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Nature of Odor Components In Diesel Exhaust

Offensive exhaust odors are characteristic of diesel engines. One problem in control and reduction of odor is lack of understanding of odorant sources and mode of formation. The solution of this problem depends on identification of the odorants so that study of their formation and control can be undertaken. A human panel performed odor assessments in studying raw and modified diesel exhaust and synthetic blends representing portions of diesel exhaust. Their assessments were used in determining odorant identity and quantitative contribution to exhaust odor. Low molecular weight aldehydes appear to contribute little to diesel odors. The sulfur and nitrogen oxides have been examined as odorants but of these apparently only nitrogen dioxide is a potential odor contributor.

Considerable attention is being given to the role of diesel exhaust in air pollution. The well-known diesel odor is one of the more offensive characteristics of the exhaust, and the origin and abatement of this odor are being studied. In these studies odors are determined with the response of a human panel as the best available means to measure odor. However, the panel determinations do not directly indicate the chemical nature of the odorant materials. Furthermore, human panel measurements are inherently tedious and require elaborate preparation of the experimental conditions to produce reliable results. For these reasons, identification of the odorant will aid both in understanding the origin of the odor and in developing chemical analytical methods to replace human odor rating. Work done thus far by the Bureau of Mines is discussed in this report.

Experimental Techniques

The high potential number of odorous compounds in diesel exhaust made odorant identification by detailed analysis impractical. Diesel exhaust components were separated by volatility and by chemical nature. The odor distribution among the fractions was determined. In a typical experiment, the exhaust sample was treated by a fractionation method that was designed to remove a specific class of components;

odor levels in the sample were then determined by using a human panel. Resultant data were used to define odor levels associated with the components that were removed by the treatment. Conclusions about the quantitative contribution to the total odor of various components were verified on some occasions by using synthetic mixtures of these components. Procedures for sampling, sample handling, fractionation treatments, and odor measurements are described in detail in the following paragraphs.

Exhaust Sampling and Sample-Handling Procedures

In most odor evaluation work, samples were treated for the fractionation and presented to the panel by means of the system shown in Figures 1 and 2. In this system exhaust was drawn from the engine's tailpipe with an aspirator, rather than with a pump, to preclude distortion of sample by contact with pump walls. The exhaust sample was routed to the aspirator through a filter and on through one or two treatment trains connected in parallel. Each treatment train consisted of either a cold trap or a filter or a scrubber or a series of scrubbers or a bypass line. The resultant treated or bypassed sample stream was diluted with odor-free air to a ratio of 100:1, and this mixture was presented to the panel for odor evaluation. The filter holder and tubing in front of the treatment train were kept at 50-70°C. Dilution air was heated to 27-30°C to aid in cleanup of the system. (Cleanup seemed adequate since odor check at the end of each day's program showed that odor fell to trace level 30 seconds after exhaust was cut off from the system.)

The effect of a scrubbing or filtration method on the odor intensity was measured as the difference of the ratings of odor of exhaust treated by the particular method and the odor of a reference exhaust stream. Generally the reference stream was the same exhaust sample used in the study of the particular treatment method. It was not subjected to the particular treatment but otherwise was handled in the same manner. For this reason two alternate paths in the exhaust treatment system were used — one bypassing and one passing through the scrubber or filter being studied. Flow was equalized in

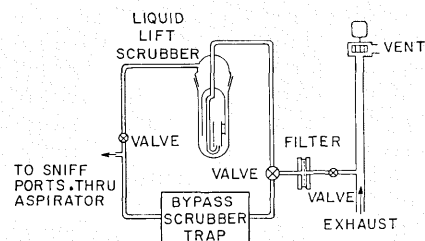


Figure 1. Exhaust sampling system.

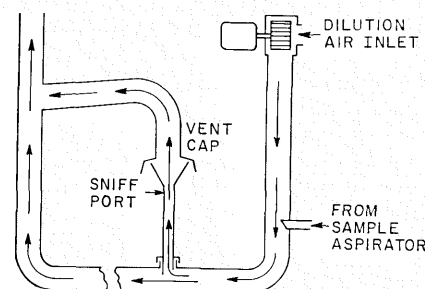


Figure 2. Dilution and sniff port system.

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the two paths whenever possible to permit rapid interchange in presenting the two sample streams.

Pure compounds were rated as odorants by passing the vapor and diluent directly to the odor presentation outlets without using the scrubbers and filters. Rating of these materials was also on a comparative basis. Nitrogen was the reference material, and all flows of samples, aspirating air, and dilution air were maintained constant to ensure consistent background odor effects.

The materials examined as odorants were the nitrogen oxides, sulfur dioxide, and some of the aldehydes. All were present in mixtures with nitrogen at concentration levels corresponding to the highest levels expected in diluted exhaust. The carbonyl compounds in the exhaust were analyzed by a method of Camin (1967)¹ based on gas chromatography of the 2,4-dinitrophenylhydrazones.

The dilution and sniff tube assembly that was used in all work with exhaust, pure components, and synthetic blends is shown in Figure 2. The sniff port was capped by a vent line when it was not in use to prevent escape of exhaust odor into the room. Air flow and pressure were regulated to provide the desired dilution ratio and flow rate of sniff tube output.

Fractionation Equipment and Procedures

Filtration. A glass fiber filter was used to filter the exhaust. A heated metal filter holder was placed before the scrubbers and aspirator when filtration was required. The nonfiltered exhaust was conducted to the aspirator from the exhaust duct through straight tubing with a ball valve for control. This minimized the filtering effect of the apparatus itself.

Scrubbers and Trap. Scrubbers were of the liquid-lift type. These were used only at 4.5 liters/minute gas flow and with 15 ml of liquid. This style of scrubber was used since it allows high flow rates without foam and spray. A copper coil trap was used in open-tube trapping at -80°C .

Scrubber Materials. Several solvents and reagent solutions were studied for their effect on odor and their retention of exhaust compounds. Table I shows a representative list of scrubber solutions along with their efficiencies in removing selected test compounds. The values given are percent removal of the compounds from gas stream at 4 minutes' scrubbing. Analysis was by gas chromatography. The chemical and physical characteristics of the scrubber materials are as shown in Table I.

Odor Evaluation

The odor evaluation method is similar to that outlined by Turk (1967),⁴ and

involves a panel of people who were selected and trained by prescribed procedures. Odor intensity of the exhaust sample is determined by comparison with that of a set of standards. Combinations of odorous materials are selected to simulate diesel exhaust odor, and a set of 12 mixtures, each having twice the concentration of that of the previous mixture, is the basis of the diesel odor intensity scale. These mixtures are assigned numbers 1 through 12, and the panelists rate exhaust odors by means of these numbers.

These exhaust odor ratings represent an odorant concentration scale corresponding to the original Turk bottle series. Although these exhaust ratings give no actual odorant concentrations, they provide values of relative odorant changes.

The Turk scale is based on the Weber-Fechner law which may be represented by

$$I = K \ln C^* \quad (1)$$

where, I is odor intensity, C^* is an odorant activity term, and K is a constant. C^* is proportional to the amount of odorant present and for a mixture could be evaluated as $\sum k_i c_i$ where c_i is concentration and k_i is a constant for component specific odor intensity.

The bottle series was set up to correspond to

$$C^* = R^n C^*_0 \quad (2)$$

where, R is the ratio of the concentrations of adjacent standards and is 2.0

for the bottle series. The $(n - 1)$ th standard from the first member of the series is represented by n . If equation (2) is substituted in equation (1)

$$I = K \ln R^n C^*_0 \quad (3)$$

K may then be determined by differentiation

$$dI/dn = K \ln R$$

The scaling of I is such that for each change of n by one unit I also changes by one; that is, I corresponds to n and

$$dI/dn = 1$$

Therefore

$$K = 1/\ln R, \text{ and } I = \ln C^*/\ln R \quad (4)$$

In base 10 logs,

$$I = \frac{\log C^*}{\log R} = K' \log C^*$$

Either form of equation (4) should represent an odor scale of the type used. For $R = 2.0$, $K' = 3.32$.

Equation (4) is used to measure the contribution of classes of odorants to the total odor with the assumption that the K value of this equation is determined only by the R in equation (2). The assumption that K is independent of odorant identities is supported by Appell (1967),⁵ who states that a single constant is correct for all odorants. It should be pointed out that if a pair of odorants had different K values it would be possible to combine them to a mix-

Table I. Efficiencies of scrubber and trap methods, removal of test compounds (percent).

Scrubber and Trap Methods	Test Compounds						
	Propion-aldehyde	Acro-lein	Propene	Buta-diene	Nonane	Decene-1	p-Xylene
H ₂ O, 0°C	16	22	0	0	0	0	0
NH ₂ OH soln, 0°C	98	94	0	0	0	0	0
H ₂ SO ₄ (concd), 55°C	97	96	24	29	0	69	21
H ₂ SO ₄ , 4% Ag ₂ SO ₄ (concd), 55°C			85	87	0	86	88
Open tube, -80°C	3	13	0	0	88	89	87
Ethanol, -80°C	93	91	1	37	86	90	89

Water, 0°C: This was used both for its own effect as a solvent and as a convenient reference material in the study of other scrubber materials. In addition to the water soluble materials, this scrubber removes the low volatility components. It may also remove materials with which it can react, but no such compound has been studied. The effect on the highly soluble compounds may be represented by the removal of ethanol from the gas stream; it is reduced by 91% at 4 minutes by all of the water solution scrubbers. The water scrubber method was examined by chromatographic means for its effect on the low volatility components of diesel exhaust. In runs of 4 - 10 min through the scrubber, a distinct separation around the C₁₃ and C₁₄ hydrocarbon range appeared. Almost no material above C₁₄ passed the scrubber.

Hydroxylamine, 0°C: This reagent for carbonyl compounds was selected from several because of its high efficiency of aldehyde removal and its low toxicity and freedom from odor. It was prepared fresh for each use as a water solution, 0.6 M NH₂OH and 0.6 M NH₂OH·HCl.

Sulfuric acid, 55°C: This reagent was selected because it absorbs organic oxygenates and the higher molecular weight unsaturated hydrocarbons. It was used at 55°C to reduce its viscosity and to increase its reaction rate. The reagent was preceded by a cold water scrubber to prevent excessive dilution of the H₂SO₄ with water in the sample stream.

Sulfuric acid plus 4% silver sulfate, 55°C: The added silver sulfate increases the absorption efficiency of the sulfuric acid for low molecular weight olefins and aromatic hydrocarbons. It was used in the same manner as the pure sulfuric acid.

Open tube, -80°C : This is preceded by a cold water scrubber to remove water from the sample stream. Copper tubing was used since heat transfer through glass and stainless steel was too low for effective trapping at the standard flow rates. This was determined by comparison of trapping efficiency values of copper and stainless steel tube traps during experiments leading to the results on pure-compound trapping efficiencies.

Ethanol, -80°C : This reagent was used as a nonselective solvent in an attempt to develop a concentration and isolation method for diesel exhaust. It was preceded by a cold water scrubber.

Sodium bicarbonate, 5%, 0°C: This was used by Reckner, et al. (1965),² and Wessler (1966)³ and was also applied here to compare this work with that of others. Although this reagent probably is used as a selective reagent for acids, there is no evidence that it is superior to water in acid removal.

ture that would not obey the Weber-Fechner law on dilution.

Results and Discussion

Effects of Exhaust Treatments

Filtration. The effect of filtration of the exhaust gas by fiberglass filter sheet was studied. The exhaust of a 2-stroke cycle engine was used. Smoke levels at all engine operating modes were normal. The values in Table II under "Exhaust sample" are the averages of diesel intensity (*I*) ratings discussed previously. The "Differences" column is the first rating minus the second. This column shows the effect of filtration on the odor level—a positive value for odor enhancement and a negative value for odor reduction. Apparently from the difference values in Table II, filtration may cause some increase in the odor. The average of these values over all modes is +0.2 intensity (*I*) unit; using the relation $I = 3.32 \log C^*$ this represents an increase in total odorant of 16%. However, no particular significance can be attached to the exact intensity values for the filtration experiments, though they appear sufficiently reliable to assume that filtration has no more than a minor influence on odor. The problem of measuring the flow of unfiltered exhaust into the dilution system made accurate dilution for presentation to the odor panelists difficult. This causes results to be less reliable for the filtration experiments than for subsequent work in which all exhaust samples were filtered.

Scrubbing and Trapping. All other work following the filtration studies dealt with filtered exhaust passed through the scrubbers and traps described in the experimental section. Data of Table III show effects of these treatments on the intensity rating of exhaust averaged over several operating modes for a 2-stroke cycle engine (engine A), a turbocharged 4-stroke cycle engine (B), and a normally aspirated 4-stroke cycle engine (C). Table IV summarizes results for individual operating modes for engine B. Both tables list odor change values unless otherwise indicated. These odor difference values represent averages from four or more replicated measurements for each treatment. In each paired rating the difference value is obtained by subtracting the *I* number of the second cited member of the pair from that of the first. The difference value therefore represents the amount of odor reduction by the first method from the odor level passing the second treatment method. The cold water scrubber was chosen for reference because the filtered and partially dried exhaust could be handled easily. A second cold water scrubber was also placed before the sulfuric acid, open tube, and ethanol scrubbers. The difference values are therefore the odor

Table II. Diesel odor intensities of filtered and unfiltered exhaust, *I* units (Engine A).

Engine mode		Exhaust Sample		Difference
rpm	Load	Filtered	Unfiltered	
1800	$\frac{3}{4}$	3.3	2.7	+0.7
1800	Full	2.8	3.2	-0.3
Idle	0	3.5	3.2	+0.3
Acceleration		4.7	4.5	+0.2

Table III. Effect of exhaust treatment on diesel odor intensity, *I* units.

Scrubber or treatment	Engine A	Engine B	Engine C
Odor intensity, all modes averaged			
Nonscrubbed (filtered)	3.4	4.6	4.1
Odor intensity change, all modes averaged			
H ₂ O, 0°C vs nonscrubbed	-0.6	-1.0	-0.8
Hydroxylamine, soln, 0°C vs H ₂ O, 0°C	-0.3	-0.2	0
H ₂ SO ₄ , concd, 55°C vs H ₂ O, 0°C	-0.2	-0.8	-1.5
H ₂ SO ₄ + 4% Ag ₂ SO ₄ , 55°C vs H ₂ O, 0°C		-1.1	-1.8
Open tube, -80°C vs H ₂ O, 0°C	-0.2	-1.0	-0.7
Ethanol, -80°C vs H ₂ O, 0°C	-0.7		
5% NaHCO ₃ , 0°C vs H ₂ O, 0°C	0		

Table IV. Odor intensities and odor intensity changes by exhaust scrubbing, *I* units (Engine B).

Treatment	Engine mode, rpm and (load)					
	Idle	1200 ($\frac{1}{2}$)	2100 ($\frac{1}{2}$)	1200 (F)	2100 (F)	Accel.
Odor intensity, average of 20 measurements						
H ₂ O, 0°C	3.3	3.4	3.5	3.5	3.6	
Odor intensity, average of 4 measurements						
H ₂ O, 0°C vs nonscrubbed	-1.2	-0.7	-1.2	-1.0	-0.7	
Open tube -80°C vs H ₂ O	-0.7	-0.7	-1.5	-1.0	-1.0	
Hydroxylamine, 0°C vs H ₂ O, 0°C	+0.5	-1.0	-0.2	0	0	
H ₂ SO ₄ (concd) 55°C vs H ₂ O, 0°C	-0.2	-0.2	-1.5	-1.0	-0.7	-1.0
H ₂ SO ₄ (concd) + 4% Ag ₂ SO ₄ , 55°C vs H ₂ O, 0°C	-1.0	-1.0	-1.7	-1.2	-1.0	-0.7

Table V. Diesel odor intensity values of pure components of exhaust.

Odorant	Concentration, ppm	Odor intensity, <i>I</i> units		
		N ₂	Odorant	Difference
Sulfur dioxide	6.0	0.86	2.16	1.30
Nitrogen dioxide	2.0	0.43	2.51	2.08
Nitric oxide	20.0	1.8	2.0	0.2
Formaldehyde	0.3	0.47	0.45	-0.02
Acrolein	0.027	0.71	0.63	-0.08
Crotonaldehyde	0.0043			

reductions in excess of that caused by the water scrubber alone. The hydroxylamine and NaHCO_3 solutions would act as cold water scrubbers in addition to their chemical action; the difference values are attributed to this chemical action in excess of that caused by water scrubbing alone.

The odor reduction by the water scrubber itself is fairly important as shown by the data of Table III. The change in odor intensity of exhaust from engine B is particularly significant since it represents removal of half of the total odorant present in the original exhaust. Water scrubbing of engine C exhaust removes about 40% of the total odorant.

Table I shows that the more volatile hydrocarbons are not absorbed by water and that low molecular weight carbonyls are removed only to about 20%. This indicates that odor reduction by water scrubbing is not caused by removal of lower molecular weight hydrocarbons and that the carbonyls are not the predominant part of the odorant removed. Results of hydroxylamine scrubbing discussed below support this interpretation of carbonyl odorant removal. Odorants removed by water scrubbing could include hydrocarbons above C_{14} , unidentified types of polar materials that would be soluble in water, and materials that could react with water.

Odor contribution by carbonyl compounds was explored by means of the hydroxylamine scrubber. In the odor ratings of engine A exhaust a dilute acid scrubber was used following the hydroxylamine solution, for fear that the hydroxylamine solution might give off odor. In subsequent tests no odor contribution from the hydroxylamine solution itself was detected; therefore, in work with engines B and C the dilute acid scrubber was omitted. Because a second cold aqueous scrubber provides some additional odor reduction, the amount of odor reduction in exhaust of these engines probably represents the more realistic contribution of the hydroxylamine scrubber. If calculations of the odorant reductions are made using the intensity values of Table III for the unscrubbed exhaust and the water and hydroxylamine scrubbed exhaust from engine B — it appears that of total odorant removed, carbonyls removed by hydroxylamine account for about 6%, carbonyls removed by water for about 1%, and compounds other

than carbonyls removed by water for about 49%. There is no change in the odorant level of engine C exhaust by the hydroxylamine scrubber.

Concentrated sulfuric acid removes about 21% of the total odorant of engine B exhaust beyond that removed by water and 38% of engine C odorant, based on values of Table III. This effect on odor should be due to the adsorption of organic oxygenates or unsaturated hydrocarbons between C_{10} and C_{14} . Sulfuric acid can also absorb other materials such as organic nitrogen and sulfur compounds if they are present. The addition of silver sulfate increases the odorant removal to about 27% for the engine B exhaust and to 42% for the engine C. The Ag_2SO_4 should affect only the olefins and aromatic hydrocarbons not absorbed by the acid scrubber. A significant amount of odor escapes the $\text{H}_2\text{SO}_4 - \text{Ag}_2\text{SO}_4$ scrubber, and this odor level probably exceeds the amount expected to pass the acid scrubber and the preceding water scrubber due solely to scrubber-contact inefficiency. Following this scrubber combination, the odor intensity rating for engine B exhaust was 2.1. Some of the remaining odor might have been due to nitrogen and sulfur oxides present in the exhaust.

The open tube trap at dry ice temperature removes about 25% of engine B odorant and 21% of engine C odorant. The efficiency of the trap falls off for materials of higher volatility than C_8 (paraffin) as shown by both Table I and chromatographic examination of trapped diesel exhaust. This indicates that a significant part of the odor is contributed by material of low volatility and therefore high molecular weight range. No particular conclusions can be made from results of the ethanol scrubber because it is quite nonselective in its performance.

In the engine A exhaust treatment, the 5% solution of NaHCO_3 does not change the intensity ratings and probably has the same effect as water. Since water should be a good solvent for carboxylic acids and weaker acids would not react with the NaHCO_3 solution, no particular difference in behavior may be expected.

Table IV shows the intensity rating results for each engine mode used with the scrubber treatments. The engine B exhaust was used in this study. (The

average for all engine modes with each treatment method are given in Table III.) Each value in Table IV is the average of four replicate experiments, except for the column showing I ratings of water scrubbed exhaust. Analysis of the original odor rating values established a confidence interval of ± 0.61 for the scrubber class mean and ± 0.27 for the mode averages, all at 80% confidence. Data in the column for absolute intensity ratings of water scrubbed exhaust are averages of 20 measurements in each case. They indicate the rather slight effect of engine mode on odor intensity.

Pure Component Odorant Rating

Along with the program described for classification of diesel exhaust odors by groups and volatility, pure compounds were assessed as odor contributors by presenting them, appropriately blended, to odor panelists. The objective of this phase of the program was to establish the contribution of the major odorants to the diesel odor and to examine those components which were present in large amounts but not otherwise associated with odor. All compounds were presented to the panelists at the upper concentration levels found in exhaust. Table V lists the materials that were examined. In the table, the values are averages of the diesel intensity ratings, and the differences listed in the last column represent the odor contribution relative to the nitrogen sample used in the comparative rating. The concentrations listed represent dilutions of 100 to 1 of the levels found typically in exhaust.

Sulfur content in diesel fuel varies considerably but 1% was assumed for calculating the amount of SO_2 in exhaust by complete oxidation. This is the maximum level set for sulfur by ASTM standards for No. 2D diesel fuel. One percent sulfur fuel would yield about 600 ppm SO_2 by complete oxidation in raw exhaust under stoichiometric conditions. If the intensity value of 4.6 for engine B filtered exhaust, shown in Table III, is taken as a typical odor level, the difference value of 1.3 for SO_2 would represent about a 10% contribution to the total odor. Most fuels contain appreciably less than 1% sulfur, and so odor contributed by SO_2 probably will be unimportant except under unusual conditions.

Table VI. Aldehyde composition of diesel exhaust by chromatographic analysis.

Exhaust carbonyls	ppm
Formaldehyde	18.3
Acetaldehyde	3.2
Acrolein	} ^a 2.9
Acetone	
Propionaldehyde	
iso-Butyraldehyde	
n-Butyraldehyde	0.3
Crotonaldehyde	} ^a 0.4
Valeraldehyde	
Hexaldehyde	0.2
Benzaldehyde	0.3

^a Unresolved peaks.

olefins and aromatics may be minor contributors. Hydrocarbons, however, are the dominant organic material in diesel exhaust and must be considered as potential odorants pending direct examination. The oxygenates other than carbonyls include many types of chemical families that are strong odorants. The more likely oxygenates are those that are reasonably stable toward dehydration and fragmentation at combustion temperatures. Unstable materials of the hydrocarbon or oxygenate families are suspects since diesel odor is known to change or disappear on standing. The other sources listed are considered less likely but have not been eliminated.

The scrubber data show that differences do occur in exhaust odor levels. It is reasonable to expect engines to differ in odor and that no single, dominant odorant will be found for all engines and modes. Likewise, fuel may have an effect on odor, further complicating the search for odorants.

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A typical upper concentration level of oxides of nitrogen in diesel exhaust is 2000 ppm. The amount present as NO₂ depends on circumstances not affecting most of the other exhaust components. The manner of mixing with air and the reaction time both affect the conversion of NO to NO₂. For example, rapid mixing of exhaust with a large excess of air hinders the formation of NO₂; but emission of exhaust into stagnant air with diffusion of oxygen into NO-rich regions promotes high conversion. Likewise, fresh exhaust should have less NO₂ owing to short reaction time. For these reasons no conversion value could be assigned to exhaust encountered under ordinary conditions. For convenience, a 10% conversion to yield 200 ppm NO₂ was assumed. Using the same exhaust intensity rating mentioned, the difference value of 2.1 would represent approximately an 18% contribution to the total odor. Obviously then the NO₂ contribution could vary from negligible to dominant under extreme conditions.

The NO₂ levels in the sniff tube lines were checked while introducing exhaust from engine B in several operational modes. The exhaust dilution was the standard 100:1. Only one mode produced appreciable amounts of NO₂; this was idle with the sniff gas containing 0.5 ppm NO₂. The other modes examined were at one-half and full-rated power, and the highest concentration in any case was 0.06 ppm NO₂.

The contribution of NO to odor was checked in the same manner assuming a nitric oxide level of 2000 ppm. Both the NO blend and the matching N₂ were aspirated into the dilution system using nitrogen gas carrier, and the slight odor of the nitrogen carrier is assumed to have caused the somewhat high intensity values. The very small difference value indicates that NO makes no direct contribution to odor.

A typical analysis of carbonyl compounds in exhaust is summarized in Table VI. Besides the advantage of detailed information on composition, the DNPH chromatographic method provides a formaldehyde value more accurate than that obtained previously by colorimetric means. For pure compound testing, a 30-ppm level was used for formaldehyde, and the results are shown in Table V. Apparently, formaldehyde makes a little contribution to the total odor.

Of the remaining aldehydes, those considered most likely to contribute to diesel odor are acrolein and crotonaldehyde. Unfortunately, these are not well resolved in the chromatogram (see Table VI); therefore, blends containing acrolein and crotonaldehyde were prepared as if the chromatograph peaks represented only these two compounds. Results in Table V indicate that these compounds do not contribute to the measured odor.

Leonardos, *et al.* (1969),⁶ have determined the threshold odor levels of formaldehyde and acrolein. These are 1.0 and 0.2 ppm in air, respectively. Since these concentrations are appreciably greater than those presented to the panel, their failure to detect the odor would be expected. The odor intensity of diesel exhaust is ordinarily in the range 3-5 units which is considerably above the threshold level. If the exhaust was diluted to threshold level, the concentrations of these aldehydes would be very small fractions of their thresholds.

These observations on the contribution of formaldehyde and acrolein to diesel odor are the same as that of Linnell and Scott (1962).⁷

Conclusions

Apparently, the common impression of aldehydes being the major odorants in diesel exhaust is incorrect, at least for most aldehydes known to be present in diesel exhaust. Sulfur contributes very little to the odor as sulfur dioxide. No search was made for other forms in which sulfur may occur in diesel exhaust. Odor due to NO₂ can be a considerable part of the total odor depending on atmospheric and other circumstances during emission of the exhaust.

These generally negative results leave most of the source of the odor unidentified. Some possible sources are (1) the hydrocarbons, either unchanged from the fuel or formed during combustion; (2) organic oxygenates other than carbonyls; (3) high molecular weight carbonyls that are retained by the water scrubber; (4) reactive or unstable compounds destroyed by water, oxygen or other means; and (5) nitrogen or sulfur compounds. The scrubber experiments give no clear indication that hydrocarbons are important odorants, although the effect of Ag₂SO₄ in H₂SO₄ indicates that the low molecular weight