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DIESEL EXHAUST CONTAMINATION OF TUNNEL AIR

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By John C. Holtz and R. W. Dalzell

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DIESEL EXHAUST CONTAMINATION OF TUNNEL AIR

by

John C. Holtz[1] and R. W. Dalzell[2]

ABSTRACT

The Bureau of Mines studied air contamination caused by diesel exhaust in a 10,000-ft ventilated tunnel. Sequential air samples were taken at the ends and middle of the tunnel during an operating cycle. Observed and calculated results for carbon dioxide, carbon monoxide, and nitrogen oxides were essentially in agreement. Nitrogen dioxide was present only in trace amounts. It was found that contamination was related to the volume of ventilating air, the number of haulage trips, train speed, and engine load.

INTRODUCTION

For many years the Bureau of Mines has studied diesel exhaust and its contaminating effects on the air in mines and tunnels. The results show that more information about the contamination of underground air by exhaust from moving haulage trips is needed.[3]

In the approval investigations of mobile diesel-powered equipment under Bureau of Mines schedule 24,[4] the engine is attached to a dynamometer and the fuel system is adjusted to reduce the maximum fuel-injection rate and prevent the discharge of excessive carbon monoxide and smoke in the exhaust. The derated engine is then tested over a range of loads and speeds to determine the composition and volume of the exhaust. The results are used to calculate

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[3]Holtz, John C. Safety With Mobile Diesel-Powered Equipment Underground. BuMines Rept. of Inv. 5616, 1960, 87 pp.

[4]Bureau of Mines. Procedure for Testing Mobile Diesel Powered Equipment for Non-Coal Mines. Schedule 24, Mar. 29, 1949, 13 pp.; F.R., v. 14, No. 67, Apr. 8, 1949, 1 p.; v. 14, No. 113, June 14, 1949, 7 pp.

_____. Mobile Diesel Powered Equipment for Non-Coal Mines: Tests for Permissibility and Suitability; Fees. Amendments to Schedule 24, Apr. 23, 1955, 2 pp.; F.R., v. 20, No. 80, 2 pp.

the recommended ventilation that, under any engine operating condition, will dilute the exhaust to a safe hygienic concentration. The recommended ventilation is made part of the approval and approval plate.

When properly adjusted diesel equipment is used for haulage, mine-air analyses often show lower concentrations of contaminants than would be expected from exhaust dilution in recommended ventilation. Because a dilution effect from the large volume of air traversed by the haulage trip seems probable, the suggestion has been made that recommended ventilation may be higher than necessary. The objectives of this investigation are to develop an explanation for this observation and to evaluate the suggestion.

A recent ventilation survey at a tunnel project showed the volume of moving air was less than the total recommended ventilation for the number of diesel locomotives used underground. With the cooperation of the contractor, extensive observations of exhaust contamination were made by taking sequential air samples at three stations along the tunnel. The results are presented herein and are correlated with the movement of diesel equipment and of ventilating air.

TUNNEL CONDITIONS

The tunnel was being driven in metamorphic rock from a shaft located at one end. The test was made when the face advance was at 10,000 ft; the ultimate length of the tunnel will be 25,000 ft. Operations were at about 1,000 ft below sea level, and, although the tunnel was being driven under a bay, pressurized operations were neither necessary nor anticipated.

Positive-displacement blowers on the surface supplied ventilating air by blowing or exhausting through a duct along the crown of the tunnel. The end of the vent duct was maintained within 70 ft of the face. Shortly before blasting, the ventilating system was adjusted to exhaust through the duct. During the test, exhausting ventilation was used for about 170 min and then was changed to blowing ventilation for 110 min. The face operating cycle (blasting, mucking, and drilling) was about 240 min.

The volume of air flowing in the tunnel near the shaft bottom ranged from about 10,000 to 19,000 cfm. The lower volume was observed when the ventilation system was exhausting. When blowing, airflow increased to about 15,000 cfm. The maximum flow occurred when blowing ventilation was augmented by compressed air from drills operated at the face while preparing for blasting. Observed air velocities near the shaft ranged from about 70 to 125 fpm; velocities at other locations were lower because of duct leakage. The cross section of the tunnel averaged 150 ft^2.

Mucking began promptly after blasting and required about 100 min. Muck was moved in four loaded trains.

Four diesel-powered locomotives were used. All were maintained in good condition, and their fuel systems were adjusted properly for underground operation. Three were approved 10-ton locomotives driven by turbocharged engines.

Recommended ventilation for each was 16,000 cfm. The fourth was a nonapproved 12-ton locomotive. These locomotives hauled trains at an average speed of 900 fpm (approximately 10 mph). Passing tracks were installed at intervals of 1,750 ft.

Observations made before and during the test showed the source of air contamination was diesel exhaust. Blasting gases were removed effectively during exhausting ventilation. Other extraneous gases were not observed.

TEST PROCEDURE

Sequential air samples were taken during an operating cycle at three stations along the tunnel. These were located at 300 ft, 5,080 ft, and 9,895 ft inby the centerline of the shaft. They have been designated as the shaft, middle, and face stations, respectively.

At each station an observer sampled the air in the center of the tunnel with vacuum bottles at successive 10-min intervals. Two samples were taken in rapid succession; one was taken in a dry bottle, the other was taken in a bottle containing an absorbing solution for nitrogen oxides. These samples were supplemented in the same time sequence by tests with portable indicators for determining carbon monoxide and nitrogen dioxide.

Vacuum bottle samples were returned to the laboratory for analysis. The dry samples were analyzed by gas chromatography to determine carbon dioxide, oxygen, carbon monoxide, methane, and nitrogen. The solution in the wet samples was recovered and analyzed for total nitrogen oxides by the phenoldisulfonic acid method.

In addition, each observer kept a log of the diesel trains passing his station. This record identified the locomotive, the time it passed, the direction of travel, the number of cars, and whether the cars were loaded or empty. Changes in direction of ventilation were also recorded.

Ventilation was measured on the day before the tunnel-air samples were taken. Observations during the test indicated ventilation had not changed.

OBSERVED RESULTS

Analytical results for the air samples are plotted in figures 1, 2, and 3. These figures show the observed contamination at the shaft, middle, and face stations, respectively. In each, the concentrations of carbon dioxide, carbon monoxide, nitrogen oxides, methane, and oxygen, determined in the bottle samples, are plotted as solid circles at the time the sample was taken. Open circles show the average concentrations of carbon monoxide determined with portable indicators. Concentrations of nitrogen dioxide determined with portable indicators have not been plotted. Trace amounts were observed in many tests, but the maximum concentration was less than 1 ppm.

Notations and arrows show when the ventilation system was exhausting or blowing, the direction of the air movement, when the face was blasted, the start and end of mucking, and the start and end of drilling.

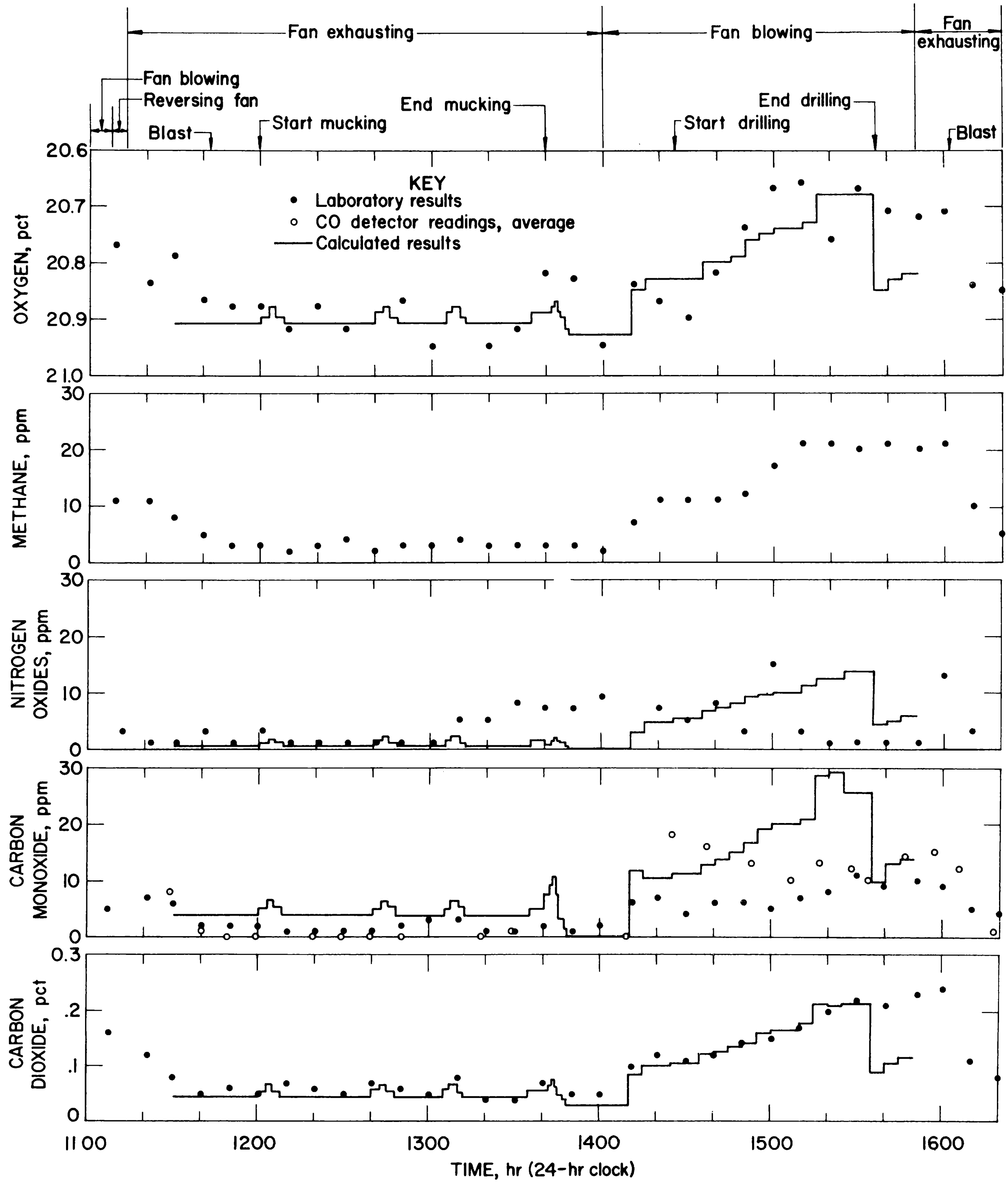

FIGURE 1. - Diesel Exhaust Contamination at the Shaft Station.

Figures 1 and 2 also show line graphs representing calculated air analyses. The calculations could be made for conditions at the shaft station between 1130 and 1550, and at the middle station between 1240 and

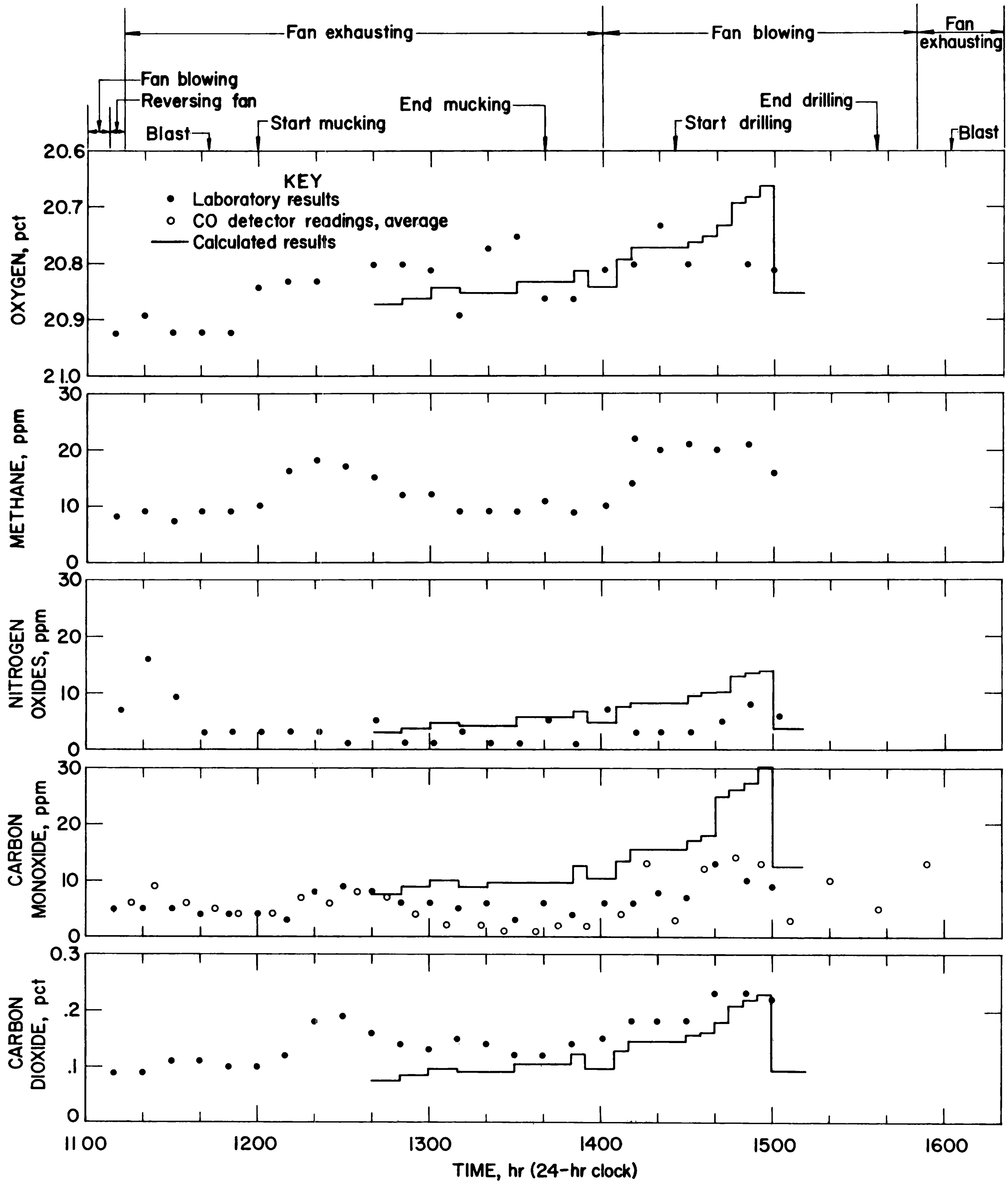

FIGURE 2. - Diesel Exhaust Contamination at the Middle Station.

1510.[5] Only a single calculation at 1400 could be made at the face station. The concentration of methane in the engine exhaust was not known; consequently,

[5]Time designations are based on a 24-hr clock.

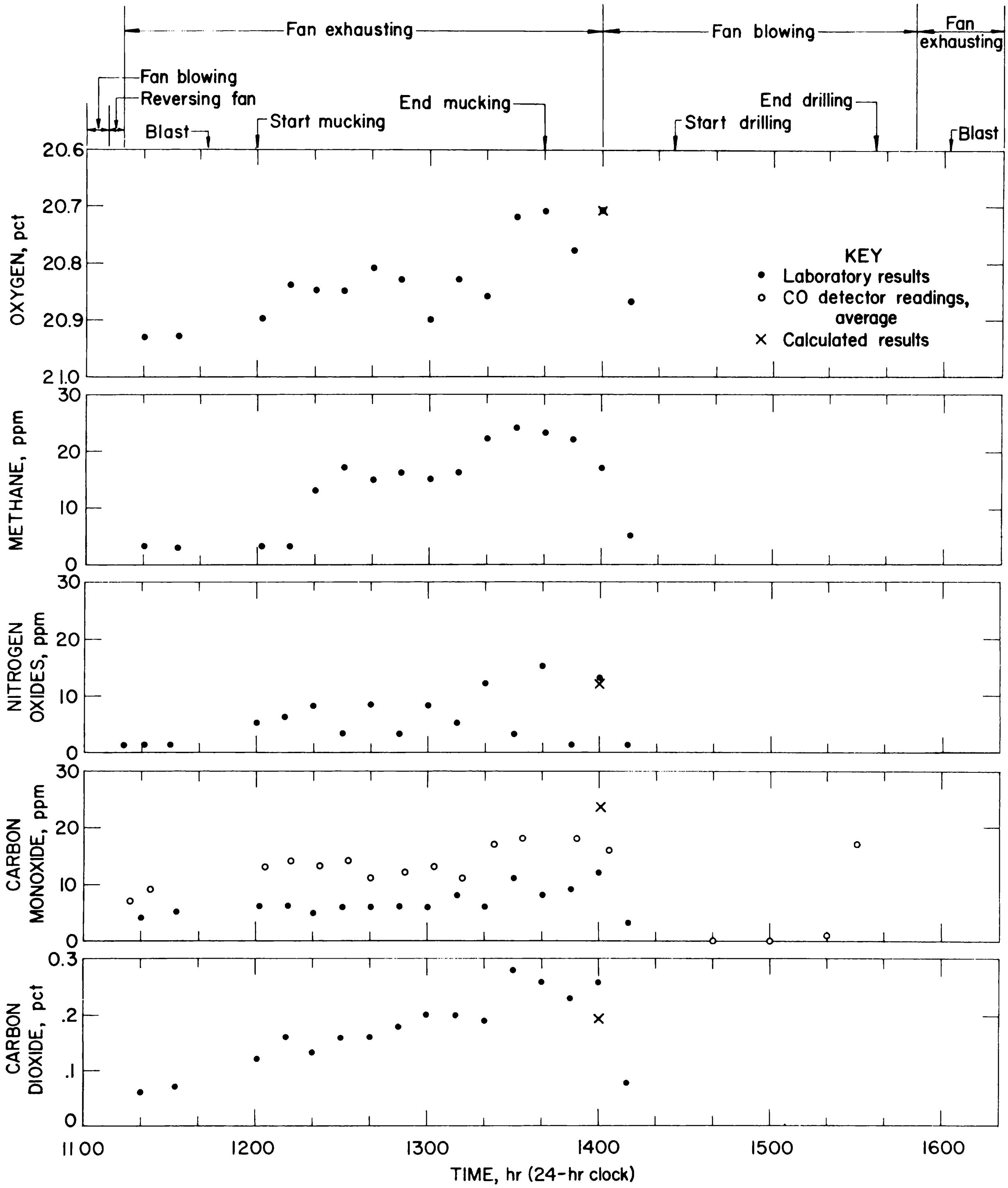

FIGURE 3. - Diesel Exhaust Contamination at the Face Station.

concentrations of this contaminant could not be calculated.[6] The method of calculation will be discussed later.

[6] Subsequent analyses of diesel exhaust from a different engine at four operating conditions showed methane in concentrations ranging from 5 to 110 ppm.

Locomotive and air movements are depicted in figure 4. The heavier solid and dashed lines (nearly horizontal) show trips by the four locomotives. Their slope represents an average speed of 900 fpm, determined from the observed times when longer trips passed more than one observation station. This speed was assumed for all shorter trips and was used in estimating the elapsed time when a locomotive was standing at a passing track with the engine idling. Vertical sections of the trip lines show the elapsed time when a locomotive was standing or working in a local area. Notations on lines representing moving trips show train load.

Lighter solid lines at a steeper slope represent movement of air through the tunnel in the direction indicated by the arrows. These lines begin at the shaft top at successive 10-min intervals and are continuous until the air represented by them leaves the tunnel. Their direction and slope change abruptly at 1400 when the ventilation system was reversed from exhausting to blowing. Their slope is adjusted to the average air velocities measured in each fifth of the tunnel length.

Tables of effective ventilation for different ventilating conditions and locations in the tunnel are shown at the top of figure 4. These are useful in calculating exhaust dilution. Their derivation will be considered later.

Ventilation directly affects both the concentration of exhaust contamination and the rate at which this contamination moves through the tunnel. Figure 5 shows the measured ventilation at tunnel conditions. Three conditions are shown: exhausting, blowing with no drilling, and blowing while drilling. The measurements were made at approximately 2,000-ft intervals along the tunnel and include the effect of leakage into or from the vent duct. This leakage causes ventilation to decrease along the tunnel from the shaft to the face. Changes in ventilation affect the diluted concentration of exhaust where it originates, and, during blowing ventilation, dilution increases as the contaminated air travels through the tunnel.

The ventilation volumes also include leakage from a compressed air line, averaging 0.12 cfm per foot of tunnel length. This leakage dilutes contamination under all ventilating conditions.

Tunnel contamination also is related to the volume and composition of exhaust emitted by the locomotives. Determination of these data is difficult in field tests; therefore, this information was abstracted from laboratory test results obtained during the approval investigation. Estimated volumes of the three principal objectionable contaminants for three operating conditions are given in table 1; a loaded train, an empty train, and an idling locomotive. Although the locomotives operated at many loads, consideration of these three was sufficient to correlate observed and calculated results. The volumes of carbon dioxide have been corrected and do not include the amount in the normal air aspirated by the engine. Previous investigations have shown that ventilation adequate for diluting these three products is sufficient to control other gases in the exhaust.

MODE OF TUNNEL VENTILATION	LOCOMOTIVE ACTIVITY	AVERAGE EFFECTIVE VENTILATION, cfm				
Fan exhausting,	Standing, idling	10,500	10,350	10,050	9,450	9,150
	Inbound	124,500	124,650	124,950	125,550	125,850
	Outbound	145,500	145,350	145,050	144,450	144,150
Fan blowing, no drilling	Standing, idling	14,250	13,200	12,150	11,100	10,500
	Inbound	149,250	148,200	147,150	146,100	145,500
	Outbound	120,750	121,800	122,850	123,900	124,500
Fan blowing, drills operating	Standing, idling	18,000	17,100	16,050	15,150	14,400
	Inbound	153,000	152,100	151,050	150,150	149,450
	Outbound	117,000	117,900	118,950	119,850	120,600

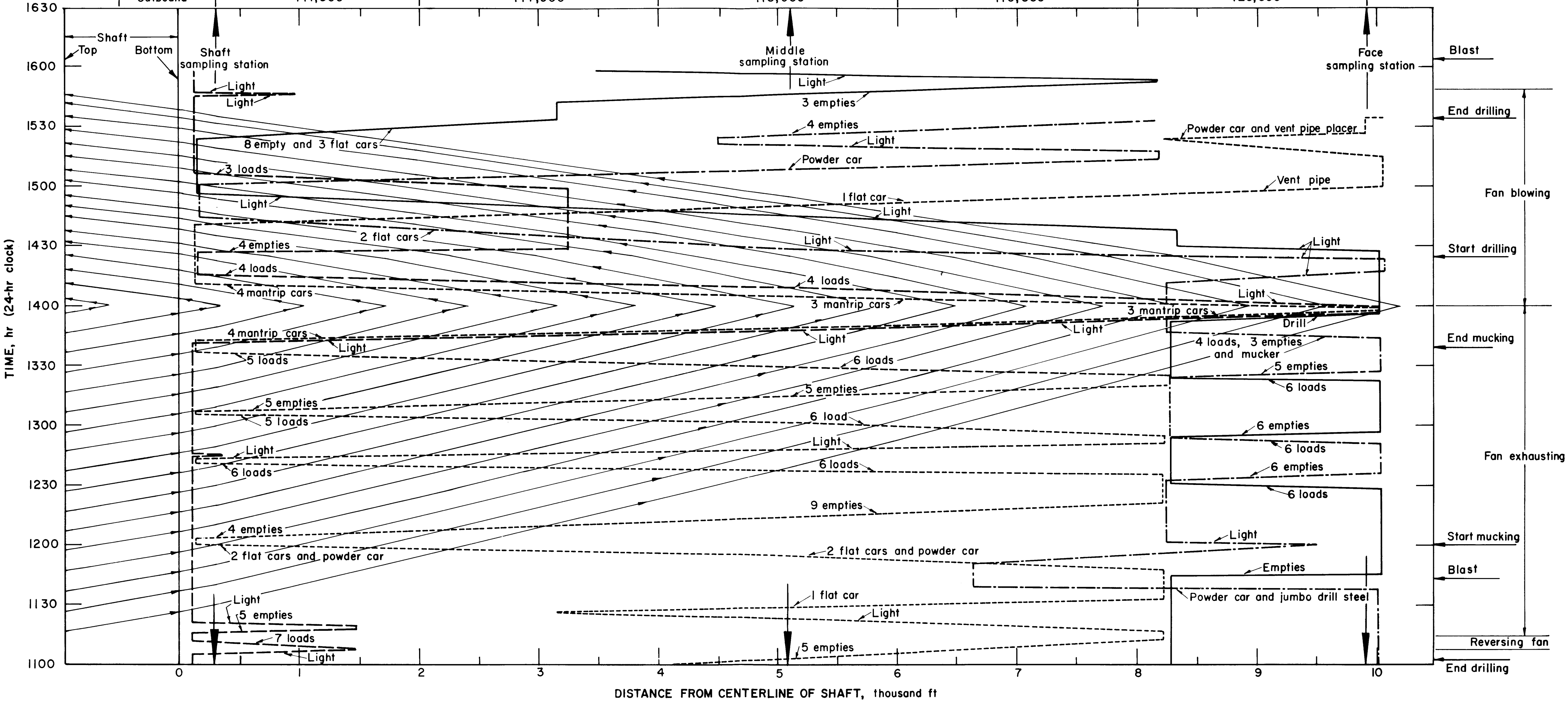

FIGURE 4. - Trip Chart of Locomotive and Air Movements.

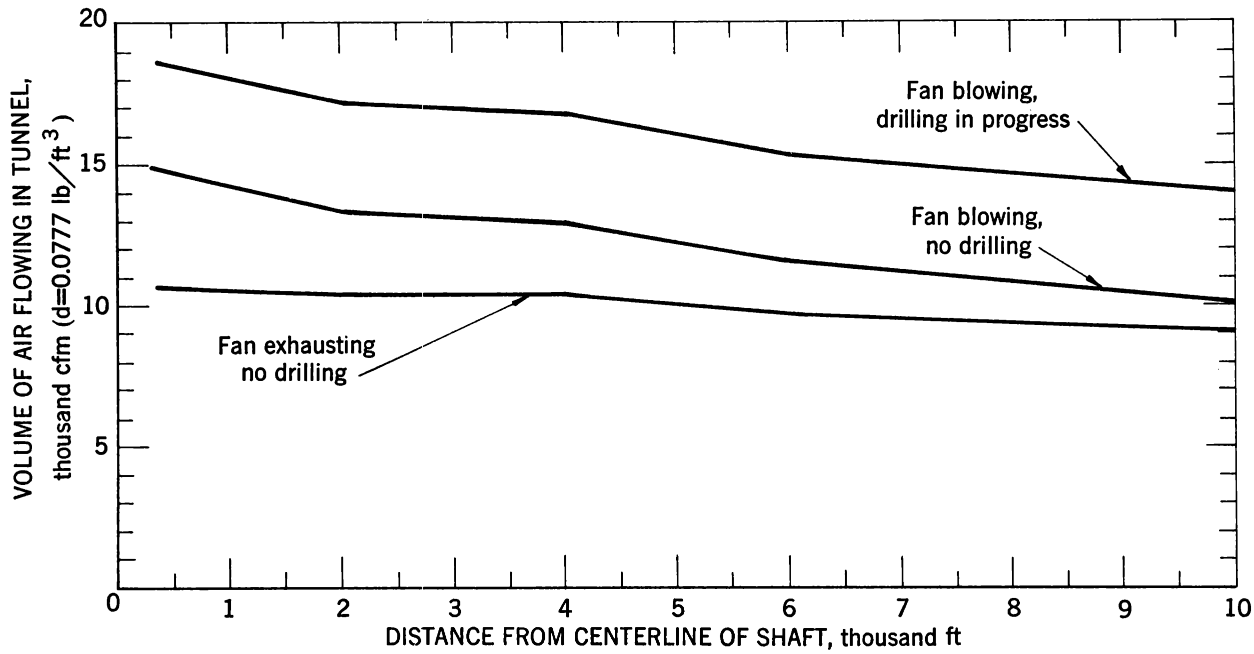

FIGURE 5. - Volume of Tunnel Ventilation.

TABLE 1. - Estimated volume of diesel exhaust products

Contaminant, cfm	Train		
	Loaded	Empty	Idling
Carbon dioxide................	20.5	12.0	1.5
Carbon monoxide...............	.17	.19	.04
Nitrogen oxides...............	.18	.09	.005

The volumes of exhaust products for the loaded and empty trains were estimated from calculated power requirements. The calculations considered train weight, track resistance, train speed, and engine efficiency. The track was nearly level, but a higher than normal resistance was used because the track was sinuous and not ballasted. The two engine loads were about 90 and 30 pct of the maximum derated power.

CALCULATED RESULTS

Effective Ventilation

Study of mine-air analyses in relation to the trip chart showed that exhaust from a standing locomotive was diluted in the volume of flowing air. In contrast the exhaust from a moving locomotive was diluted and distributed in the volume of tunnel air traversed by the trip. Also, contamination always increased when successive trips traveled through the same air. These deductions suggested two criteria that have been applied in calculating the total concentration of contamination. The first is the concept of effective ventilation. The second is that each operating locomotive increases contamination by an increment depending upon effective ventilation and engine load. When contamination results from multiple sources in the same air, total contamination is the sum of the individual incremental contaminations.

Simply stated, effective ventilation is the volume of air flowing around a locomotive in a specific time interval. It is calculated as the vector sum of the locomotive and air velocities multiplied by the cross-sectional area of the tunnel. A standing locomotive represents a special case where locomotive velocity is zero and effective ventilation coincides with measured ventilation. Effective ventilation is expressed in cubic feet per minute.

At the shaft station during exhausting ventilation, measured airflow was 10,500 cfm. This volume is the effective ventilation for a locomotive standing at this location. Because the area of the tunnel is 150 ft^2, air velocity is 70 fpm.

At this same place the vector velocity for an outbound haulage trip is 900 plus 70, or 970 fpm. Multiplying by the tunnel area gives an effective ventilation of 145,500 cfm. Similarly, effective ventilation for an inbound trip is (900 - 70) 150, or 124,500 cfm. Obviously, effective ventilation for a haulage trip is many times that for a standing locomotive.

The incremental increase in contamination is calculated by dividing effective ventilation into the volume of an exhaust product emitted by the engine. Carbon dioxide increments are calculated as a percentage and those for carbon monoxide and total oxides of nitrogen are expressed in parts per million. These units correspond to those used for reporting gas analyses in the observed ranges of concentration. The sum of the individual increments of a particular contaminant affecting a specific volume of air gives the air analysis directly except for carbon dioxide. For carbon dioxide the sum of the increments represents only carbon dioxide from the fuel burned in the engine. To this sum the carbon dioxide in normal air, 0.03 pct, must be added to obtain the air analysis.

Illustrative Calculations

General

Correlation of calculated and observed results involves time relationships. The trip chart (fig. 4) is helpful in understanding time effects. For example, during exhausting ventilation one locomotive worked continuously at the shaft bottom from the start of the test until about 1345. Contamination from this source was carried through the entire tunnel by the ventilating air and incremental contaminations from subsequent haulage trips and idling locomotives increased total contamination. When the ventilation system was reversed at 1400, some air containing exhaust from the idling locomotive at the shaft bottom had just reached the face. This air then traversed the tunnel in the opposite direction and arrived at the shaft again about 1535, long after the operating causing the contamination had ceased. Thus contamination from a standing locomotive was distributed through the tunnel by air movement. It pervaded the tunnel for a distance equal to the air velocity multiplied by the time the engine was operated.

As the velocity of haulage trips was much higher than that of the air, exhaust contaminated the wake of the trip. The length of this contamination is calculated as the vector sum of the trip and air velocities multiplied by the elapsed time for the trip. For the test conditions an increment of contamination was detected when the haulage trip passed an observation station. Effects of this contamination persisted until the air in which the trip began or ended reached the observation station. In some instances increments of contamination from haulage trips passed the middle station but did not reach the face station. Reversal to blowing ventilation caused this contamination to reappear at the middle station later during the test.

In order to correlate observed and calculated contamination it is assumed that exhaust from a locomotive is diluted immediately and completely in the effective ventilation. Thereafter, an increment of contamination is stable, except for leakage affecting measured ventilation; its concentration is unaffected by changes in air velocity or direction; and it travels at air speed.

Standing Locomotive

Calculated increments of contamination from the exhaust of a locomotive standing with its engine idling are plotted in figure 6 for the observed range of effective ventilation. The curves show the diluted concentrations of carbon dioxide, carbon monoxide, and nitrogen oxides. These results are specific for the locomotives and conditions observed in this tunnel. They do not apply to other diesel engines or situations involving different conditions.

Use of these curves is illustrated for the locomotive standing at the shaft while ventilation is exhausting and effective ventilation is 10,500 cfm. At this ventilation the increments of contamination added to the airstream are 0.0142 pct carbon dioxide, 3.81 ppm carbon monoxide, and 0.48 ppm nitrogen oxides. The resulting analysis of tunnel air containing only this contamination is 0.0142 pct plus 0.0300 pct carbon dioxide in normal air or 0.0442 pct carbon dioxide and the selected concentrations of the other two exhaust products.

At the shaft station (fig. 1) this contamination is found in observed results throughout most of the test except from 1348 to 1410. During this short period normal air passed because the locomotive causing contamination left the shaft and traveled into the tunnel. Normal air following the locomotive flowed into the tunnel for about 1,000 ft (fig. 4) and then returned to the shaft station without being contaminated when the ventilation system was reversed. Thereafter, this exhaust increment was part of the total contamination at the shaft station until about 1535. More contamination was added to air containing this increment by haulage trips and other idling locomotives.

Moving Locomotive

Calculated increments of contamination from a moving locomotive in much greater effective ventilation are plotted in figures 7 and 8. Figure 7 shows carbon dioxide contamination from loaded and empty trips. The greater increment for the loaded trip is caused by the engine operating at a higher load and generating more carbon dioxide as shown in table 1.

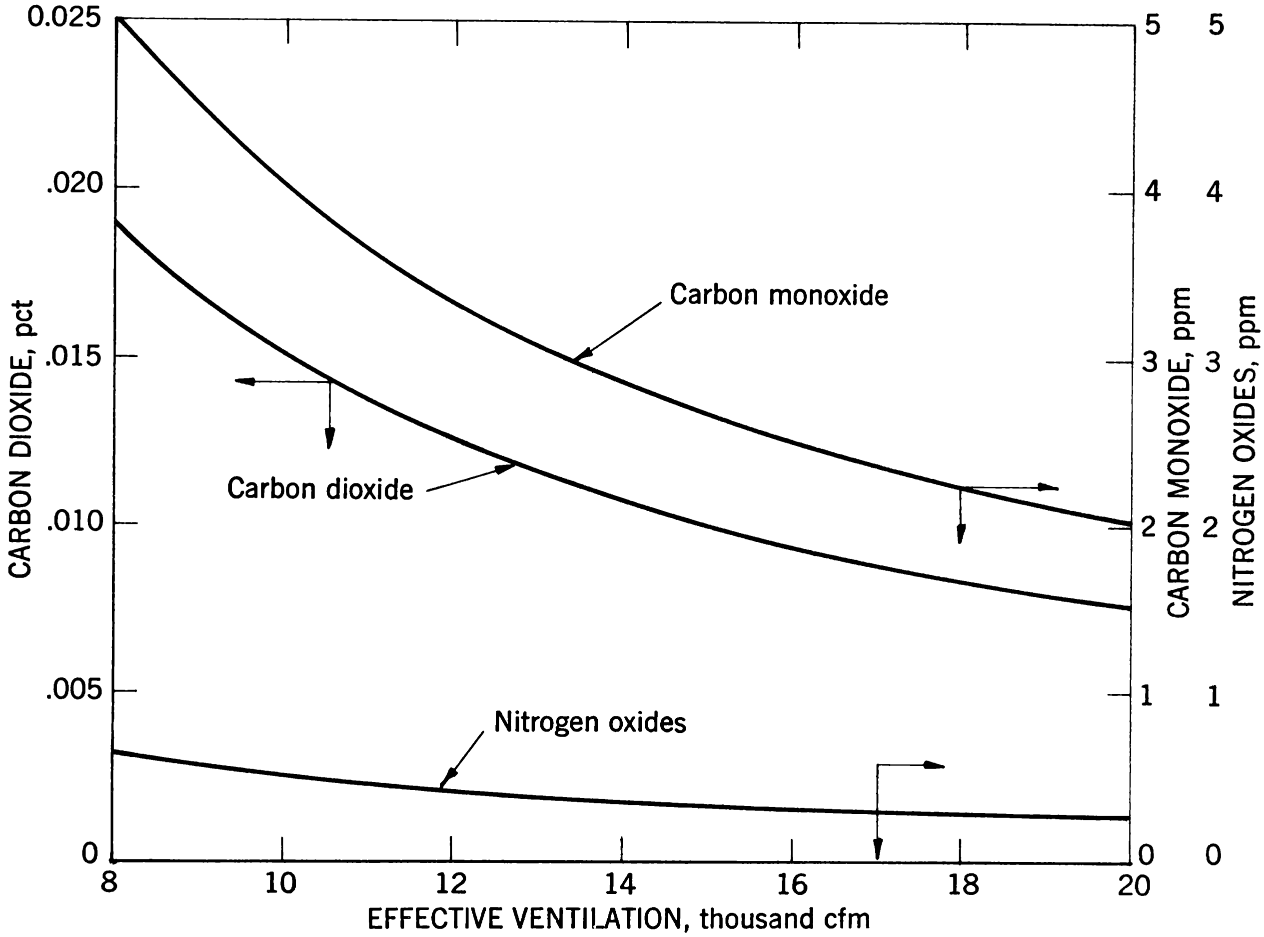

FIGURE 6. - Calculated Exhaust Contamination of Tunnel Air by a Diesel Locomotive Standing With Engine Idling.

Figure 8 shows incremental contaminations for carbon monoxide and nitrogen oxides. The increment of carbon monoxide from the loaded trip is less than from the empty trip. This performance is typical of many diesel engines. At constant engine speed the volume of carbon monoxide in the exhaust is greater at no load than at medium loads. At high loads carbon monoxide increases and may become excessive if the fuel-injection system is not derated properly.

To illustrate the application of these data, consider an outbound loaded trip passing the shaft station during exhausting ventilation. From figure 4, effective ventilation is 145,500 cfm. Incremental contamination by carbon dioxide as determined from figure 7 is 0.0141 pct. Increments of carbon monoxide and nitrogen oxides from figure 8 are 1.16 and 1.24 ppm, respectively. Comparison of these increments with those from the locomotive idling at the shaft is interesting. Carbon dioxide from the two widely different operating conditions is essentially the same, 0.0141 and 0.0142 pct. Carbon monoxide from the trip is 1.16 ppm in contrast with 3.81 ppm from the idling locomotive. For nitrogen oxides contamination from the trip is 1.24 ppm but that from the idling locomotive is only 0.48 ppm.

During the early part of the test at the shaft station an outbound loaded trip was followed closely by an inbound empty trip. Effective ventilation for

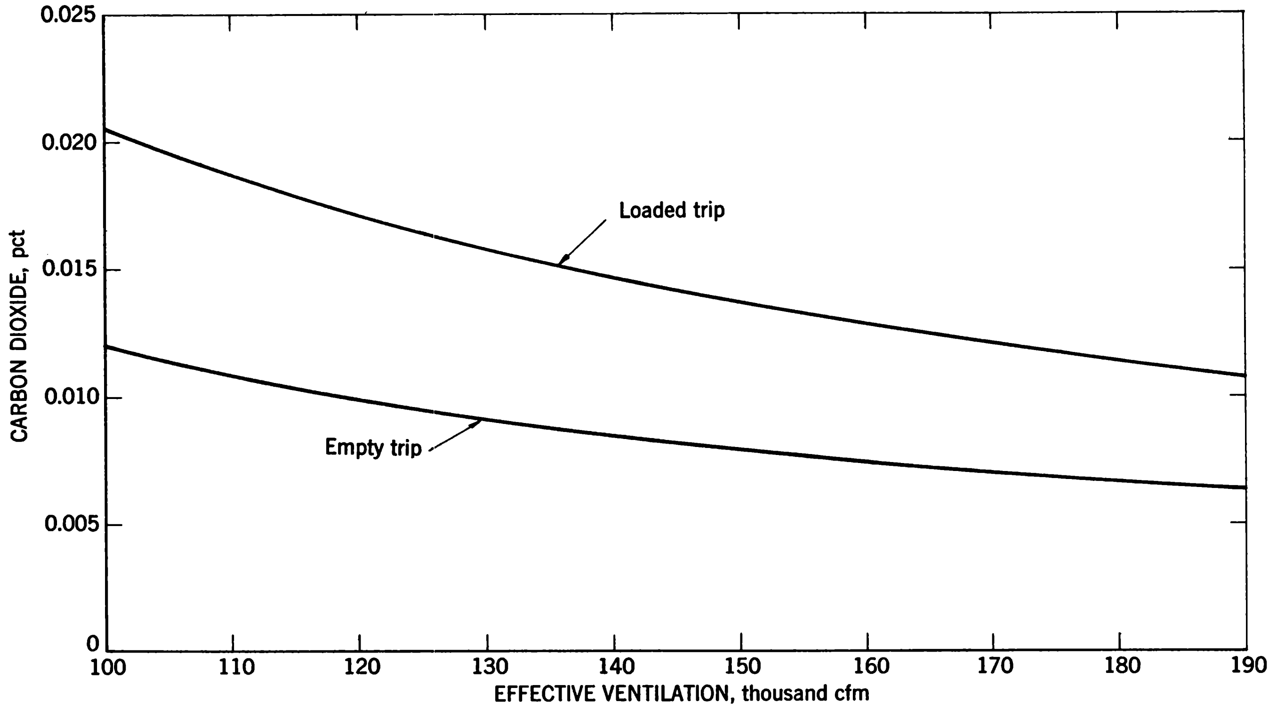

FIGURE 7. - Calculated Carbon Dioxide Contamination of Tunnel Air by a Moving Diesel Locomotive.

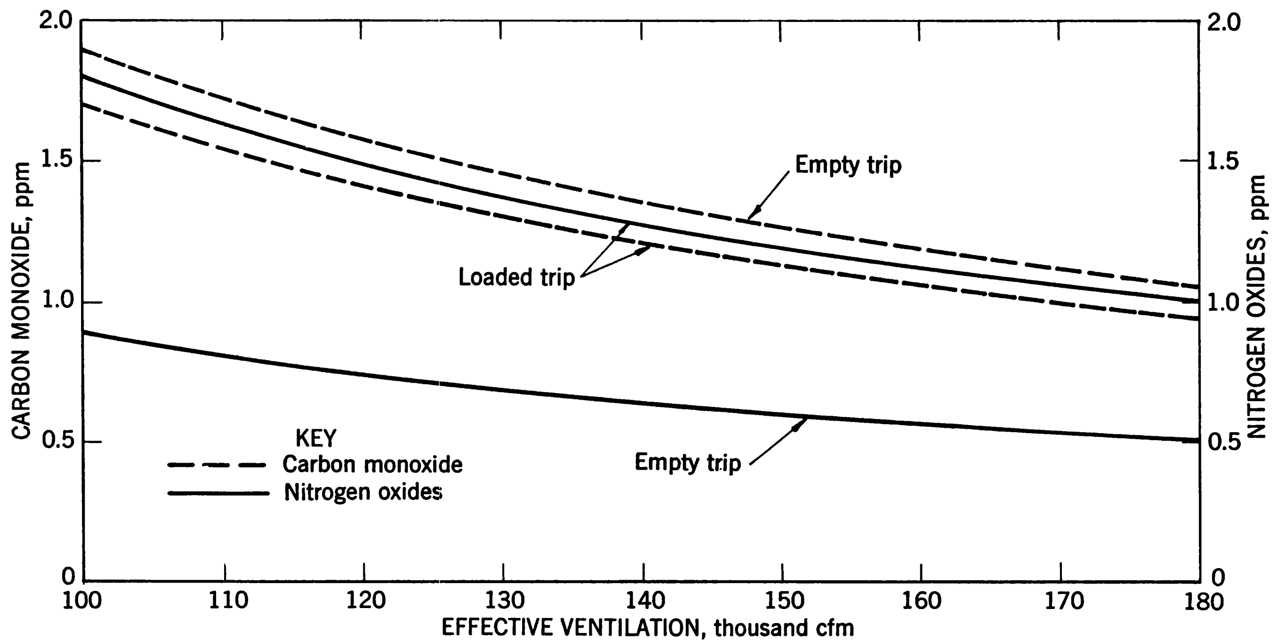

FIGURE 8. - Calculated Carbon Monoxide and Nitrogen Oxides Contamination of Tunnel Air by a Moving Diesel Locomotive.

the latter trip was 124,500 cfm. From figures 7 and 8, the incremental contaminations are 0.0095 pct carbon dioxide, 1.52 ppm carbon monoxide, and 0.72 ppm nitrogen oxides. In contrast with the outbound trip the increments for carbon dioxide and nitrogen oxides have decreased but that for carbon monoxide has increased.

Cumulative effects from the idling locomotive and these two trips occur at the shaft station three times early in the test (fig. 1). The expected air analysis for carbon dioxide is 0.0142 + 0.0141 + 0.0095 + 0.0300 or 0.0678 pct. Observed results for carbon dioxide were 0.07, 0.07, and 0.08 pct. Corresponding concentrations for carbon monoxide and nitrogen oxides are 6.49 ppm (3.81 + 1.16 + 1.52) and 2.44 ppm (0.48 + 1.24 + 0.72). The calculated concentration for carbon monoxide is higher than the observed concentrations. Results for nitrogen oxides are in better agreement.

Oxygen

Calculation of oxygen concentration by a similar method is cumbersome. Instead, the products of complete combustion for diesel fuel containing 86 pct carbon and 14 pct hydrogen were calculated. The dry products were then assumed to be diluted with normal air. The results are plotted in figure 9 to show the relationship of carbon dioxide and oxygen in air contaminated by diesel exhaust. This relationship closely approximates that for most distillate diesel fuels when the loss of oxygen is caused only by combustion. When gain or loss of oxygen occurs for other reasons, figure 9 will not apply.

Use of figure 9 is illustrated for conditions at the shaft station when the recurring condition of the previous example causes carbon dioxide to increase to 0.0678 pct. The corresponding oxygen concentration is 20.88 pct. This calculated result is in good agreement with the observed result in figure 1.

Dilution From Air Leakage

So far, illustrative calculations have been based on a few simultaneous incremental contaminations observed at the shaft station. When the concept of effective ventilation was applied initially in calculating total contamination for more complicated conditions the results were high. The cause was traced to dilution by air leakage from the vent duct and compressed-air line.

During blowing ventilation this dilution can be determined directly from the airflow measurements along the tunnel. The fractional ratio of the air volume at the source of contamination to that at an observation station has been called the dilution factor. This factor multiplied by the incremental contamination calculated at the source corrects for dilution by air leakage between the source and an observation station. The factor decreases with distance between the source and an observation station. Although dilution of each incremental contamination may be different depending upon source location, it is the same when increments travel between two fixed points in the tunnel. Moreover dilution is different in the two periods of blowing ventilation and two factors must be applied sequentially to an incremental contamination affected by both conditions.

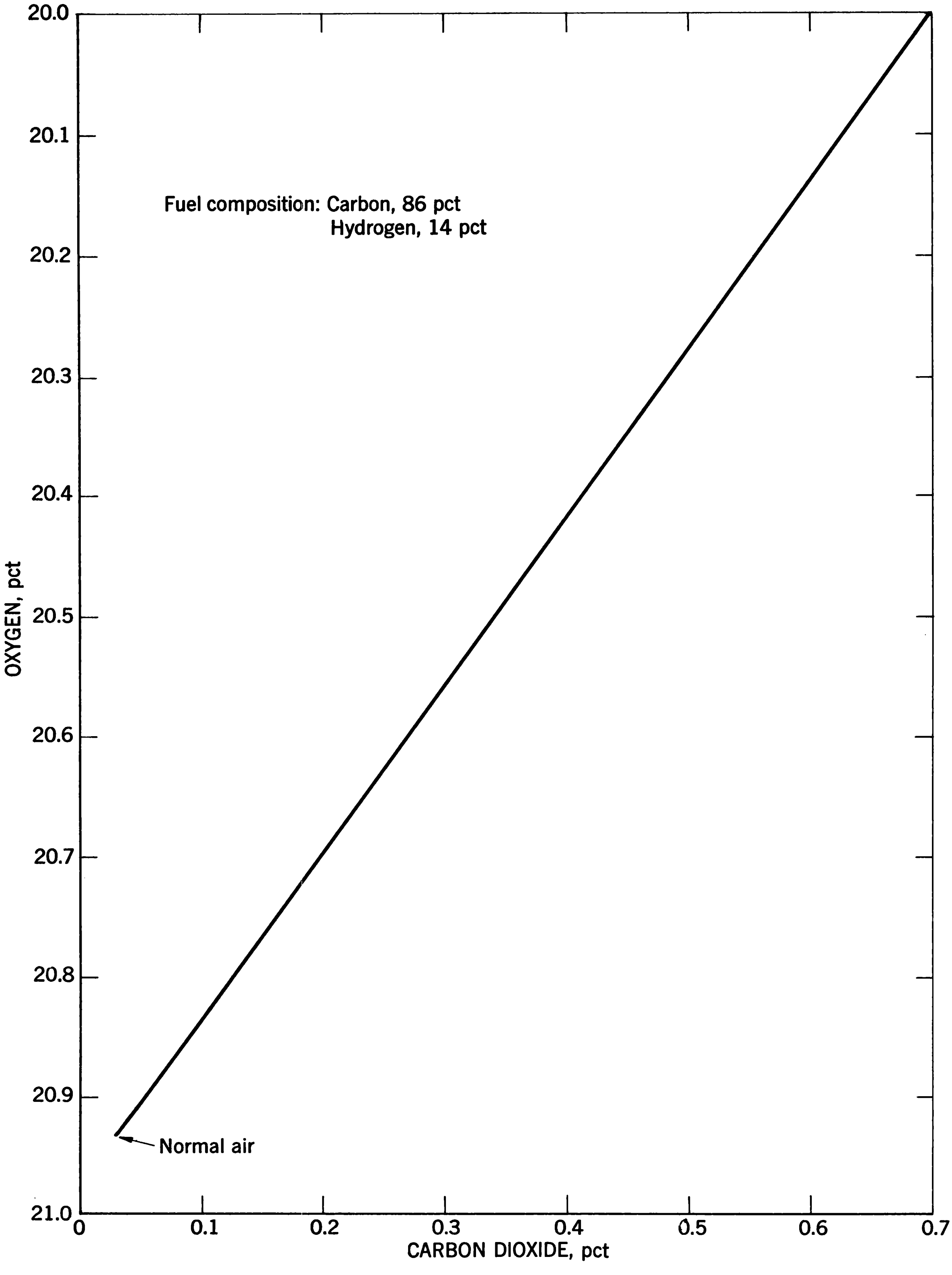

FIGURE 9. - Oxygen and Carbon Dioxide in Air Contaminated by Exhaust From Complete Combustion of Diesel Fuel.

During exhausting ventilation leakage into the vent duct does not affect the concentration of contamination but dilution is caused by leakage from the compressed-air line. An approximate dilution factor was determined as the ratio of the results of two calculations. In each the volume of flowing air in the tunnel minus the total compressed-air leakage at that location was divided by the volume of flowing air.

During both blowing and exhausting ventilation dilution effects increased along the tunnel in the direction of airflow.

Because dilution factors are simple to calculate, and are specific for these test conditions, no tabulation has been made. Instead their effect is illustrated in a calculation of contamination at the shaft station from 1425 to 1435 in table 2. The first column shows the sources of contaminations affecting the tunnel air represented by the air line in figure 4 that passes the shaft station at 1320. This air flows into the tunnel about 3,000 ft. At 1400 its direction is reversed and it arrives at the shaft station again at 1425.

Initial contamination is from No. 6 locomotive idling at the shaft bottom. The second incremental contamination, an outbound, loaded trip pulled by No. 1 locomotive, occurs at about 1,500 ft in the tunnel. Then two incremental contaminations are added in rapid succession at 2,000 ft from an inbound, empty trip by No. 6 locomotive and a man trip by No. 1 locomotive (considered as an empty trip).

After the ventilation system is reversed, other incremental contaminations are added at 2,200 ft by No. 1 locomotive pulling the outbound man trip; at 2,000 ft by No. 6 locomotive on an outbound, loaded trip; and near the shaft station by No. 6 locomotive on an inbound, empty trip.

The preceding air line, leaving the shaft station at 1310, shows the same contaminating sources. It reaches the shaft station again at about 1435. Thus, the air analysis calculated in table 2 represents contamination in air passing the shaft station between 1425 and 1435.

The third column shows the effective ventilation selected from figure 4, when this air first intersects the sources of contamination. Using these effective ventilations and figures 6, 7, and 8, the increments of contamination tabulated in the fourth, fifth, and sixth columns are determined.

Dilution factors obtained from ventilation rates shown in figure 5 and compressed-air leakage are tabulated in the seventh and eighth columns. Where two factors are involved their product is entered in the ninth column. Finally, the tenth, eleventh, and twelfth columns (air analysis) give the product of the dilution factor and the original contamination. The air analysis totals are given at the bottom of the table.

The calculated and observed results can be compared on figure 1. Considering the number of conditions affecting the calculation, the results are in good agreement.

TABLE 2. - Calculated contamination at shaft station from 1425 to 1435

Contamination source		Effective ventilation, cfm	Original contamination			Dilution factors			Air analysis		
Locomotive No.[1]	Activity		Carbon dioxide, pct	Carbon monoxide, ppm	Nitrogen oxides, ppm	Exhausting	Blowing	Product	Carbon dioxide, pct	Carbon monoxide, ppm	Nitrogen oxides, ppm
Trips before 1400, ventilation exhausting											
6..........	Idling at shaft	10,500	0.0142	3.80	0.48	0.968	0.919	0.890	0.0126	3.38	0.43
1..........	Outbound loaded	145,500	.0141	1.16	1.24	.981	.919	.901	.0127	1.05	1.12
6..........	Inbound empty	124,500	.0095	1.52	.72	.988	.919	.908	.0086	1.38	.65
1..........	Inbound mantrip	124,500	.0095	1.52	.72	.988	.919	.908	.0086	1.38	.65
Trips after 1400, ventilation blowing											
1..........	Outbound mantrip	121,800	.0098	1.55	.74	-	.944	.944	.0092	1.46	.69
6..........	Outbound loaded	120,750	.0170	1.41	1.48	-	.952	.952	.0162	1.34	1.41
6..........	Inbound empty	153,000	.0078	1.25	.59	-	1.000	1.000	.0078	1.25	.59
Total.....	-	-	-	-	-	-	-	-	[2] [3].1057	11.24	5.54

[1] Number identifies a specific locomotive on the trip chart, see figure 4.
[2] Normal air contains 0.0300 pct carbon dioxide; this concentration has been included in this total.
[3] From figure 9, the oxygen concentration corresponding to 0.1057 pct carbon dioxide is 20.83 pct.

DISCUSSION OF RESULTS

Although results of this investigation are specific for the conditions observed in this tunnel, general deductions are possible that apply to the ventilation, dilution, and movement of exhaust from diesel haulage in other mines and tunnels. These aspects are emphasized in this discussion.

The validity of these general deductions is supported by the agreement of observed and calculated results. Interrelationships were complex and involved three rates of ventilation. Locomotives moved in two directions or worked in a specific location; engine loads varied; and leakage of the vent duct and compressed-air line complicated the problem. Nevertheless the effects were related by rational assumptions and simple calculations. Diesel exhaust was the only contaminant of the tunnel air. Blasting gases were not a factor; they were removed effectively during exhausting ventilation. Moreover, no other source of similar contaminant gases was observed.

Dilution of exhaust was determined by effective ventilation. Two conditions were apparent. First, the exhaust of a locomotive standing or working in a local area was diluted in the air flowing through that area. For this condition effective ventilation is the same as measured ventilation. Secondly, the exhaust of a moving locomotive was diluted in the air through which it passed. For this condition effective ventilation is the vector sum of the locomotive and air velocities multiplied by the area of the haulageway. In this test effective ventilation for moving locomotives was 10 to 15 times greater than measured ventilation. For this reason incremental contamination in the wake of haulage trips was low even though measured ventilation was less than recommended for an approved locomotive. Unfortunately, effective ventilation is not the only criterion that affects accumulation of exhaust contamination.

As air moves through the tunnel, an increasing number of incremental contaminations ia added by haulage trips. Therefore, contamination increases with air travel distance. For example, air leaving the shaft station at 1130 arrived at the middle and face stations about 1240 and 1355, respectively. The carbon dioxide concentrations at the three stations were 0.08, 0.16, and 0.25 pct, respectively, in air volumes of 10,500, 10,000, and 9,000 cfm. The volumes of carbon dioxide in these air quantities were 8.4, 16.0, and 22.5 cfm. In addition, some contamination was lost by leakage into the vent duct.

When ventilation was reversed, contaminated air at the face station changed direction and flowed back to the shaft station. This air traveled more rapidly during blowing ventilation and additional contamination was added by other haulage trips. It arrived at the shaft station at 1535 with a carbon dioxide concentration of 0.22 pct while ventilation was at the high blowing rate (18,750 cfm); the volume of carbon dioxide in the air was 41.2 cfm. The lower concentration of contamination reflects dilution by leakage from the vent duct and compressed-air line.

Analysis of the movement and behavior of contamination caused by reversing ventilation shows that care must be taken to select a reversal cycle and air rate that will provide the best control of contamination. Theoretically, a ventilation cycle can be predicted in which some contaminated air will shuttle from end to end of a tunnel indefinitely and contamination will increase with each traverse. When ventilation is the same in both directions, the cycle should be unbalanced and flow in one direction maintained as long as possible. The time for this part of the cycle must be long enough for at least one air change. The reverse part of the cycle should be as short as possible.

Locomotive speed during haulage trips averaged 900 fpm. Observations indicated this speed was controlled primarily by the speed governor on the engine. After the locomotive reached a speed corresponding to the governed engine speed, the operating load of the engine decreased automatically. For empty trains the engine load was low and carbon dioxide contamination from the locomotives was low. In addition the high locomotive speed in relation to air speed was an important factor in causing high effective ventilation for haulage trips.

Calculations to determine the composition and volume of contamination in locomotive exhaust indicated track resistance was high. This was attributed to the sinuous, unballasted track and short radius curves at passing tracks. If the track had been maintained in better condition, air contamination may have been reduced.

Locomotives used underground must have sufficient power to accelerate rapidly to reduce effects from certain ventilation anomalies. As locomotives accelerate in the direction of airflow from standing to twice the air speed, effective ventilation decreases from the measured ventilation rate to zero when the locomotive and air velocities are the same. Thereafter, effective ventilation increases as the locomotive speed increases and equals the measured ventilation again when the locomotive velocity is twice the air velocity. This effect has little practical significance in air contamination when haulage trips accelerate rapidly.

Most discussions cite the piston effect of moving vehicles as an advantage in increasing ventilation. Berger and McGuire[7] have shown that this effect is not sufficient for safety under conditions of natural draft. They observed that train movement in a railway tunnel reversed the direction of natural flow and caused air to move in the direction the train was traveling. Exhaust contamination in the wake of a train was high (0.53 pct carbon dioxide) and decreased slowly in the following air. This contamination was related to the volume of air passing the train by calculations similar to those for determining effective ventilation. In their tests train speed was 15 mph and the ratio of frontal area of the train to tunnel area was about 50 pct.

Similar effects were not observed in this test. Factors contributing to negligible piston effect are positive mechanical ventilation; low haulage

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[7]Berger, L. B., and L. H. McGuire. Observations on the Use of a Diesel Freight Locomotive Through a Railway Tunnel. BuMines Rept. of Inv. 3887, 1946, 20 pp.

speed, 10 mph; low ratio of train frontal area to tunnel area, about 25 pct; and exhaust diffusers on approved locomotives cause rapid and uniform mixing of exhaust in tunnel air. Similar conditions apply in many mines and tunnels. Nevertheless, the possibility of adverse effects from piston action should be considered when locomotive speed and the ratio of train frontal area to tunnel area is higher.

Carbon Dioxide

In the preceding discussion total contamination was evaluated by considering changes in carbon dioxide concentration. This was suggested by the agreement of observed and calculated results. The large volume of carbon dioxide in the exhaust changes in nearly direct proportion to engine load and can be estimated with reasonable accuracy. Moreover, carbon dioxide in diesel exhaust is affected less by improper adjustment of the fuel system, combustion chamber design, and imperfections in fuel-injection nozzles, and can be determined accurately in samples of tunnel air.

If carbon dioxide concentration in tunnel air is the criterion for evaluating exhaust contamination, its concentration should not exceed 0.25 pct. When this concentration is not exceeded and the engine fuel system is adjusted properly for operation underground, the concentrations of other exhaust components will be physiologically acceptable.

Carbon Monoxide

Observed carbon monoxide contamination showed changes similar to those for carbon dioxide but was lower than calculated. Several reasons support the validity of the lower observed results. First, carbon monoxide in the exhaust during idling was estimated conservatively. Secondly, at 1,000 ft below sea level a greater weight of air flows through the engine because of increased barometric pressure and combustion probably occurs at lower fuel-to-air ratios than those used in estimating exhaust composition. From qualitative considerations such conditions result in less carbon monoxide in the exhaust of loaded trips and slightly more for empty trips but the quantitative effects cannot be predicted easily. These considerations will not apply at higher elevations where proper adjustment of the fuel system is more important because the lower barometric pressure reduces the weight of air flowing through the engine and causes operation at higher fuel-to-air ratios that may be critical at high engine loads.

Carbon monoxide in the tunnel was determined in air samples sent to the laboratory and with portable detectors. Detector results were slightly higher than laboratory results, but, despite individual differences, results by the two methods are in agreement. Thus, the usefulness of portable detectors for rapid evaluation of carbon monoxide in the underground atmosphere was demonstrated. Since all observed results were below 20 ppm, no direct health hazard from this toxic gas was indicated.

Nitrogen Oxides

Nitrogen oxides in undiluted engine exhaust show great variations with changes in engine load and appreciable variations at constant load. Nevertheless, calculated results agreed with the observed concentrations reasonably well.

Industrial hygienists seem to agree that the concentration of total nitrogen oxides is not a good criterion for evaluation of their physiological effects. Instead, a ceiling threshold limit value (TLV) is given as 5 ppm for nitrogen dioxide.[8] Nitrogen dioxide concentrations determined with portable detectors during this test did not exceed 1 ppm. Thus toxic nitrogen dioxide was not especially significant as an air contaminant in this test. Under other conditions different results might be found because the formation of nitrogen dioxide is related to the concentration of total nitrogen oxides and the amount formed increases as the time available for reaction increases.

Methane

Methane from exhaust contamination was not anticipated, but the sensitive method used in analyses of the air samples consistently showed its presence. Also, the observed variations are similar to those for carbon dioxide. No observations during the test indicated a source of methane other than diesel exhaust.

Oxygen

Observed and calculated results for oxygen agreed well and showed that reduced oxygen concentrations were related to carbon dioxide contamination. The minimum observed concentration of 20.66 pct has no important physiological significance. Other considerations suggest that ample ventilation will avoid changes in the combustion process within the engine that would increase toxic carbon monoxide in the exhaust. Such effects should not be significant if oxygen in the underground air is maintained above 20.5 pct.

Evaluation of Exhaust Contamination

The undesirable physiological properties of the three principal objectionable gases in diesel exhaust, carbon dioxide, carbon monoxide, and nitrogen dioxide, are recognized in published TLV.[9] Nearly all workers may be exposed to TLV concentrations of the individual gases for 8 hr, day after day, without experiencing adverse effects. Mixtures of some gases may have additive effects that should be controlled by the relationship expressed in the formula

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots . \frac{C_n}{T_n} = 1,$$

[8] American Conference of Governmental Industrial Hygienists. Threshold Limit Values for 1966: Recommended and Tentative Limits. Adopted at the 28th Annual Meeting of the American Conference of Governmental Industrial Hygienists, Pittsburgh, Pa., May 16-17, 1966, 28 pp.

[9] Work cited in footnote 8.

in which C is the observed concentration in the ambient air mixture and T is the TLV concentration. If the indicated summation yields a number >1, the mixture is considered undesirable for 8-hr exposure of workmen. Although this relationship may not accurately indicate physiological effects from diesel exhaust contamination, evaluations using it should be conservative and safe.

The observed analysis of one of the more contaminated air samples was 0.23 pct carbon dioxide, 13 ppm carbon monoxide, and 0.8 ppm nitrogen dioxide. The respective TLV concentrations for these gases are 0.50 pct, 50 ppm, and 5 ppm. Substituting these values in the formula gives

$$\frac{0.23}{0.50} + \frac{13}{50} + \frac{0.8}{5} = 0.46 + 0.26 + 0.16 = 0.88.$$

Exposure to contaminated air of this composition could be considered acceptable but approaching a marginal condition at unity.

The foregoing formula is suggested for evaluating the physiological hazard from diesel exhaust contamination in underground air. Action to decrease contamination should anticipate an evaluation >1.

CONCLUSIONS

Contamination of underground air by the exhaust of diesel haulage equipment is related to effective ventilation, the number of trips during an air change in the haulageway, and engine load and adjustment. The fuel system of diesel equipment must be adjusted to eliminate excessive carbon monoxide in the exhaust.

Effective ventilation is calculated as the vector sum of the locomotive and air velocities multiplied by the cross-sectional area of the haulageway. The result is expressed in cubic feet per minute, the same units used in ventilation measurements.

For a standing locomotive effective ventilation is the measured air volume flowing around the locomotive. In many instances incremental contamination by carbon dioxide and carbon monoxide from an idling locomotive was greater than that from loaded haulage trips. Because contamination from a standing locomotive, or one working in a limited area, may pervade the haulageway and be increased by exhaust from haulage trips, the engine of standing equipment should be shut off when practicable.

In this investigation effective ventilation for haulage trips was 10 to 15 times the lowest measured ventilation. The length of tunnel contaminated in the wake of a trip was the vector velocity multiplied by the elapsed time for the trip.

Total contamination of flowing air was the sum of incremental contaminations from locomotives passed by the air plus those from trips passing through it. Contamination increased along the tunnel in the direction of the airflow. Air velocity affected the concentration of contamination as well as the time when contaminated air was discharged from the tunnel.

Trips moved at a nearly constant velocity controlled by the speed governor on the engine. This condition applies when the locomotive has ample power for pulling the trip. Because the governor controls the fuel-injection rate, the volume of exhaust contamination varies with the trip load. On level track the engine operates at maximum load only during acceleration. These observed operating conditions partly explain low observed contamination although measured ventilation was less than that recommended for one approved locomotive.

Reversal of the ventilation system changed the direction of air travel but did not affect directly the concentration of contamination. Some contamination traversed the tunnel twice before being discharged at the shaft. This behavior is a factor in selecting the ventilation cycle for tunnels. An improper cycle could cause some contamination to shuttle within the tunnel continuously and be increased with each shuttle movement while locomotives are operating. Ventilation in one direction should be continued until at least one air change is accomplished; flow in the opposite direction should be continued for a shorter time.

During blowing ventilation, leakage from the vent duct and compressed-air line reduced the concentration of contamination. During exhausting ventilation, dilution was caused only by leakage from the compressed-air line.

Effects from the number of haulage trips, engine load, effective ventilation, ventilation reversal, and vent duct and compressed-air leakage were combined in calculating contamination. This procedure gave results in good agreement with observed analyses. Agreement was best for carbon dioxide, which was the exhaust contaminant appearing in the greatest concentration. Calculated results for carbon monoxide and nitrogen oxides were higher than observed results. Nitrogen dioxide was observed only in trace amounts.

Calculation methods developed in this investigation can be applied in designing the volume of ventilation for diesel haulage in proposed mines and tunnels. However, such calculations must anticipate the changing conditions that will develop during the life of the project.

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