^2} \exp(-\alpha(j)^2 \cdot Ed \cdot t) \int_0^{r_2} sf(s)Jo(\alpha(j)s)ds \qquad (3)$$

The Bessel function Jn(x) can be found in typical numerical tables of Bessel functions.7/ The numbers α(j) are square roots of the eigenvalues associated with the eigenfunctions of equation(3). The variable s is a variable of integration.

A significant problem with the solution to the above problem is that it neglects the effect of the orifice plate at the tunnel entrance. Such a mixing orifice is allowed as a mixing enhancer. The effect of the orifice should be large enough to void the results of any model which ignored its effect. Thus, further work is needed to incorporate the effect of the orifice before analytical results can replace the empirical.

In summary, the dilution tunnel for a HDD single dilution system should have a diameter of 18 inches minimum as specified in the "Draft Recommended Practice." For the primary tunnel of the double dilution system, the diameter should be at least 8 inches. Also, the required residence time for the secondary tunnel should be reduced from 2 to 0.25 seconds.

Tunnel Length

A. Caterpillar

1. Comments (§86.1310-83(b)(8)(b)(i)(A)( ))

"Why must particulate probe be 'approximately 10 tunnel diameters downstream of the point of where the exhaust enters the primary-dilution tunnel' if good mixing has been achieved? The tunnel length could be quite short if mixing vanes and a smaller tunnel diameter were allowed. Centrifuging of the particulate is unlikely because of its very small size.

2. Analysis

The proposed tunnel length is necessary for two reasons. First, it provides adequate time for gaseous phase hydrocarbons to come to equilibrium with particulate matter before sampling takes place in the case of single dilution. Second, sufficient distance is needed for thorough mixing of exhaust and dilution air. Even if interaction between particulate and gaseous emissions were not important, mixing vanes could not be used to achieve quick mixing since it has been shown that a measureable decrease in particulate emissions from diesels can occur due to particulate deposition on mixing exhancers, such as baffles.8/ Thus, the use of mixing vanes should still be prohibited.

Although mixing vanes should be prohibited, the "Draft Recommended Practice" does allow the use of a mixing orifice at the engine exhaust inlet to the primary dilution tunnel (see Figures 83-3 and 83-4). This orifice causes the exhaust and dilution air flow to become more turbulent, thus enhancing the mixing. Particulate deposition should not occur with the mixing orifice as the exhaust inlet plane is located at the mixing orifice plane or just downstream of the plane. The mixing orifice is the only mixing enhancer allowed in the "Draft Recommended Practice".

The mixing length of 10 diameters is generally accepted as a length for good mixing in a tunnel with turbulent flow. In some cases, mixing may also be achieved by using a shorter tunnel length than the recommended 10 tunnel diameters. At present, data are not available showing the extent of mixing for tunnel lengths less than 10 tunnel diameters. If good mixing is demonstrated with data (i.e., tunnel transverse study), then the acceptance of a shorter mixing length would be considered. Any reconsideration of length would also have to take into account the effects on residence time in the case of single-dilution (see previous comment, Tunnel Diameter). In the absence of the data, the recommended tunnel length should remain at 10 tunnel diameters.

Transfer Tube

A. Caterpillar

1. Comments (§86.1310-83(b)(8)(b)(i))

"(D) The available literature supports a length greater than 35 inches for a 0.5 inch inside diameter line. Besides, shouldn't the length be a function of the inside diameter of the line being used since only a minimum diameter is specified in the preceding paragraph? (E) An example of a 'sharp bend' would be helpful."

2. Analysis

The "Draft Recommended Practice" states that the particulate transfer tube should not be longer than 35 inches. A length greater than 35 inches will allow additional cooling by convection (see Cummins' comment in Section I, Single vs. Double Dilution). This may cause additional interaction of gaseous hydrocarbons on the particulate surface which could result in a higher particulate measurement.

The diameter of the transfer tube is also required to be at least 0.5 inches. The use of a diameter less than 0.5 inches is prohibited as this could cause high pressure drops along the transfer tube which could result in a great variation of the transfer tube flow rate as a function of temperature. Also, the use of a smaller diameter could bring about particulate deposition on the tube walls. While the use of a larger diameter is allowed, this could also result in more cooling by increasing the residence time in the transfer tube, assuming that the flow rate would remain constant. If a larger diameter were coupled with a longer transfer tube, the residence time would increase even further. More heat would be lost by convection and the possibility of increased particulate readings would be much greater than increasing either the diameter or the length alone. Thus, the maximum length of the particulate transfer tube is at least necessary to help prevent a possible increase in paritculate readings.

It is not known what available literature supports a length greater than 35 inches for a 0.5-inch inside diameter. Thus, the particulate transfer tube length of 35 inches and diameter of 0.5-inch minimum should remain as a requirement unless supporting data show otherwise.

The requirement, "Free of sharp bends," does appear to be difficult to define and should therefore be deleted. This requirement was made so that particulate deposition would be minimized. The requirement should be revised to read, "Designed to minimize deposition of particulate." For example, this may mean making bends as gradual as possible and eliminating obstructions such as sensors. This requirement should be added to the proposed test procedure description.

Heat Exchanger

A. Caterpillar

1. Comment (§86.1310-83(b)(8)(b)(iv)(B) and (viii))

"We assume that these gas temperatures can also be controlled with standard type heat exchangers as long as they are not located in the mixture stream ahead of the particulate filter. This would be like the SwRI secondary dilution system."

2. Analysis

That is correct.

Microgram Balance

A. Cummins

1. Comment (§86.1312-83(b))

"A 100mm Pallflex filter weighs about 300mg. If we expect a 10mg loading, then 0.01mg weighting accuracy should be sufficient. Microgram readability is not required."

B. Caterpillar

1. Comments (§86.1312-83(b))

"Measurement capability to one microgram is more than is needed. A 10 microgram capability would be more than adequate. Also, can the readability and precision both be one microgram?"

C. Analysis

Before analyzing the necessary measurement capability of the weighing balance, the terms readability, accuracy, and precision should be clarified as their meanings seem to be confusing in these comments and in the "Draft Recommended Practice." Readability is defined as the closeness with which the scale of the instrument may be read.[9] Accuracy is defined as the deviation of the reading from a known output, usually expressed as a percentage of full scale reading.[9] Precision is defined as the ability to produce a certain reading within a given accuracy,[9] or the closeness of repeated measurements to one another for measurements of the same quantity.[10] An example of the distinction between accuracy and precision can be shown for a particulate sample that has a true weighing of say 100 micrograms, but the microgram balance shows weighings of 102, 103, and 104 micrograms in three different weighings. From these values it can be seen that the weighing balance could not be depended on for an accuracy better than ±4 percent (4 micrograms) while a precision of ±1 percent is indicated since the maximum deviation from the mean is only 1 microgram. This example also shows that the accuracy can be improved to but not beyond the precision of the instrument of calibration.

The "Draft Recommended Practice" states that the microgram balance should have a precision (standard deviation) of one microgram. The term "precision" should be revised to "accuracy" because the deviation from the true weighing of a particulate sample is of primary concern here. The above definitions and example show that if precision only is specified, then the accuracy may be poor or even unknown. Thus, the term "precision," as stated in the "Draft Recommended Practice," should be replaced with "accuracy" in the proposed test procedure.

The necessary measurement capability, or accuracy, of the weighing balance can be determined through an uncertainty analysis.[9] The general equation for measuring uncertainty of an experiment can be expressed as follows:

$$WR = \left[\left(\frac{\partial R}{\partial X_1} W1\right)^2 + \left(\frac{\partial R}{\partial X_2} W2\right)^2 + \ldots + \left(\frac{\partial R}{\partial X_n} Wn\right)^2\right]^{1/2} \qquad (1)$$

Where:

X_i = input variables.

W_i = uncertainty in the input variable, X_i.

R = the final measurement, a function of the input variables X_1, X_2, X_3, ..., X_n.

WR = uncertainty in the result, R.

This uncertainty analysis can be applied to the weighing of diesel particulate test samples. This can be accomplished in three major steps. First, the total weight of the particulate as a function of individual measurements must be determined. Second, the uncertainty of each independent variable must be established. Third, the particulate weight function and the uncertainties of each independent variables can be substituted into equation (1) to determine the uncertainty of the total sample weight. After these steps have been performed, the necessary accuracy of the balance can be discussed.

The weight of a particulate sample can be determined from the following equation:

$$P = (f_{1p} - f_{1c}) + (f_{2p} - f_{2c}) \qquad (2)$$

Where:

P = total particulate weight.
f_{1p} = weight of primary filter plus particulate.
f_{1c} = weight of primary filter.
f_{2p} = weight of back-up filter plus particulate.
f_{2c} = weight of back-up filter.

The uncertainties for each of the four weighings f_{1p}, f_{1c}, f_{2p}, and f_{2c} are e_{1p}, e_{1c}, e_{2p}, and e_{2c}, respectively. These uncertainties are due to weighing balance error only. The errors due to dust, humidity, faulty handling, etc., are not included.

If equation (2) is substituted into equation (1), the partial derivatives of P with respect to f_{1p} and P with respect to f_{2p} become 1. The partial derivatives of P with respect to f_{1c} and P with respect to f_{2c} are equal to -1. Thus, equation (1) would be revised to:

$$WR = [(e_{1p})^2 + (-e_{1c})^2 + (e_{2p})^2 + (-e_{2c})^2]^{1/2} \qquad (3)$$

If the uncertainty in each weight due to the weighing balance accuracy is 10 micrograms, as suggested by Caterpillar and Cummins, then equation (3) would yield the square root of 400, or 20 micrograms. Thus, for weighing balance errors only, the uncertainty of any particulate weighing is 20 micrograms. Since other errors are involved with the weighing of particulate, such as faulty handling of the filter or contamination from dust, the uncertainty of each particulate sample weight due to the weighing procedure alone is greater than 20 micrograms.

In addition to the accuracy of the weighing procedure, the overall accuracy of transient test procedure results for particulate measurement is affected by many other factors. For example, accurate measurements of temperature and flow rates are necessary to assure that proportional sampling occurs during a transient test cycle. Because these and other factors contribute to overall accuracy, good measurements are required for each of these factors. For the weighing balance, it should be reasonable to require an accuracy of ±1 percent of the particulate sample weight when considering the other factors involved with determining the overall accuracy.

An accuracy of ±1 percent for the weighing balance would require the most sensitive detection for filter loadings of engines with low particulate emissions. Low filter loadings can occur with smaller engines, such as the IHC DTI-466B engine. Present Southwest Research testing data show that this engine emits about 4.33 grams of particulate during a hot or cold start cycle.2/ With a particulate transfer tube flow rate of about 1.6 CFM and an overall flow rate of 2000 CFM*11/, the filter loading for this engine is currently about 3.5 mg. A ±1 percent change of this filter loading would require that the uncertainty in each weighing is no worse than ± 35 micrograms. A weighing balance with an accuracy of 10 micrograms and consequently an uncertainty of ± 20 micrograms should provide the necessary accuracy for this particulate measurement. It is also likely that a weighing balance with an accuracy of ±10 micrograms could be used to accurately measure particulate emissions from other engines that are currently marketed.

Future reductions could easily bring the filter loadings for the IHC DTI-466B engine down to 2 mg or less. A 1 percent change of this filter loading would mean that the accuracy must be better than ±20 micrograms. However, it has been shown above that the uncertainty of a particulate sample weight is greater than ±20 micrograms if the weighing balance has an accuracy of 10 micrograms. Therefore, the accuracy of the weighing balance should be better than 10 micrograms.

The recommended heavy-duty diesel test procedure also states that if a change of more than ±1 percent of the nominal filter loading occurs in the weight of the reference filter during the conditioning period, then all filters in the process of being stabilized must be discarded and any test repeated. In the case of the IHC DTI-466B engine this nominal loading could be 2 milligrams with future reductions in particulate emissions. Once again, a 1

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* For this engine, Southwest Research used a flow rate of about 2000 CFM. This is not to be confused with the assumed flow rate of 3000 CFM used in other sections of this report.

percent change of this filter loading would mean that the accuracy must be better than ±20 micrograms during the conditioning period. The change of weight in the reference filter is determined by two weighings, one for the weight of the filter before and one for the weight of the filter after the conditioning period. If the weighing balance has an accuracy of 10 micrograms, then the overall uncertainty due to the weighing balance alone would be the square root of 200, or 14 micrograms (see equation 3 above). This alone would provide the necessary accuracy for the weighings of the reference filter. However, as mentioned above, many other sources of errors are involved during the weighing period, such as faulty handling or changes in humidity. These other sources of errors could decrease the overall accuracy of the weighing procedure from ±14 micrograms to over ±20 micrograms. Therefore, an accuracy of 10 micrograms for the weighing balance may not provide a safe enough margin for accurate weighings of the reference filter and this may result in many needless filter rejections.

Accuracy is at best equal to readability, and information on microgram balances shows that nearly all microgram balances currently sold have an accuracy equal to readability.12/13/14/15/16/ For this analysis, it will be assumed that accuracy and readability are the same. For engines with no particulate control, a balance with an accuracy and readability of 10 micrograms should be adequate. However, for future engines with particulate control, both the accuracy and the readability should be better than 10 micrograms. Present literature on microgram balances does not show balances having a readability between 1 microgram and 10 micrograms.12/13/14/15/ For example, a 5 microgram readability and accuracy may be sufficient in many cases for engines with particulate control, but available information only shows balances with readability and accuracy either to the nearest 1 microgram or to the nearest 10 micrograms. A one microgram accuracy and readability is thus necessary for future engines with particulate control to assure proper measurements and this requirement should be included in the proposed test procedure.

The cost of a microgram balance with an accuracy and readability of 1 microgram is approximately $1500 more than a balance with an accuracy and readability of 10 ug.16/ This cost should be small compared to the overall cost of the test equipment particularly considering that one balance can service a number of test cells.

Air Filter - Cyclonic Separator

A. Cummins

1. Comments (§86.1310-83, Figure N83-3 and 4)

"The schematic drawing in Figure N83-4 shows a dilution air filter which appears to be constructed with three different types of elements.

Because of the very large size of a filter system anticipated to be required for handling 10,000 SCFM, it is necessary to have a more explicit description of dilution air filtration requirements. The amount and type of filtration required will determine size, cost, facility requirements, etc.

The use of a cyclonic separator is also specificed presumably for particulate removal. This concept is effective where relatively large particles such as catalyst pellets, etc., are concerned but will not be effective in removing the submicron particulates found in diesel exhaust. It is recommended that the requirement for the cyclonic separator be deleted for diesel engine testing."

2. Analysis

The three divisions of the air filter in Figure 83-4 have no significance. Thus, the illustration of the air filter in the proposed test procedure should not show these divisions.

In general, an air filter is illustrated in Figure 83-4 to show the need to filter ambient air before it enters the primary dilution tunnel. If the air inlet is left unfiltered, suspended particulate could enter and cause an increase in the particulate measurement of the diesel engine exhaust. The size of this increase can be estimated if the particulate concentration of the dilution air is assumed to be the National Ambient Air Quality Standard of 75 micrograms per cubic meter. For a double dilution system with a primary dilution tunnel ratio similar to that used by Southwest Research, or about 4:1, a CVS flow rate assumed to be 3000 CFM, and a secondary dilution ratio of 3:1 the equivalent weight of the particulate originating from dilution air is about 0.38 gm for a 20 minute hot or cold start cycle. The suspended particulate in the dilution air of the secondary tunnel may represent as much as 75 percent of this effect. This particulate weight should have the greatest effect, in terms of grams per brake horsepower-hour (gm/BHP-hr), on the emission test results for engines performing the least amount of work over a transient test cycle. For example, the IHC DTI-466B only produces 12.04 BHP-hr over the transient cycle.2/ The emission results from tests on this engine could increase by as much as 0.03 gm/BHP-hr with an equivalent amount of approximately 0.02 gm/BHP-hr originating from the dilution air of the secondary tunnel, if the ambient air is left unfiltered with the above conditions. This contribution to particulate measurements may be enough to offset emission results which are usually recorded to the nearest 0.01 gm/BHP-hr. Any filter, of course, would reduce this effect dramatically.

While the "Draft Recommended Practice" only required filtration of the primary dilution air, it is apparent from this analysis that the secondary dilution air should require filtering also, especially when considering that approximately 75 percent of the contribution of background particulate to the particulate measurement originates from the secondary dilution air. For the proposed test procedure a filter should then be required for the dilution air entrance of the secondary tunnel.

As manufacturers would be the prime beneficiary of good filter design and they are the most knowledgeable about their individual systems, the actual size and design of the filters has been left up to the manufacturers. In this way, each manufacturer can choose a filtration system that he believes is the most cost-effective.

The cyclonic separator, also diagrammed in Figure 83-4, was based on the proposed test procedure for light-duty diesel vehicles. A comment was submitted that addressed the need for the cyclonic separator in the light-duty diesel proposed test procedure, and it was concluded that cyclonic separators should be necessary for catalyst vehicles only.1/ The cyclonic separator was made optional for light-duty diesel vehicles, and the same should be done here in Figure 83-4 for heavy-duty diesel engines.

III. Temperature Residence Time Specifications

Primary-Dilution Air Temperature

A. Caterpillar

1. Comments (§86.1310-83(b)(5)

> "Has the need to control primary-dilution air temperature so closely been demonstrated? This will require special conditioning of the dilution air, but in our case, a temperature range of 60°F to 100°F would not require special conditioning."

2. Analysis

The recommended temperature range of 77±9°F (25±5°C) for the dilution air entering the primary dilution tunnel was based on the dilution air temperature required for the light-duty diesel test procedure.5/ The use of a dilution air inlet temperature outside of this range may affect particulate and gaseous hydrocarbon interactions, which may affect particulate measurements. At the present time no data are available showing the effects of the inlet dilution air temperature outside of this range. If data are submitted showing no effect, then the required temperature range could be made larger. However, until data are submitted demonstrating that there is no effect, the required dilution air inlet temperature should remain at 77±9°F as stated in the "Draft Recommended Practice."

Water Temperature

A. Cummins

1. Comments (§86.1310-83(b)(2)(b))

"Is there a requirement as to the maximum or minimum allowable water temperatures used for heating or cooling the heat exchanger? Can steam or 180°F water be used when the heat exchanger is being used in the heating modes?"

2. Analysis

There is no specification for water temperature. Both steam or 180°F water can be used.

Residence Time

A. Caterpillar

1. Comments (§86.1310-83(b)(8)(b)(iii)(B))

"Shouldn't this read '----two seconds minimum----'?"

2. Analysis

The original intent of the "Draft Recommended Practice" was to read ". . . two seconds minimum. . . ." However, based on the analysis of tunnel diameter in Section II, Equipment Specifications, the residence time should be revised to 0.25 seconds in the secondary dilution tunnel. This change should be made in the proposed test procedure.

IV. Engine-Related Requirements

Exhaust System Length and Diameter

A. Cummins

1. Comments (§86.1310-83(b)(3) and §86.1308-83(b)(3)(i)(A)

"Cummins in-use minimum exhaust system length is approximately 12 feet. In order to 'share' one CVS system between two adjacent test cells, we would require an additional 25 feet of insulated stainless steel tubing to reach the CVS system inlet. We recommend that EPA specify a maximum length from engine to CVS system of 35 feet and allow manufacturers to choose the portion designated 'stock' exhaust system and make up the remaining length with stainless steel insulated tubing. We also recommend that the maximum inside diameter of the stainless steel tubing be raised from 5" to 6" because a 600 hp engine may not be able to meet typical in-use full load exhaust restriction requirements with a 5" diameter tube.

B. Caterpillar

1. Comments (86.1308-83(b)(3)(i)(A)

"At original certification, the engine manufacturer may not know all of the "in-use applications of the engine" in order to establish minimum exhaust system length. The EPA should specify range for acceptable exhaust system length such as 15 ±5 ft.

C. Analysis

The exhaust system length should be kept at a minimum to prevent convective cooling and particle deposition, as this would tend to artificially lower particulate measurements. Based on Cummins' comment, a 12 foot exhaust system length would appear to be a reasonable minimum length. Thus, since the minimum in-use exhaust system length is difficult to determine for each engine, an exhaust system length of 12 feet maximum should be recommended in the proposed test procedure.

The length of the tubing from the exhaust system to the entrance of the primary dilution tunnel must also be restricted to prevent excessive particulate deposition. The maximum length of 12 feet specified in the "Draft Recommended Practice" was based on the light-duty diesel (LDD) proposed test procedure. In the LDD Summary and Analysis of Comments, General Motors also commented on the length of the tailpipe.1/ Since that time, we have run data justifying a longer pipe length of 20 feet, if it is smooth and insulated.17/ Otherwise a maximum length of 12 feet still applies if the pipe is uninsulated. Thus, the tubing length from the exhaust system to the dilution tunnel in the proposed heavy-duty diesel test procedure should require a length of not more than 12 feet (365 cm) if uninsulated, and of not more than 20 feet (610 cm) if insulated and composed of smooth stainless steel tubing. Use of a longer length could be considered if further data were presented.

To arrive at an appropriate pipe diameter for accomodating the exhaust flows of heavy-duty diesel (HDD) vehicles, the HDD flow rate will be compared to the LDD flow rate. The maximum diameter of the tubing from exhaust to tunnel entrance is 4 inches in the LDD test procedure. An EPA study shows that a larger diameter may cause an increase in measurement of particulate emissions.17/ However, a larger diameter for heavy-duty testing is necessary to meet the full load exhaust requirements of some heavy-duty diesel engines. The largest light-duty diesel vehicle has an engine displacement that is about one-third to one-half the size of engines used to power the heavier Class VII and Class VIII vehicles. The rated engine speed for a light-duty diesel vehicle is also approximately 50 percent higher than the engine speed for Class VII and Class VIII heavy-duty diesel vehicles.18/ Thus, on the basis of engine displacement and engine speed, the exhaust flow rate should be roughly twice that for the larger heavy-duty diesels than for light-duty diesels. In addition, the predominant use of turbochargers on the larger heavy-duty diesel engines would increase the exhaust flow to even more than twice that of light-duty diesel vehicles. Cummins' request for a 6 inch exhaust pipe would be a 50 percent increase over the light-duty pipe in terms of diameter and a 125 percent increase in terms of cross sectional area. Given that the exhaust flow of heavy-duty diesels is more than twice that of light-duty diesels, an increase to 6 inches would only take into account the increased exhaust flow and no more. Thus, the request should be accepted and the specification changed to a maximum of 6 inches. A diameter larger than 6 inches would be considered in the future if sufficient data would show no effect on particulate measurement.

Exhaust Back Pressure

A. Caterpillar (86.1308-83(b)(3)(ii)(B)

1. Comment

"Again, at original certification, the engine manufacturer may not be able to identify 'the maximum back pressure application of the engine,' but the manufacturer's recommended maximum exhaust back pressure limit for the engine would be specified. The EPA should allow for this possibility."

2. Analysis

It is acknowledged that because of the many in-use applications of a heavy-duty diesel engine, it may be difficult to identify the maximum back pressure application of the engine. Therefore, the manufacturer's recommended maximum exhaust back pressure limit for the engine should be acceptable for the particulate test procedure.

V. Filter Weighing Procedure

Post Test Filter Stabilization Period

A. Caterpillar

1. Comments (86.1339-83(a)(b) and (e)

"The upper limit of 56 hours is unreasonable. For any test that is run late on any Friday, a person will have to work on the weekend to weigh the filters. Also, new filters weighed on a Friday could not be used for a Monday morning test. A new filter weighed early on Friday should be usable anytime (during normal working hours) on Monday. Also, a particulate sample obtained early on Friday should be allowed to be weighed on Monday. An upper limit of 80 hours should be adequate."

2. Analysis

The upper limit of 56 hours for the post test filter stabilization period was based on the upper limit specified for the light-duty diesel (LDD) test procedure. This conclusion from the LDD test procedure came from allowing Saturday testing to be weighed on Monday. Some facilities in the heavy-duty diesel engine industry may not be able to have Friday test results weighed before Monday morning. The upper limit of 56 hours should be increased to 80 hours to cover the additional time needed. This additional time should not affect filter stabilization. It is also possible that new filter weighings on Friday cannot be used until normal working hours on Monday, and that particulate samples received on late Friday cannot be weighed until Monday. Thus, an upper limit of 80 hours is recommended for these weighings also.

References

1/ "Summary and Analysis of Comments on the Nature of Proposed Rulemaking for the Control of Light-Duty Diesel Particulate Emissions from 1981 and Later Model Year Vehicles," SDSB, EPA, October 1979.

2/ Southwest Research Institute Diesel Baseline Emissions Summary, EPA, June 1, 1980.

3/ Telephone conversation with Brad Levin of Beckman Instruments, Inc., Automotive Test Instruments Operations, August 20, 1980 and September 28, 1980.

4/ "Air Quality Criteria for Carbon Monoxide," U.S. Dept. of Health, Education, and Welfare, No. AP-62, March 1970, p. 5-3.

5/ "Standard for Emission of Particulate Regulation for Diesel-Fueled Light-Duty Vehicles and Light-Duty Trucks," FR Vol. 45, No. 45, March 5, 1980, pp. 14496-14525.

6/ Churchill, R.V., and Brown, J.W., *Fourier Series and Boundary Value Problem*, pp. 207-210, 3rd Ed., McGraw Hill, 1978.

7/ Gray, A., and G.B. Mattews: *A Treatise on Bessel Functions and their Applications to Physics*, 2nd Ed., Dover Publications, Inc., 1966.

8/ Black, Frank, "Comments on Recommended Practice for Measurement of Gaseous and Particulate Emissions from Light-Duty Diesel Vehicles," ORD, EPA, April 13, 1978.

9/ Holman, J.P., *Experimental Methods for Engineers*, McGraw-Hill, Inc., Second Edition, 1971, pp. 37-38.

10/ Zar, Jerold H., *Biostatistical Analysis*, Preatice-Hall, Inc., 1974, pp. 4.

11/ Telephone conversation with Sherrill Martin of Southwest Research on July 17, 1980.

12/ "Scientech, Inc., Electronic Top-Loading Balance," Scientech, Inc., Series 222, March 1978.

13/ "Cahn Series-20 Automatic Electrobalance," Cahn Ventron Corp., 1978.

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14/ "Sartorius Balances and Scales," Brinkman Instruments, Inc.

15/ "Mettler Balances," Mettler Instrument Corporation, 1978.

16/ Telephone conversation with Ray Giles of Mettler Instruments Corporation, Inc., August 25, 1980.

17/ Penniga, T., "Evaluation of Exhaust Collection Configuration on Diesel Particulate Measurement," TAEB, EPA, May, 1979.

18/ Automotive Industries, April 1978, pp. 79-85, 94-99.