

Information Circular 9118

Face Ventilation for Oil Shale Mining

**By Edward D. Thimons, Carl E. Brechtel, Marvin E. Adam,
and Joseph F. T. Agapito**



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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

bhp	brake horsepower	hp	horsepower
Btu/h	British thermal unit per hour	in	inch
ft	foot	in w.g.	inch, water gauge
ft ²	square foot	lb	pound
ft ³	cubic foot	lb/ft ³	pound per cubic foot
ft/min	foot per minute	mg/m ³	milligram per cubic meter
ft·min/ft	foot per minute per foot	mg/min	milligram per minute
ft ³ ·min/bhp	cubic foot per minute per brake horsepower	min	minute
ft ³ /st	cubic foot per short ton	µm	micrometer
gal	gallon	pct	percent
h	hour	ppm	part per million
		ppt	part per trillion

FACE VENTILATION FOR OIL SHALE MINING

By Edward D. Thimons,¹ Carl E. Brechtel,² Marvin E. Adam,³ and Joseph F. T. Agapito⁴

ABSTRACT

This Bureau of Mines report presents expected levels of air pollutants in the face areas of oil shale mines, based upon data collected by the authors and previous investigators. Ventilation requirements to maintain these pollutant levels below their threshold limit values and Federal and local mine air quality standards are discussed. Two practical face ventilation systems are discussed in terms of actual in-mine test experience.

INTRODUCTION

Oil shale mine entries typically will have cross-sectional areas of 1,500 ft² or more. Face ventilation systems, to effectively dilute and remove pollutants from the face area of these mines, will be critical to the successful operation of the underground oil shale industry. The large diesel-powered equipment and heavy face blasting needed in oil shale mines create substantial ventilation requirements. Furthermore, it is possible that some oil shale mines will be classified as gassy, which will introduce additional ventilation problems and requirements.

For ventilation personnel to deal with these problems, they must understand the levels of pollutants to be expected and the threshold limit values (TLV's) of these pollutants. It will also be most helpful to them to have some knowledge of what face ventilation systems have already been tested and of how these systems performed. The purpose of this report is to provide this information.

Under a Bureau of Mines contract, J. F. T. Agapito & Associates conducted a detailed study to establish face ventilation requirements for oil shale mines, design face ventilation systems to satisfy these requirements, and test and evaluate the most promising of these designs in an oil shale mine. The information presented in this report was obtained under that program.

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FACE VENTILATION REQUIREMENTS

This section reviews background data on mine air pollutant production to help establish air quantities. The quality of air at the face must meet regulatory requirements. In some cases, there may be multiple requirements. For example, Colorado State law requires that 75 ft³/min of fresh air be used to ventilate each brake horsepower of engine capacity; it also requires the maintenance of TLV's for various air pollutants, as specified by the Mine Safety and Health Administration (MSHA). The main sources of air pollutants expected to impact face ventilation requirements follow:

Loading operations.--Noxious gases, diesel particulates, and dust are produced during loading operations at the face. These are especially severe for

mines designed for front-end loaders with truck haulage.

Blasting.--Large quantities of noxious gases and dust are generated by face blasting.

Strata gas.--Methane can occur both as free gas in solution with groundwater and as absorbed gas in solid solution with the kerogen in oil shale. The existence of methane has not been reported for properties at the southern rim of the Piceance Creek Basin, but it has been observed during development mining in the Uinta Basin and central portion of the Piceance Creek Basin.

Specific air pollutants of concern produced during oil shale mining and their allowable concentrations or TLV's are listed in table 1. These values are

TABLE 1. - Threshold limit values of air pollutants expected in oil shale mining

Pollutant	TLV ¹	Exposure criterion	Maximum excursion
CO ₂ppm..	5,000	TWA	ND
CO.....ppm..	50	TWA	75
NO.....ppm..	25	TWA	37.5
NO ₂ppm..	5	C	5
Formaldehyde.....ppm..	2	C	2
H ₂ S.....ppm..	10	TWA	20
Methane.....ppm..	10,000	C	10,000
Respirable dust ²mg/m ³ ..	1.4-0.7	TWA	ND
Total dust.....mg/m ³ ..	3.6-1.9	TWA	ND

C Maximum value not to be exceeded.

ND Not defined.

TWA Time-weighted average.

¹Based upon American Conference of Governmental Industrial Hygienists Standards of 1973.

²Estimated based upon a range in quartz content between 5.4 and 12.6 pct.

derived from the American Conference of Governmental Industrial Hygienists Standards of 1973 (as specified by MSHA). TLV's are generally based upon the time-weighted average exposure over a specified time period. However, additional restrictions can be imposed by the maximum excursion value, which is defined as the maximum allowable concentration that personnel can be exposed to at any time. Dust TLV values listed in table 1 are estimates based upon data published on the particle size of oil shale dust and on measurements of quartz content. The parameters that affect the dust TLV's include quartz content, respirable mass, and diesel particulates. Diesel particulates are counted in the total dust mass and the total respirable dust mass; they have the effect of reducing quartz content. This impacts the TLV, because it is a strong function of quartz content.

DIESEL ENGINE EMISSIONS

It has been generally accepted that the production of nitrogen oxides (NO) and carbon monoxide (CO) by the large-capacity diesel loading equipment would govern the quantity of fresh air required at the face. However, studies of the production of diesel particulates by Breslin (1)⁵ and Daniel (2) suggest that the requirement to limit particulate concentrations may be the governing factor.

Gaseous emission studies by Markworth (3) compared the performance of three engines whose peak horsepower ranged from 800 to 1,200 hp for potential application to oil shale mining and illustrated that pollutant production rates varied over a large range. Emissions for the cleanest engine tested in the study are listed in table 2, along with the required quantity of fresh air, assuming ideal dilution. The required quantity of fresh air was determined for the additive effects of CO and NO_x using the inequality in this equation as suggested by Bossard (4):

$$\frac{C_{CO}}{TLV_{CO}} + \frac{C_{NO_x}}{TLV_{NO_x}} < 1.0 \quad (1)$$

where C = pollutant concentration, ppm.

The tests were conducted using both fresh air and fresh air containing 1.5 pct methane in the form of natural gas to compare emissions for nongassy and gassy conditions. The addition of methane produced a large increase in CO production, which required an increase of ventilation air of 43 to 91 pct of the original quantity, depending on operating horsepower. The 1.5-pct methane content exceeds the maximum methane concentration of 1.0 pct allowed under MSHA regulations, but

⁵Underlined numbers in parentheses refer to items in the list of references at the end of this report.

TABLE 2. - Comparison of engine exhaust and required ventilation

Brake horsepower ¹	Conc, ppm		Exhaust flow, ² ft ³ /min	Required ventilation, ³ ft ³ /min
	CO	NO _x		
With no methane:				
561.....	100	488	1,814	36,140
823.....	150	538	2,257	55,330
With 1.5 pct methane:				
561.....	875	506	1,830	69,060
823.....	713	513	2,276	79,170

¹From Markworth (3) for a turbocharged, after-cooled Caterpillar D-348 engine with precombustion engine and water scrubber.

²Estimated from Markworth (3) by subtracting mass flow of natural gas and extrapolated to 0.062 lb/ft³ density from 0.075 lb/ft³.

³Assuming ideal dilution.

illustrates that methane in the mine air could impact pollutant production. Based upon table 2, in the nongassy environment the engine would require 64 to 67 ft³·min/bhp to meet the TLV's; in the gassy environment it would require 96 to 123 ft³·min/bhp.

OIL SHALE DUST AND DIESEL PARTICULATES

Both diesel particulates and oil shale dust must be considered in assessing the impact of particulate production on face ventilation requirements in oil shale mining. Dust data reported by Volkwein (5) are summarized in table 3. The average dust mass was 1.45 mg/m³, and average quartz content was 5.8 pct.

A group of dust measurements was reported by Brechtel (6) which included measurements of dust production due to blasting and loading operations in an underground oil shale mine. Dust produced by a face blast (1,900 lb ANFO) in oil shale has an average total mass of 13.2 mg/m³, with less than 2 pct of the dust having a particle diameter of less than 0.7 μm. The dust had a light brown color. Particulates measured during simulated loading operations showed that the fine fraction (<0.74 μm) increased to 53 to 73 pct of the total mass and was black in color. This led to the conclusion that most of the fine particles were

diesel particulates. Quartz content analyses listed in table 4 support this conclusion in that quartz contents of the fine fractions were below detection limits. Quartz contents were similar in range to the Volkwein (5) data, averaging 4.4 pct.

The rates of production of respirable oil shale dust and diesel particulates are estimated in table 5, using both particle gradation measurements made during the loading and the measured ventilation flow. At an average production rate of 6,220 mg/min, face ventilation capacities in the range of 157,000 ft³/min would be required to maintain respirable particulates at a TLV of 1.4 mg/m³ (assuming 5.4 pct quartz). These measurements are probably not representative of expected conditions because--

1. The material being loaded was partly comprised of cuttings from a roadheader miner and may have contained a disproportionately large amount of fine material.

2. The diesel equipment was very old and poorly maintained. The generation of particulates during loading operations will be an important parameter in face ventilation requirements. Oil shale dust production must be limited by good mining practice such as wetting the muckpile and roadways, and diesel particulate production must be minimized by engine

TABLE 3. - Comparison of measured respirable dust concentration and TLV (5)

General location	Alpha quartz content, pct	Respirable dust, mg/m ³	
		Measured conc	TLV ¹
Drilling: On jumbo.....	3.5	2.05	1.82
Blasting: Around corner from face.	14.0	NA	.63
Scaling:			
Operator position.....	6.7	2.68	1.15
Outside machine.....	.9	.94	2.00
Mucking:			
Av on sides of crosscut.....	² 2.7	² .63	2.13
Inside loader cab.....	² 11.1	² 1.05	.76
Outside loader cab.....	NA	2.18	NA
Roof bolting: In or near bolter...	² 1.8	² .63	2.63
Average.....	5.8	1.45	1.59

NA Not available.

¹Based on quartz content.

²Average of values from several locations.

TABLE 4. - Quartz content of dust sample collected during simulated loading operations (6)

Loading operation and sample type	Mass conc, mg/m ³	Quartz con- ³ tent, mg/m ³	Quartz as pct of total mass
With truck shutdown:			
Filter cartridge.....	4.63	0.296	6.4
Dichotomous sampler:			
Coarse (2.5 to 15 µm).. Fine (<2.5 µm)..... Total.....	.72 2.34 3.06	.085 .030 .115	NAp ND 3.8
With truck idling:			
Dichotomous sampler:			
Coarse (2.5 to 15 µm).... Fine (<2.5 µm)..... Total..... Overall average.....	.58 3.16 3.74 3.81	.075 .040 .115 .175	NAp ND 3.1 4.4

NAp Not applicable. ND Not detectable.

TABLE 5. - Estimated proportions of oil shale dust, diesel particulates, and projected production rates based upon simulated loading tests (6)

	Loading		
	With truck shut down		With truck idling
	Worker floor location	Operator location	
Height above floor.....ft..	5	12	12
Av dust mass, mg/m ³ :			
Total ¹	2.8	5.1	5.8
Respirable.....	2.5	3.6	5.1
Oil shale dust:			
Pct of respirable mass ²	21	18	16
Est production rate ³mg/min..	1,070	1,320	1,660
Diesel particulates:			
Pct of respirable mass ²	79	82	84
Est production rate ³mg/min..	4,030	6,020	8,740
Est total respirable dust production.....mg/min..	5,100	7,340	10,400

¹13.2 for blasting.

²Assumes that total fine fraction (<0.7 µm) is diesel particulates.

³Based upon measured ventilation airflow of 72,000 ft³/min.

selection and good maintenance in order to meet governing particulate TLV's.

BLASTING

Blast rounds planned for room and pillar operations require the detonation of up to 2,000 lb ANFO. Although careful control of explosive composition limits air pollutant production, studies of blast-produced air pollutants by Rogers (7) and Abata (8) indicate that the large quantities of ANFO required for oil shale

mining will produce considerable amounts of noxious gases. Table 6 compares estimated production to measurements for a full-face shot at the Colony Mine (6). The table suggests that production of blast-produced air pollutants can be adequately predicted if the mass of ANFO being detonated is known. Ventilation of noxious gases in the face area is not a critical parameter after the shot, because personnel do not enter the heading for some time. However, if gassy conditions exist, methane gas may be

liberated by face blasting and require implementation of special ventilation practices to minimize the hazard.

METHANE OCCURRENCE IN OIL SHALE MINING

Publicly available information on the occurrence of methane in oil shale suggests that it occurs both as a free gas, as gas in solution with groundwater, and as absorbed gas in solution with kerogen. Table 7 summarizes public data on methane occurrence in oil shales of the Green River Formation. Oil shale mining and exploration conducted in central Piceance Creek Basin tracts and the Uinta Basin have encountered methane. The outcrop and erosional exposure at the

TABLE 6. - Comparison of estimated and measured concentrations of gases produced by full-face blast at Colony pilot oil shale mine (6)

Pollutant	Concentration, ppm	
	Estimated ¹	Measured ²
CO ₂	³ 2,721	³ 1,520
CO.....	190	155
NO _x	88	69
NO.....	47	50
Density....lbft ³ ..	0.062	0.062

¹Based upon Abata (8), with a total of 1,890 lb ANFO and an estimated dilution volume of 878,400 ft³.

²These concentrations would vary for different blasting patterns, methods of initiation, and fuel oil content.

³Includes background atmospheric CO₂.

southern rim apparently has allowed the methane to bleed off, while in the central Piceance Creek and Uinta Basins, confinement due to the hydrologic system may have contained the gas.

Recent work by Sapko (9) presents the results of measurements of methane released by mining operations in the Mahogany Zone at the U-a, U-b oil shale lease in the Uinta Basin, and is particularly pertinent to ventilation design. Methane released from oil shale rubblized by blasting ranged from 2.3 to 22.5 ft³/st with an average value of 13.3 ft³/st. Other work by Schatzel (10) reports that methane given off by core samples obtained from the Mahogany Zone at C-b tract averaged 6.2 ft³/st after 125 days of monitoring. Total methane content of the core samples was not determined, but similar measurements by Matta (11) suggested that after 21 days of monitoring as much as 40 pct of the methane had been released.

The deep saline oil shale sequence (R1-R5 zones) found in the Central Piceance Creek Basin is known to have a much higher gas content than the oil shales of the overlying leached sections (R6, Mahogany [R7], and R8 zones). Data reported by Sapko (11) for saline oil shales rubblized by blasting indicated a range of 2.4 to 56.7 ft³/st. These data are not applicable to mining in the leached section because of differences in stratigraphic environment.

Production of methane by groundwater entering the mine and by desorption from

TABLE 7. - Summary of publicly available data on methane occurrence in oil shale

Type of occurrence, by site	Range in magnitude of occurrence	Reference
Free gas, ft ³ /min: C-b tract.....	55 - 1,600	12
Gas in groundwater, ft ³ /10 ³ gal H ₂ O: C-b tract.....	5.9 - 64.8	13
Gas absorbed by kerogen, ft ³ /st:		
Uinta Basin.....	2.3 - 22.5	9
Uinta Basin.....	7.6 - 33.2	14
C-a tract.....	.8 - 15.2	15
C-b tract.....	.03- 32.6	13
C-b tract.....	6.2	10
Horse Draw (saline zone).....	2.4 - 56.7	9

the excavation boundary is expected to be handled by the main mine ventilation system. Two specific types of occurrence could impact face ventilation, as described in the following paragraphs.

Sudden Inflow of Methane-saturated
Water or Free Methane

Methane inflows could result from the intersection of (1) natural fractures that were connected to a localized aquifer with high methane saturation or (2) a localized reservoir of free methane. This type of situation was reported by Stellavato (12) during shaft sinking operations at the C-b tract, where a sudden inflow of water and methane produced initial methane release rates of 1,600 ft³/min. The water inflow dropped to 13 pct of its initial value within 24 h, and the methane production dropped to 55 ft³/min. There are informal reports of this type of methane occurrence in drilling operations during resource evaluation. The apparent randomness of occurrence (methane was encountered in one out of three shafts sunk in close proximity at C-b) and rapid reduction in water-methane production encountered to date suggest small, localized reservoirs (gas or groundwater), isolated from the main hydrologic system. In this case, the frequency of occurrence might be small, and the hazard represented would be reduced.

This type of methane occurrence would be most hazardous if a methane layer developed owing to localized, high-volume methane flow from fractures intersecting the roof of a heading. Methane layering results when buoyant effects due to the density contrast between methane and air are of greater magnitude than the turbulent mixing energy of the airstream at a given velocity.

Research on methane layering is reported in detail by Bakke (16), who proposed "layering numbers" to evaluate the potential for methane layering at varying ventilation air velocities, methane production rates, and excavation widths. The layering number (L) is calculated by the equation

$$L = \frac{U}{37[(V/W)^{1/3}]}, \quad (2)$$

where L = methane layering number,

U = ventilation air velocity,
ft/min,

V = methane flow rate, ft³/min,

and W = excavation width, ft.

This expression was developed for air flowing uniformly along a heading without any equipment to enhance mixing. Bakke (16) suggests that a layering number of 5 represents an optimum for limiting the layer length. Further increase in air velocity beyond the velocity necessary to produce a value of 5 does not reduce the length of the layer appreciably. At layering numbers below 2, the buoyant effects dominate and the methane layering will be pronounced.

The methane layering problem is heavily dependent upon the location of the methane source and the degree of localization of the production. Distributing a given production over a long section of roof tends to reduce the layering problem. If the methane is produced from the floor or walls, the ventilation air can mix and disperse the methane more effectively. Bakke (16) notes that once the methane is well mixed in air, restratification due to the density contrast is minor.

The magnitude of potential methane layering problems in oil shale mining is difficult to estimate because of the lack of operating data on methane production. Figure 1 shows the relationship between methane inflow rate and required air velocity to achieve methane layering numbers of 2 and 5. An air quantity of 100,000 ft³/min for face ventilation in a 55-ft-wide by 30-ft-high opening gives an average velocity of 61 ft/min. The resulting methane layering number would be below the critical value of 2 for methane inflows above 50 ft³/min, indicating that layering in the face heading area will be a problem given sufficient methane inflow. The problem may be compounded by the large cross-sectional area of the

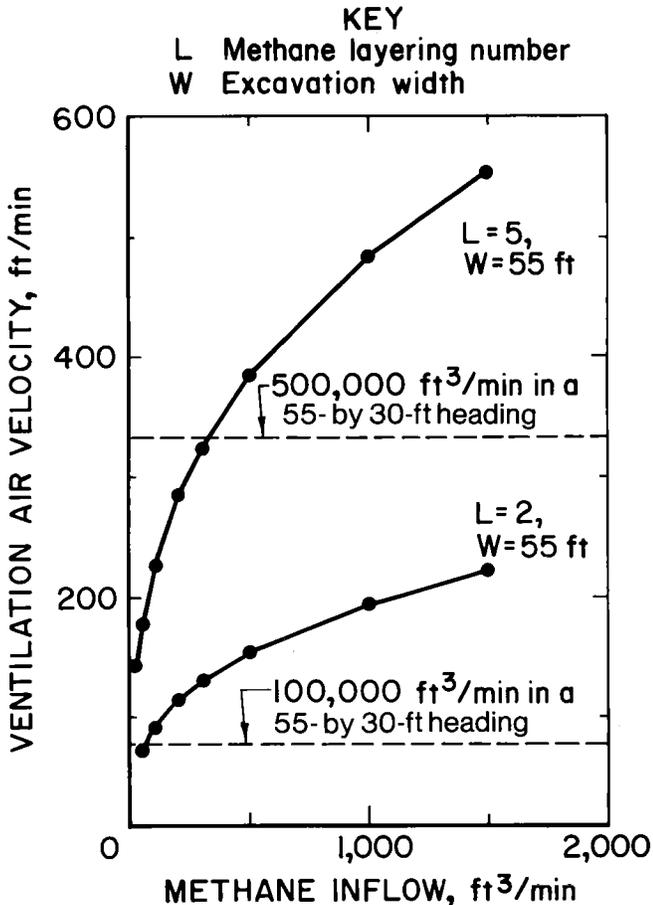


FIGURE 1.—Ventilation velocities required to achieve methane layering numbers of 2 and 5 versus methane inflow.

openings. Ventilation using a ducted system results in very high velocity at the immediate face but relatively low velocity throughout the heading. Increasing the average air velocity requires a large increase in flow rate through the duct, which would result in large energy costs. An alternative would be to increase local mixing by using an auxiliary jet fan. The use of a jet fan as the main face ventilation system would be an effective way to increase air mixing, because the jet fan uses the heading itself as a duct and the average air velocity is higher (200 to 400 ft/min). Bakke (16) emphasizes that air velocity is the critical factor.

Flow in the last open crosscut is expected to range from 400,000 to 800,000

ft³/min based upon a survey by Brechtel (6) of oil shale companies. A value of 500,000 ft³/min would give air velocities above 300 ft/min and result in a layering number above 2 for a quite large inflow of methane.

Blast-Released Methane

The magnitude of the methane concentration that could result from face blasting in methane-saturated oil shale is difficult to estimate because of the lack of definitive data on methane content and because of the interaction of methane release rate and ventilation airflow in the heading. Measurements of methane production during oil shale mining operations at the Horse Draw facility are reported by Richmond (17) and Sapko (11). A typical curve of methane concentration in ventilation air after a blast (fig. 2A) indicates that the methane concentration reached its peak value shortly after the blast. Figure 2B shows a semilog plot of the data, illustrating the generally linear relationship expected for the dilution of gas in a room of fixed volume ventilated by a constant flow rate of fresh air. Based upon room volume, 80 pct of the total methane liberated by the blast was mixed with the room air within 5 min after the blast. Figure 2 shows data for 60 st of blasted shale; it is not known how a blast rubblizing several thousand tons of oil shale would affect the rate of methane release.

A typical face heading 50 ft wide by 30 ft high, advancing 30 ft, would produce 2,808 st of rubblized shale (density of approximately 124.8 lb/ft³) and could release a large volume of methane. Assuming an average saturation of 13.3 ft³/st, a single blast could produce approximately 44,000 ft³ of methane, as suggested by the data from Sapko (9). If all the methane were released instantaneously in a 50-ft-wide by 30-ft-high heading, 300 ft long and mixed uniformly, this would result in a methane concentration of 8 pct.

MAXIMUM LENGTH OF DEADHEADING

Regulatory guidelines govern the length of the deadheading in coal mining by stipulating a limit of 100 ft of advance before breaking through a new crosscut. For oil shale mining, this requirement

would be impractical. Based upon operational considerations and typical room and pillar dimensions, it was estimated that 300 ft would be an acceptable deadheading length before breakthrough to the last open crosscut.

FAN SYSTEM DESIGN

A group of seven conceptual designs of large-capacity face ventilation systems was developed as part of this study.

The concepts were evaluated for mine operation compatibility, projected ventilation effectiveness, and cost. The highest ranking concepts were a jet fan

system for nongassy oil shale mining and a reversible fan with rigid duct for gassy oil shale mining.

The design of each system was based upon commercially available equipment. Each system had a common design basis, including

1. 100,000-ft³/min capacity.
2. Low power consumption.
3. Components that must be handled with a minimum of special equipment.
4. Two-speed operation to conserve power consumption when full flow was not needed.

DESIGN OF THE JET FAN SYSTEM

Jet fans (free-standing, unducted fans) are commonly employed in the mining industry. The application of the jet fan for ventilation of a dead-end heading is illustrated in figure 3. The fan is located along the upstream corner of the last crosscut and projects air in a high-velocity turbulent jet along the wall toward the face. The jet expands with increasing distance from the fan until, ideally, air is flowing toward the face in half the opening and exhausting back

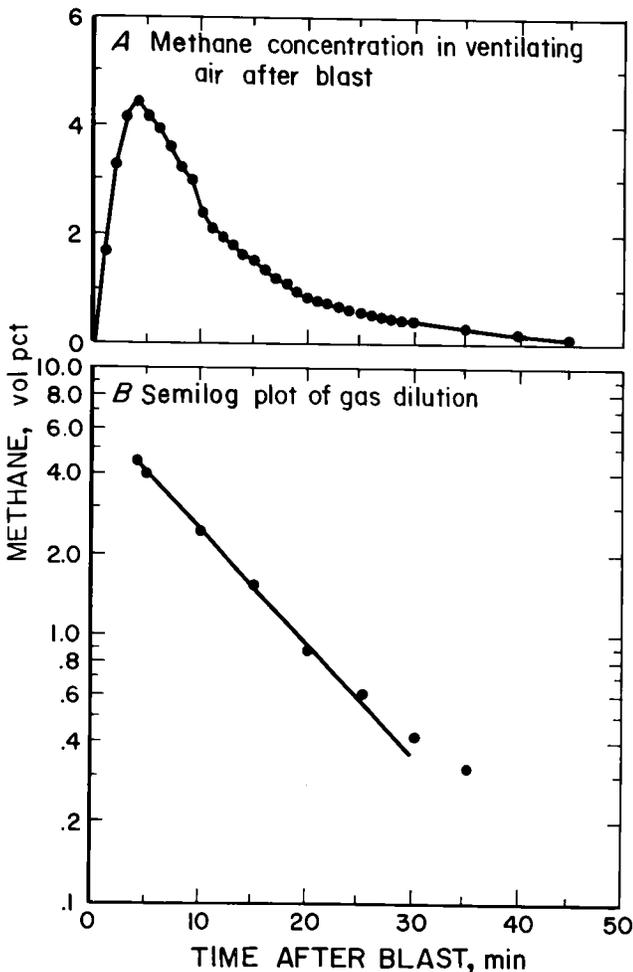


FIGURE 2.—Typical curve of methane concentration in exhaust air after blasting oil shale in the saline zone at Horse Draw. Total methane = 4,088 ft³, which represents 60 ft³/st oil shale.

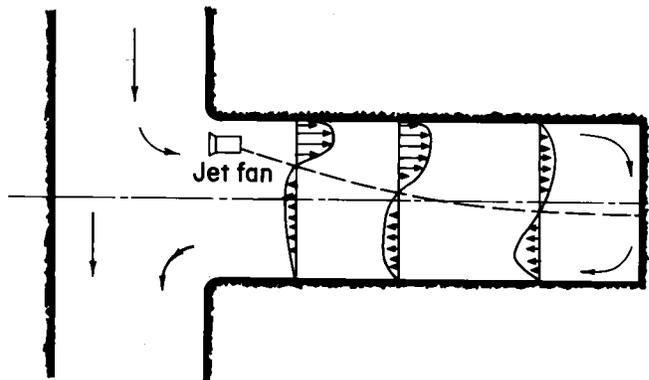


FIGURE 3.—Schematic of dead-end heading ventilated by jet fan.

to the last open crosscut in the other half. The jet grows through the action of frictional forces at the boundary of the jet, where the relatively still air is accelerated or entrained into the jet. In this process, the initial momentum of the jet of air is transferred to an ever greater mass, thereby reducing the velocity of flow. By the process of entrainment, the jet fan delivers a volume much greater than its inlet volume to the face, resulting in high air velocities and enhanced mixing. The entrained portion of the air delivered to the face is recirculated; therefore the dilution capability of the jet fan is dependent upon the amount of fresh air entering the inlet. Recirculation at the inlet is generally 20 to 40 pct, depending upon inlet location.

The key to the design of the jet fan system was characterization of the complex action of the turbulent jet. Although detailed analysis has been performed by Abromovich (18), a simplified method derived by McElroy (19) from empirical studies was chosen for this project. McElroy developed a group of equations to describe the decay in centerline velocity with increasing distance from the fan outlet. These equations are correlated with four phases of behavior, as illustrated in figure 4. For round jets, phases 1 and 2 are combined so that the jet centerline decay is predicted for each phase as described below.

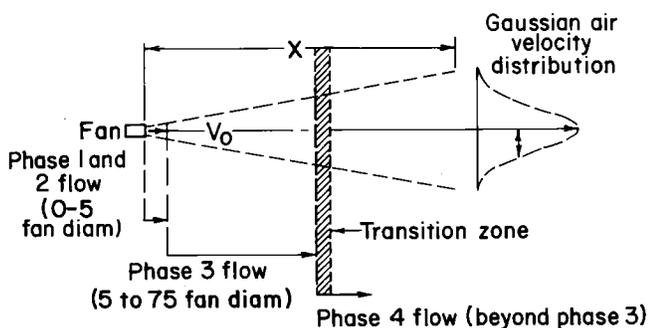


FIGURE 4.—Plan view of freely expanding turbulent jet illustrating McElroy's different phases of velocity decay.

Phases 1 and 2

The centerline velocity, V_x , at a distance, X , from the fan outlet is characterized by

$$V_x = aV_o, \quad (3)$$

where V_o = outlet or discharge velocity

and a = a constant (1.0-1.2).

The centerline velocities are fairly well characterized by this expression for a distance of up to five times the outlet diameter. The constant a is apparently related to outlet velocity, decreasing with decreasing velocity.

Phase 3

The centerline velocity, V_x , at a distance, X , from the fan outlet is characterized by

$$V_x = (KV_o D)/X, \quad (4)$$

where K = a constant (3-10),

D = outlet diameter,

and X = distance from the outlet.

Phase 4

After phase 3, a transition zone occurs in which the centerline velocity, V_x , decays rapidly to the range that is predicted using the flow rate and one-half the area of the opening. After the transition zone, the centerline velocity appears to follow the equation

$$V_x = fV_o D/109X, \quad (5)$$

where f = a constant related to the ratio of outlet diameter to opening dimension

and $g = 0.026f$.

The constants f and g are empirically developed, with

$$f = 12.2 (DS)/W \quad (6)$$

where S = aspect ratio of the fan outlet (1.0 for a round jet)

and W = large dimension of the opening.

McElroy's equations were developed for jets expanding freely in all directions. Placement of the fan along the wall, as illustrated earlier in figure 3, constrains the growth of the jet and increases the distance in which phase 3 behavior is observed. This is incorporated into the predictive equation 3 by increasing the value of the constant K .

McElroy's (19) equations are similar to work reported by Krause (20) and were checked by fitting the relationships to experimental data from Lewtas (21) and Spendrup (22). K values were found to vary between 5.0 and 11.3 for fans located within three fan diameters from the wall. Distance from the fan outlet to the transition zone was found to be an approximately linear function of outlet velocity divided by discharge diameter, as shown in figure 5.

The zone of the heading that is of critical importance in mining applications is the transition zone and beyond. At this point, the entrainment action increases rapidly, causing a rapid decrease in flow velocity. The design process must ensure that the jet can force air to the face with sufficient velocity to provide good mining and face sweep.

Application of the design equations was compared to field measurements for a 39-in-diam fan tested at Union Oil Co. of California's Parachute Creek shale oil project by Spendrup (22). Figure 6 shows good correlation of the predictive equations and measured data near and beyond the transition zone.

Design of a jet fan for this work was based upon the following:

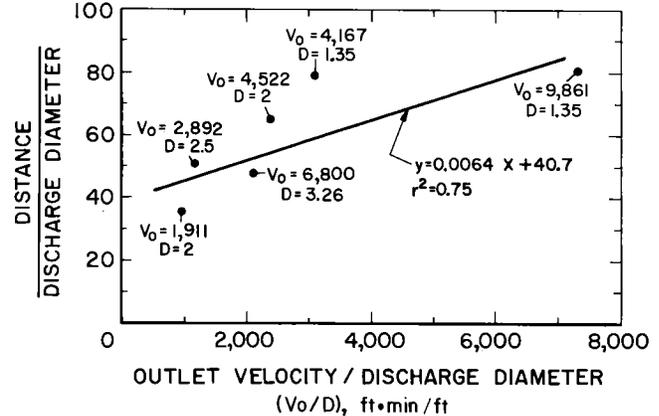


FIGURE 5.—Approximate distance to transition zone (phase 4 flow) as a function of outlet velocity normalized to outlet diameter for fans located adjacent to a wall.

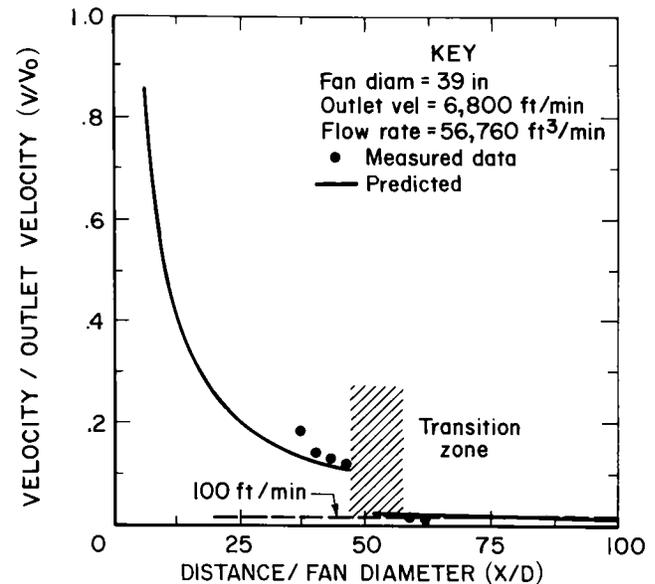


FIGURE 6.—Jet fan penetration versus velocity curve for large jet fan tested in oil shale mining.

1. Flow capacity based upon expected rates of pollutant emissions at the face.
2. Fan diameter selected such that the jet reaches the face with 100-ft/min velocity.

Using $K = 5.0$, a flow rate of 100,000 ft^3/min , and opening dimensions of 55 ft wide by 30 ft high, fans with diameters between 48 and 60 in were predicted to project air in the range of 300 ft with a

minimum velocity of 100 ft/min. Based upon this, a 55-in-diam fan was selected.

DESIGN OF THE DUCTED FAN SYSTEM

Design methods for ducted fan systems are described elsewhere by Hartman (23), Jorgensen (24), and Daly (25). The primary design concerns in this work were whether to use a blowing or exhausting system and the size of ducting needed to optimize power consumption yet allow handling without special equipment.

A reversible system was selected for this work to establish a relative comparison between blowing and exhausting ventilation. This selection required rigid duct, and from practical considerations, it appeared that 54-in-diam round or 62-by 40.5-in oval ducts were as large as could be handled conveniently by a two-member crew without specialized equipment. This size was also a practical minimum, since a system ventilating a distance of 300 ft would be operating at approximately 5.0-in-wg total pressure, requiring around 120 hp.

Operation of this type of system for ventilation of a dead-end heading is illustrated in figure 7, for both blowing and exhausting modes. Positioning of the inlet is a critical parameter in eliminating recirculation. In the blowing mode, the inlet should be around the corner and upstream in the last open cross-cut. For the exhausting mode, this system was designed to project the jet of

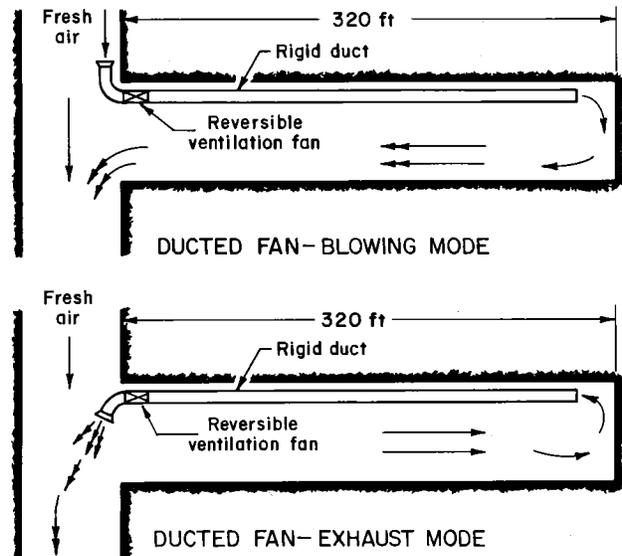


FIGURE 7.—Schematics of the ducted fan system operating in dead heading.

exhaust air downstream but across the opening of the deadheading. The high velocities of the jet were expected to minimize recirculation of the exhaust air. If this approach were unsuccessful, exhaust mode operations would have to utilize auxiliary ducting at the roof to carry the exhaust downstream past the opening. This would require a more complicated dampered control system with a branching duct to pass the exhaust duct up along the roof to the downstream side of the face heading in such a way that it did not interfere with mine traffic.

APPLICATIONS OF TRACER GAS TESTING RESULTS

Sulfur hexafluoride (SF_6) tracer gas was used to measure the average performance of the face ventilation systems. Different models of tracer gas release were designed to simulate the production of diesel emissions, blast fumes, and methane in the face area. Measurements of the tracer gas concentration throughout the room, and especially in the face area, provided data on the uniformity of mixing and the average ability of the systems to dilute air pollutants. These tests were described in detail by Brechtel (6).

The results of the tracer gas testing are compared using a uniform measure of the efficiency of the face ventilation system, called dilution efficiency. For a perfect system, all of the air passing through the fan would be uniformly mixed with all of the tracer gas released in the face area. The resulting dilution efficiency would equal 1.0. Dilution efficiency is calculated using equation 7:

$$E_d = Q_E / Q_F, \quad (7)$$

where E_d = dilution efficiency,

Q_E = quantity of air actually ventilating the room, as measured by tracer gas dilution, ft^3/min ,

and Q_F = measured outlet flow rate of the fan, ft^3/min .

In an actual mining situation, the value of the dilution efficiency would be less than 1.0 because of recirculation, efficiency of mixing at the pollutant source, turbulence, last open crosscut flow, and measurement error. The tracer gas tests measured the combined effects of these parameters and allowed these effects to be accommodated in the design of ventilation capacity.

TRACER GAS DETERMINATION OF DILUTION EFFICIENCIES

The tracer gas tests were conducted in Exxon's Colony pilot mine in crosscut 7, shown in figure 8. The mine ventilation system was capable of supplying 124,000 ft^3/min of fresh air, and a brattice wall channel was constructed to bring the air past the test room at velocities between 250 and 300 ft/min . The test room was nominally 55 ft wide by 30 ft high and was closed at a depth of 320 ft by a

brattice wall constructed on top of an existing muckpile.

The tracer tests were designed to simulate different types of mine air pollutant production. The tests included--

Simulation of blast clearing.--This test was designed to simulate the fan's effectiveness at clearing a heading after blasting. The test room was sealed, and SF_6 gas was released to give a uniform concentration of approximately 1 ppb. The fan was run for a short time to mix the gas uniformly. The mine ventilation system was then started, and the fans were used to clear the tracer gas from the room.

Simulation of hot diesel exhaust.--This test was designed to simulate the system's ability to dilute diesel emissions (gaseous and particulates). A 50,000-Btu/h kerosene space heater was placed in the face area, with the exhaust routed through a vertical stack to be released 15 ft above the floor. Tracer gas flowing at a constant rate was mixed in the hot gas stream before the outlet. The space heater generated a stream of hot gases with a buoyancy similar to that of engine emissions. The mine ventilation and face ventilation systems were started, and the steady-state concentration for SF_6 was measured.

Simulation of methane layering.-- SF_6 was mixed with 52.4 mol pct He in air to simulate the density of methane gas. It was released from very small holes along a 50-ft-long pipe that was suspended at the roof. The pipe would simulate the intersection of a crack that is conducting methane gas into the mine at roof level, with the lighter density of the mixture causing the tracer gas to form a layer similar to methane. The tracer gas was released at a rate of 0.833 ft^3/min for 120 min, and gas samples were taken to see if the tracer would form a roof layer similar to that formed by methane. The fans were then started to test their effectiveness at breaking up the layer.

Simulation of methane emissions from a muckpile.--In this test, the mixture of air, helium, and SF_6 was released from a group of pipes laid out in the face

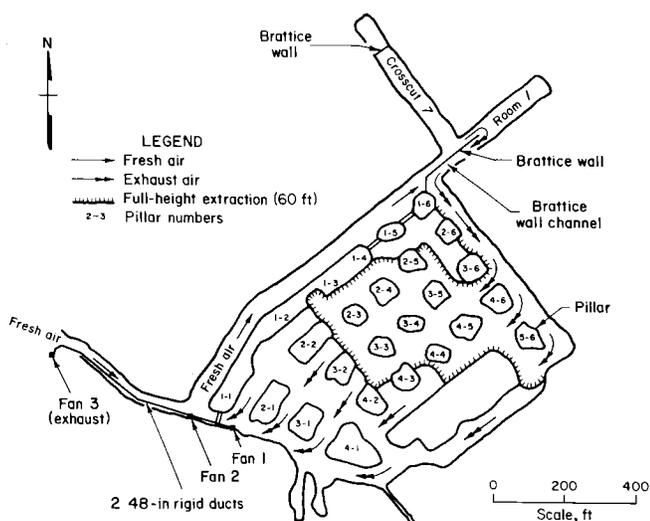


FIGURE 8.—Schematic of Colony Mine showing mine ventilation system and location of test room in crosscut 7.

area to simulate methane desorbing from freshly blasted muckpile. The tracer gas was released for 45 to 60 min, and then the fans were started. The steady-state concentration was measured to establish the effectiveness of the two systems.

Measurement of fan inlet recirculation.—The inlet recirculation volume was measured by releasing tracer gas directly into the fans. The concentration in the air around the inlet was measured. The concentration of air coming out the fan is governed by the release rate of the tracer gas and the amount of tracer gas recirculated into the outlet.

Figure 9 shows a schematic of the measurement grid established in the test room and illustrates the location of the fans during the testing. Figure 10 shows the sampler locations used during each type of tracer gas test. Identical tracer gas concentrations, tracer gas release rates, and sampler locations were used for each fan in each type of test to assure that the results would be directly comparable.

TEST RESULTS

Dilution efficiencies measured during the tracer gas tests are compared in table 8. Tests were not repeated because of the extensive setup required; therefore, there is no measure of the reproducibility of the data. In one instance, a tracer gas of the wrong concentration was released, requiring a

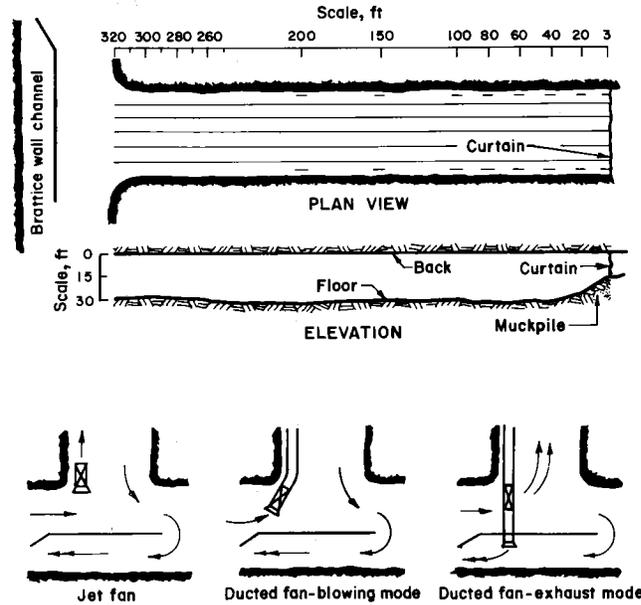


FIGURE 9.—Test room grid system showing location of fans during tracer gas tests.

repetition of the test. Dilution efficiencies for the two tests were 0.80 and 0.83, even though the concentration of SF₆ in the released gas differed by a factor of 1,000. The average values listed in the tables are mean values of the dilution efficiencies measured at each sample point throughout the test room. The values for the face area are averages of the samples located 40 to 60 ft from the face. The jet fan delivered superior performance in the diesel exhaust and methane from muckpile tests. The ducted system was superior in the

TABLE 8. - Comparison of dilution efficiencies measured in tracer gas tests

Simulation type	Jet fan (88,400 ft ³ /min)	Ducted fan, blowing (90,700 ft ³ /min)
Blast clearing: Average..	0.75	0.98
Diesel exhaust:		
Face area.....	.71	.63
Average.....	.78	.74
Methane layering:		
Face area.....	.57	.77
Average.....	.59	.83
Methane from muckpile:		
Face area.....	.74	.59
Average.....	.60	.60

¹0.79 in exhausting mode (73,000 ft³/min).

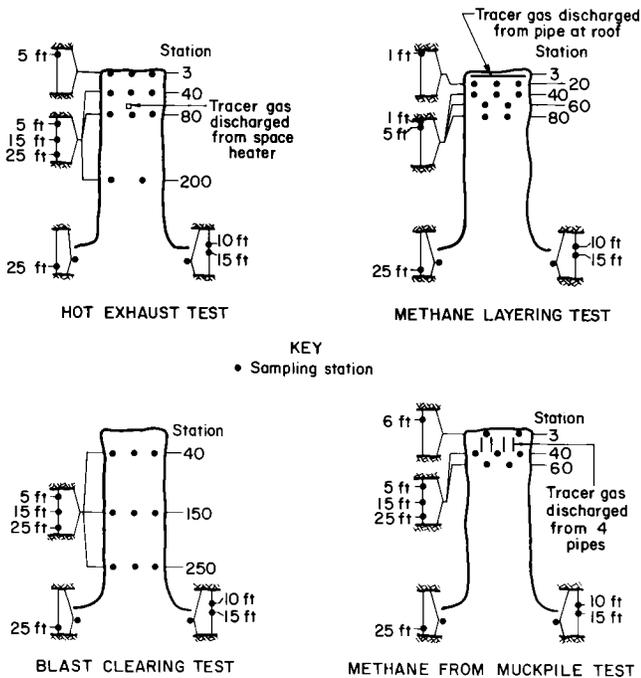


FIGURE 10.—Schematic showing tracer gas sampling points and tracer gas release point for various simulations.

blast clearing and methane layering tests. The overall performance of both systems was good, and the data indicate that the fans provided effective ventilation.

The methane layering test showed that the helium-air mixture could be used to simulate the buoyancy of methane. Both fan systems were effective at breaking up the tracer gas layer; however, the flow rate of the gas was very small ($0.83 \text{ ft}^3/\text{min}$). Much larger release rates would be needed to gauge the effectiveness of the jet fan and ducted fan in dealing with significant flow rates of methane. The ducted systems appear to have been more effective at breaking up the tracer gas layer. This is due mostly to the fact that the duct outlet delivered the fresh air at high velocity directly at the point of tracer gas release.

IMPACT OF FAN RECIRCULATION

Inlet position and conditions are important because they govern the amount of inlet recirculation. The field characterization of the test systems was conducted in a manner that would reflect real operating conditions. Inlet

recirculation measurements were performed using the tracer gas and showed recirculation volumes of 23.8 and 28.4 pct for the jet fan and ducted fan, respectively. The jet fan value was typical, but the ducted fan value was higher than expected. The ducted fan recirculation was caused by poor positioning of the inlet. The fan should have been placed farther upstream in the last open crosscut to eliminate recirculation. Inlet recirculation is expected with the jet fan, but care must be taken to locate the fan inlet as far into the last open crosscut as possible to maximize performance. Efficiency of the jet fan could be further increased by flexible ducting on the inlet placed well upstream in the last open crosscut.

Dilution efficiencies corrected for the inlet recirculation are compared with the measured values in table 9, which shows that inlet recirculation has a strong effect in the reduction of dilution efficiency in these tests.

IMPACT OF FAN OUTLET LOCATIONS

Positioning of the jet fan is critical to its performance. Previous work by Lewtas (21) and Dunn (26) indicates that location of the fan within three diameters of the wall extends the depth of penetration of the jet by constraining its growth. Anemometer and smoke velocity measurements were made for several different directions and heights of the fan centerline. Results, listed in table 10, indicate that the fan had its greatest penetration when angled slightly down and into the corner. Directing the flow into the corner at too great an angle reduces penetration by causing the air to bounce off the adjacent wall. Wall roughness was probably a factor in this problem. Elevating the fan above the corner caused a large reduction in penetration and velocity.

Position of the duct outlet has been shown to have a major effect on the performance of ducted systems in the exhaust mode. Measurements of the effect of discharge location on the ducted system were made in this study to evaluate the effect of positioning for the blowing mode.

TABLE 9. - Potential increase in dilution efficiency resulting from elimination of inlet recirculation

Simulation type	Jet fan (88,400 ft ³ /min)		Ducted fan, blowing (90,700 ft ³ /min)	
	With recirculation	Without recirculation	With recirculation	Without recirculation
Diesel exhaust:				
At face.....	0.71	0.87	0.63	0.81
Average.....	.78	.97	.74	.98
Methane layering:				
At face.....	.57	.80	.77	1.0
Average.....	.59	.82	.83	1.0
Methane from muckpile:				
At face.....	.74	.90	.59	.86
Average.....	.79	.96	.60	.89

TABLE 10. - Locations, orientations, and face air velocities for jet fan

Test ¹	Distance from face, ft	Height above floor, ft	Orientation in vertical plane, ft	Angle from axial section-- line A	Peak velocity, ² ft/min	
					At 100 ft from face	At 60 ft from face
1.....	306.7	8.5	Level.....	0°.....	557	NA
2.....	306.7	17.3	...do.....	0°.....	170	NA
3.....	305.5	³ 4.0	...do.....	0°.....	717	489
4.....	305.5	³ 3.4	Down 5°.....	Left 5°.....	522	NA
5.....	305.5	³ 3.7	Down 2-1/2°...	Left 2-1/2°.....	690	439
6.....	305.5	³ 3.7	...do.....	Left 1°.....	618	NA
7.....	305.5	³ 3.9	Down 1°.....	...do.....	726	550

NA Not available.

¹All tests were run with fan located 18.4 ft left of the room centerline.

²Measured in lower left-hand quadrant of room cross section.

³Fan removed from scissors lift and mounted on blocks on the floor.

TABLE 11. - Duct discharge locations and face sweep velocities for ducted fan--blowing

Discharge distance from face, ft	Offset from room centerline, ft	Height of duct centerline above floor, ft	Discharge duct section	Average face sweep velocity, ft/min
58.3	20.9	2.5	54-in-diam round..	NA
30.5	21.0	2.6	Large oval ¹	532
30.5	21.0	2.6	Small oval ²	456
78	21.0	13.0	Large oval ¹	1,095

NA Not available. ¹62 by 40.5 in. ²55.8 by 36.5 in.

Results are listed in table 11. The highest face sweep velocities were observed with the duct centering elevated 13 ft above the floor and the discharge 78 ft from the face. This position was selected as the minimum distance at which

a rigid duct system run along the floor could escape destruction during blasting. Face blasting at the Colony Mine threw a great deal of rubble along the floor for several hundred feet. Ducting run along the roof very close to the face

suffered no damage during the same blast. Installation of large, rigid ducting along the roof would be more labor intensive, and the floor installation appeared to be a more desirable approach from the operating standpoint.

The methane layering simulation illustrated the potential utility of being able to orient the duct outlet so that high-velocity flow can be directed at localized pollutant production.

CASE STUDIES OF PERFORMANCE IN PROJECTED OPERATING CONDITIONS

The primary advantage of performing tracer gas tests to characterize the performance of a face ventilation system is that the actual dilution efficiency of the system is measured at the point of maximum pollutant production. Once the efficiency is known, the total air capacity required to ventilate a known rate of pollutant production can be calculated using the efficiency factor and assuming linearity. Dilution efficiencies measured during the in-mine tests in this project were applied to the examples of projected mine air pollutant production discussed earlier. This illustrates the application of the results of the tracer gas tests and evaluates the capability of the two ventilation systems to perform under actual mining operation.

BLAST-PRODUCED POLLUTANTS

Projected versus measured blast-produced air pollutant levels were presented earlier in table 6. The dilution efficiencies measured in the blast clearing tests can be used to calculate the time to reduce the concentrations of noxious gases after the blast to their TLV's.

The dilution efficiency is the ratio of the air quantity delivered to the face divided by the fan outlet volume. Therefore, the dilution efficiency (E_d) multiplied by the fan flow rate is approximately the effective flow (Q_e). For a given room volume (V), the time to reach TLV is given by equation 8:

$$T = (V/Q_e) (\ln C_o - \ln TLV), \quad (8)$$

where T = time to reach TLV, min,

$$Q_e = \text{effective flow rate} = E_d \times Q_{Fan}, \text{ ft}^3/\text{min},$$

$$V = \text{room volume, ft}^3,$$

and C_o = peak concentration, ppm.

Table 12 lists estimated times for the fan systems tested in this study to ventilate the test room to TLV's for various blasting fumes. The peak concentrations are those observed in measurements of blasting fumes produced by face blasting at Colony. The maximum time of 20 min to clear the dust is clearly acceptable from an operating standpoint.

TABLE 12. - Estimated time to clear blast-produced pollutants to TLV's

Pollutant	Est conc after blast, ppm	TLV, ppm	Time to dilute to TLV, ¹ min	
			Jet fan ²	Ducted fan-blowing ³
CO ₂	450	5,000	NAP	NAP
CO.....	155	50	8.8	6.6
NO _x	69	25	7.9	5.9
NO.....	69	25	7.9	5.9
Dust ⁴	13.3	1	20.1	15.0

NAP Not applicable.

¹Room volume (V) = 514,600 ft³; $Q_e = E_d \times Q_{Fan}$.

² $Q_{Fan} = 88,400$ ft³/min; $E_d = 0.75$.

³ $Q_{Fan} = 90,700$ ft³/min; $E_d = 0.98$.

⁴Approximate; based on weight.

DIESEL EMISSIONS

Dilution efficiencies measured during the tracer testing can be used to estimate the actual air volumes the fan must move in order to dilute the diesel emissions in the face area to TLV. Earlier engine emissions measured on a clean diesel engine in the 1,000-hp range were listed to obtain projected ventilation requirements. Actual fan flow rates can be estimated by dividing the ideal air requirements by the dilution efficiency.

Table 13 compares the ventilation requirements based upon the combined effects of CO and NO_x. Based upon the engine emissions data and the measured dilution efficiencies, the jet fan system can effectively maintain the regulatory air quality with 95 to 98 ft³·min/bhp in a nongassy mining environment. The ducted fan in the blowing mode would require 107 to 110 ft³·min/bhp. This assumes the use of modern, clean-operating, and well-maintained diesel engines. If this is not the case, then the ventilation requirements will increase significantly. The ventilation air requirements would also be strongly affected if methane concentrations in gassy mining conditions are high enough to impact engine carbon monoxide production. At 1.5 pct methane, which is greater than the maximum allowable operating concentration, the ventilation requirements would be increased to 136 to 173 ft³·min/bhp

for the jet fan system and to 153 to 195 ft³·min/bhp for the ducted fan system.

Data on diesel particulate emissions are not definitive. In general, Branstetter's (27) results suggest that diesel particulate emissions will not be a problem with clean-burning, well-maintained engines.

The tracer gas measurements included the effect of the buoyancy resulting from engine exhaust temperature; however, tracer flow rates in these tests were well below the exhaust flow rates for diesel engines in the 500- to 1,000-hp range. Stratification would be a function of pollutant flow rate, as in the case of methane layering; however, in this case, stratification may help maintain air quality at the operator's level by concentrating the pollutants near the roof.

METHANE EMISSIONS

Projection of the type and magnitude of problems that may occur in oil shale mining under gassy conditions is difficult because there are few published data on methane occurrence. Available data suggest that methane production during mining in the Mahogany Zone may occur in the Central Piceance Creek and Uinta Basins; however, the degree of methane saturation appears to be well below that found in many operating coal mines. The large size of openings planned in oil shale

TABLE 13. - Comparison of required fan outlet flow rates (assuming clean-burning diesel engine in the 800-hp range)

Brake horsepower	Conc in exhaust, ppm		Exhaust flow, ft ³ /min	Ventilation flow, ft ³ /min		
	CO	NO _x		Ideal ¹	Actual	
					Jet fan ²	Ducted fan ³
With no methane:						
561.....	100	448	1,814	36,140	54,990	61,970
823.....	150	538	2,257	55,330	77,910	87,810
With 1.5 pct methane:						
561.....	875	506	1,830	69,060	97,270	109,620
823.....	713	513	2,276	79,180	111,520	125,680

¹Calculated using equation 1.

²Dilution efficiency in face area = 0.71.

³Dilution efficiency in face area = 0.63.

mining tends to create greater potential for methane layering problems. This is offset somewhat by the large ventilation air requirements imposed due to the diesel loading and hauling equipment.

The tracer gas simulations of methane layering and methane from the muckpile indicated that roof layering in large openings without ventilation would be a potential problem. Both the jet fan and the ducted fan were effective in breaking up the roof layer and in reducing the tracer concentration at very low tracer flow rates. Work by Bakke (16) on methane layering predicted that the tracer gas layer would be broken up at operating flow rates of the two fan systems because of the very low flow rates of the tracer gas. Further testing at higher tracer gas flow rates using the helium-air mixture would provide a potential tool for extrapolating the currently available work on methane layering numbers to oil shale mining.

The most clearly identified problem associated with methane occurrence in oil shale mining is the release of the gas from a blasted muckpile. It was estimated earlier that methane concentrations of 8 pct could occur in a 300-ft-long heading as a result of a face blast. Clearly, this estimate is directly dependent upon the assumed methane saturation ($13.3 \text{ ft}^3/\text{st}$), which is not well defined. Other parameters that would affect the peak concentration include--

1. The assumption of instantaneous release of the methane.
2. The volume of the room.
3. The containment of all of the methane in the room.

Observations developed from work performed on this project tend to support the assumptions listed above. Blasting fume concentrations measured in a face blast at Exxon's Colony Mine were close to projected values based upon the mass of ANFO detonated and the volume of the heading (55 ft wide by 30 ft high by 465 ft long). The fumes were vertically stratified, but tended to be uniformly distributed throughout the length of the room. The fumes generally were contained in the room until ventilation was begun.

Measurements of methane produced by blasting of saline zone oil shale (11) suggest that 80 pct of the total methane produced by the blast had been released within 5 min.

If the methane released by blasting produces very high initial concentrations in the face heading, the operator will be required to implement special procedures to eliminate the hazard. These might include--

1. Reducing the size of the individual blast to reduce the quantity of methane released.
2. Increasing the quantity of fresh air flowing in the last open crosscut.
3. Implementing special ventilation procedures in the face heading.

The quantity of methane released by a particular blast could be reduced by reducing the depth of blastholes. This approach may be undesirable, since the economic aspects of oil shale mining require maximum productivity.

The tracer gas tests performed in this study indicated that the concentration of a blast-produced air pollutant being exhausted from the face area is instantaneously equal to the general concentration throughout the room. If the initial concentrations of methane are very high, operation of the face ventilation system pushes methane into the last open crosscut at a high rate initially. The rate decays as the concentration of methane in the face area is reduced. If the face ventilation system is to be operated at high capacity, the last open crosscut flow must be capable of diluting the initial methane production to a safe level. Planned open crosscut flows might have to be increased, depending upon the magnitude of methane saturation.

Another alternative is to control the rate at which the methane is removed from the face, so that the quantity of fresh air in the last open crosscut is always enough to dilute the methane to a safe level. This could be accomplished by operating the ducted system at a reduced flow rate in the blowing mode, as illustrated in figure 11. This configuration might be enhanced by using a jet fan blowing parallel to the last open

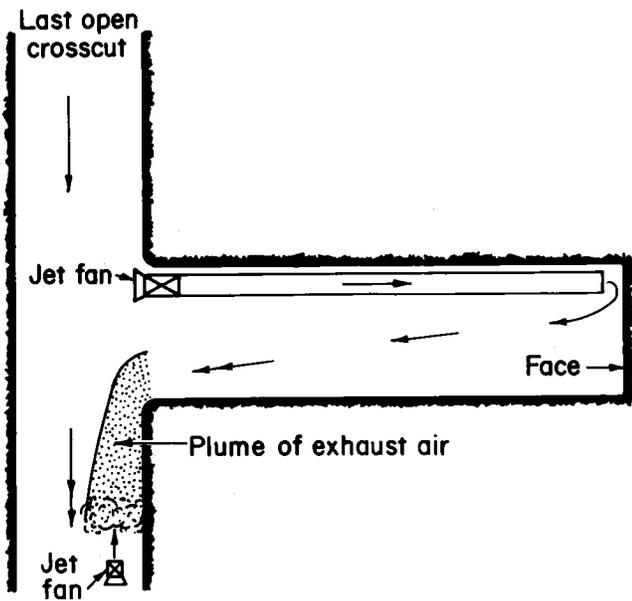


FIGURE 11.—Ducted system operating in blowing mode with jet fan to assist methane plume mixing.

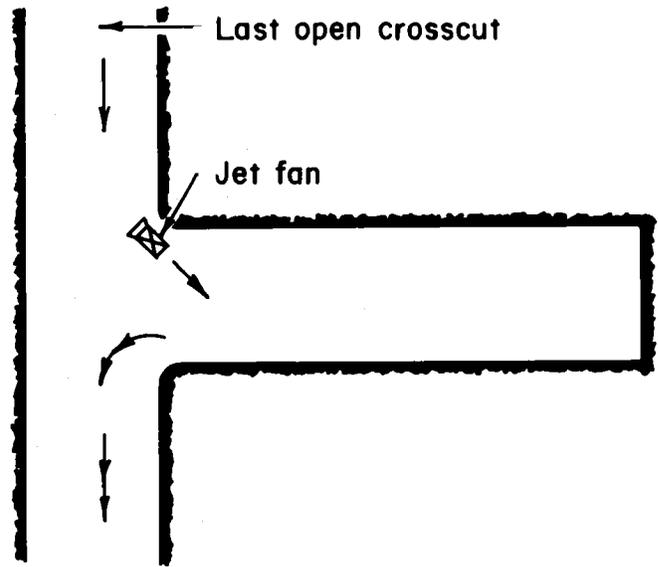


FIGURE 12.—Reorientation of jet fan to minimize inlet recirculation and reduce effective room airflow rate for methane dilution.

crosscut (with or counter to the flow) to enhance mixing of the plume of exhaust gas.

Proposed rules recently published in the Federal Register (28) clarify and revise MSHA's existing standards for gassy metal and nonmetal mines. They specify that auxiliary fans shall be operated so that recirculation is minimized, which may make the use of jet fans possible in gassy conditions. A jet fan could be repositioned so that it projects the airstream across the room, as illustrated in figure 12. This would reduce both the effective flow rate of air in the room and the quantity of methane reaching the last open crosscut.

The jet fan might be left running during the blast. This could help to reduce the magnitude of the peak concentration reached in the face heading. The overall effectiveness of this approach is unknown, because it is a function of the methane release rate. However, if the buildup to peak concentration occurs in about 5 min, a large portion of the methane could be removed during the initial release period. This would significantly reduce both the magnitude of peak concentration and the level of the hazard that the methane presents.

GENERAL CONCLUSIONS ON FACE VENTILATION

Major conclusions derived from the field testing of two of the large-capacity face ventilation systems follow:

1. Face air quantities generally will be governed by the requirement to maintain air quality TLV's.
2. Control of particulate concentrations will be a critical parameter in the design of face ventilation systems.
3. Both face ventilation systems showed high dilution efficiencies and were effective in ventilating the face area at a distance of 320 ft.

4. Proper positioning of fan inlets to minimize recirculation directly impacts the ventilation performance. For both the jet fan and the ducted fan, the inlet should be placed as far as possible into the last open crosscut. Flexible ducting on the fan inlet side, which runs upstream in the last open crosscut, would also greatly reduce recirculation. Fan inlet recirculation probably reduced the dilution efficiencies between 17 and 27 pct in these tests.

5. Overall performance of the two systems was similar. The ducted system performed better in the blast clearing and methane layering tests. The jet fan performed better in the hot diesel exhaust and methane from muckpile tests.

6. The superior performance of the ducted fan in the methane layering test was due to the fact that its outlet was very near the source of the tracer gas. This emphasized the fact that high air velocity is the critical parameter in controlling layering.

7. Both systems, in the blowing mode, were effective at breaking up a tracer gas layer formed with low tracer gas flow rates. Further simulations at higher flow rates are required to extrapolate the capability of the system in dealing with layering.

8. The jet fan provides a higher average air velocity throughout the heading. This high velocity would tend to make the jet fans more effective in breaking up methane layers than a ducted system, although the background concentration of methane might be higher because of higher fan inlet recirculation.

9. Based upon power consumption per effective cubic foot per minute of airflow, the jet fan delivered similar performance with less power consumption than the ducted system.

10. The jet fan was more efficient at a flow rate of 60,000 ft³/min than at 88,400 ft³/min and delivered similar dilution rates at both rates. This suggests some interaction between the turbulent jet and room dimensions that is not well understood.

11. Operation of the ducted fan in the exhaust mode reduced its dilution efficiency by 19 pct as compared to efficiency using the blowing mode.

12. The ducted fan tests indicate that the blowing mode operation is more efficient than the exhaust mode in the large openings found in oil shale mining; however, the exhaust mode might be more effective in situations with high dust production. Overall cost and installation labor could be reduced by using collapsible ventilation tubing and operating the fan in the blowing mode exclusively. However, collapsible tubing has disadvantages, including being prone to leakage, being more easily damaged, and having its cross section reduced by bends or external obstructions.

13. The design capacity of the fan systems (100,000 ft³/min) will be sufficient for room and pillar mining operations in oil shale, provided that diesel engines with low emissions are used. Operation of these engines in a gassy environment may require an increase in ventilation air requirements.

REFERENCES

1. Breslin, J. A., A. J. Strazisar, and R. L. Stein. Size Distribution and Mass Output of Particulates From Diesel Engine Exhausts. BuMines RI 8141r, 1976, 10 pp.
2. Daniel, J. H., Jr. Diesels in Underground Mining. A Review and an Evaluation of an Air Quality Monitoring Methodology. BuMines RI 8884, 1984, 36 pp.
3. Markworth, V. O., and C. D. Wood III. Large Diesel Engine Testing for Oil Shale Mining (contract J0265023, Southwest Res. Inst.). BuMines OFR 2-79, 1978, 98 pp.; NTIS PB 291 585/AS.
4. Bossard, F. C., J. J. LeFever, J. B. LeFever, and K. S. Stout. A Manual of Mine Ventilation Design Practices. Floyd C. Bossard and Associates, Inc., Butte, MT, 1983, pp. 6-1 to 6-5.
5. Volkwein, J. C., and P. F. Flink. Respirable Dust Survey of an Underground Oil Shale Mine and Associated Milling Facility. BuMines IC 8728, 1977, 23 pp.
6. Brechtel, C. E., M. E. Adam, and J. F. T. Agapito. Development of Effective Face Ventilation Systems for Oil Shale Mining (contract H0134033, J. F. T. Agapito and Associates). BuMines OFR 14-86, 1985, 146 pp.; NTIS PB 86-159829.
7. Rodgers, S. J. Analysis of Toxic Fumes Generated During Shot Firing (contract J0166092, MSA Res. Corp.). BuMines OFR 28-78, 1977, 38 pp.; NTIS PB 280 116.
8. Abata, D. L., J. H. Johnson, B. C. Bunting, and J. Robb. Monitoring of Mine Air Blast Pollutants From Six Explosives Tested in an Underground Mine (grant G0177130, MI Technol. Univ.).

BuMines OFR 44-79, 1978, 99 pp.; NTIS PB 295 676.

9. Sapko, M. J., E. S. Weiss, and K. L. Cashdollar. Methane Released During Blasting at the White River Oil Shale Project. Paper in Nineteenth Oil Shale Symposium Proceedings. CO Sch. Mines, Golden, CO, 1986, pp. 59-68.

10. Schatzel, S. J., D. M. Hyman, and A. Sainato. Case Study of Methane Occurrence in the Cathedral Bluffs Shale Oil Mine, Colorado. Paper in Nineteenth Oil Shale Symposium Proceedings. CO Sch. Mines, Golden, CO, 1986, pp. 38-46.

11. Sapko, M. J., J. K. Richmond, and J. P. McDonnell. Continuous Monitoring of Methane in a Deep Oil Shale Mine. Paper in Fifteenth Oil Shale Symposium Proceedings. CO Sch. Mines, Golden, CO, 1982, pp. 320-340.

12. Stellavato, N. Results of the Geologic Mapping Program During Shaft Sinking and Subsequent Station Development at C-b Tract. Paper in Fifteenth Oil Shale Symposium Proceedings. CO Sch. Mines, Golden, CO, 1982, pp. 115-136.

13. Shell Oil Co. Oil Shale Tract C-b, Environmental and Exploration Program. Summary Rep. 5, 1975, 36 pp.; available from Area Oil Shale Office, Minerals Management Service, Grand Junction, CO.

14. Matta, J. E., J. C. LaScola, and F. N. Kissell. Methane Absorption in Oil Shale and Its Potential Mine Hazard. BuMines RI 8243, 1977, 13 pp.

15. Smolniker, H. M. Preliminary Report on Gas Testing of Selected Intervals of Oil Shale Core From Core Hole Map 2-A. Memo to E. L. Grossman, Rio Blanco Oil Shale Co., June 22, 1978; available from Area Oil Shale Office, Minerals Management Service, Grand Junction, CO.

16. Bakke, P., and S. J. Leach. Principals of Formation and Dispersion of Methane Roof Layers and Some Remedial Measures. Min. Eng. (London), July 1962, pp. 645-658.

17. Richmond, J. K., M. H. Sapko, L. F. Miller, and L. E. Dalverny. Explosion Hazards in Gassy and Non-gassy Oil Shale Mines. Paper in Fourteenth Oil Shale Symposium Proceedings. CO Sch. Mines, Golden, CO, 1981, pp. 61-74.

18. Abromovich, G. N. The Theory of Turbulent Jets. MIT Press, Cambridge, MA, 1963, pp. 444-475.

19. McElroy, G. E. Air Flow at Discharge of Fan-Pipe Lines in Mines. II. Effect of Size and Shape of Pipe and of Adjacent Walls on Velocity and Entrainment Ratios. BuMines RI 3730, 1943, 30 pp.

20. Krause, D. Freistrahlen bei der Sonderbewettung (Free Jets in Auxiliary Ventilation). Neu Bergbautechnik, v. 2, No. 1, Jan. 1972, pp. 44-52.

21. Lewtas, T. A. Assessment of Induction Fan Effectiveness (contract J0387223, Foster-Miller Associates, Inc.). BuMines OFR 81-82, 1980, 62 pp.; NTIS PB 82-235987.

22. Spendrup, J. Private Communication of Velocity Measurements Made in Tests of Jet Fans at the Union Oil Company of California's Oil Shale Mine, 1983; available from Alan Salter, Union Oil Co., 2777 Crossroads Blvd., Grand Junction, CO 81501.

23. Hartman, H. L. Mine Ventilation and Air Conditioning. Ronald Press Co., 1961, pp. 73-103.

24. Jorgensen, R. Fan Engineer Inc. Buffalo Forge Co., Buffalo, NY, 1983, pp. 3-1 to 3-34.

25. Daly, B. B. Wood's Practical Guide to Fan Engineering. Wood of Colchester, Ltd., Colchester, England, 1979, pp. 75-104.

26. Dunn, M. F., F. S. Kendorski, M. O. Rahim, and A. Mukherjee. Testing Jet Fans in Metal/Nonmetal Mines With Large Cross-Sectional Airways (contract J0318015, Engineers International). BuMines OFR 106-84, 1983, 132 pp.; NTIS PB 84-196393.

27. Branstetter, R., R. Burrahm, and H. Dietzmann. Relationship of Underground Diesel Engine Maintenance to Emissions. Volume II (contract H0292009, Southwest Res. Inst.). BuMines OFR 110(2)-84, 1983, 216 pp.; NTIS PB 84-195528.

28. Federal Register. U.S. Mine Safety and Health Administration (Dep. Labor). Safety Standards for Gassy Metal and Nonmetal Mines. V. 50, No. 107, June 4, 1985, pp. 23,612-23,660.