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DEVELOPMENT OF EFFECTIVE FACE VENTILATION SYSTEMS FOR OIL SHALE MINING

J.F.T. AGAPITO & ASSOCIATES, INC.
GRAND JUNCTION, CO

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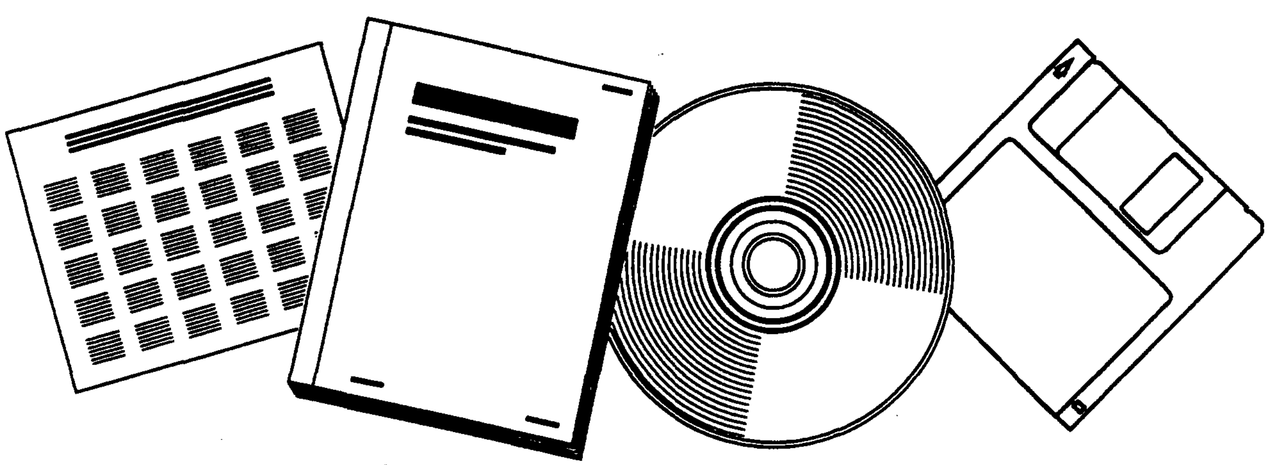

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OCTOBER 1985

DEVELOPMENT OF EFFECTIVE FACE VENTILATION SYSTEMS FOR OIL SHALE MINING

Contract H0134033

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16. Abstract (Limit: 200 words)

This project describes the design and testing of large face ventilation systems for oil shale mining. A design data base was generated by reviewing general industry practice, oil shale industry planning, and technical literature. Conceptual designs for seven different systems were developed and evaluated for suitability. A large, free-standing, jet fan and reversible fan with rigid duct were selected for fabrication and testing. The two systems were field tested in a dead-end heading 55 ft wide by 30 ft high and 320 ft long. System performance was optimized using measurements of airflow direction and air velocity. Total system performance was then measured using SF_6 tracer gas released to simulate blast fumes, hot diesel exhaust, methane layering, and methane from a blasted muckpile. Field testing indicated that both systems delivered similar performance. The jet fan offered some clear advantages because of its mobility, ease of operation, and lower power requirement. It also offered some functional advantages in ventilating for methane because of its high average velocity.

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FOREWORD

This report was prepared by J. F. T. Agapito & Associates, Inc. under USBM Contract No. H0134033. The contract was initiated under the Bureau of Mines Health and Safety program. It was administered under the technical direction of the Pittsburgh Mining and Safety Research Center, with Mr. E. D. Thimons acting as the Technical Project Officer. Mr. Doyne Teets was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of the contract for the period of September, 1983 to April, 1985. This report was submitted by the authors in October, 1985.

Both the Colorado Mining Association and the U. S. Department of Energy acted as joint sponsors of this work with the Bureau of Mines. Technical overview of the work was provided by members of the Oil Shale Advisory Committee of the Colorado Mining Association. Members of the committee included:

Mr. L. A. Weakly, Exxon Company, USA - Committee Chairman

Mr. David Cole, Colorado Mining Association

Mr. Sam Vera, Mobil Oil Company

Mr. David Starbuck, White River Shale Oil Corporation

Mr. John Shaler, Cathedral Bluffs Shale Oil Company

Mr. Alan Salter, Union Oil Company of California

Dr. Art Hartstein, U. S. Department of Energy

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1.0 INTRODUCTION

1.1 PROJECT SCOPE

This report is submitted to the U. S. Bureau of Mines in partial fulfillment of the requirements of Contract No. H0134033. The project was undertaken as a joint effort between the Colorado Mining Association (CMA), the Department of Energy (DOE), and the Bureau. These three agencies recognized that the large openings proposed for room and pillar oil shale mines, coupled with the very large diesel powered equipment required for production, would create substantial ventilation problems at the working face. Bureau technical representatives working in conjunction with members of the Oil Shale Advisory Committee of the CMA structured a research program designed to investigate the application of large, conventional ventilation equipment to the working headings in oil shale mines. Because of the quantities of air required to ventilate a single oil shale heading in an oil shale mine, the ventilation equipment is as large or larger than that for an entire panel in a typical coal mine.

The program was structured into four major elements:

- o Phase I - Technical Review and Design Basis
- o Phase II - Systems Conceptual Designs and Comparative Evaluations
- o Phase III - Final Design and System Fabrication
- o Phase IV - In-Mine Testing

This report is primarily a presentation of results from Phase IV of the project, with summaries of the results of Phases I, II and III presented to provide background information.

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1.2 PHASE I SCOPE: TECHNICAL REVIEW AND DESIGN BASIS

Phase I of the project was performed to establish the technical design criteria for the ventilation systems. Preliminary guidelines, identified in the initial development of the research programs, were to be reevaluated by gathering information from:

- a general literature survey;
- a survey of current ventilation planning of prospective major oil shale mining operations;
- a survey of active non-coal mining operations in Canada and the United States; and
- field measurements of air pollutant levels in a typical oil shale mine.

1.3 PHASE II SCOPE: SYSTEM CONCEPTUAL DESIGNS AND COMPARATIVE EVALUATION

In Phase II of the project, a group of seven ventilation system conceptual designs were generated. These systems were based upon commercially available products with proven application and reliability. The seven conceptual designs were then evaluated from a cost-benefit-performance standpoint in an effort to identify which would be superior in this particular application. The systems' evaluations included:

- compatibility and utility in room and pillar mining;
- projected ventilation performance; and
- estimated cost.

The evaluation was based on ranking indices for each category and on a summary index to allow the evaluation of total system potential.

The results of this comparative evaluation were presented to the oil shale advisory group of the CMA, along with recommendations as to which two of the seven system concepts should be fabricated and field tested. The Committee selected the following systems for field testing:

- o a free standing, two-speed jet fan; and
- o a two-stage, reversible fan with rigid duct.

1.4 PHASE III SCOPE: FINAL DESIGN AND SYSTEM FABRICATION

Final designs were prepared for the two systems selected by the advisory group. Bids were then sought from manufacturers of the various components, and after a selection process was completed, orders for the components were placed with various vendors.

1.5 PHASE IV SCOPE: IN-MINE TESTING

The two face ventilation systems fabricated in Phase III were tested in a dead heading at Exxon's Colony Pilot Oil Shale Mine. Performance was characterized by using SF_6 tracer gas tests and by measuring air velocities and direction. A suite of five tracer gas measurements was made to characterize each system's ability to dilute air pollutants in the working face. These tests were to simulate the following underground situations:

- o clearing of pollutants liberated by face blasting;
- o hot diesel exhaust emissions;
- o methane layering due to the intersection of a local gas pocket;
- o methane or blast pollutants emitted from the muckpile at the face; and
- o fan inlet recirculation.

1.6 REPORT CONTENT

This report is divided into five sections. Section 1.0 contains the introduction and a description of the project scope. An executive summary is presented in Section 2.0, which includes the conclusions and recommendations. Section 3.0 summarizes the work in Phases I, II, and III, where the technical basis for design was developed and the fabrication of face ventilation systems was completed. Results of the field characterization of the two face ventilation systems are presented in Section 4.0. Section 5.0 presents the application of the test results to face ventilation in oil shale mining.

1.7 ACKNOWLEDGEMENTS

Technical conduct of this project was by J. F. T. Agapito & Associates, Inc., with Dr. J. F. T. Agapito responsible for overall management of the effort. Mr. C. E. Brechtel acted as project administrator and technical director, with engineering support by Mr. M. E. Adam. Field support was provided by the MRI Engineering Group of Space Ordinance Systems in the areas of underground air pollution monitoring and tracer gas testing. Dr. Malcolm J. McPherson of Mine Ventilation Services, Inc. acted as technical consultant and provided both advice and review.

Field measurements were performed at the Exxon Colony Pilot Mine in Parachute, Colorado. Drs. W. S. Keifer and J. Downs of the MRI Engineering Group were responsible for the design and operation of the air quality monitoring system. Mr. R. Hillestadt of the MRI Engineering Group provided field support in the tracer gas tests.

Exxon Company, U.S.A. played an important part in this work by providing the site for the field measurements. The authors would like to thank specifically Mr. Alan Weakly of the Exxon Colony project for his support and enthusiasm in this work. We also wish to thank Mr. John Shaler and Mr. Steve Springer of Cathedral Bluffs Shale Oil Company for their help in arranging the loan of a large generator used in the field testing.

2.0 EXECUTIVE SUMMARY

2.1 SUMMARY

This project included the design, fabrication and testing of two large capacity face ventilation systems for application to room and pillar mining of oil shale. A design data base was first established by reviewing face ventilation literature, surveying operating oil shale companies and other large opening non-coal mines, and field monitoring of air pollutants in oil shale test mining. A group of seven conceptual designs was developed applying large, conventional equipment and proven ventilation techniques. The seven designs were compared and evaluated based upon mine operational compatibility, face ventilation effectiveness and estimated cost. A subjective ranking system was established for each of the three categories and a composite rank used to identify the best candidates. The system evaluation and the ranking were presented to the Oil Shale Advisory Committee of the Colorado Mining Association for identification of the two systems to be fabricated and tested in this study. The two systems were:

- o A free standing, jet fan system, consisting of a two-speed, 55 in. diameter fan with 100 hp motor, capable of a 100,000 cfm flow rate.
- o A reversible fan with rigid duct, utilizing a 55 in. diameter fan with 2 - 125 hp stages capable of 100,000 cfm connected to a 54 in. diameter rigid steel duct.

The two fans were tested at Exxon's Colony Pilot Mine near Parachute, Colorado. The fans were tested at identical locations in a dead-end heading 55 ft wide by 30 ft high and 320 ft long.

The last open crosscut flow was 124,000 cfm, and the peak fan test flows were 88,400 cfm and 90,700 cfm for the jet fan and ducted fan systems, respectively.

The fan performance was characterized by measuring both air velocity and flow direction, and by sulfur hexafluoride (SF_6) tracer gas testing. The tracer gas was used to measure the system's effectiveness in simulations of the following:

- clearing of blast produced pollutants;
- hot diesel exhaust;
- methane layering;
- methane from a muckpile; and
- fan inlet recirculation.

2.2 CONCLUSIONS

- SF_6 tracer gas testing was an effective method to characterize face ventilation performance.
- The results of the tests performed in this study were dependent on the fan location, duct outlet, tracer gas release point, rate of tracer gas flow, room dimensions and ventilation volume.
- Both systems showed high dilution efficiencies and were effective in ventilating the face area at a distance of 320 feet. Table 1 presents dilution efficiencies and percentages of inlet recirculation measured for the two systems in the various tests.
- The rates of inlet recirculation of the two systems reduced the dilution efficiencies by a range of 17 to 27 percent.

TABLE 1. - Comparison of face ventilation system performance

Test	Dilution efficiency*	
	Jet fan (88,400 cfm)	Ducted fan-blowing (90,700 cfm)
Blast clearing dilution efficiency	0.75	0.98
Hot diesel exhaust dilution efficiency at face	0.71	0.63
Methane layering dilution efficiency at face	0.57	0.77
Methane from muckpile dilution efficiency at face	0.74	0.59
Fan inlet recirculation (%)	23.8	28.4

* Dilution efficiency - measured air flow at the face divided by fan flow rate

Methods of eliminating or minimizing inlet recirculation will produce increased system performance.

- 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.
- A mixture of 52.4 mole percent helium in air with the SF_6 tracer gas was effective in simulating the layering of methane in still air. Both fan systems, in the blowing mode, were effective in breaking up the simulated methane layer at low rates of tracer gas release. Tests with higher rates of tracer gas release are necessary to develop definite data on the systems' capability to deal with methane layering.

- o 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.
- o The jet fan required less power per effective cfm of air flow because it does not incur appreciable friction loss due to the use of ducting.
- o The jet fan was more efficient at a flow rate of 60,000 cfm than at 88,400 cfm. The face air flow rates measured for an outlet flow of 60,000 cfm were similar to the values measured at an outlet flow of 88,400 cfm. This suggests some interaction between the turbulent jet and room dimensions that is not well understood.
- o Operation of the ducted fan in the exhaust mode reduced its dilution efficiency by 19 percent as compared to the blowing mode.
- o 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. 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 does have disadvantages, including being prone to leakage, being more easily damaged, and having its cross section reduced by bends or external obstructions.
- o The design capacity of the fan systems (100,000 cfm) should be sufficient for room and pillar mining operations in

non-gassy oil shale, providing that diesel engines with low emissions are used, and that good mining practices are followed to minimize dust production. Operation of the large engines in a gassy environment may require an increase in ventilation air requirements, because the presence of methane increases carbon monoxide emissions.

2.3 RECOMMENDATIONS

The SF_6 tracer gas testing has proven to be very useful as a definitive measure of ventilation system effectiveness. Further studies of face ventilation should be performed using the tracer gas.

Review of industrial literature indicates that methane layering is a potential problem for oil shale mining under gassy conditions, and further work is necessary to measure the face ventilation systems' effectiveness at breaking up layers produced by high inflow rates. These tests showed that a helium/air/SF_6 mixture could be used to simulate layering of methane. However, the release rates were very low, and the effectiveness of the face ventilation systems in breaking up the layers was not a true indication of system performance at higher and potentially dangerous rates of methane inflow.

The use of jet fans for ventilation of dead-end headings needs further investigation to develop a better understanding of the interaction between the turbulent jet and room dimensions. These tests showed that reducing the jet fan flow rate to 60,000 cfm from 88,000 cfm did not reduce the total quantity of air effectively diluting the tracer gas at the face. Similar data was reported by

Volkwein (14) for jet fan measurements at Union Oil Company of California's oil shale mine. Further work may indicate ways to increase performance at the higher flow rates. Currently, some jet fans in South Africa have nozzle modifications to produce a vortexing action in the jet, thereby increasing the reach of the fresh air. This might be adapted to oil shale mining.

The advantage of further jet fan research is shown clearly by its lower power consumption per cfm of air delivered to the face. The jet fan used less power than the ducted fan, but delivered similar performance. This is possible because the high friction losses that occur in ducting are eliminated with the jet fan.

3.0 DEVELOPMENT OF THE DATA BASE FOR DESIGN OF FACE VENTILATION SYSTEMS

3.1 INTRODUCTION

A general background of oil shale room and pillar mining is needed to develop a perspective of various problems associated with the face ventilation of working areas. Virtually all of the major oil shale projects have been designed to mine the Mahogany or R7 zone, which is the shallowest high kerogen layer in the Green River Formation. Planned mining systems include both room and pillar mining with surface retorting, and modified in-situ retorting. In both cases, rooms with cross-sectional areas up to 1650 ft^2 may be excavated.

Planned production rates must be very high because of the relatively low value per ton of oil shale and the high cost of processing. Full-scale operations are projected to produce between 50,000 to 90,000 bbls per day, requiring daily tonnages of 69,000 to 124,000 tons (assuming 32 gal/ton). These production rates would be generated in room and pillar panels utilizing very large front end loaders and trucks, or large load-haul dump and conveyor belt systems. Large quantities of air pollutants would be generated in the face area by the diesel equipment and by the quantities of explosives used to rubblize the shale. Methane liberated by blasting the shale or by intersection of local reservoirs is also a potential problem.

Design of effective face ventilation systems necessitated the development of a data base to help quantify the requirements of the oil shale industry and regulatory agencies of the government. The data base was developed from:

- o a survey of the operating oil shale companies;
- o a survey of large opening mines in the USA and Canada;
- o air quality monitoring during simulated oil shale mining operations;
- o publicly available literature; and
- o regulatory guidelines and requirements.

Design criteria were developed from the data base, and used as input to the design of seven face ventilation concepts. These seven concepts were compared and ranked on the basis of projected ventilation performance, compatibility with mining operations, and estimated cost. The ranking identified two systems as the best candidates for fabrication:

- o a free standing, two-speed jet fan; and
- o a two-speed, reversible fan with rigid duct.

3.2 SURVEY OF OPERATING OIL SHALE COMPANIES

A survey of the oil shale companies was conducted to develop ideas on the range of mining plans under consideration. The companies and operations are identified in Table 2. The survey questionnaire contained questions concerning mine excavation dimensions, types of equipment, expected face ventilation requirements, and expected air pollutants. The results of the survey are presented in Table 3.

Of the companies surveyed, only Union Oil Company has proceeded past the planning stage to the development of a mining operation. The responses of the other companies represent various stages of the planning process.

TABLE 2. - Oil shale companies surveyed to establish the data base

Company	Project	Expected type of mining
Exxon Company, USA	Colony Property, Parachute, CO	Room and pillar
Union Oil Company of California	Parachute Creek Shale Oil Project, Parachute, CO	Room and pillar
White River Shale Oil Corporation	Tracts U-a and U-b, White River Project, Uinta Basin, UT	Room and pillar
Cathedral Bluffs Oil Shale Company	Tract C-b, Piceance Creek Basin, CO	Room and pillar and modified in-situ retorting
Mobil Alternative Energy Company	Parachute Property, Parachute, CO	Room and pillar
Rio Blanco Oil Shale Company	Tract C-a, Piceance Creek Basin, CO	Modified in-situ retorting
Paraho Development Corporation	Paraho-Ute Project, Uinta Basin, UT	Room and pillar
Cliffs Engineering, Inc.	Generic Study, Piceance Creek Basin, CO	Room and pillar

3.3 SURVEY OF LARGE OPENING MINES IN THE USA AND CANADA

Because oil shale mining operations are only in the planning stage, a survey of other large opening mining operations was conducted to acquire data on face ventilation practices throughout the mining industry. Over 30 mining operations were contacted and sent follow-up questionnaires designed to give engineering data on mining methods and ventilation systems. The survey was only

TABLE 3. - Summary of responses to survey of oil shale companies

	Range	Average
Daily production (tons/day)	15,000-70,000	33,000
Number of panels	2-8	3.5
Production per panel (tons/ day - upper heading)	7,500-15,000	11,000
Number of entries per panel	6-11	8
Size of excavation (width x height - ft)	40x30-60x25	50x28
Total fresh air per panel (mcfm)	0.9-1.5	1.3
Last open crosscut flow (kcfm)	400-800	570
Type of face ventilation	Blowing fan with ducting - 5	NA
	Free standing jet fan - 1	NA
Size of fans and ducting (in.)	40-84	64
Projected fan hp	50-125	77
Projected face air velocity (ft/min)	60-100	77
Explosive consumption (ANFO lbs/ton shale)	0.5-0.6	0.57
Type of haulage	Front end loader-truck - 4, LHD and feeder breaker	NA
Size of front end loader (yd^3)	14-18	16
Size of truck (tons)	50-100	75
Size of LHD (yd^3)	13-15	14
Expected air pollutants of concern		
- CO_2	4*	--
- CO	4	--
- NO_X	4	--
- CH_4	3	--
- Dust	4	--

* Number of the companies identifying this gas as "of concern" in ventilation

marginally successful, with ten operations responding. The lack of response is attributed to several factors:

- The economic recession of 1982 - 1984, which resulted in shutdowns or large reductions in staff at many mining operations.
- Several operations felt the questionnaire requested sensitive information, and did not reply.

Results of the survey that are pertinent to face ventilation are summarized in Table 4. Openings ranged from 49 to 2625 ft^2 in cross-section. Control of diesel pollutants appeared to be the governing factor for establishing both air volume and air velocity requirements when diesel equipment was being used. Face air velocities averaged 76 ft/min for the mines employing diesel haulage. Clearing of blasting produced pollutants was not mentioned as a controlling factor, with typical times to clear a heading reported to be between one and seven hours.

Face ventilation techniques mainly utilized ducted fans to deliver air directly to the face; however, free standing jet fans were used in two salt mining operations. The average face air volume was roughly 25,000 cfm, varying between 5,000 and 60,000 cfm. Fan horsepowers varied from 8 to 100 hp.

Although not definitive, the data gathered in the survey indicated that face ventilation requirements were established to maintain regulatory air quality standards. Volumes varied as a function of size of equipment, heading geometry, and the ventilation system. The face ventilation equipment employed was typical of mines of all sizes, with size and capacity adjusted by volume requirements. Even though the excavation dimensions in some

TABLE 4. - Summary of results of the survey of large opening mines in the USA and Canada

Operation	Mineral	Mining method	Haulage	Type of face ventilation	Flow in last open crosscut (cfm)	Face velocity (ft/min)	Face fan size (in.)	Face fan capacity (cfm)	Fan horsepower (hp)	Excavation dimensions (ft)	Total mine ventilation vol. (cfm)	Annual production (10^6 tons)
Potash Corp. of Saskatchewan Lanigan Division Saskatchewan, CANADA	Potash	Long room and pillar	Electric	Push/pull with dividing brattice	30,000	63	38	20,000	40	40x16	450,000	2.2
Union Carbide Corp. Bishop, CA	Copper, moly tungsten	Room and pillar	Diesel LHD	Blowing fans with collapsible tubing	20,000	130	24	15,000	18	10x12	200,000	0.8
International Salt Retsof Mine Retsof, NY	Salt	Room and pillar	Diesel shuttle car	Free standing jet fan	70,000	62	72	60,000	50	65x12.5	--	3.0
Cargill, Inc. Cayunga Mine Lansing, NY	Salt	Room and pillar	Diesel LHD	Free standing jet fan	60,000-100,000	63	38	25,000	10	32x12	240,000	0.9
Amax Lead Company Boss, MO	Lead, zinc	Room and pillar	Diesel trucks	Ducted fans	100,000	80-100	32-45	30,000-60,000	75-100	32x12	440	2.2
Inco Metals Company Thomson Mine Manitoba, CANADA	Nickel	Cut and fill, VCR	Diesel LHD	Ducted fans	--	50	27	12,000	8	7x7	625,000	2.1
Brunswich Mining and Smelting Bathurst, NB, CANADA	Lead-zinc, copper	Mechanized cut and fill	Diesel truck	Ducted fans	100,000	100	38	30,000	40	75x35	1,300,000	3.6
Mines Gaspé, Ltd. Murdochville, Quebec CANADA	Copper-moly	Room and pillar	Diesel truck	Ventilation sub-drift	36,000	15	--	--	--	49x49	560,000	1.2
Rio Algom, Ltd. Panel Mine Elliot Lake, Ontario CANADA	Uranium	Room and pillar	Diesel LHD	Aux. fans with ducting	23,000	100	36-38	25,000-40,000	40-75	12x20	680,000	1.6
Allied Chemical Corp. Alchem Mine Green River, WY	Trona	Room and pillar	Electric	Fans with flexible duct Exhaust fans with rigid duct	18,000	36	18	5,000	10	9x18	900,000	1.6

of the mines were similar to those of oil shale mines, the production rates were much smaller in all cases. The maximum size haul truck employed was 35 tons, compared to the 75 to 100 ton size planned for oil shale mining. Diesel loading equipment ranged from 5 to 8 yds^3, as compared to 13 to 18 yds^3 for oil shale mining. Explosives consumption ranged from 250 to 1500 lbs per blast, with an average of 650 lbs, or roughly 1/3 the weight planned for use in oil shale mining.

3.4 AIR QUALITY MONITORING DURING SIMULATED OIL SHALE MINING OPERATIONS

An environmental monitoring program was scoped as part of this contract to develop air quality data for typical oil shale mining operations. However, at the time of the performance of this work, there were no operating oil shale mines in which to gather the data. Exxon Company, U.S.A. made the Colony Mine available for all experimental work performed in the project. Preparation of the mine for the face ventilation tests provided an opportunity to simulate air pollutants generated during mucking operations, and blasting experiments performed by Exxon allowed the characterization of air pollutants generated by blasting of a face round.

A plan map of the Colony Mine is shown in Figure 1. Crosscut 7 offered the best location for testing the face ventilation equipment. Exxon had used the crosscut for muck storage, and removal of the muck provided a simulation of a full scale mucking operation. The northeast end of Room 1 was the site of Exxon's face blasting test. Both test sites were 55 ft wide by 30 ft high.

Data on gaseous pollutants (CO_2, CO, NO and NO_X), dust and diesel particulates collected during the air quality monitoring are

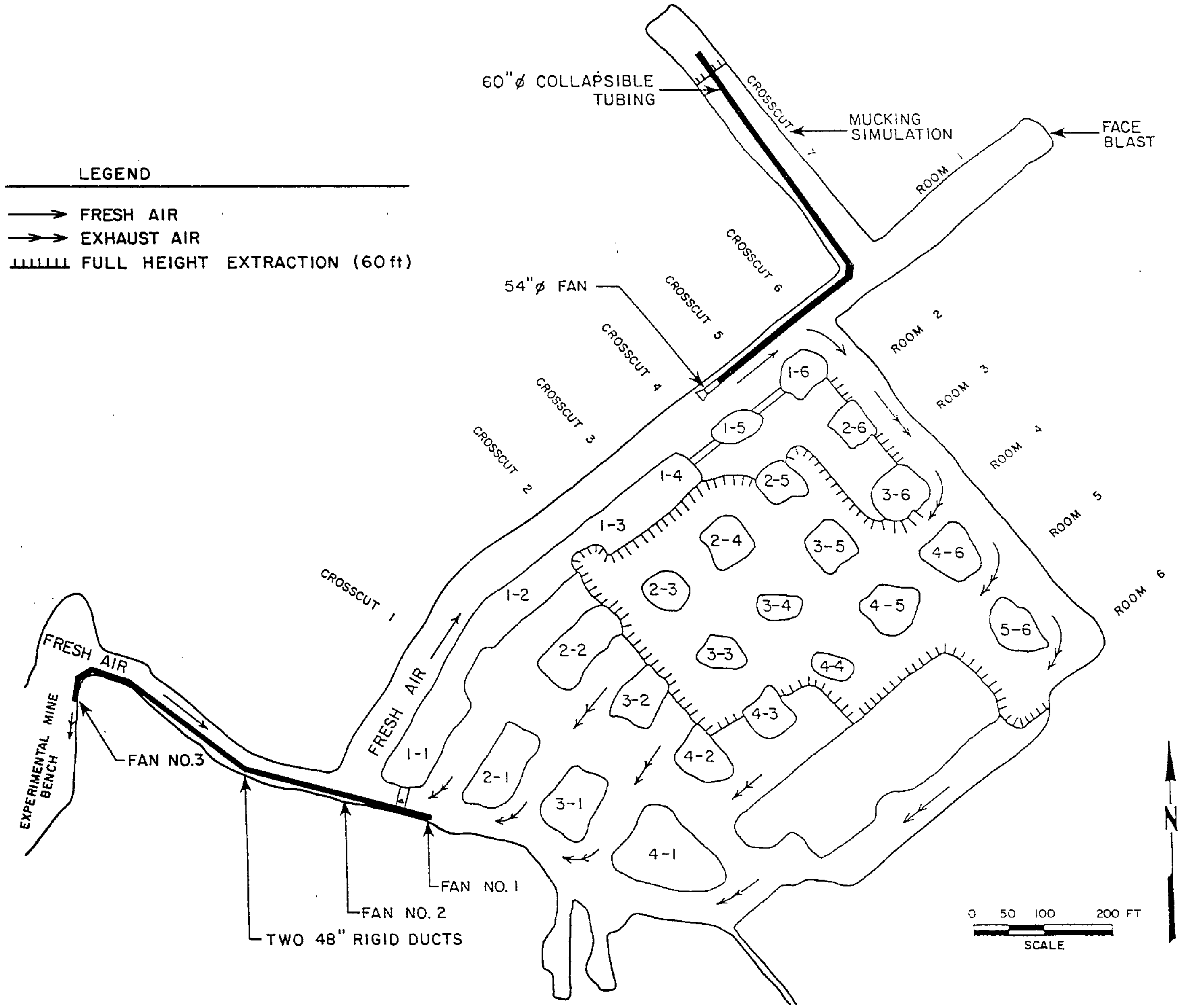

FIGURE 1. - Map of the Colony Mine showing the ventilation system and location of air quality experiments.

presented in Appendix A. The following sections summarize the results.

3.4.1 Monitoring Air Pollutants During Blasting

Air pollutant levels generated by the detonation of roughly 1890 lbs of ANFO in a full face shot were measured. Sampling points in Room 1 were located to give data on the uniformity of gaseous pollutant distribution. The data indicated that the pollutants were horizontally stratified, with the concentrations being as much as 35 percent higher at 20 ft above the floor than at 10 ft above the floor. The concentrations at each horizon were fairly uniform along the length of Room 1.

Peak concentrations measured within 20 min. after the blast agreed fairly well with concentrations predicted from blast emissions data obtained in previous Bureau of Mines research studies by Rogers (1) and Abata (2). Peak concentrations were 1620 ppm, 155 ppm, 69 ppm and greater than 50 ppm for CO_2, CO, NOX (NO_2 + NO), and NO, respectively.

The total dust concentration sampled after the blast was 13.15 mg/m^3, with the respirable portion being approximately 1.86 mg/m^3. Ninety-eight percent of the dust mass had aerodynamic particle diameters of greater than 0.68 micron.

3.4.2 Monitoring Air Pollutants During Mucking

A mucking operation was simulated using a 525 hp Huff[1] 400C loader and Wabco[1] 35 ton truck. The test attempted to simulate an

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[1] Reference to specific brands, equipment of trade names in this report is made to facilitate understanding, and does not imply endorsement by the Bureau of Mines.

actual face mucking operation by moving muck from one side of the room to the other, and cycling the fully loaded truck in and out of the room on an average of every 7.9 minutes. Both gaseous and particulate emissions were monitored.

A ventilation flow rate of 72,000 cfm was delivered to the face of crosscut 7 by collapsible vent tubing. The ratio of fresh air per brake horsepower of the front-end loader was 137 cfm/hp during the test. The results of the monitoring are discussed in the following two sections.

3.4.2.1 Gaseous Diesel Pollutants

Time-weighted average concentrations reached during steady-state production indicated that the pollutants were horizontally stratified because the hot exhaust was more buoyant than the cooler air. Depending on the type of pollutant, concentrations at 25 ft above the floor were 1.7 to 3.5 times the concentration at 5 ft above the floor. Leaving the truck idling while it was being loaded increased the concentration of CO by 60 percent, while CO_2, NOX and NO increased between 15 to 23 percent.

The equipment used in these tests is old, and was used in the mining of the pilot mine in the mid 1960's and early 1970's. Concentrations were carefully monitored during the test to ensure that the time-weighted average exposures of personnel during the test were within TLV requirements. The longest duration of operation of the loader was a total of 2.5 hours. Stratification of the pollutants kept the high concentrations above the level of the operators and measurement personnel.

3.4.2.2 Dust and Diesel Particulate Sampling

Dust and diesel particulates were sampled during both the mucking simulation and blasting tests using cascade impactors, dichotomous samplers and filters. Dust produced by the face blast in oil shale had an average total mass of 13.2 mg/m^3, with less than 2 percent of the dust having a particle diameter of less than 0.7 microns. The dust had a light brown color. Particulates measured during simulated loading operations (FEL and truck) showed that the fine fraction (less than 0.7 microns) increased to between 53 and 73 percent of the total mass, with the fine fraction being black in color. This led to the conclusion that most of the fine particles were diesel particulates. The quartz content of the fine fractions was below detection limits, but averaged 4.5 percent in the fraction with diameters greater than 2.5 microns.

The rates of production of respirable oil shale dust and diesel particulates were estimated to range between 5,000 - 10,000 mg/min. based on the particle gradation measurements and the measured ventilation flow during the loading simulation. The average particulate production rate was estimated to be 6,220 mg/min., but it is probably not representative of actual operating conditions because:

- The material being loaded was comprised mostly of cuttings from a Dosco miner, and may have contained a disproportionately large amount of fine materials.
- The diesel equipment was very old and poorly maintained.

3.4.2.3 Temperature Stratification During Mucking

Vertical temperature profiles were measured during the test to correlate pollutant stratification with increased buoyancy of exhaust gases. Time-weighted average temperature measurements made during the steady-state portion of the tests indicated temperature differences of 4.7°F between 10 and 25 ft above the floor.

3.5 DESIGN CRITERIA

General design criteria for this project were based on the requirements of the largest planned room and pillar oil shale mine, and included:

- o capability to ventilate a 50 ft wide by 30 ft high dead heading;
- o maximum operating brake horsepower per heading - 1000 hp; and
- o a system capable of supplying 100 cfm per brake horsepower.

These requirements were projected to be adequate to meet regulatory requirements for minimum air quality underground.

Face air quantities of 100 cfm per brake horsepower are based upon experience in operating mines. Colorado's state law requires 75 cfm per brake horsepower, but also specifies that air quality meet the same TLV's as specified by MSHA in CFR 30, Parts 0 to 199 (4). Typical operations deliver between 100 and 120 cfm per brake horsepower [Sadik and Jensen (5); Holding and van der Walt (6)] in openings with cross-sectional areas of 150-200 ft^2. Simple application of these quantities assumes that an increase of a factor of 8 to 10 in a cross-sectional area will not have an effect on the dilution efficiency. This, in fact, is one of the primary questions to be answered by this project.

Gaseous emission studies on three engines in the 1000 hp range by Markworth and Wood (7) indicate that ventilation air requirements vary depending upon the manufacturer. The engines required between 91 cfm/bhp and 292 cfm/bhp assuming ideal dilution. Data obtained from field measurements in this study indicated that the 525 hp loader required approximately 137 cfm/hp.

The design guideline of 100,000 cfm was accepted for these systems for the following reasons:

- o The value of 100 cfm/bhp appears to lie in the middle of the range of industry practice.
- o Recent mine planning suggests that 1000 hp engines are not needed for oil shale mining. Front end loader horsepower is more likely to be in the range of 700 hp.
- o The tracer gas tests to be conducted in the present study were to give a measurement of the dilution efficiency at the face.

Air quality requirements established by MSHA (CFR 30, part 57.7) were to govern the quantity of fresh air delivered to the face. Specific air pollutants expected in oil shale mining and the regulatory threshold limit values (TLV) accepted by the ACGIH (8) are listed in Table 5. The range of dust TLV values listed in Table 5 consists of 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:

- o quartz content;
- o respirable mass; and
- o diesel particulates.

Diesel particulates are counted in the total dust-mass and total respirable dust-mass, and have the effect of reducing quartz

TABLE 5. - Maximum allowed concentrations of air pollutants expected in oil shale mining

Pollutant	TLV[1]	Maximum excursion	Exposure criterion[4]
CO_2	5,000 ppm	- -	TWA
CO	50 ppm	75 ppm	TWA
NOX	25 ppm	37.5 ppm	TWA
NO_2	5 ppm	- -	C
Formaldehyde	2 ppm	- -	C
H_2S	10 ppm	20 ppm	TWA
Methane[5]	10,000 ppm	- -	C
Respirable dust[2]	1.4 - 0.7 mg/m^3	ND[3]	TWA
Total dust[2]	3.6 - 1.9 mg/m^3	ND	TWA

1 Based upon ACGIH (8)

2 Estimated based upon expected quartz content between 5.4 and 12.6 percent

3 ND - Not Defined

4 TWA - time weighted average - C = maximum value not be be exceeded

5 Maximum allowable limit for safe operation

content. This impacts the TLV because it is a strong function of quartz content.

There are four main sources of air pollutants expected to tax face ventilation systems in oil shale mining:

- Noxious gases, diesel particulates and dust produced during mucking operations. This represents the most difficult situation in the case of a mining system using front end loaders and trucks.
- Noxious gases and dust produced by blasting.
- Methane production from the groundwater system or by desorption of gas in solution in the oil shale strata.
- Methane or noxious gases trapped in the muckpile.

It generally has been accepted that nitrogen oxides and carbon monoxide produced by the operation of large capacity loading equipment will be the critical parameter governing the required face air capacity. However, studies of the production of diesel particulates by Breslin, et al. (9) and Daniel (10) suggest that the requirement to limit particulate concentrations may be the governing factor. Expected levels of production of these pollutants are examined in the following sections to develop design criteria for the face ventilation systems.

3.5.1 Gaseous Diesel Emissions

Laboratory studies by Markworth and Wood (7) compared the gaseous emissions of three engines in the 1000 hp range for potential application to oil shale mining. Gaseous emissions for the cleanest engine tested are listed in Table 6, along with the required quantity of fresh air assuming ideal dilution.

TABLE 6. - Comparison of engine exhaust production and required ventilation based on data from Markworth and Wood (7)

Brake[1] horsepower	Without addition of 1.5% natural gas: Concentration[2] (ppm) CO	Without addition of 1.5% natural gas: Concentration[2] (ppm) NOX	Without addition of 1.5% natural gas: Exhaust[3] flow (cfm)	Without addition of 1.5% natural gas: Required[4] ventilation (cfm)	With addition of 1.5% natural gas: Concentration[2] (ppm) CO	With addition of 1.5% natural gas: Concentration[2] (ppm) NOX	With addition of 1.5% natural gas: Exhaust[2] flow (cfm)	With addition of 1.5% natural gas: Required[4] ventilation (cfm)
561	100	488	1,814	36,140	875	506	1,830	69,060
823	150	538	2,257	55,330	713	513	2,276	79,170

1 At 2000 rpm - from Figure 26, Markworth and Wood (7)

2 From Figure 26, Markworth and Wood (7)

3 Estimated from Tables B-2, Markworth and Wood, by subtracting mass flow of natural gas and extrapolated to 0.062 lbs/ft^3 density from 0.075 lbs/ft^3

4 Assuming ideal dilution

The required ventilation air is determined for the additive effects of carbon monoxide and nitrogen oxide using equation (1), as presented by Bossard, et al. (11).

$$\frac{C_{CO}}{TLV_{CO}} + \frac{C_{NOX}}{TLV_{NOX}} \leq 1.0 \qquad (1)$$

where: C = concentration of pollutant (ppm)
TLV = threshold limit value (ppm)

The tests were conducted using both fresh air and fresh air with 1.5 percent natural gas added to simulate gassy mine conditions. The presence of the natural gas produced a large increase in carbon monoxide emissions requiring between a 43 and 91 percent increase in fresh air requirements assuming ideal dilution. In a nongassy operation, 100,000 cfm would provide roughly 1.8 times the ventilation requirement for this engine operating at 823 hp.

3.5.2 Diesel Particulate Emissions

There is little data available on particulate emissions that would allow extrapolation to large horsepower engines. Measurements during the mucking simulation indicated that between 53 and 74 percent of the mass of the dust collected was probably diesel particulates. Mass concentrations ranged between 1.77 and 4.45 mg/m^3, and were generally above the TLV at a ventilation flow rate of approximately 137 cfm per horsepower. The equipment used in this study was very old, and the test results are not representative of those that might be found with modern, well-maintained engines. However, the results illustrate that compliance with the particulate TLV may be a critical problem in face ventilation.

Data reported by Branstetter, et al. (12) from studies of the effect of engine maintenance on emissions were used to project particulate production at 800 hp in Table 7. The data were collected on used engines with horsepowers of around 250-330. Average brake horsepower specific particulate production ranged from 0.026 to 0.29 g/bhp-hr for the turbocharged engines, and between 0.036 to 0.83 g/bhp-hr for the naturally aspirated engines, at operating speed and full load. The rates of production vary, depending upon engine condition, speed and load. The table illustrates that dilution of the diesel particulates may require air volumes as large as those required for the gaseous pollutants discussed earlier in Section 3.5.1. The magnitude of the problem can be reduced by using clean burning engines with a good maintenance program. Breslin, et al. (9) reported higher levels of particulate production, which emphasizes the importance of this issue.

3.5.3 Blasting Pollutants

The face ventilation systems designed in this study will be required to clear blast pollutants from the face very rapidly. The test blasts performed at Colony gave a measure of the level of various pollutants, and the time to clear the heading to TLV's can provide an assessment of the effectiveness of the proposed 100,000 cfm flow rate.

Time to clear a heading is estimated using equation (2), as presented by Matta, et al. (13).

$$T = (V/Q)\ (\ln C_0 - \ln TLV) \qquad (2)$$

TABLE 7. - Extrapolation of data on diesel particulate production for the 800 hp range

Engine type	Estimated brake horsepower specific rate of particulate production[1] (mg/bhp-min.)	Estimated production for a 800 hp engine (mg/min.)	Ventilation[1] required (cfm)
Turbo charged	4.8	3,840	67,800
Naturally aspirated	13.8	11,040	194,900

[1] Estimate based upon average values of data from used engines (Branstetter, et al., 12)

[2] Required to dilute to the TLV of 2.0 mg/m^3

where: T = time (min.)
V = room volume (ft^3)
Q = air flow rate (cfm)
C_o = initial concentration (ppm)
TLV = threshold limit value (ppm)

Matta, et al. (13) and Volkwein (14) reported measurements of jet fan effectiveness in the order of 24 to 50 percent of its outlet capacity, due to the influence of heading size and length, and fan capacity. Assuming that the fan capacity is reduced to 50 percent, the time to dilute the various gases to TLV is listed in Table 8. Clearly, the maximum time - 20 minutes to dilute the carbon monoxide to TLV - is acceptable within the present mining plans.

TABLE 8. - Estimated time to dilute blast pollutants to TLV's assuming 100,000 cfm

Gas pollutant	Peak concentration (ppm)	TLV (ppm)	Time to reach TLV (min)
CO_2	1120	5000	NA
CO	155	50	20
NO	69	25	18

3.5.4 Dust

Data on dust production during oil shale mining has been reported by Volkwein and Flink (3) for oil shale mining operations at Anvil Points. The data is summarized in Table 9, and indicates that dust can present a potential problem to oil shale mining.

TABLE 9. - Comparison of measured respirable dust concentration and TLV [based upon data from Volkwein and Flink (3)]

	General location	Measured respirable dust concentration (mg/m^3)	Alpha quartz content (%)	Respirable dust TLV based upon quartz content (mg/m^3)
Drilling	On Jumbo	2.052	3.5	1.820
Blasting	Around corner from face	--	14.0	0.625
Scaling	Operator's position	2.679	6.7	1.150
	Outside machine	0.941	0.9	2.00
Mucking	Average on sides of crosscut	0.633[1]	2.7[1]	2.130
	Inside loader cab	1.045[1]	11.1[1]	0.763
	Outside loader cab	2.184	--	--
Roof bolting	In or near bolter	0.629[1]	1.8[1]	2.631

1 Average of values from several locations

During the mucking simulations in this study, average concentrations of respirable dust exceeded estimated TLV's because of the large particulate mass introduced by the diesel engine. Although these measurements were not representative of anticipated operating conditions, 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 practices such as wetting the muckpile and roadways, and diesel particulate production must be minimized by engine selection and good maintenance in order to meet governing particulate TLV's.

3.5.5 Methane Occurrence in Oil Shale Mining

Data on methane occurrence in the oil shales of the Green River Formation is limited. Publicly available information suggests that methane can occur as free gas in solution with groundwater and as absorbed gas in solution with kerogen. The deep saline oil shale sequence (R1-R5 zones) found in the central Piceance Creek Basin is known to have a much greater gas content than the oil shales of the overlying leached zone (R6, Mahogany and R8 zones). Data on methane content in the saline zones has been generated in the Bureau of Mines studies by Sapko, et al. (15); however, it is not generally applicable to mining in the Mahogany zone. Oil shale mining and exploration programs conducted in the central Piceance Creek and Uinta basins have encountered methane. The outcrop and erosional exposure at the southern rim of the Piceance Creek basin apparently have 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.

Table 10 summarizes the publicly reported occurrences of methane in oil shale. Production of methane by groundwater entering the mine and by desorbtion from the excavation boundary is expected to be handled easily by the mine ventilation system. Two specific types of occurrence that impact face ventilation are:

- <u>Sudden inflow of methane saturated water or free methane flowing from a localized reservoir:</u> Methane inflows of this type could result from the intersection of natural fractures that were connected to a localized reservoir with high methane saturation. This type of situation was reported by Stellavato (<u>16</u>) during shaft sinking operations at the C-b tract. Stellavato (<u>16</u>) reported a sudden inflow of water with initial methane release rates of 1600 cfm. The water inflow dropped to 13 percent of its initial value within 24 hours, and the methane production dropped to 55 cfm. There are informal reports of this type of methane occurrence in drilling operations during resource evaluation. The apparent randomness of occurrence (i.e., methane was encounted in one out of three shafts sunk in close proximity at C-b) and rapid reduction in water/methane production suggest small, localized groundwater reservoirs, isolated from the main hydrologic system. In this case, the frequency of occurrence would be very small and the hazard represented by the event would be reduced.

  This type of methane occurrence would be most hazardous if a methane layer developed due to localized, high volume flow from fractures intersecting the roof of a heading.

TABLE 10. - Summary of publicly available data on methane occurrence in oil shale

Type of occurrence	Site	Range in magnitude of occurrence	Source of data
Free gas in groundwater	C-b tract	5.9-64.8 ft^3/1000 gal. water	Shell Oil Co. (17)
	C-b tract	275-1067 ft^3/1000 gal. water	Stellavato (16)
Gas absorbed by kerogen	Uinta Basin	7.6-33.2 ft^3/ton	Matta, et al. (18)
	C-a tract	0.8-15.2 ft^3/ton	Smolniker (19)
	C-b tract	0.03-32.6 ft^3/ton	Shell Oil Co. (17)
	Horse Draw*	2.40-56.7 ft^3/ton	Sapko, et al. (15)

* in the saline zone

Methane layering results when the buoyant effects, due to the density contrast between methane and air, are of greater magnitude than the turbulent mixing energy of the air stream at a given velocity. Research on methane layering is reported in detail by Bakke and Leach (31), who propose "layering numbers" to evaluate the potential for layering for varying ventilation air velocity, methane production rate and excavation width. The layering number (L) is calculated by equation (3).

$$L = \frac{U}{37\left(\sqrt[3]{V/W}\right)} \qquad (3)$$

where: L = methane layering number

U = ventilation air velocity (ft/min)

V = methane flow rate (cfm)

W = excavation width (ft)

This expression is applied to air flowing uniformly along a heading without any equipment to enhance mixing. Bakke and Leach (31) suggest that a layering number of 5 represents an optimum for limiting the layer size. 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 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 and Leach (31) note that once the methane is well mixed in air, restratification due to diffusion is a minor effect.

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. The relationship between methane inflow rate and required air velocity to achieve methane layering numbers of 2 and 5 is shown in Figure 2. An air quantity of 100,000 cfm for face ventilation in a 55 ft wide by 30 ft high opening gives an average velocity of 66 ft/min. The resulting methane layering number would be below the critical value of 2 for flows above 50 cfm, and indicates 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 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 the use of auxiliary jet fan(s).

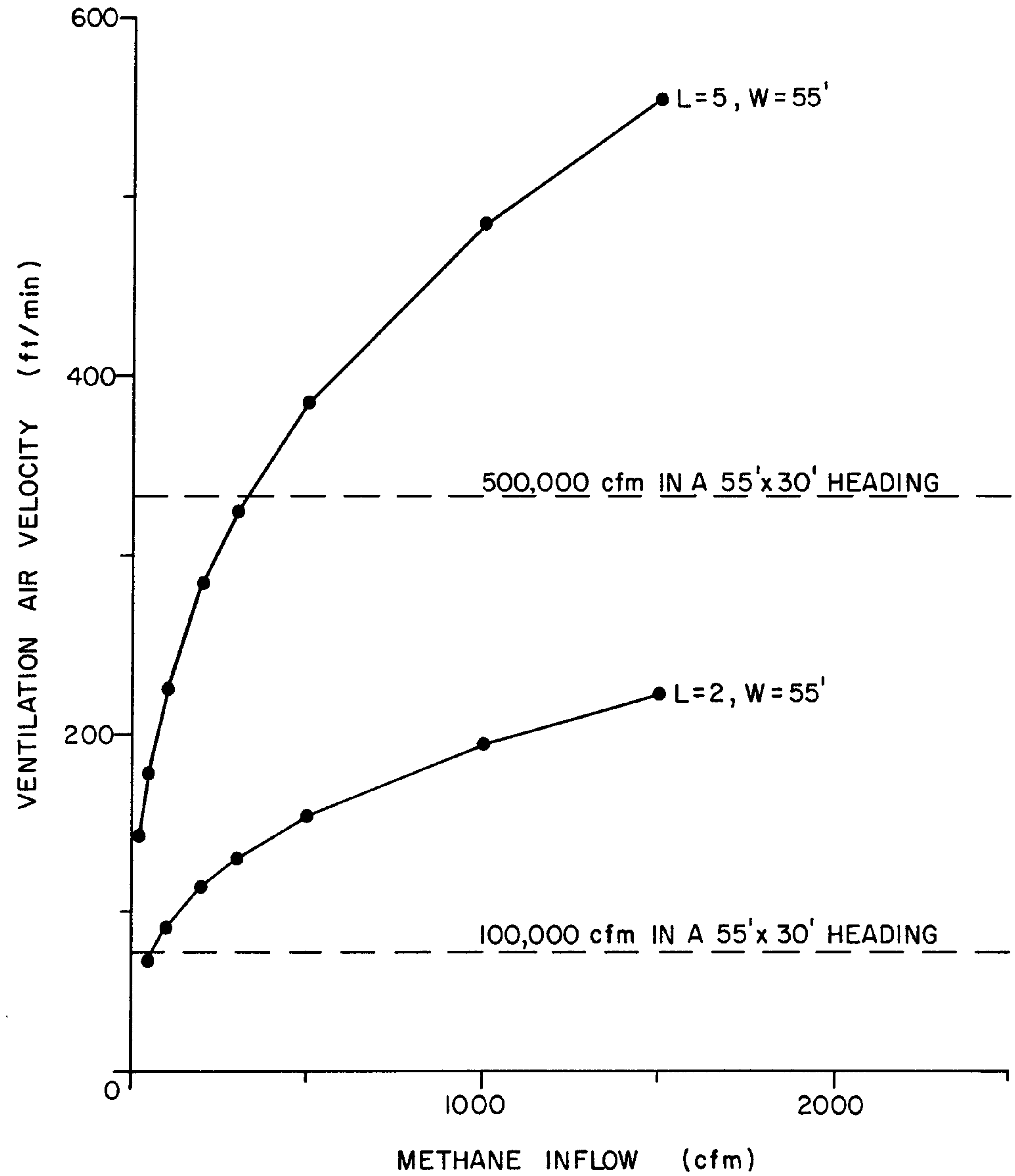

FIGURE 2. - Ventilation velocities required to achieve methane layering numbers of 2 and 5 versus methane inflow.

The use of a jet fan as the main face ventilation system would be an effective way to increase air velocity. Because the jet fan uses the heading itself as a duct, the average air velocity is higher (200 - 400 ft/min.). Bakke and Leach (31) emphasize that air velocity is the critical factor.

Flow in the last open crosscut is expected to be in the 500,000 cfm range, and would give air velocities above 300 ft/min., resulting in layering numbers above 2 for a quite large inflow of methane.

o Blast released methane produced by rubblizing oil shale during mining. 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 ventilating air flow in the heading. Measurements of methane production during oil shale mining operations at the Horse Draw facility are reported by Richmond, et al. (32) and Sapko, et al. (15). A typical curve of methane concentration in ventilation air after a blast is shown in Figure 3, which indicates that the methane concentration reached its peak value shortly after the blast. The figure also shows a semi-log 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. The linearity suggests that further production of

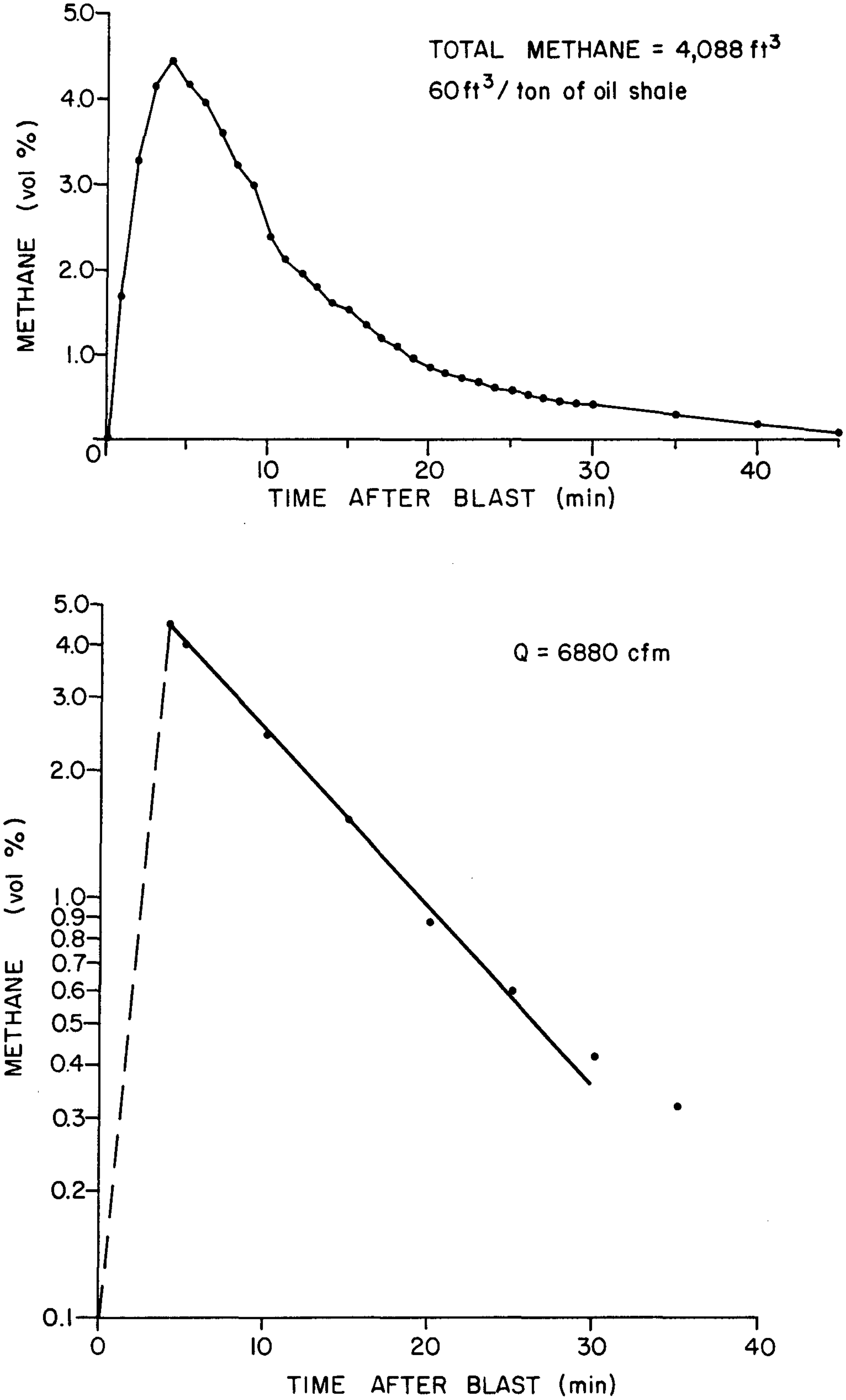

FIGURE 3. - Typical curve of methane concentration in exhaust air after blasting oil shale in the saline zone at Horse Draw [from Richmond, (32)].

methane is small. Based upon the back calculated room volume, 80 percent of the total methane liberated by the blast was mixed with the room air within five minutes after the blast. This is based upon 60 tons of blasted shale. In a blast rubblizing several thousand tons of oil shale, the rate of release of methane might be reduced.

Estimation of the methane content in a face heading after a blast is completely dependent upon dilution volume, tonnage, methane saturation and ventilation practice. A typical face heading 50 ft wide by 30 ft high, advancing 30 ft, would produce 2808 tons of rubblized shale (density of approximately 124.8 lbs/ft^3), which could release a large volume of methane. Assuming an average saturation of 16 ft^3/ton (mid range of the C-b data, Table 10), a single blast could produce approximately 44,000 ft^3 of methane. If the methane were released instantaneously in a 50 ft wide by 30 ft high heading, 300 ft long and mixed uniformly in still air, this could result in a methane concentration of 10 percent.

3.5.6 Maximum Length of Dead Heading

The high productivity in oil shale mining will require that face headings advance a distance of several crosscuts prior to breaking through on a new last open crosscut. This distance will vary according to the layout of each mine. A distance of 320 ft was selected for the tests in this study. Based upon a room span of 50 ft and a pillar dimension of 55 ft, this would require that every third crosscut become a last open crosscut.

3.6 CANDIDATE FACE VENTILATION SYSTEMS AND SELECTION

A group of seven conceptual designs was developed for face ventilation in oil shale. These included:

- Free standing jet fan: This system is a simple, free standing fan with well-designed inlet and outlet. The fan is located along the wall at the last open crosscut, and projects a jet of air forward to the face.
- Reversible fan with rigid duct: This is a typical ducted fan arrangement designed to use a large oval, fiberglass duct. The duct is placed on the floor until near the face area, then elevated to avoid destruction during blasting.
- Modified push/pull system: This system utilized a typical ducted blowing fan arrangement with a free standing, jet fan to increase return air velocities. Fresh air is carried to the face in 60 in. diameter collapsible ventilation tubing. The jet fan is stationed near the last open crosscut, and propels the exhaust air out of the heading.
- Jet fan in brattice wall system: In this system, a brattice wall was constructed to carry air along one wall of the heading to the face. The air flow was created by a large capacity jet fan stationed inside the brattice wall channel with its flow directed towards the face.
- Fan with extendable boom mounted duct: In this system, the fan was mounted on a trailer with an extendable boom with a length of roughly 140 feet. A flexible duct on the inlet was planned so that the fan could be located far enough

inside the heading to allow a collapsible duct mounted on the boom to be extended to within 30 - 60 ft of the face.

- o Common manifold system with large central fan: This system utilized a very large capacity, adjustable pitch fan with a rigid duct manifold that allowed ventilation of multiple headings. The system was designed to work in the exhaust mode. A 72 in. diameter round duct connected the fan to each heading, and a large oval duct was used to carry the air to the face in each heading.
- o Machine mounted secondary ventilation systems: A variety of secondary ventilation systems were examined, including diffuser fans, spray fans, and Venturi scrubbers. These systems would be machine mounted and function in conjunction with a main face ventilation system.

Evaluation criteria were developed to rank the designs and facilitate the selection of those to be tested. Each design was subjectively evaluated on the basis of mine operational compatibility, projected face ventilation effectiveness, and cost estimates for equipment and operations. The designs were ranked based on each of the these three criteria, and a simple linear sum of the ranks was used to develop a composite. Table 11 presents the ranking scores for all systems.

The jet fan and the reversible fan with rigid duct were the top ranked designs, and they were selected for fabrication and testing in the project.

3.6.1 Free Standing, Jet Fan

Photographs of the jet fan fabricated and tested in this program are shown in Figures 4a and 4b. The fan was a 55 in. diameter

TABLE 11. - Summary of conceptual design ranking

Face ventilation system	Rank			Rank sum	Overall rank
	Mining compatibility	Projected ventilation effectiveness	System cost		
Jet fan	1	2	1	4	1
Reversible fan with rigid duct	2	1	5	8	2
Modified push/pull	4	3[2]	2	9	3
Fan with extendable boom mounted duct	3	3[2]	6	12	4
Jet fan with brattice wall	5	6	3	14	5
Machine mounted[1] secondary ventilation equipment	6	7	4	17	6
Common manifold with large central fan	7	5	7	19	7

[1] Machine mounted secondary ventilation equipment requires a main face ventilation system to deliver the required fresh air to the face.

[2] Modified push/pull and fan with extendable boom mounted duct rank evenly.

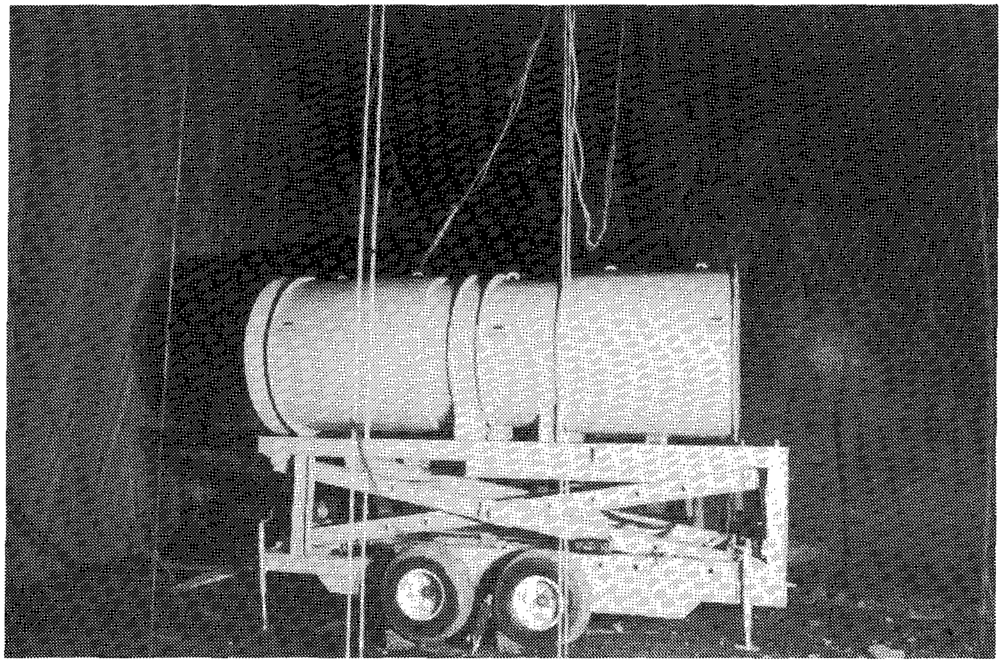

FIGURE 4a. - Photograph showing testing of the jet fan

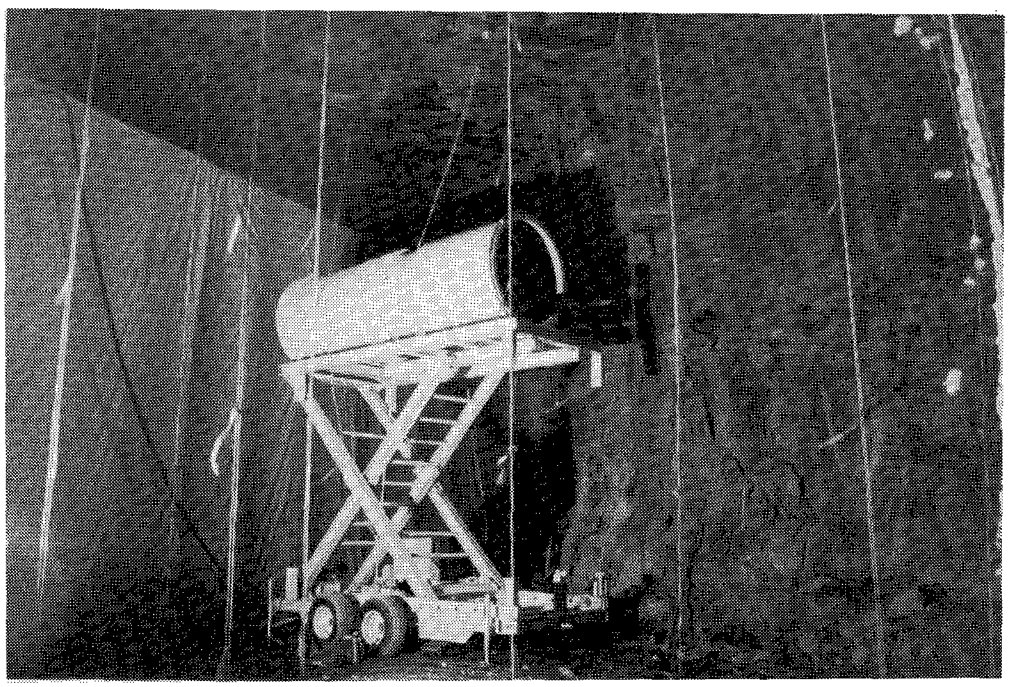

FIGURE 4b. - Photograph showing jet fan in an elevated position.

Spendrup[1] model AMF 1400-70-12 with a 100 hp motor. The motor was wound to operate at 2 speeds, 1180 rpm and 1760 rpm. It was mounted on a custom manufactured, scissors lift capable of elevating the fan centerline to a height of about 17 ft above the floor. Both inlet and outlet silencers were installed to ensure quiet operation.

The thrust developed by the jet fan at a flow rate of 100,000 cfm and 0.075 lbs/ft^3 density would be 196 pounds. In its raised position, this thrust would generate a moment of 3330 ft-lbs, which is only a minor portion of the moment required to overturn the structure.

Jet fans (free standing, un-ducted fans) are commonly employed in the mining industry. Their use is based upon the action of an expanding, turbulent jet. The turbulent jet has received considerable attention in many engineering studies, and was analyzed in detail by Abramovich (<u>20</u>). Empirical studies with specific application to mining were reported by McElroy (<u>21</u>), Krause (<u>22</u>), and Lewtas (<u>23</u>). Figure 5 shows a plan view of a dead-end heading being ventilated by a jet fan. The fan is located

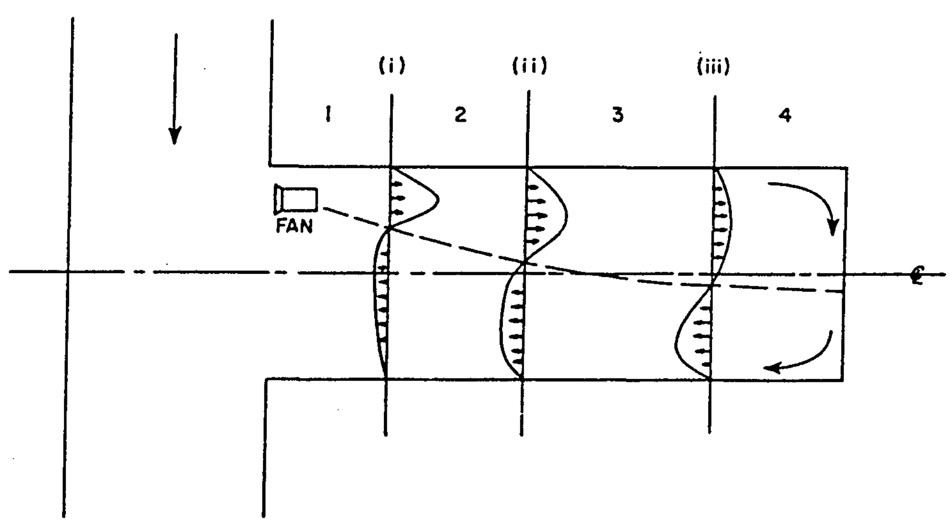

FIGURE 5. - Plan view of heading showing idealized ventilation path.

along the upstream corner of the last open crosscut, and projects air at high velocity along the wall towards the face. The jet expands with increasing distance from the fan until, ideally, air is flowing towards the face in half the opening and flowing back towards the last open crosscut in the other half. The growth of the jet is due to the action of frictional forces at the boundary of the jet, which accelerate additional air in the direction of the face. In the process, the initial momentum of the jet is transferred to an ever greater mass, thereby reducing the velocity of flow. By the process of entrainment, the jet fan is able to deliver a volume much greater than the intake volume; however, much of it is recirculated. At the last open crosscut, mass is conserved. Free standing, jet fans can have significant recirculation at the inlet, depending upon location.

For a fixed quantity of air flow, the primary design problem in the case of the jet fan is to determine the outlet velocity required to assure that the air reaches the face with some minimum velocity. In this project, the minimum acceptable velocity was set at 60 ft/min at a face 300 ft from the last open crosscut. McElroy (21) presented a group of empirical relations that were useful in this work. McElroy's equations were checked against lab data presented by Lewtas (23) and field measurements made during jet fan research by Union Oil Company for oil shale mining (Spendrup, 24). Figure 6 presents normalized centerline velocity versus normalized distance for a 39 in. diameter jet fan tested at Union Oil's oil shale mine. The results show good correspondence between predictions and measurements.

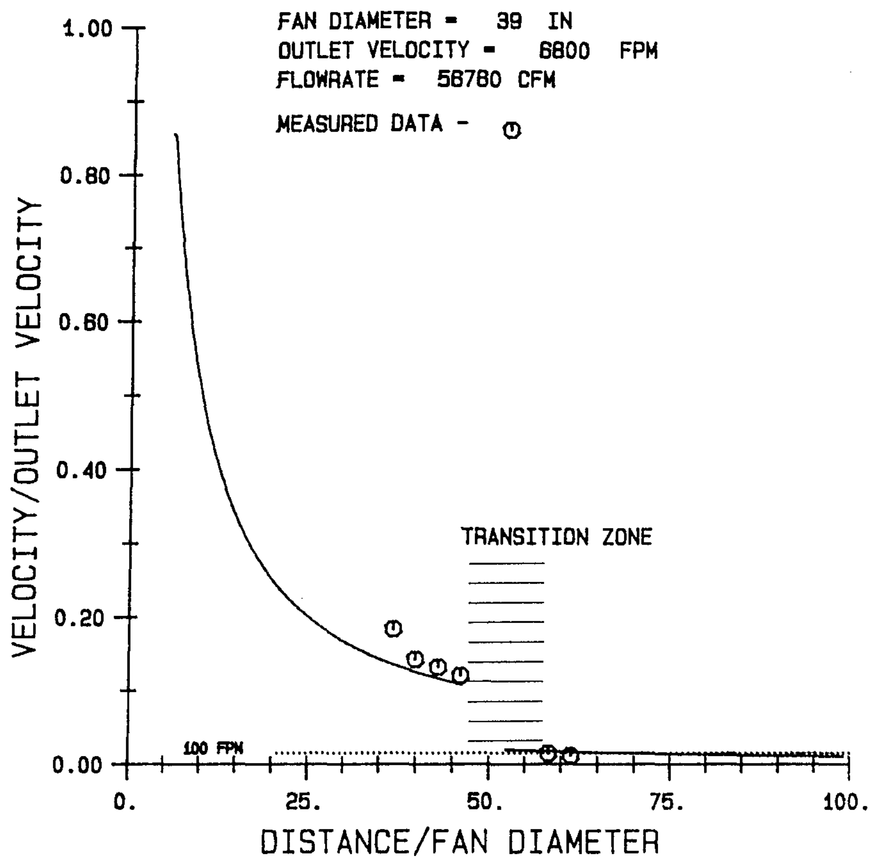

FIGURE 6. - Normalized centerline velocity versus normalized distance for a large jet fan tested in oil shale mining [Spendrup (24)].

Using this technique, a 54 in. fan was predicted to produce velocities of 124 ft/min at a distance of 300 ft, and was selected as the optimal size.

3.6.2 Reversible Fan with Rigid Duct

A photograph of the reversible fan with rigid duct is presented in Figure 7. The fan was a 55 in. diameter, 2-stage, Spendrup[1] model AMF 2400-70-12. Each stage was powered by a 125 hp motor,

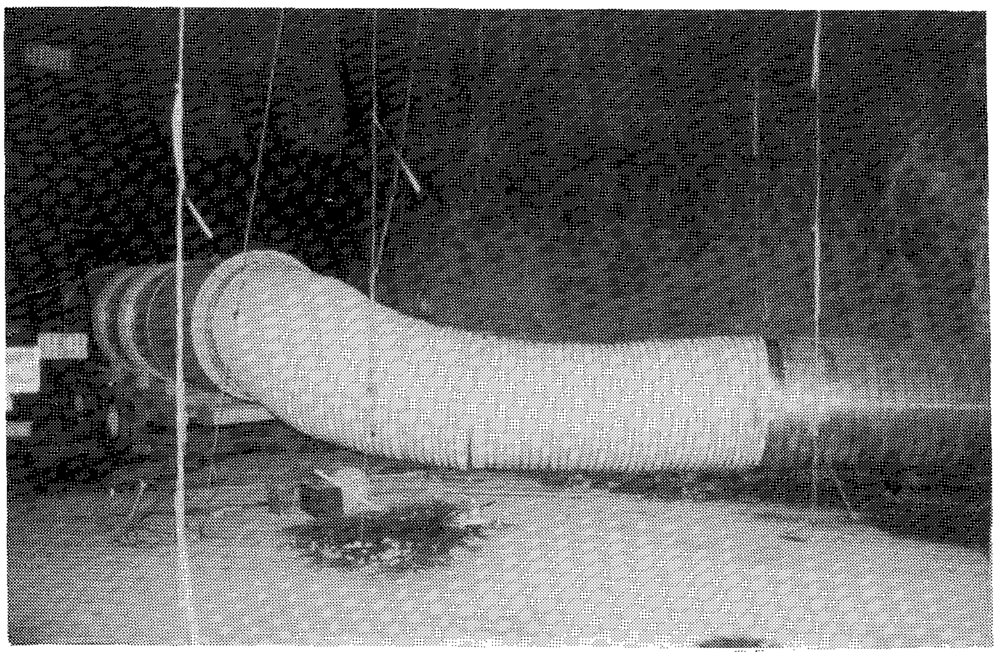

FIGURE 7. - Photograph of the 55 in. diameter fan connected to rigid ducting.

and the fan was equipped with inlet and outlet silencers. The outlet was connected to a 54 in. diameter flexible duct, and reinforced with a spiral wound wire, which was, in turn, connected to a 54 in. diameter steel duct.

Both motors were reversible, and the fan could operate at full capacity using both stages, or roughly at half capacity using the second stage. The system was designed to use a large, oval fiberglass duct (62 in. by 40.5 in.). The oval duct was replaced by a 54 in. diameter round steel duct in the test system to reduce the fabrication expense. Figure 8 shows an elevated nozzle constructed at the face using a 62 in. by 40.5 in. steel oval duct.

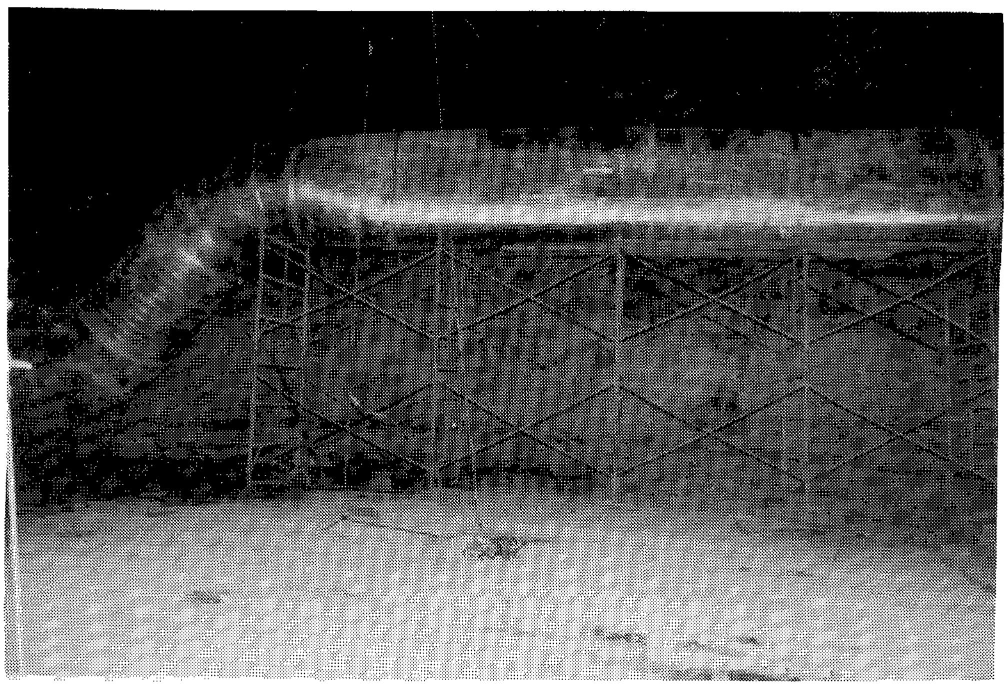

FIGURE 8. - Photograph of the elevated oval nozzle.

The ducting was run to the face on the floor, with the nozzle elevated on scaffolding. Placing the outlet closer to the face might improve performance; however, damage due to blasting would be significant on a floor mounted system. The outlet was located 75 ft from the face while in the blowing mode and 30 ft from the face while in the exhaust mode.

The use of ducted fans has a proven history of successful operation in room and pillar operations (McLendon, 25 and Hagood, 26) where dust and methane are problems. The advantages of a rigid ducted system as compared to a jet fan are:

- elimination of fan inlet recirculation;
- capability of both blowing and exhaust mode operation; and
- high air velocity at the face.

Disadvantages include:

- minimum entrainment to increase air exchange at the face;
- low air velocity on return path;
- high initial cost, operating cost and energy consumption;
- high labor cost for assembly, disassembly and the transport of the duct; and
- high potential for damage due to blasting and operations.

A schematic of the operation of the reversible system in the blowing mode is presented in Figure 9. The fan would be angled down the last open crosscut in the exhaust mode, with the high

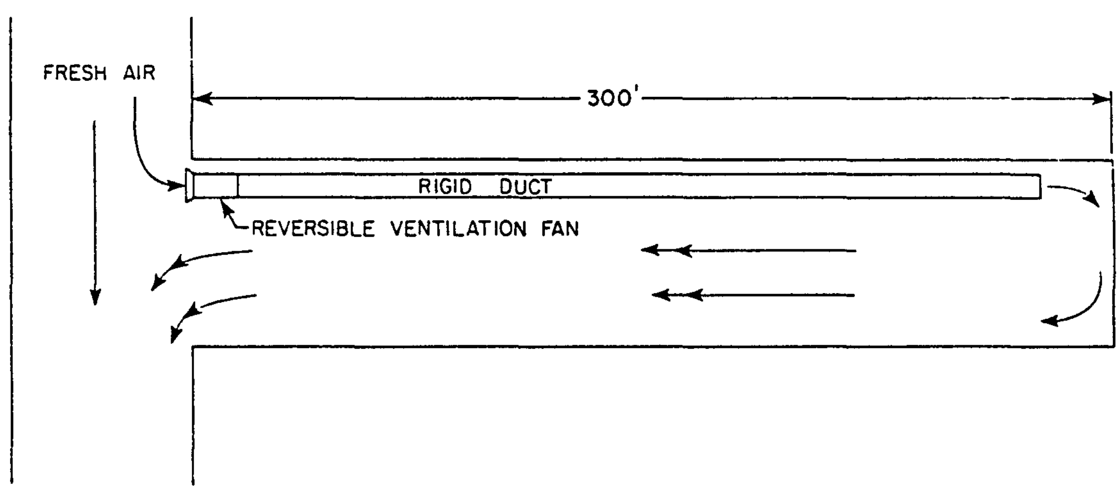

FIGURE 9. - Schematic of reversible fan in rigid duct system.

velocity of the jet of air preventing most of the exhaust air from recirculating. This type of installation has not been proven, and will result in some reduction in performance due to inlet recirculation in both operating modes. However, the substantial increase in system complexity caused by the use of an inlet duct network that would allow operation in both modes and eliminate recirculation is not considered to be practical with this size system. If this type of reversible system proves inoperable, then replacement by some type of push-pull system may be required.

Standard design techniques for ducted fan systems were used to develop the specifications for the system (Daly, 27), with the mine design criteria used in this study requiring a fan capable of delivering 100,000 cfm at a total pressure of approximately 6.0 in. w.g. This performance capability is available in single stage fans; however, this two-stage fan was offered at less cost than a single-stage fan with a 200 hp motor. Furthermore, the two-stage design with a total of 250 hp gave it the capability of greater than 100,000 cfm at higher pressures. Since these fans will be available to the sponsoring oil shale companies for future testing, the extra capacity was desirable in case future mine plans required high flow capacity. Operating efficiency of the ducted system was not optimum because of the overcapacity.

4.0 IN-MINE CHARACTERIZATION OF FAN PERFORMANCE

4.1 INTRODUCTION

Tracer gas techniques were chosen to characterize the overall performance of the fan systems. Sulfur hexafluoride (SF_6) tracer gas has been used in underground ventilation studies by the U. S. Bureau of Mines by Thimons, et al. (28), Thimons and Kissell (29), and Matta (13). The gas is inert, does not occur naturally, and is detectable in concentrations as low as one part per trillion (10^{-12}). The use of tracer techniques in this study allowed definitive characterization of the performance of the fan systems. Very small amounts of the gas were released in the face area, and the ability of the fan system to dilute the tracer was measured.

The tracer gas data was supplemented by air velocity surveys and flow direction studies. These data were used to establish the optimum location of the jet fan prior to the tracer tests.

4.2 TEST ROOM LAYOUT

A test layout that would simulate the configuration of a room and pillar mining operation was needed for the fan tests. This would include the flow at the last open crosscut to circulate fresh air past the fan inlet. The configuration was developed at Crosscut 7 of the Colony Mine by building a brattice wall to channel the total mine air flow past Crosscut 7, as shown in Figure 10.

The brattice wall channel was nominally 20 ft wide by 30 ft high. Total mine air flow through the channel was measured by an

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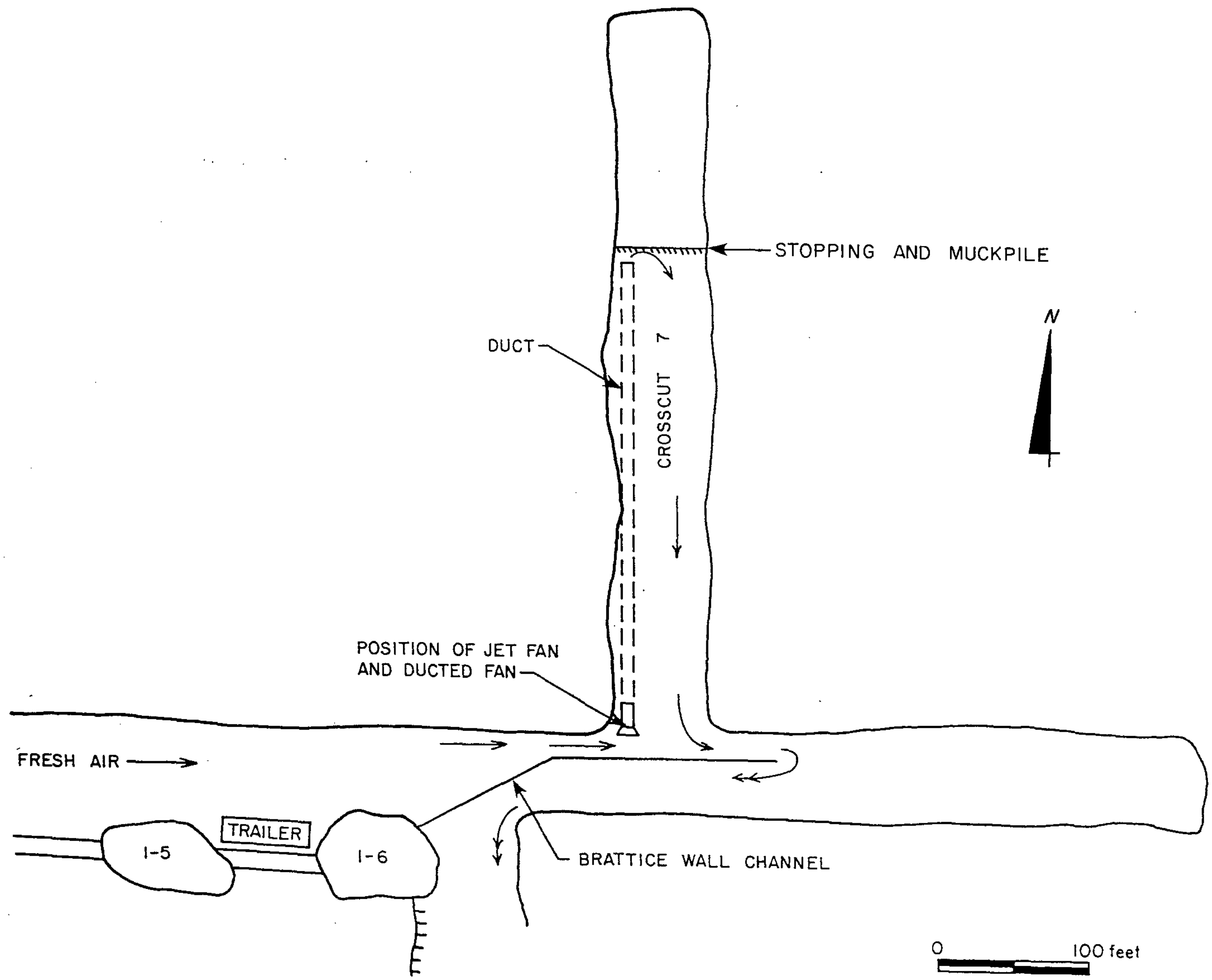


FIGURE 10. - Test room configuration.

anemometer survey to be 124,000 cfm, with the velocities varying between 140 to 313 ft/minute. A stopping was built on top of the stored muck at a distance of 320 ft from the crosscut to close the room. The room dimensions were nominally 55 ft wide by 30 ft high.

A sampling grid was developed in the test room to fix the points of measurement. A photograph of the test room and grid system is shown in Figure 11. The grid points were surveyed in, and ram set

FIGURE 11. - Photograph of grid system established in Crosscut 7.

screws placed at the floor and ceiling. PVC ropes were stretched from roof to floor, and orange plastic flagging tied to each rope at constant distances below the roof. The plastic flagging was used to map the direction of air flow throughout the heading.

Figure 12 shows a plan view of the grid system. Labeling of the grid is based upon distance from the face - for example, Section 1+50 is at a distance of 150 feet. Lateral sections are labeled alphabetically, with D lying at the center of the drift.

4.3 AIR VELOCITY AND AIR FLOW DIRECTION

Air velocity and flow direction were studied to supplement the tracer gas data and to optimize the location of the jet fan.

4.3.1 Optimization of Jet Fan Location

Optimization of the jet fan location has received attention in previous studies by Lewtas (23). It is generally accepted that the optimum location is as close as possible to the corner on the inby side of the heading. This study sought to confirm the previous work and to investigate the effect of elevating the fan along the wall.

The fan axis was aligned along lateral section line A, and a group of seven positions was investigated to try to establish the location with the best performance. Table 12 summarizes the results. The lowest position of the fan on the scissors lift was 8.5 ft above the floor. To test in lower positions, the fan was dismounted and placed on blocks. Comparison of the results indicated that the fan was most effective in position 7, with the axis of the fan very slightly directed into the lower corner. In this position, peak forward velocities of 550 ft/min were measured at 60 ft from the face at a height of about 6 ft along lines B and C. The face air motion was very turbulent, with forward velocities dropping to zero periodically.

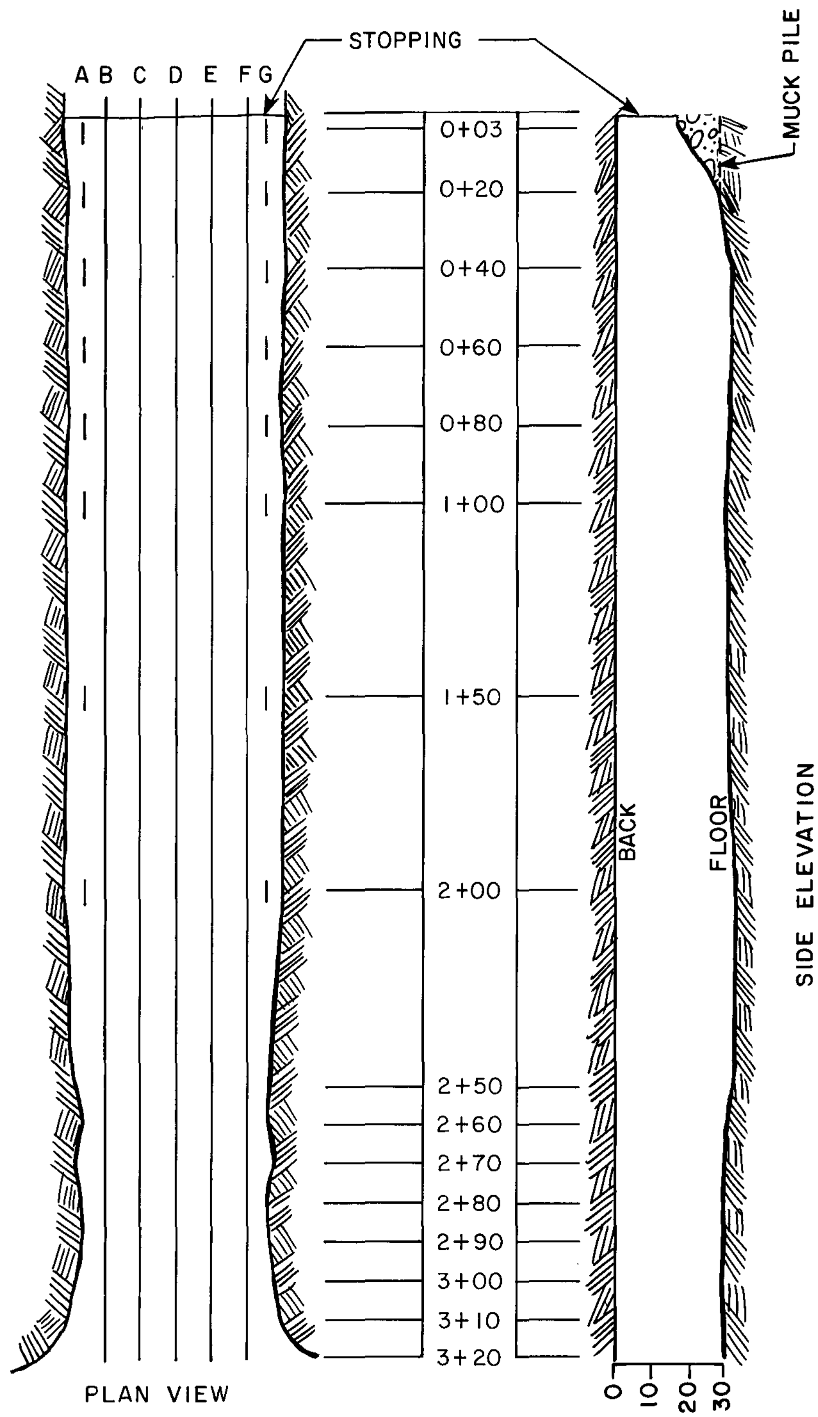


FIGURE 12. - Plan view of test room grid system.

TABLE 12. - Locations, orientations and face air velocities for jet fan

Test No.	Distance from face (ft)	Distance from room centerline (ft)	Height above floor (ft)	Orientation in vertical plane (ft)	Angle from axial section line A	Peak air veloc.[2] (ft/min) At 100 ft from face	Peak air veloc.[2] (ft/min) At 60 ft from face
1	306.7	Left 18.4	8.5	Level	0°	557	--
2	306.7	Left 18.4	17.3	Level	0°	170	--
3	305.5	Left 18.4	4.0[1]	Level	0°	717	489
4	305.5	Left 18.4	3.4[1]	Down 5°	Left 5°	522	--
5	305.5	Left 18.4	3.7[1]	Down 2½°	Left 2½°	690	439
6	305.5	Left 18.4	3.7[1]	Down 2½°	Left 1°	618	--
7	305.5	Left 18.4	3.9[1]	Down 1°	Left 1°	726	550

[1] Fan dismounted from scissors lift and mounted on blocks on the floor

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

The ability of the fan to project air to the face was reduced by elevating the fan above the floor. At 17.3 ft, the peak forward velocity had dropped to 170 ft/min, and the forward stream of air began moving off of the left wall and across to the right wall at 150 ft from the fan outlet.

Figures 13a and 13b show the growth of the jet at various cross sections along the length of the heading. The figure illustrates the variation in velocity through the cross section and the relative areas of forward and return air flow. The contours of constant velocity are generated by point measurements made by one monitor. The entire cross section took roughly two hours to survey; therefore, the contours are only illustrative of the flow pattern, and not an accurate measurement of total flow rate. The diagrams show that the jet has expanded to take up half of the heading at a distance of 150 ft from the face. The idealized pattern of flow, shown earlier in Figure 5, is fairly representative of the action of the jet fan. In the immediate face area, the forward velocities drop very rapidly as the air turns and forms the return air stream.

4.3.2 Duct Outlet Configurations for the Reversible Fan

A series of tests was conducted to evaluate the effects of outlet configuration on the performance of the ducted fan. Table 13 presents the various configurations examined. The lateral face sweep velocities were very high for all positions, with average velocities varying from 455 to 1095 ft/min. All positions produced very high face sweep velocities. The elevated position was chosen because it would be required in actual operations to protect the ducting from blast damage.

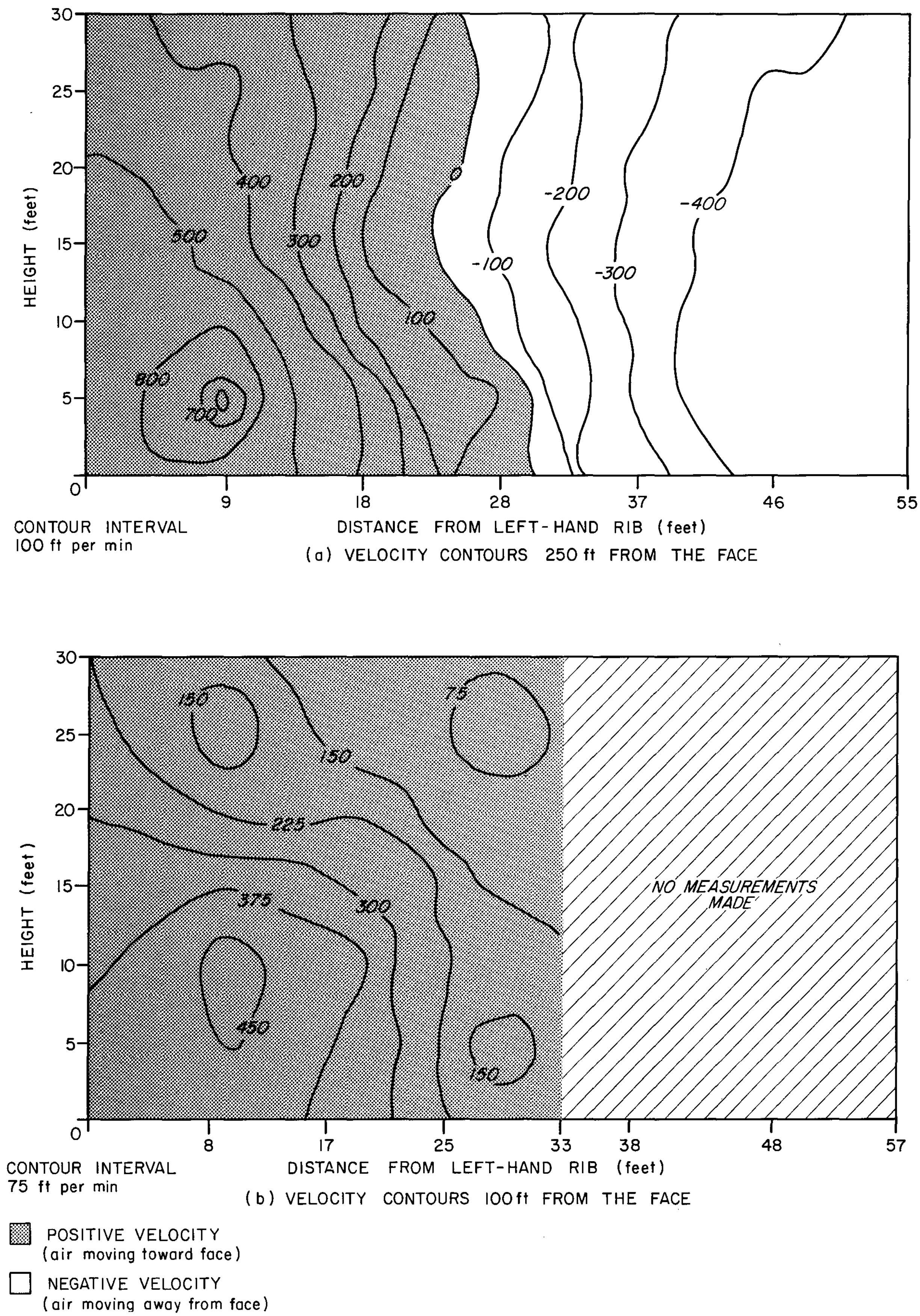


FIGURE 13. - Air velocity contours at various cross sections in the test room - jet fan position 7.

TABLE 13. - Discharge locations and face sweep velocities for the ducted system - blowing mode

Test No.	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.)
1	58.3	21.0	2.5	54 in. dia. round	--
2B	30.5	21.0	2.6	Large oval[1]	532
3	30.5	21.0	2.6	Small oval[2]	456
4	78	21.0	13	Large oval	1095

[1] 62 in. x 40.5 in. oval

[2] 55.8 in. x 36.5 in. oval

4.4 TRACER GAS TESTING TECHNIQUES AND DATA ANALYSIS

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 fans' effectiveness at clearing a heading after blasting. The test room was sealed and SF_6 gas released to give a uniform concentration of approximately 1000 ppt (1000×10^{-12}). The fan was run for a short period of 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/hr kerosene space heater was placed in the face area with the exhaust routed through a vertical stack to dump 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 engine emissions. The mine ventilation and face ventilation systems were started, and the steady-state concentration of SF_6 measured.
- Simulation of methane layering: SF_6 was mixed with 52.4 mole percent helium 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. The tracer gas was released at a uniform rate for 45 to 60 min., and gas samples were taken to see if the tracer would form a roof layer similar to methane. The fans were then started to test their effectiveness at breaking up the layer.

- <u>Simulation of methane emissions from a muckpile</u>: In this test, the mixture of air, helium and SF_6 was released from a group of pipes laid out in the face area to simulate methane desorbing from a 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.
- <u>Measurement of fan inlet recirculation</u>: The inlet recirculation volume was measured by releasing tracer gas directly into the fan. The concentration in the air coming out the fan and the concentration of the air around the inlet were both measured. The concentration of the air coming out of the fan is governed by the release rate of the tracer gas, and the amount of tracer gas recirculated into the inlet.

Tracer gas was released using mass flowmeters that were calibrated for atmospheric density at the test room elevation. Gas samples were gathered during the tests using Model SS12-9 sequential environmental gas samplers manufactured by Demaray Scientific Instruments, Ltd.[1] These samplers were programmable so that both the time for initiation of the first sample and the length of time to draw each sample could be varied. Samples were drawn into 30 cc plastic syringes continuously during the sample interval so that the concentration of the tracer gas was averaged. Sample times used in this study were 5, 10 and 20 minutes. Sampler layouts varied according to which type of simulation was being conducted. These layouts are shown in Appendix B for each test.

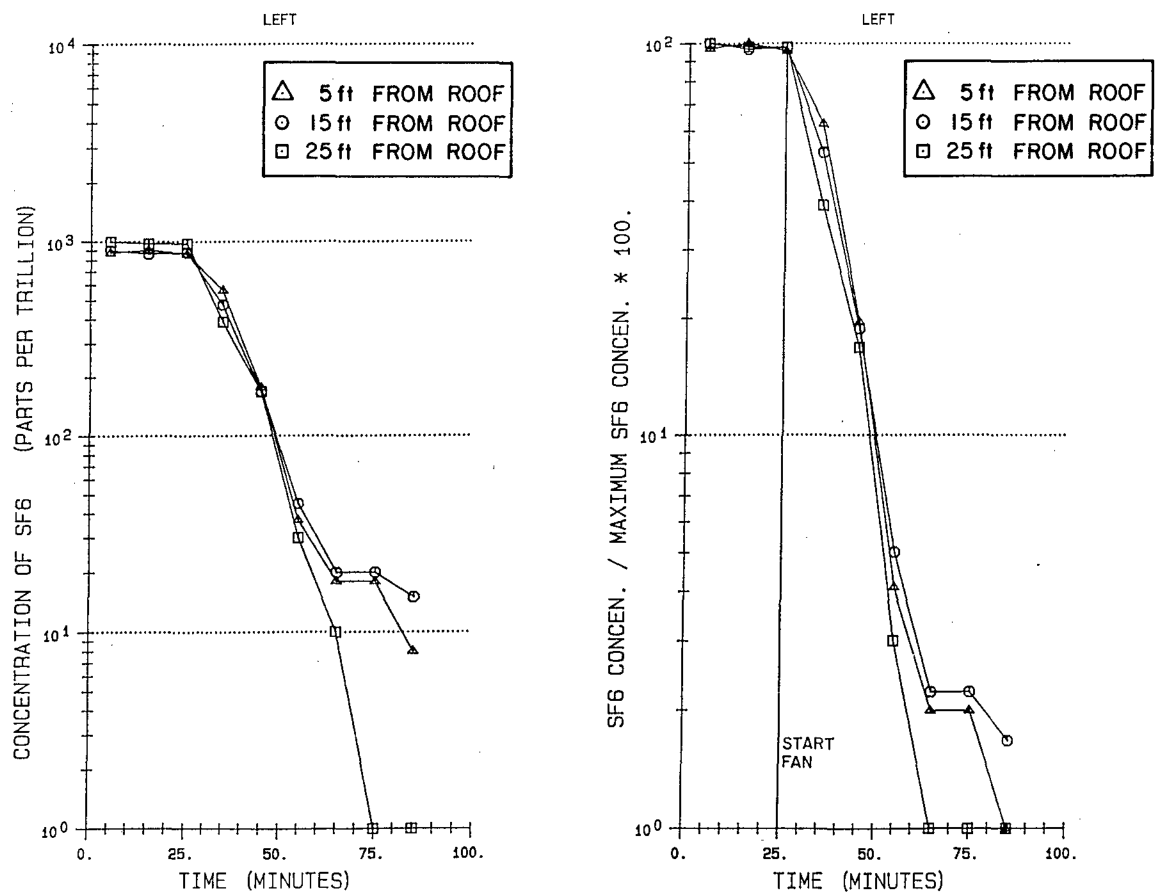
The results of tracer gas tests can be directly extrapolated to full scale pollutant concentrations. This is done by normalizing parameters to the peak concentrations, rate of tracer gas release, volume of test room and volume of ventilation air flow. This study employed two fundamental types of SF_6 release:

- o release of a fixed quantity of SF_6, and mixing that quantity uniformly throughout the test room; and
- o steady-state release of SF_6.

Analysis of the dilution of these two types of release are described in the following sections.

4.4.1 Release and Dilution of a Fixed Quantity of SF_6

This type of SF_6 release was used in the simulation of the clearing of blast produced pollutants. In this measurement, the tracer gas was mixed uniformly in the test room and diluted by the fan system. Figure 14 presents a dilution curve from a blast clearing test for a vertical array of samplers at cross section 0+40 and line D. Samples were located at 5, 15 and 25 ft from the roof. Figure 14a is the logarithm of concentration plotted versus time, and Figure 14b is the same data with SF_6 concentration normalized to the peak concentration measured at each sampler



(a) Concentration versus time

(b) Normalized concentration versus time

FIGURE 14. - Logarithm of concentration versus time for jet fan in the blast clearing simulation test.

location. Figure 14-b can be used to extrapolate the tracer gas data to actual blast produced pollutant levels. By assuming the peak pollutant concentration is equal to 100 percent, the time to reach a certain percentage of the peak value can be read directly from the curve.

In another form of analysis, Matta (13) employs equation (4) for the experimental decay of gas concentration in a room being ventilated by an airflow, (Q):

$$C = C_o e^{-(Q/V)t} \tag{4}$$

where: C = concentration at time t_2

C_o = initial concentration at time t_1

Q = ventilation air flow (cfm)

V = room volume (ft^3)

t = $t_2 - t_1$(min.)

A normalized dilution rate (D_r) can be calculated by setting the room volume (V) to a value of 1.0 ft^3 and writing equation (5) in logarithmic form:

$$D_r = \frac{\ln C_o - \ln C}{t_2 - t_1} \tag{5}$$

where: D_r = normalized dilution rate (min^{-1})

D_r is actually the air flow (cfm) per cubic foot of room volume.

D_r was determined from curves like Figure 14a using least-square fitting of the linear portion of the curve. Comparison of the normalized dilution rate (D_r) for various locations throughout the room indicates the uniformity of the ventilation effect.

To quantify the effectiveness of the ventilation systems, a parameter that is normalized to the fan flow rate is needed. A measure of air delivery or dilution efficiency can be derived by normalizing the delivered air as measured by the tracer gas dilution to the fan outlet volume. In this study the parameter, dilution efficiency (E_D) as calculated by equation (6) is used to quantify ventilation performance.

$$E_D = Q_E/Q_{FAN} \qquad (6)$$

where: E_D = dilution efficiency

Q_{FAN} = fan flow rate (cfm)

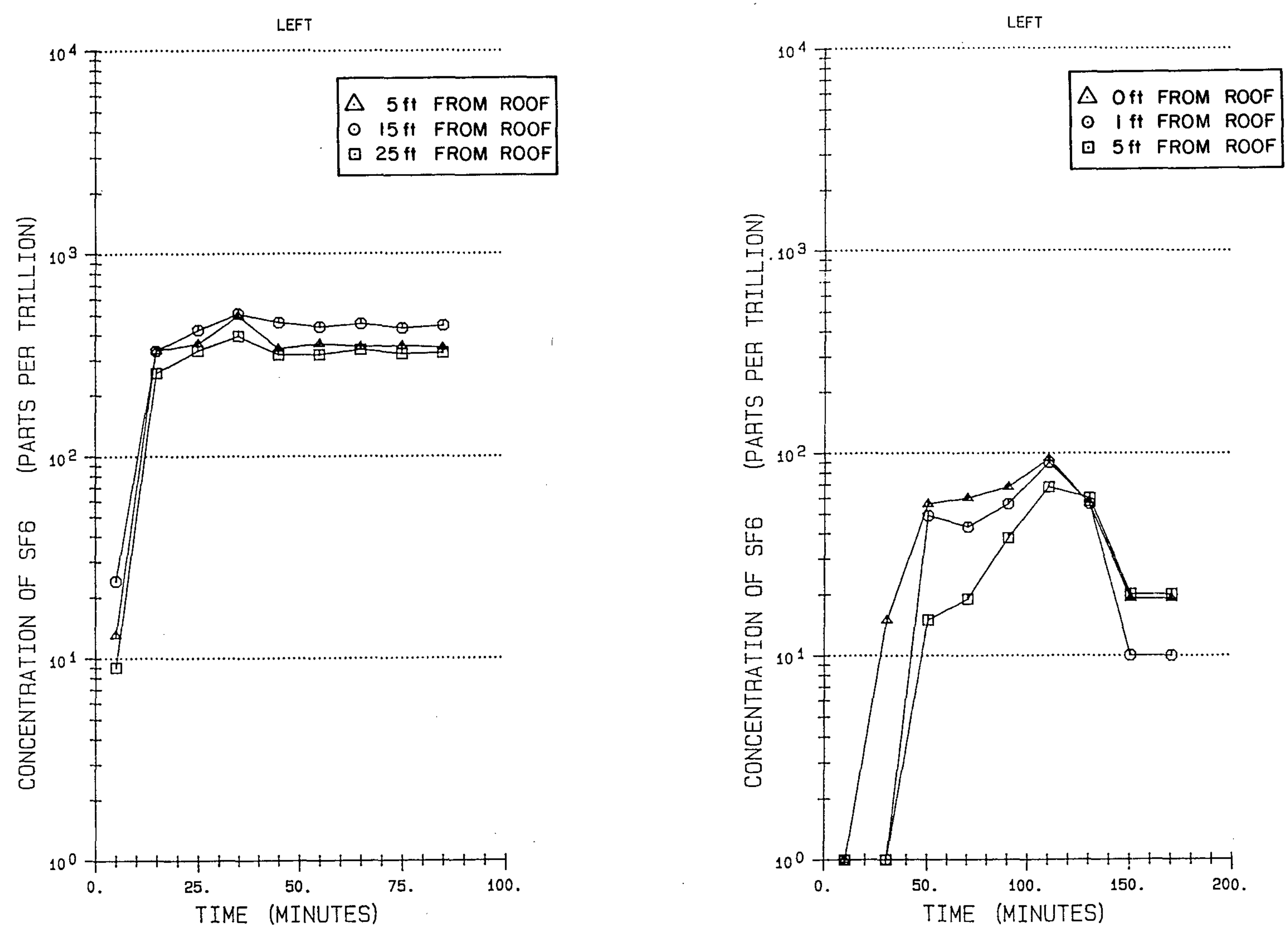
Q_E = effective dilution flow = (cfm)

For the blast clearing test, the effective dilution flow is calculated by multiplying the room volume (v) by the average normalized dilution rate (D_r). Dilution efficiency has been used previously by Haney, et al. (30), and termed the Face Ventilation Index (FVI).

For perfect performance, the dilution efficiency is equal to 1.0.

4.4.2 Steady-State Release of SF_6

The steady-state type of SF_6 release was used in the diesel exhaust, methane layering, methane from muckpile and fan recirculation tests. Figure 15 presents plots of the log of SF_6



(a) Diesel exhaust simulation

(b) Methane layering simulation

FIGURE 15. - Logarithm of SF_6 concentration versus time for steady-state emissions of tracer gas in diesel exhaust and methane layering tests.

concentration versus time for a vertical array of samplers at cross section 0+40 and lateral section D in the diesel-exhaust (Figure 15a) and methane layering (Figure 15b) tests for the jet fan. Figure 15a shows the buildup of SF_6 concentration to a steady-state value, due to a constant flow rate of SF_6. Figure 15b shows the buildup of an SF_6 layer along the roof in still air; the fans are then started, and the SF_6 concentration drops to a steady-state value as the ventilation system breaks up the layer. In this type of release, the rate at which SF_6 is released is a constant, and the action of the face ventilation system will establish a steady-state concentration that is a function of the system's ability to deliver air to the face and effectively mix it with the tracer gas. The ideal concentration is equal to the flow rate of the SF_6 gas divided by the flow rate of the fan. The dilution efficiency is the ratio of the ideal concentration divided by the average steady-state concentration measured at a given location, as calculated by equation (7).

$$E_D = C_{ideal} / \overline{C}_{ss} \qquad (7)$$

where:

E_D = dilution efficiency

$\overline{C}_{ss}$ = steady-state concentration of SF_6

C_{ideal} = ideal concentration of SF_6 assuming perfect dilution

The calculation of C_{ideal} is given by equation (8).

$$C_{ideal} = q_{SF_6}/Q_f \qquad (8)$$

where: q_{SF_6} = flow rate of SF_6 (cfm)

Q_f = fan flow rate (cfm)

A value of 1.0 indicates that the face ventilation system is performing at perfect effectiveness.

4.5 TRACER GAS TEST RESULTS

4.5.1 Blast Clearing Simulation

Four pulse-release tests were conducted using the two fan systems. The tests included:

- Measurement of SF_6 dilution rate due to air sweep in last open crosscut, then operation of the jet fan at 88,400 cfm.
- Measurement of SF_6 dilution rate with operation of the jet fan at 60,000 cfm.
- Measurement of SF_6 dilution rate for ducted fan in exhaust mode at a flow rate of 73,000 cfm. The fan was ducted through the brattice wall so that the air was dumped directly into the mine exhaust air.
- Measurement of SF_6 dilution rate for the ducted fan in blowing mode at a flow rate of 90,700 cfm.

Each of the four tests employed identical sampler layouts (shown in Appendix B) and tracer gas release. The brattice wall channel was closed with panels of brattice, and the mine fans were shut off. Air containing 101 ppm SF_6 was released throughout the room at a rate of 0.177 cfm (5 l/min.) for a period of 30 minutes. For the blowing mode tests the face ventilation system was then run for a short period to mix the tracer uniformly. The resulting average concentration of SF_6 in the test room was 947 parts per trillion (ppt).

The samplers were allowed to take their first sample, then the curtain was lifted and the mine fans started to establish the last open crosscut flow through the brattice wall channel. The face ventilation systems were then started to clear the heading.

Figure 16 shows a comparison of the ventilation performance from the four different tests. The curves are normalized to the concentration at the time the face fans were turned on, and are average values for the vertical arrays of samplers hung at lateral section line D 40 ft from the face. The figure compares the rate of SF_6 concentration decay for the different tests, and indicates that the ducted system in the blowing mode clears the tracer gas very rapidly. The jet fan had the second highest rate of clearing, and the ducted fan in the exhaust mode was the slowest.

Several samples were taken during the test of the jet fan at 88,400 cfm to measure the effect of the last open crosscut air flow in ventilating the room. Air flow was detected as far into the room as section 1+50 with normalized dilution rates of -0.034 (section 2+50) and -0.022 (section 1+50) due to the sweep effect in the crosscut. Based upon a room volume of 514,600 ft^3, flow rates of 17,500 cfm and 11,300 cfm were generated by the 124,000 cfm flow through the brattice wall channel.

Table 14 compares the performance of the two fan systems in the four blast clearing simulations. The jet fan tests showed a dilution efficiency of 1.0 at low speed (60,000 cfm), and dropped to a dilution efficiency of 0.75 at full speed (88,400 cfm). The calculated effective flow rates at both speeds were very similar, within 2 percent, even though the fan outlet flow at full speed was 147 percent of the flow at low speed. A similar result was

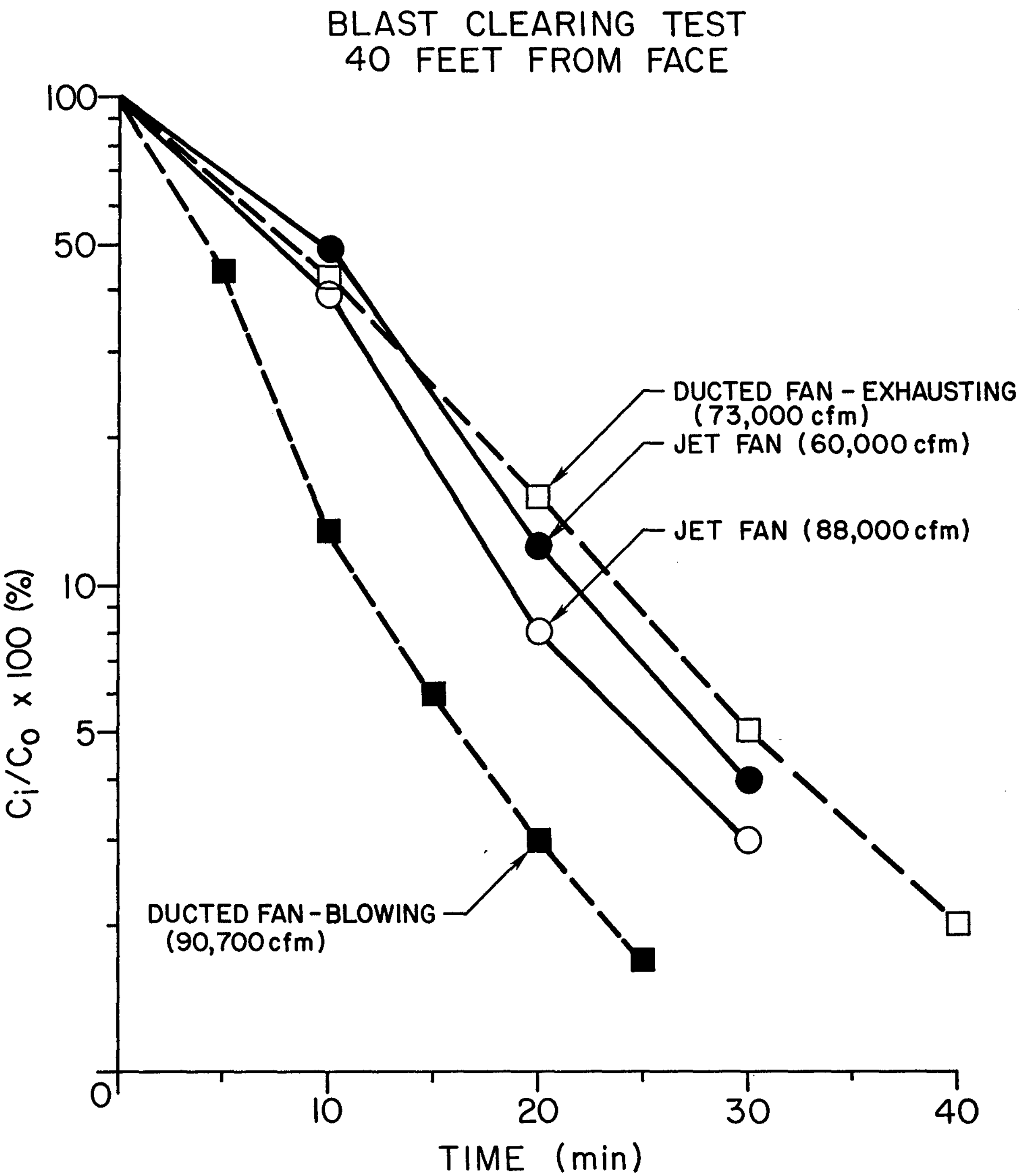


FIGURE 16. - Comparison of jet fan and ducted fan performance in the blast clearing test 40 ft from the face.

TABLE 14. - Comparison of fan systems' performance in the blast clearing tests

	Jet fan		Reversible fan	
			Exhausting	Blowing
	(88,400 cfm)	(60,000 cfm)	(73,000 cfm)	(90,700 cfm)
Average normalized dilution rate ($min.^{-1}$) with face ventilation operating				
0+40	-0.132 ± 0.027	-0.128 ± 0.008	-0.101 ± 0.007	-0.181 ± 0.172
1+50	-0.112 ± 0.018	-0.123 ± 0.026	-0.111 ± 0.009	-0.166 ± 0.016
2+50	-0.143 ± 0.014	-0.143 ± 0.037	-0.125 ± 0.031	-0.171 ± 0.007
Calculated effective flow rate (cfm)				
0+40	67,930	65,900	51,970	93,140
1+50	57,640	63,300	57,120	85,420
2+50	73,590	73,590	64,330	88,000
Dilution efficiency				
0+40	0.77	1.09	0.71	1.03
1+50	0.65	1.06	0.78	0.94
2+50	0.83	1.23	0.88	0.97
Mean dilution efficiency	0.75	1.13	0.79	0.98

[1] Room volume equals 514,600 ft^3

reported by Volkwein (<u>14</u>) in tests of jet fans at Union Oil's Parachute Creek project. In a comparison of two fans with flow rates of 111,000 cfm and 87,000 cfm operating in exactly the same room configuration, the smaller fan was able to deliver a 58 percent higher effective flow rate at the face. Dilution efficiency for the larger fan ranged from 0.16 to 0.33 for various orientations, as compared to 0.36 to 0.61 for the smaller fan. These results suggest some interaction between room dimensions and the action of the fan's jet flow, which needs further investigation.

The ducted system in the blowing mode delivered the highest normalized dilution rates, ranging between -0.166 to -0.181, as compared to -0.112 to -0.143 for the jet fan. Its dilution efficiency was also greater, averaging 0.98, as compared to 0.75 for the jet fan at full flow.

The performance of the ducted system was reduced in the exhausting mode, with the dilution efficiency averaging 0.79 or 19 percent less than in the blowing mode configuration. In this test, the outlet of the fan was ducted through the brattice wall directly into the mine exhaust to prevent the exhaust from being recirculated.

4.5.2 <u>Diesel Exhaust Simulation</u>

Diesel exhaust simulations were performed for both face ventilation systems at full flow rate. Both tests employed identical sampler layouts (See Appendix B) and sample intervals of 20 minutes. A kerosene space heater with a 15 ft high exhaust pipe was located roughly 70 ft from the face near line D. The space heater was operated at 50,000 btu/hr, and 101 ppm SF_6 in the air was injected into the exhaust stream at a rate of 0.192 cfm (5.44 l/min). The exhaust stream temperature was 300°F, well below the temperature at which SF_6 begins to break up. The hot exhaust stream was designed to give the tracer gas buoyancy similar to exhaust produced by a diesel loader working at the face.

Figure 17 compares the dilution efficiency versus time for the hot exhaust tests for both fans at a distance of 40 ft from the face, using average values of the vertical array of samplers at 5, 10 and 15 ft from the roof. All mine fans and the face ventilation system were in steady operation for roughly 20 min. before the SF_6 release was begun. The SF_6 concentration built up to a steady-state within 40 minutes. Time-weighted average concentrations and dilution efficiencies were calculated for the last three sample points, and are compared in Table 15. Dilution efficiencies, calculated from the time-weighted average values, indicate that the jet fan is slightly more effective than the reversible fan. At 0+40 to 0+80, the jet fan has an average dilution efficiency of 0.70 to 0.81, slightly better than the ducted fan at 0.63 to 0.76. This advantage disappears as the distance from the face increases, with the dilution efficiency increasing to 0.86 and 0.90 at 2+00 for the jet fan and reversible fans, respectively.

Use of the heated exhaust stream was intended to simulate the buoyancy of diesel emissions. The hot exhaust produced an average stratification in SF_6 concentration of 7.5 percent of the peak concentration, with a range of 3 to 14 percent. The stratification tended to increase with distance from the face area. This is significantly less than the stratification in diesel emissions

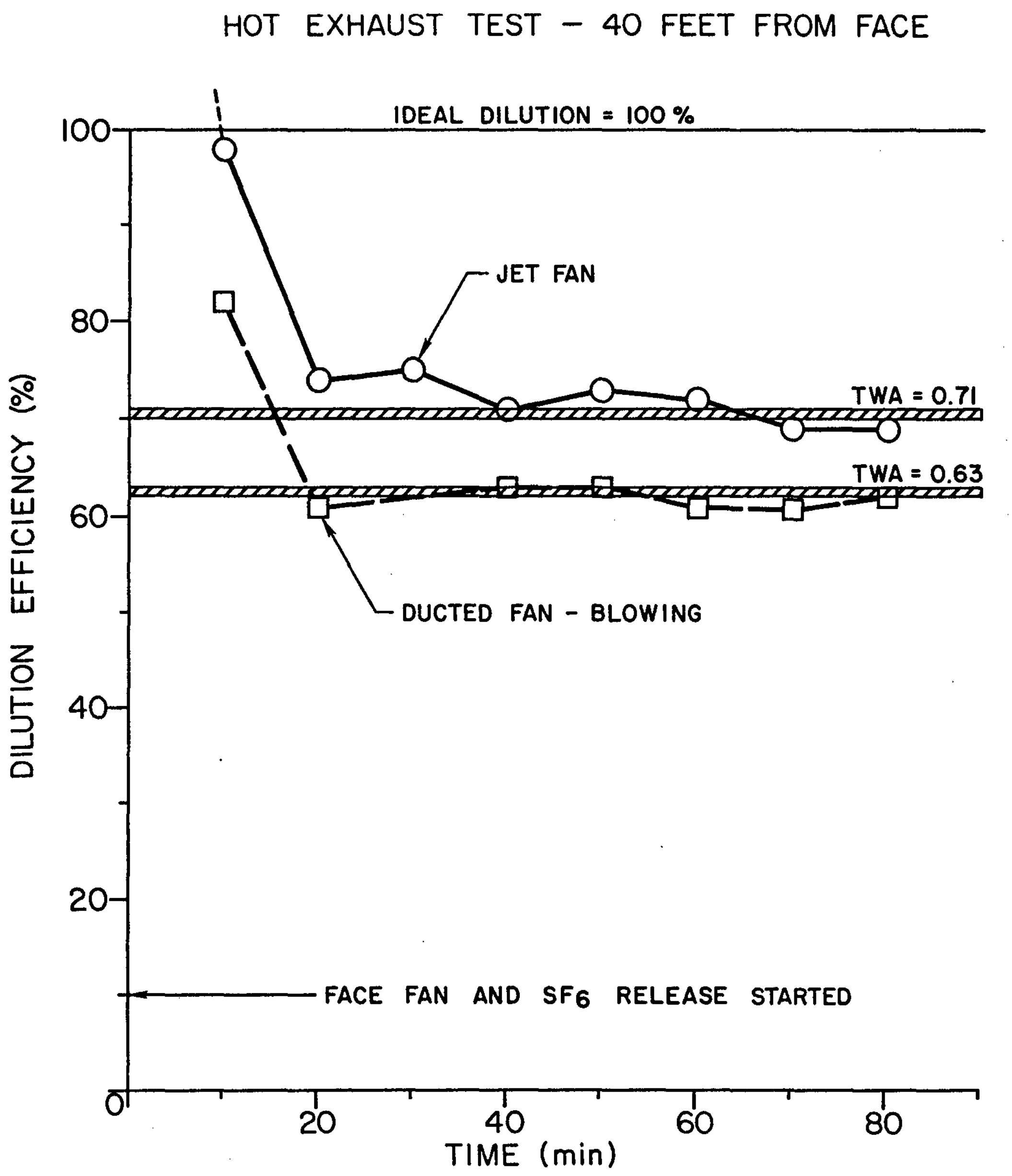


FIGURE 17. - Comparison of the performance of jet fan and ducted fan for the hot exhaust test at 40 ft from the face.

TABLE 15. - Comparison of average SF_6 concentration and dilution efficiency for the diesel exhaust test

Section	Distance from roof (ft)	Jet fan (88,400 cfm) Average SF_6 concentration ppt* (10^{-12})	Jet fan (88,400 cfm) Dilution efficiency	Ducted fan - blowing (90,700 cfm) Average SF_6 concentration ppt* (10^{-12})	Ducted fan - blowing (90,700 cfm) Dilution efficiency
0+003	6 ft	289 ± 41	0.76	227 ± 11	0.97
0+40	5 ft	320 ± 40	0.69	346 ± 32	0.63
	15 ft	315 ± 46	0.70	375 ± 71	0.59
	25 ft	310 ± 31	0.71	328 ± 52	0.67
	Mean	315 ± 39	0.70	350 ± 56	0.63
0+80	5 ft	287 ± 52	0.76	295 ± 9	0.74
	15 ft	265 ± 58	0.83	292 ± 18	0.75
	25 ft	265 ± 48	0.83	285 ± 11	0.77
	Mean	272 ± 52	0.81	290 ± 14	0.76
2+00	5 ft	268 ± 3	0.82	259 ± 9	0.85
	15 ft	266 ± 15	0.83	252 ± 10	0.87
	25 ft	236 ± 29	0.93	224 ± 11	0.98
	Mean	256 ± 25	0.86	245 ± 18	0.90
Overall mean		282	0.78	288	0.74

* ppt - parts per trillion (10^{-12})

measured during the air quality monitoring during mucking discussed in Section 3.4.2 and Appendix A. Stratification there ranged between 36 and 72 percent of the peak value, depending upon the particular air pollutant under observation.

4.5.3 Methane Layering Simulation

A group of three methane layering simulations was conducted, including:

- o Release of 1.09 ppm SF_6 in a mixture of 52.4 mole percent helium with air; ventilation with the jet fan at 88,400 cfm.
- o Release of 1.09 ppm SF_6 in a mixture of 52.4 mole percent helium with air; ventilation with the ducted fan blowing at 90,700 cfm.
- o Release of 983 ppm SF_6 in air; ventilation with the ducted fan blowing at 90,700 cfm.

The density of the 52.4 mole percent helium in air was equal to the density of methane. By releasing the helium/air mixture at the roof, it was hoped that a layer of the release gas would form. This would simulate the intersection of a fracture connected to a local source of methane and the formation of a highly concentrated methane layer along the roof.

The gas was released from a 55 ft long pipe suspended at the roof at cross section 0+003. Small holes were drilled in the pipe every foot so that the gas would be released uniformly along the roof line. Sampler layouts were identical for all of the tests, and the sample interval was 20 minutes. The gas was released for 120 min. at a rate of 0.833 cfm (23.6 l/min.) to form the layer, then the fan systems were started to see how effective they were in breaking up the layer. Figures 18, 19 and 20 show the logarithm of SF_6 concentration versus time for the jet fan test at cross sections 0+020, 0+040 and 0+060. The figures illustrate the formation of the SF_6 layer with time. The fan was started after 120 min., and the SF_6 layer broken up. The tracer gas concentration was reduced to a steady-state value shown by the last two data points.

Time-weighted average concentrations were calculated for the four samples immediately preceeding start-up of the fan systems. Table 16 lists these averages for distances of 0, 1 and 5 ft from the roof at different cross sections. In all three cases, a vertical gradient in concentration was evident, with the difference in concentration over 5 ft being between 58 and 85 percent of the average value measured at the roof. The concentration gradient observed with the 983 ppm SF_6 in air was due to diffusion and mixing of the SF_6 in still air.

After the fan systems were started, the layer was broken up fairly rapidly over a period of 40 min., and the concentration of the SF_6 was uniform between all sample points, indicating that both face ventilation systems provide good mixing action very near the roof. Time-weighted average values of the steady-state concentration of SF_6, calculated for the last two data points, are compared in Table 17. Dilution efficiencies calculated from these averages also are presented. The ducted fan system is clearly superior in this simulation, with a mean dilution efficiency of 0.83, as compared to 0.59 for the jet fan. The ducted fan was able to achieve very high dilution efficiencies near

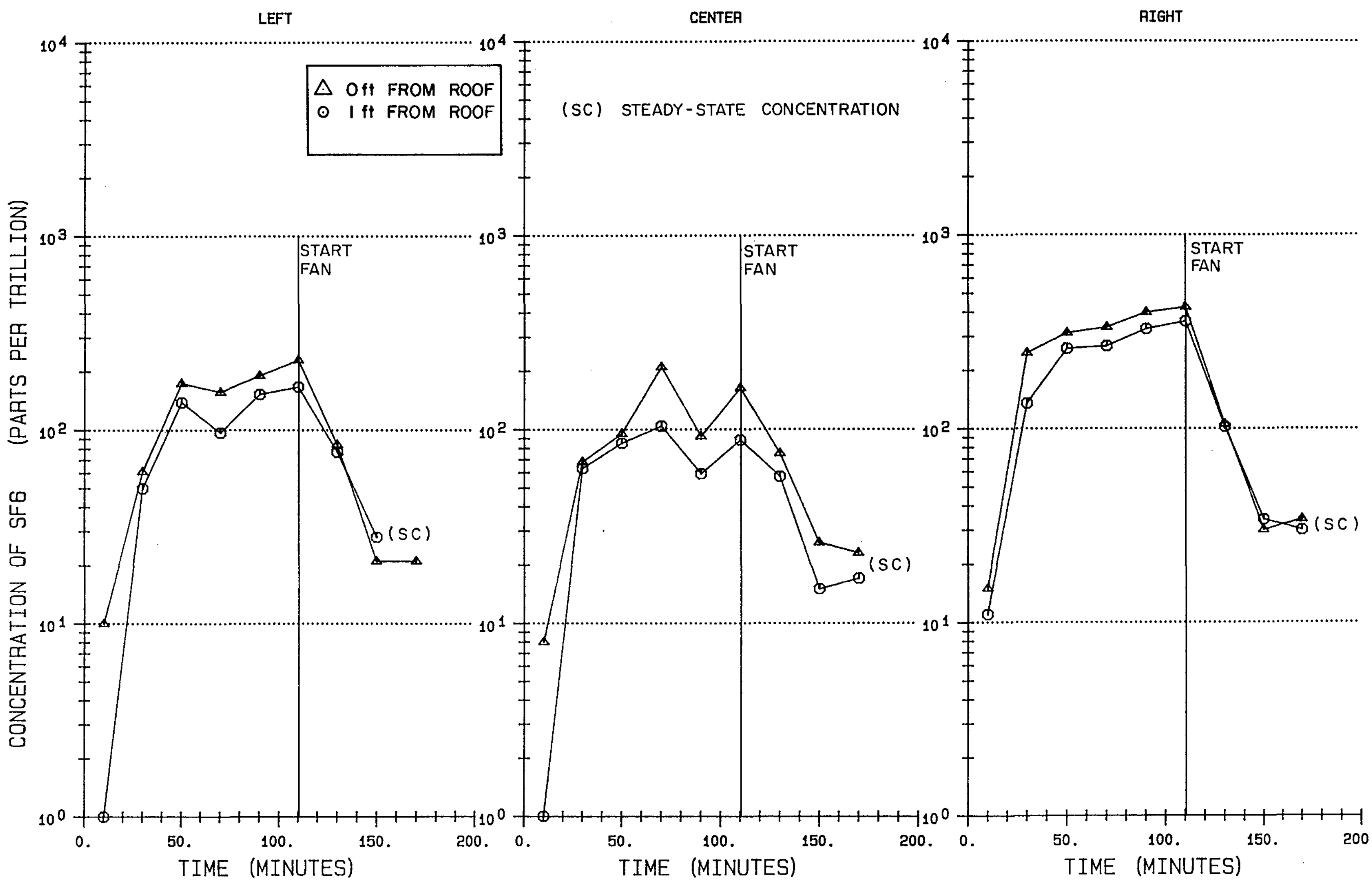


FIGURE 18. - Logarithm of SF_6 concentration versus time for the methane layering test 20 ft from the face - jet fan.

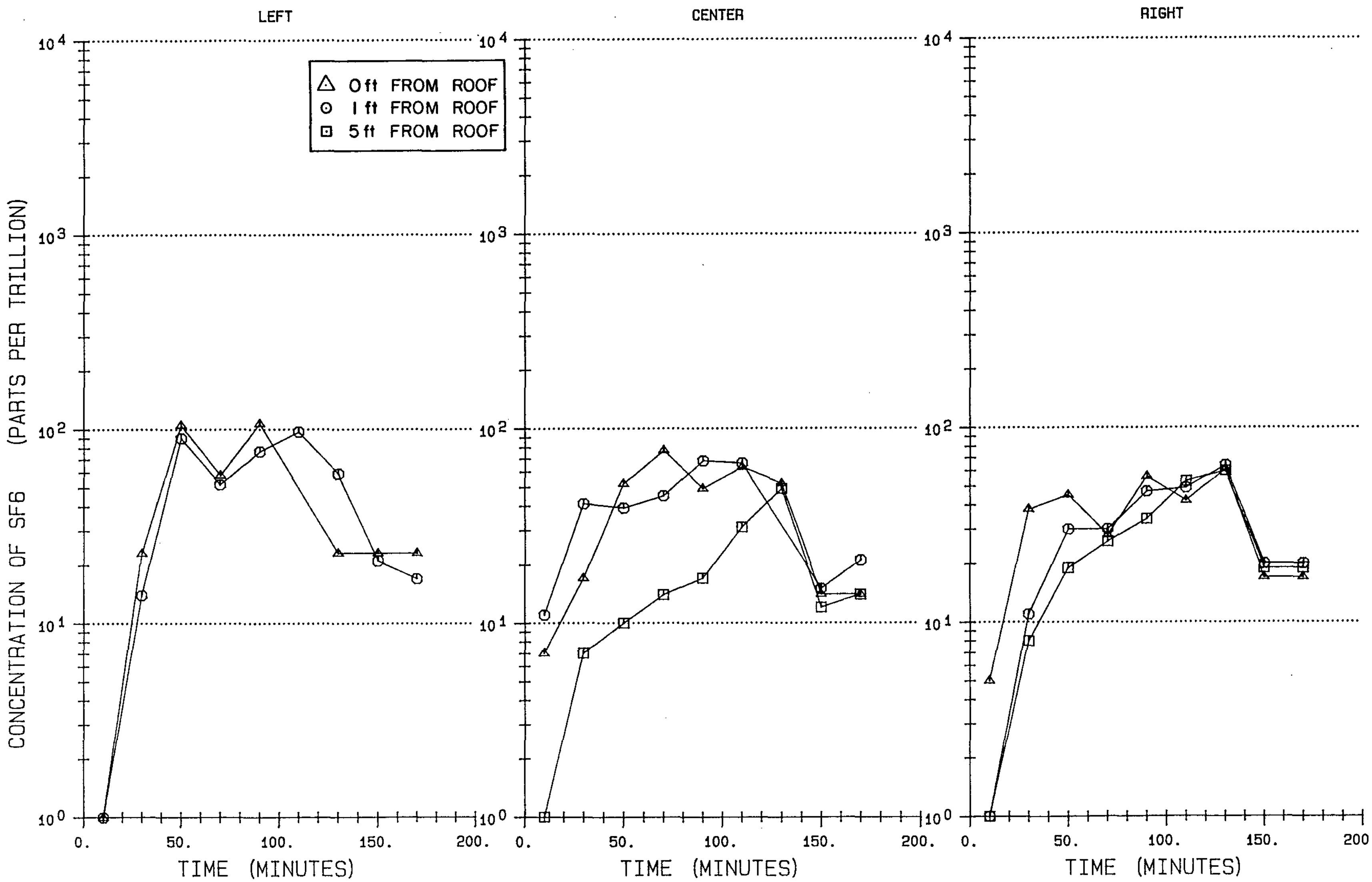


FIGURE 19. - Logarithm of SF_6 concentration versus time for the methane layering test 40 ft from the face - jet fan.

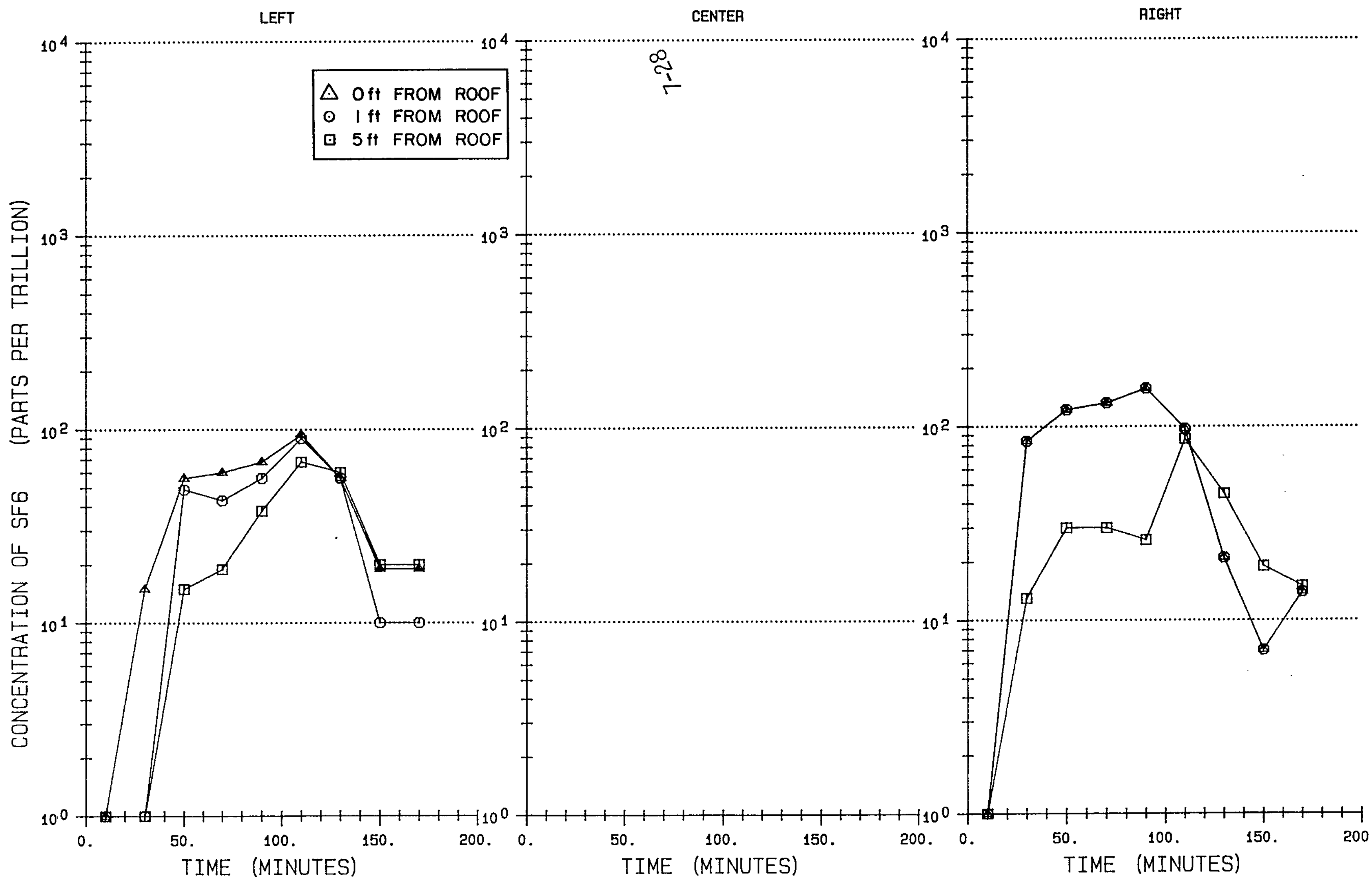


FIGURE 20. - Logarithm of SF_6 concentration versus time for the methane layering 60 ft from the face - jet fan.

TABLE 16. - Comparison of vertical concentration profiles in methane layering tests

Section	Distance below roof (ft)	Jet fan: Helium in air with 1.09 SF_6 — Avg. concentration - ppt* (10^{-12})	Ducted fan: Helium in air with 1.09 ppm SF_6 — Avg. concentration - ppt* (10^{-12})	Ducted fan: 983 ppm SF_6 in air — Avg. concentration - ppt* (10^{-12})
0+020	0	232 ± 111	382 ± 89	6085 ± 1703
	1	175 ± 102	348 ± 76	3935 ± 858
0+040	0	62 ± 25	310 ± 108	4266 ± 1742
	1	58 ± 22	213 ± 126	5259 ± 2573
	5	26 ± 14	13 ± 7	673 ± 809
0+060	0	98 ± 37	92 ± 13	2481 ± 1810
	1	93 ± 42	47 ± 26	1528 ± 1116
	5	39 ± 25	12 ± 9	323 ± 218
0+080	0	137 ± 72	72 ± 12	2911 ± 1360
	1	108 ± 89	71 ± 46	1832 ± 1395
	5	- -	29 ± 27	374 ± 285

* ppt - parts per trillion

TABLE 17. - Comparison of average steady-state SF_6 concentration for the methane layering tests

Section	Distance below roof (ft)	Jet fan (88,400 cfm): Helium in air with 1.09 ppm SF_6 — Avg. SF_6 concentration - ppt* (10^{-12})	Jet fan: Dilution efficiency	Ducted fan (90,700 cfm): Helium in air with 1.09 ppm SF_6 — Avg. SF_6 concentration - ppt* (10^{-12})	Ducted fan: Dilution efficiency	Ducted fan (90,700 cfm): 983 ppm SF_6 in air — Avg. SF_6 concentration - ppt* (10^{-12})	Ducted fan: Dilution efficiency
0+020	0	26 ± 5	0.40	9 ± 2	1.11	275 ± 78	0.69
	1	25 ± 8	0.41	10 ± 1	1.00	229 ± 34	0.83
	Mean	25 ± 7	0.41	9 ± 2	1.11	257 ± 66	0.74
0+040	0	18 ± 4	0.57	13 ± 2	0.77	249 ± 52	0.76
	1	19 ± 2	0.54	13 ± 2	0.77	272 ± 95	0.70
	5	16 ± 4	0.64	12 ± 2	0.83	214 ± 62	0.89
	Mean	18 ± 3	0.57	13 ± 2	0.77	245 ± 72	0.78
0+060	0	15 ± 6	0.69	13 ± 0	0.77	229 ± 16	0.84
	1	10 ± 3	1.03	12 ± 2	0.88	256 ± 36	0.75
	5	19 ± 2	0.54	10 ± 1	1.00	226 ± 34	0.85
	Mean	15 ± 5	0.69	11 ± 2	0.91	236 ± 30	0.81
0+080	0	16 ± 3	0.64	15 ± 4	0.67	258 ± 4	0.74
	1	12 ± 5	0.86	14 ± 3	0.71	205 ± 70	0.93
	5	--	--	12 ± 2	0.83	215 ± 47	0.89
	Mean	14 ± 4	0.74	13 ± 3	0.76	220 ± 53	0.87
Mean		17.6	0.59	12.1	0.83	238.9	0.80

* ppt - parts per trillion

the source because the position of the duct outlet delivered the full flow at very high velocities at the SF_6 release point.

This test showed that the methane simulation gas would layer in still air. The flow rate of the gas was very low, and is not a good indication of either system's ability to break up the layer at inflow rates that would produce a hazardous condition. Further testing is needed at higher tracer gas flow rates.

The release of the 983 ppm SF_6 in air in this type of simulation resulted from misidentification of the gas bottle. However, a comparison of the results of this test to the results using the mixture of helium in air supports the underlying principle of the tracer gas tests - that the dilution rates or efficiencies measured using minute quantities of the tracer gas can be extrapolated to field situations where large quantities of pollutants are produced. In this case, the difference between tracer gas concentrations was on the order of 900 percent, but the two tests of the ducted system produced virtually identical dilution efficiencies.

4.5.4 Methane From Muckpile Simulation

Simulations of methane from the muckpile were performed for both fan systems at full flow rate. These simulations tested the capability of both fan systems to dilute methane being evolved from broken shale during loading operations. Four pipes laid out along the muckpile (See Appendix B) at the face of the test room released 52.4 mole percent helium in air with 1.09 SF_6. The pipes had small holes along their length and a balanced manifold to provide an even flow of tracer gas over a large area.

SF_6 was released at a rate of 0.833 cfm (23.59 l/min.) for one hour to build up a tracer gas cloud at the face. The fans were then started to break up the tracer in the face area and measure the steady-state concentration. Sampler locations were identical for both tests, and the sample interval was 10 minutes.

Figure 21 shows a log of tracer concentration versus time for the ducted fan test at cross section 0+040.

The figure shows the tracer gas curves for each vertical array of samples at 5, 10 and 15 ft from the roof at lines B, D and F. The curves show the buildup of SF_6 and the tendency of the helium/air mixture to rise. After 40 minutes, the fan was started and the SF_6 diluted to a steady-state value. Time-weighted averages were calculated for the first four data points to develop a picture of the stratification of the tracer gas. These averages are listed in Table 18, and show that the tracer gas tended to rise to the upper levels of the room in still air. The tracer concentrations 25 ft from the roof averaged 20 percent of the SF_6 concentration 5 ft from the roof.

After the fan systems were turned on, the SF_6 concentration quickly dropped to a steady-state value. Table 19 lists the average steady-state concentration for 5, 15 and 25 ft from the roof for each cross section. Dilution efficiencies calculated from the steady-state concentrations indicate that the jet fan provided better overall dilution in the immediate face area, with an average of 0.79 compared to an average of 0.60 for the ducted system.

4.5.5 Fan Inlet Recirculation Measurements

SF_6 tracer gas was used to measure the fan inlet recirculation of both systems at full flow rate. Gas containing 101 ppm SF_6 was

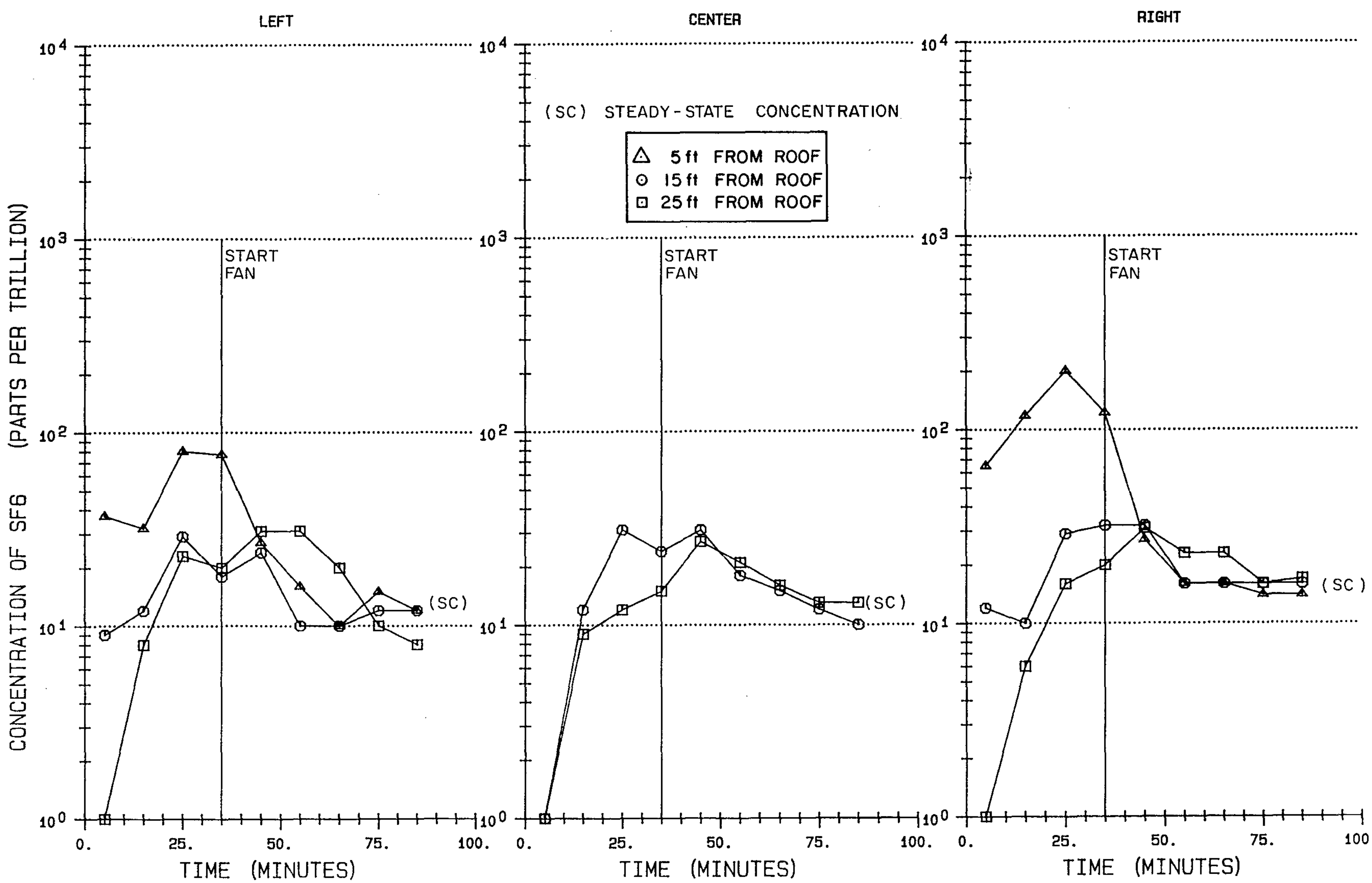


FIGURE 21. - Logarithm of SF_6 concentration versus time for the methane from muckpile test 40 ft from the face - ducted fan.

TABLE 18. - Comparison of vertical SF_6 concentration profiles in the methane from muckpile tests before the fans were started

Section	Distance from roof (ft)	Jet fan: Avg. peak concentration - ppt* - (10^{-12})	Ducted fan-blowing: Avg. peak concentration - ppt* - (10^{-12})
0+003	6	278 ± 63	114 ± 25
0+040	5	92 ± 55	105 ± 47
	15	18 ± 10	33 ± 7
	25	11 ± 8	28 ± 9
0+060	5	89 ± 36	87 ± 11
	15	18 ± 17	33 ± 9
	25	10 ± 8	26 ± 9

* ppt - parts per trillion

injected directly in the fan inlet at a rate of 0.177 cfm (5 lpm). Samplers were located in the outlet air and around the fan inlet. If the fan was recirculating, the SF_6 concentration in the outlet air stream would be greater than the ideal concentration calculated by the tracer gas flow rate divided by the fan flow rate. The concentration in the outlet stream is given by equation (9):

$$C_{OT} = \frac{q_{SF_6} + q_r}{Q_{FAN}} \qquad (9)$$

where: C_{OT} = concentration of SF_6 in the outlet air

q_{SF_6} = flow rate of SF_6 injected in the inlet (cfm)

q_r = flow rate of SF_6 recirculated (cfm)

Q_{FAN} = flow rate of the fan (cfm)

The calculation of recirculated volume is illustrated in Figure 22.

TABLE 19. - Comparison of fan performance in the methane from muckpile test

Section	Distance from roof (ft)	Jet fan		Ducted fan	
		Avg. residual SF_6 concentration - ppt* (10^{-12})	Dilution efficiency	Avg. residual SF_6 concentration - ppt* (10^{-12})	Dilution efficiency
0+003	5	23 ± 3	0.45	15 ± 1	0.67
0+040	5	14 ± 2	0.74	14 ± 4	0.71
	15	13 ± 3	0.79	17 ± 3	0.59
	25	15 ± 5	0.69	19 ± 4	0.52
	Mean	14 ± 3	0.74	17 ± 4	0.59
0+060	5	10 ± 2	1.03	16 ± 1	0.63
	15	10 ± 4	1.03	16 ± 3	0.63
	25	7 ± 5	1.47	20 ± 1	0.50
	Mean	9 ± 4	1.14	17 ± 3	0.59
Mean		13.1	0.79	16.7	0.60

* ppt - parts per trillion

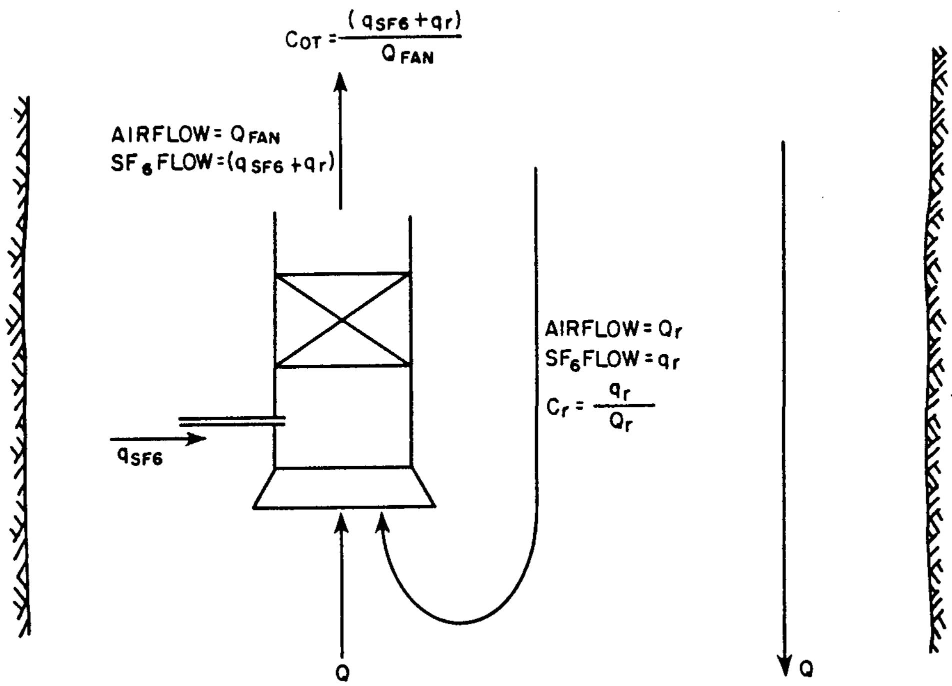


FIGURE 22. - Schematic illustrating the calculation of recirculated air volume.

The flow rate of SF_6 that was being recirculated would be equal to the average concentration of SF_6 in the air being recirculated times the flow rate of air being recirculated. The flow rate of air being recirculated was calculated by equation (10):

$$Q_r = \frac{Q_{FAN}\, C_{OT} - q_{SF_6}}{C_r} \qquad (10)$$

where: Q_r = the flow rate of air being recirculated

C_r = concentration of SF_6 in air being recirculated

Calculations were performed using time-weighted average SF_6 concentrations of the outlet air stream and air around the inlet. Data used in the calculations and the percentage of total fan flow determined to be recirculating are listed in Table 20.

During the jet fan tests, outlet air samples were taken from the downstream silencer. The concentrations were below the ideal concentration, suggesting incomplete mixing. The samples used for the analysis were collected 50 ft from the fan outlet in the centerline of the jet of air. The calculated recirculation of 23.8 percent is probably below the actual value. Based upon positioning alone, it is difficult to see why the jet fan would have less recirculation than the ducted system.

The recirculation measured for the ducted fan is due to the location of the fan and relatively small size of the last open crosscut in these tests. The recirculation could be eliminated by locating the fan around the corner, upstream in the last open crosscut.

TABLE 20. - Comparison of inlet recirculation for both fan systems

	Fan outlet flow (cfm)	Injected SF_6 flow (cfm)	Avg. concentration of SF_6 in outlet stream - ppt* (10^{-12})	Avg. concentration of SF_6 in air recirculated - ppt* (10^{-12})	Percentage recirculation (%)
Jet Fan	88,400	1.783×10^{-5}	247.8	193.8	23.8
Ducted Fan	90,700	1.783×10^{-5}	257.2	213.4	28.4

* ppt - parts per trillion

5.0 APPLICATION OF TRACER GAS TEST RESULTS TO FACE VENTILATION IN OIL SHALE MINING

The primary advantage of performing tracer gas tests to characterize the performance of the face ventilation system is that they measure the actual dilution efficiency 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. Dilution efficiencies measured during the in-mine tests in this project were applied to examples of projected mine air pollutant production in oil shale mining. This illustrates the application of the results of the tracer gas tests, and evaluates the capability of the two ventilation systems to perform in actual mining operations.

5.1 COMPARISON OF TEST SYSTEM PERFORMANCE

The testing data presented in this report applies specifically to the ventilation of a 55 ft wide by 30 ft high dead heading, 300 ft long. The effect of changing the opening cross section, or the length of the heading, on the system performance is not known.

Table 21 compares the performance of the two systems in the various tracer gas simulations. In terms of dilution efficiencies, neither system is clearly superior. The reversible ducted fan system performed better in the blast clearing and methane layering simulation. In the methane layering case, the ducted fan system was superior because it delivered its full air flow at very high velocity directly at the point of tracer gas release. The performance of the ducted system is highly dependent upon the location of the fan and the outlet end of the duct with respect to

TABLE 21. - Comparison of system performance in the tracer gas tests

Test type	Jet fan system (88,400 cfm)	Ducted fan-blowing (90,700 cfm)	Ducted fan-exhausting (73,000 cfm)
<u>Blast clearing</u>			
Normalized dilution rate ($min.^{-1}$) at 0+040	-0.132	-0.181	-.112
Average dilution efficiency	0.75	0.98	0.79
<u>Diesel exhaust</u>			
Dilution efficiency			
At 0+040	0.71	0.63	- -
Average	0.78	0.74	- -
<u>Methane layering</u>			
Dilution efficiency			
At 0+040	0.57	0.77	- -
Average	0.59	0.83	- -
<u>Methane from muckpile</u>			
Dilution efficiency			
At 0+040	0.74	0.59	- -
Average	0.79	0.60	- -
<u>Fan recirculation</u>			
Percent	23.8	28.4	- -

the pollutant source. The jet fan exhibited superior performance in the diesel exhaust and methane from muckpile tests. In the diesel exhaust test, the dilution efficiency of the jet fan was eight percent higher in the immediate face area where personnel are subjected to the largest exposures.

When compared on the basis of power consumption per effective cubic foot of air delivered to the face, the jet fan was clearly superior. The jet fan delivered similar performance with less power consumption because it does not have the large friction loss caused by ducting the air to the face. The elimination of recirculation would improve the overall performance of the ducted system and improve its power consumption per effective cubic foot of air delivered.

The jet fan system has many other operating advantages over the ducted fan system, including:

- lower capital cost;
- lower operating cost;
- mobility; and
- ease of installation.

5.2 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 which would reflect real operating conditions. Inlet recirculation measurements were performed using the tracer gas, and showed recirculation volumes of 23.8 percent and 28.4 percent for the jet fan and ducted fan, respectively. This was a typical value for the jet fan; however, it was atypical for the ducted fan. The ducted fan recirculation was caused by the poor positioning of the inlet to facilitate reversible operation. The fan normally would have been placed further upstream in the last open crosscut to eliminate recirculation.

The effect of inlet recirculation has been subtracted out of the dilution efficiencies listed in Table 21 to illustrate the projected impact on the measured dilution efficiencies. Dilution efficiencies corrected for the inlet recirculation are compared to the measured values for both fans in Table 22. Table 22 shows that inlet recirculation had a strong effect in the reduction of dilution efficiency in these tests.

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.

5.3 PROJECTED CASE STUDIES OF SYSTEM PERFORMANCE IN OPERATING CONDITIONS

The primary advantage of performing tracer gas tests to characterize the performance of the face ventilation system was 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. Dilution efficiencies measured during the in-mine tests in this project were applied to the examples of projected mine air

TABLE 22. - Potential increase in dilution efficiency resulting from elimination of inlet recirculation

Simulation type	Jet fan (88,400 cfm)		Ducted fan blowing (90,700 cfm)	
	with recirculation	without recirculation	with recirculation	without recirculation
Diesel exhaust				
At face	0.70	0.87	0.63	0.81
Average	0.78	0.97	0.74	0.98
Methane layering				
At face	0.57	0.80	0.77	1.0
Average	0.59	0.82	0.83	1.0
Methane from muckpile				
At face	0.74	0.90	0.59	0.86
Average	0.79	0.96	0.60	0.89

pollutant production discussed in Section 3.0. 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 operations.

5.3.1 Blast Produced Pollutants

Projected versus measured blast produced air pollutant levels are presented in Appendix A. The dilution efficiencies measured in the blast clearing tests can be used to calculate the time to clear a heading after the blast by using equation (11). The dilution efficiency is a measure of the ratio of effective air 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 (11):

$$T = (V/Q_e)\ (\ln C_0 - \ln TLV) \qquad (11)$$

where: T = time to reach TLV (min.)

Q_e = effective flow rate = $E_D \times Q_{Fan}$ (cfm)

V = room volume (ft)

C_0 = peak concentration (ppm)

TLV = threshold limit value (ppm)

Table 23 lists estimated times for the fan systems tested in this study to reach TLV.

TABLE 23. - Estimated time to clear blast produced pollutants to TLV's

	TLV (ppm)	Time to dilute to TLV (min.) Jet fan[1] Q_{FAN}=88,400 cfm E_D = 0.75	Ducted fan-blowing[1] Q_{FAN}=90,700 cfm E_D = 0.98
CO_2 = 420 ppm	5000	--	--
CO = 155 ppm	50	8.8	6.6
NO_X = 69 ppm	25	7.9	5.9
NO = 69 ppm	25	7.9	5.9
Dust[(2)] = 13.3 ppm	1 ppm	20.1	15.0

1 Room volume (V) = 514,600 ft^3; $Q_e = E_D \times Q_{FAN}$

2 Approximate values based upon weight ppm

5.3.2 Diesel Emissions

Dilution efficiencies measured during the tracer testing can be used to estimate actual air volumes which the fan must move in order to dilute the diesel emissions in the face area to TLV. In Appendix A, engine emissions measured on a very clean diesel engine in the 1000 hp range, by Markworth and Wood (7) were listed to obtain projected fresh air requirements. Actual fan flow rates can be estimated by dividing the ideal air requirements by the dilution efficiency.

Table 24 compares the ventilation requirements based upon the combined effects of carbon monoxide and nitrogen oxide. Based upon

TABLE 24. - Comparison of required fan outlet flow rates (assuming a clean burning diesel engine in the 800 hp range)

	Brake horse-power	Concentration in exhaust		Exhaust flow (cfm)	Ideal ventilation flow(1) (cfm)	Actual ventilation flow (cfm)	
		CO (ppm)	NOX (ppm)			Jet fan(2)	Ducted fan(3)
Without methane gas	561	100	448	1,814	39,040	54,990	61,970
	823	150	538	2,257	55,320	77,910	87,810
With 1.5% methane gas	561	875	506	1,830	69,060	97,270	109,620
	823	713	513	2,276	79,180	111,520	125,680

(1) Calculated using equation (A-1) in Appendix A

(2) Dilution efficiency in face area = 0.71

(3) Dilution efficiency in face area = 0.63

this engine emissions data and the measured dilution efficiencies, the jet fan system can effectively maintain the regulatory air quality with between 95 to 98 cfm/bhp in a non-gassy mining environment. The ducted fan in the blowing mode would require 107 to 110 cfm/bhp. This assumes the use of modern, clean operating and well-maintained diesel engines. The ventilation air requirements would be strongly affected if methane concentrations in gassy mining conditions are high enough to impact engine carbon monoxide production. At 1.5 percent methane, which is greater than the maximum allowable operating concentration, the brake specific ventilation requirements would be increased to the range of 136 to 173 cfm/bhp and 153 to 195 cfm/bhp for the jet fan and ducted fan systems, respectively.

Data on diesel particulate emissions is not definitive. In general, results of Branstetter, et al. (12) suggest that diesel particulate emissions will not be a problem with clean burning, well-maintained engines.

5.3.3 Methane Emissions

Projection of the type and magnitude of problems which may occur in oil shale mining under gassy conditions is difficult because there is little published data on methane occurrence. Available data suggests 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 mining tends to create greater potential for methane layering problems. This is offset somewhat by the large ventilation air requirements 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 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 and Leach (31) on methane layering predicted that the tracer gas layer would be broken up at operating flow rates of the two fan systems. 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. In Section 3.0, it was estimated that methane concentrations of 10 percent could occur in a 300 ft long heading due to a face blast. Clearly, this estimate is directly dependent upon the assumed methane saturation (16 ft^3/ton) which is not well defined. Other parameters that would affect the peak concentration include:

- the assumption of instantaneous release of the methane;
- the volume of the room; and
- 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 by Richmond, et al. (32) suggest that 80 percent of the total methane produced by the blast had been released after 5 minutes. The tonnage in this blast was small, and the release rate for larger blasts may be slower.

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:

- Reducing the size of the individual blasts to reduce the quantity of methane released.
- Increasing the quantity of fresh air flowing in the last open crosscut.
- Implementing special ventilation procedures in the face heading.
- Leaving the fan running during the blast.

The quantity of methane released by a particular blast could be reduced by reducing the depth of blast holes. 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 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 23. This configuration might be enhanced by using a jet fan blowing parallel to the last open crosscut (with or counter to the floor) to enhance mixing of the exhaust gas. Operation of the ducted system in the exhaust mode presents special problems, since the concentration of methane in air passing over the fan motor must be less than 1.0 percent.

Although there are safety concerns with the use of jet fans in a gassy evnironment, their use does offer some advantages. The jet fan's higher average velocity makes it much more effective in dealing with methane layering. A jet fan could be repositioned so that it projects the air stream across the room, as illustrated in Figure 24, which could reduce the effective flow rate of air out of the room and reduce the quantity of methane reaching the last open

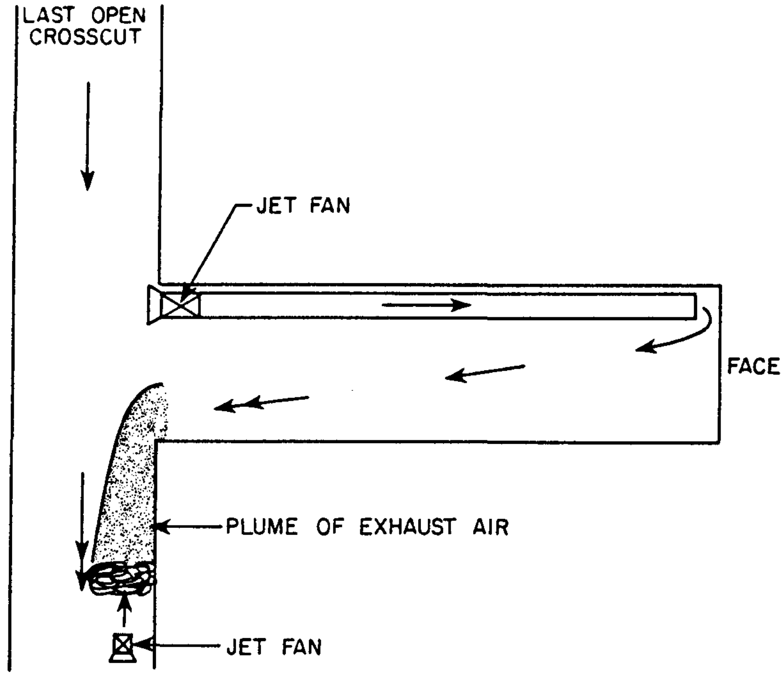


FIGURE 23. - Illustration of ducted system operating in the blowing mode with a jet fan to assist methane plume mixing.

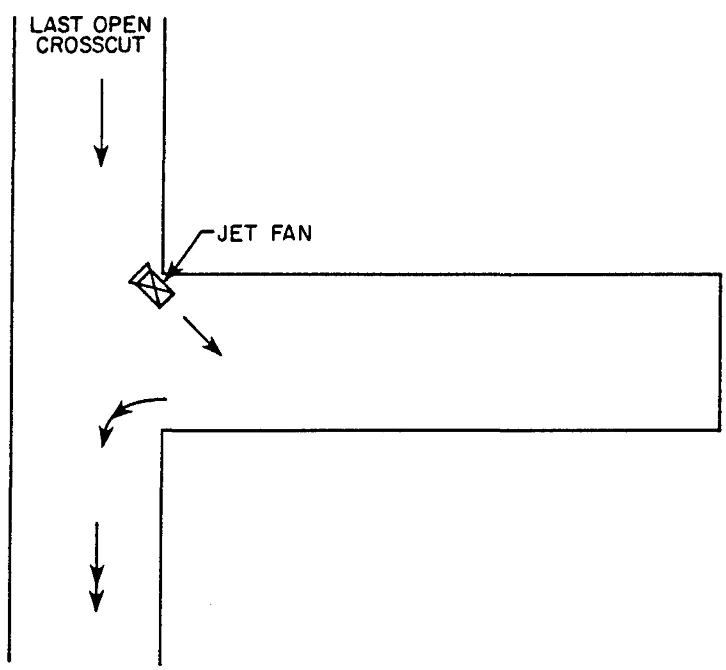


FIGURE 24. - Illustration of reorientation of a jet fan to minimize inlet recirculation and reduce effective room air flow rate for methane dilution.

crosscut. The jet fan could 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 the order of five minutes, a large portion of the methane could be removed during the initial release period. This would significantly reduce the magnitude of peak concentration and reduce the level of the hazard that the methane presents.

Inlet recirculation in the jet fan presents a potential hazard because recirculated methane passing over the motor must be below 1.0 percent. This could be eliminated by using flexible duct on the inlet and positioning the inlet upstream in the fresh air. The fan would no longer be free standing, but the use of flexible dust and lightweight materials would minimize the handling difficulties. The total system performance could be improved by 20 percent.

6.0 REFERENCES

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APPENDIX A

Air Quality Monitoring Measurements at the Colony Mine

A1.0 MONITORING OF AIR POLLUTANTS DURING BLASTING

Air pollutants produced by blasting were monitored using process instrumentation operated by the MRI engineering group of Space Ordinance Systems. The data gathered included:

- CO_2, CO, NOX and NO concentration; and
- dust size distributions and silica content.

A plan of the experimental layout is shown in Figure A-1.

The gas analyzers were located in a trailer roughly 600 ft away from the blast. Air samples were drawn continuously down tube bundles from the three points shown in Room 1. At each point, separate samples were drawn from 10 and 20 ft above the floor level. The analyzers included:

- Miran 1A[1] infrared absorption - CO_2;
- Miran 1A[1] infrared absorption - CO;
- Monitor Labs[1] chemiluminescent detector - NO; and
- Monitor Labs[1] chemiluminescent detector - NOX.

A manifold system was used to switch the different sample streams into the analyzers, giving approximately two to three minute samples at each location. Dust samples were collected at two locations using cascade impactors suspended six feet above the floor. At the location closest to the face (D1), blasted rock destroyed the pumping apparatus.

The face round being tested by Exxon was designed to excavate a 55 ft wide by 30 ft high heading, with a 30 ft pull. The round utilized 18 - 4-1/2 in. diameter holes drilled to a depth

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[1] Reference to specific brands, equipment or trade names in this report is made to facilitate understanding, and does not imply endorsement by the Bureau of Mines.

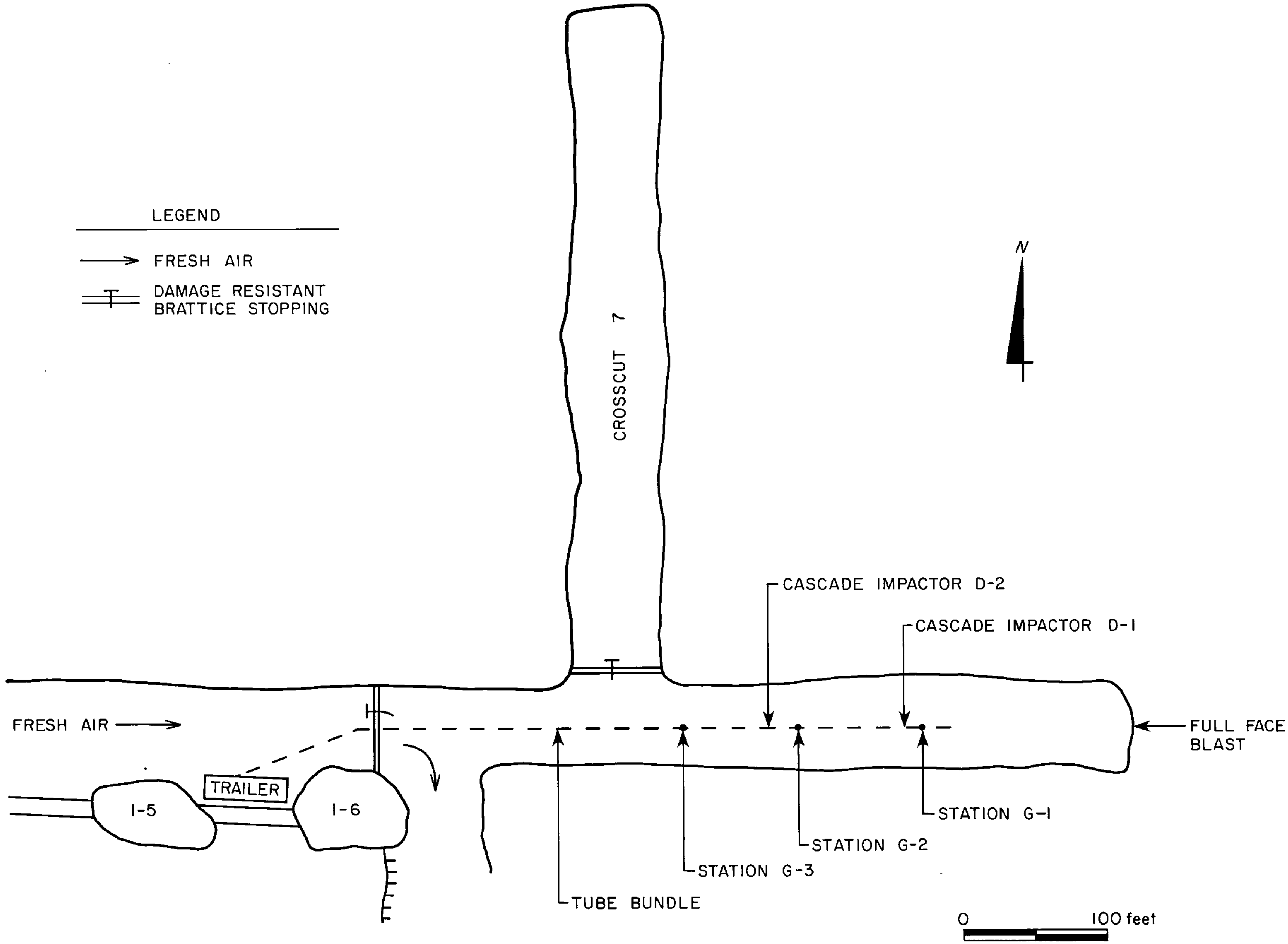

FIGURE A-1. - Location of blasting test and layout of air quality measurement system.

of 31 feet. The back 16 ft of each hole was charged with 105 lbs of ANFO initiated using a 1 lb cast booster. A 6 hole V-cut in the lower portion of the face was used to excavate the initial free face. Pre-split holes were spaced at four feet on the vertical boundaries of the round. These holes were loaded along 28 ft with a special pre-splitting charge (Splitex[1]) with a lineal density of 0.25 lbs/foot. The round was detonated using NONEL[1] detonators. Total explosives consumption was approximately 112 lbs of Splitex[1] and 1890 lbs of ANFO[1].

The instrumentation was left on with samples being drawn from station 1-Low (10 ft above the floor) while personnel evacuated the mine for the explosion. Continuous samples were drawn from this station for the first 20 minutes after the blast, then samples were drawn sequentially from the other stations. Time-concentration records are shown in Figure A-2 for the different sampling stations and a constant height above the floor (high = 20 ft; low = 10 ft). The figure shows that the distribution of the pollutants along the length of Room 1 was fairly uniform. Correlation of pollutant concentration at specific times indicates a vertical stratification with concentrations being as much as 35 percent higher at 20 ft above the floor than at 10 ft above the floor. Table A-1 lists peak values of pollutants measured in the initial 20 minutes of observation at station 1-Low, and compares them to concentrations estimated using data generated in previous studies

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1 Reference to specific brands, equipment or trade names in this report is made to facilitate understanding, and does not imply endorsement by the Bureau of Mines.

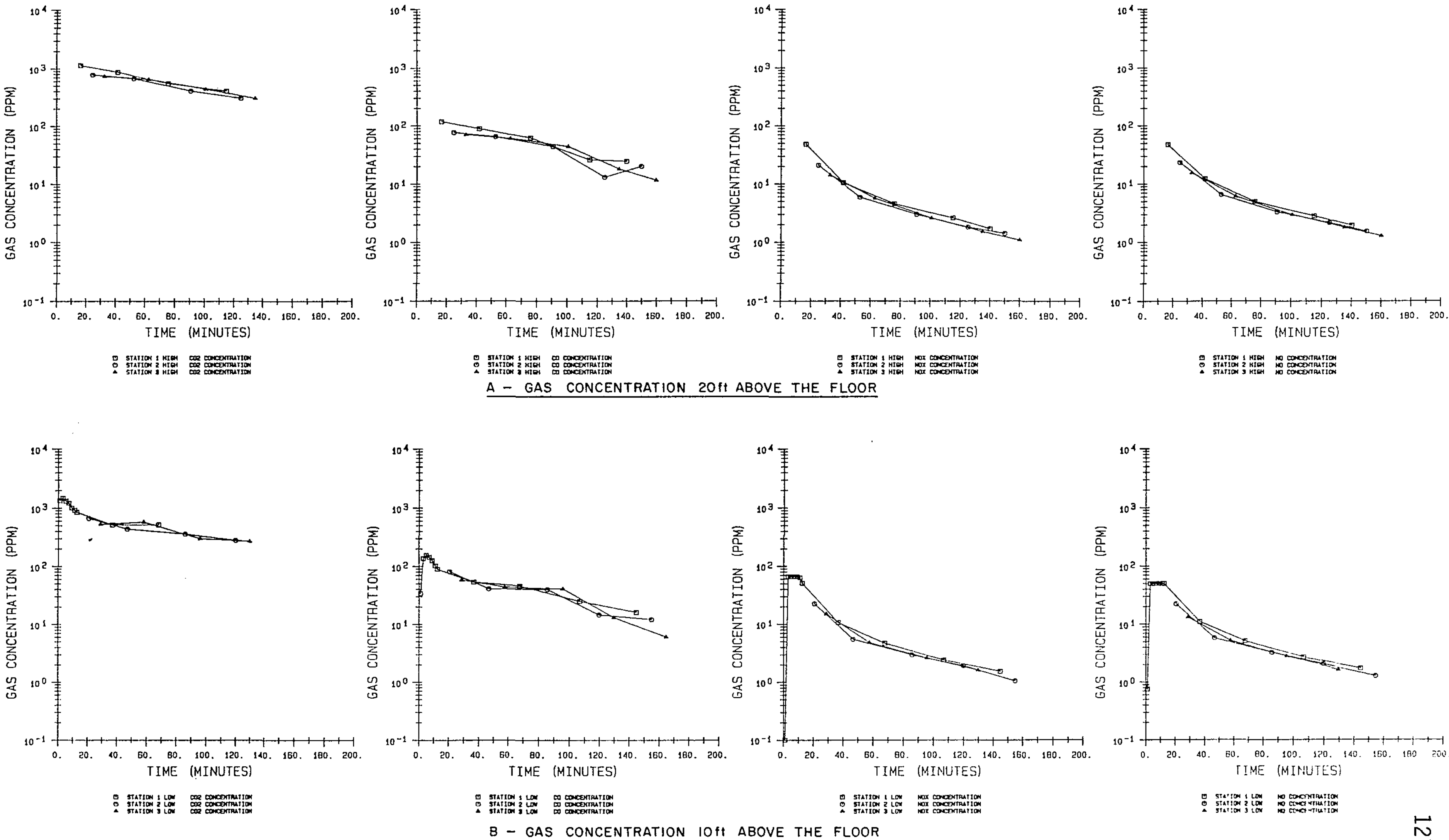

FIGURE A-2. - Time versus pollutant concentration curves for the Colony blasting test.

TABLE A-1. - Comparison of estimated and measured concentration of gases produced by blasting

Pollutant	Previous measurements[1] Rogers (1)	Abata (2)	TLV (vppm)	Estimated concentration[2] (vppm)	Measured peak concentration (vppm)
	ft^3 gas/lb ANFO	ft^3 gas/lbs ANFO			
CO_2	1.87	0.93	5000	2721[4]	1520[4]
CO	0.54	0.073	50	190	155
NO_x	0.061	0.034	25	88	69
NO	0.061	0.018	25	47	> 50

1 Density = 0.075 lbs/ft^3

2 Based upon Abata (2), with a total of 1890 lbs ANFO and an estimated dilution volume of 878,400 ft^3; density = 0.062 lbs/ft^3.

3 Density = 0.062 lbs/ft^3.

4 Includes background atmospheric carbon dioxide

(Rogers, 1 and Abata, 2) and an estimated room volume of 878,400 ft^3. Background concentrations were near zero, with the exception of carbon dioxide, whose background concentration was around 400 ppm.

Concentrations are in fairly good agreement, considering the accuracy with which the dilution volume was known. This indicates that extrapolation of data from the research studies can be used to estimate pollutant production for preliminary design of ventilation requirements.

A2.0 MONITORING AIR POLLUTANTS DURING LOADING

Diesel air pollutants and dust were measured during loading operations conducted when removing the broken muck from Crosscut 7. The area had been used to store raw shale created during experimental mining using an Alpine[1] Miner. The layout of the experiment is shown in Figure A-3.

A2.1 GASEOUS DIESEL POLLUTANTS

The concentrations of gaseous pollutants produced by the loader and truck were measured with the same instruments used in the blasting test. The instruments were mounted in a truck to facilitate movement. Gas samples were drawn to the instruments through a 1/4-in. plastic tube. The sample end of the tube was attached to a filter mounted on a surveyor's rod by which the sampling point could be elevated to 5, 15 and 25 ft above the floor. The surveyor's rod was attached to a tripod, and was moved to the various sample points indicated on the map in Figure A-3.

The equipment used in the mucking operation consisted of:

- o Huff[1]-400C front end loader with Cummings[1] VT-1710 engine; water scrubber on exhaust.
- o Wabco[1] 35 ton truck with Cummings[1] VT-1710 engine; water scrubber on exhaust.

The truck was stationed at the right-hand side of the rock pile, and loaded on the first cycle. The truck then pulled out of Crosscut 7 into the exhaust air path, and then backed into Crosscut

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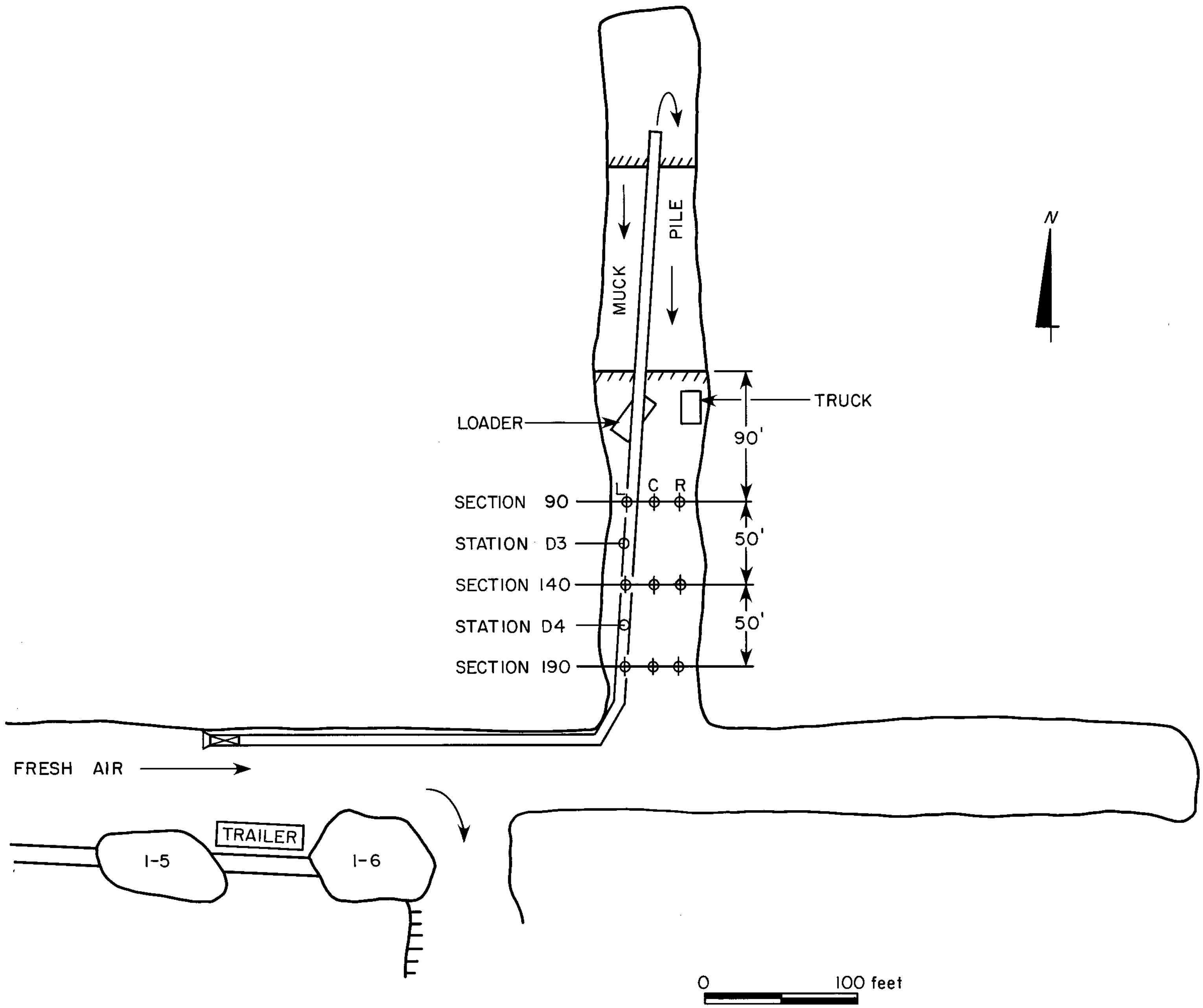

FIGURE A-3. - Schematic of Crosscut 7 showing the location of truck and loader with respect to sampling sections at 90, 140 and 190 ft from the face.

7 to its face position. In this way, the cycle simulated typical truck availability with an average cycle time of 7.9 minutes. After the truck was initially loaded, the Huff loader moved the muck from the left side of the pile to the right, simulating the action of loading the truck and working the engine rigorously.

Measurements were conducted in two separate tests. In the first test, the truck engine was shut off while being loaded, with the truck left idling in the second test. The muckpile and roads were wet down before the beginning of each test.

In both simulations, the concentrations of pollutants were carefully monitored to see that the values and time weighted exposures did not exceed regulatory TLV ceiling values.

Crosscut 7 was ventilated with 72,000 cfm of fresh air delivered by a 55 in. fan connected to 60 in. diameter collapsible vent tubing. The concentrations of pollutants for all stations have been aggregated and plotted for 5, 15 and 25 ft above the floor in Figure A-4. The figure shows the initial buildup of pollutant concentrations and the steady-state behavior resulting from the cycle. The truck cycle times are indicated on the scale above the plot. Time weighted average values for the steady-state portion of the two tests are compared in Table A-2.

The pollutants were highly stratified due to the buoyancy of the hot diesel exhaust. Depending upon the type of pollutant, the concentrations at 25 ft above the floor were 1.7 to 3.5 times the concentration at 5 ft above the floor. Leaving the truck idling as it was being loaded increased the concentration of the air pollutants. Carbon monoxide increased 60 percent with the

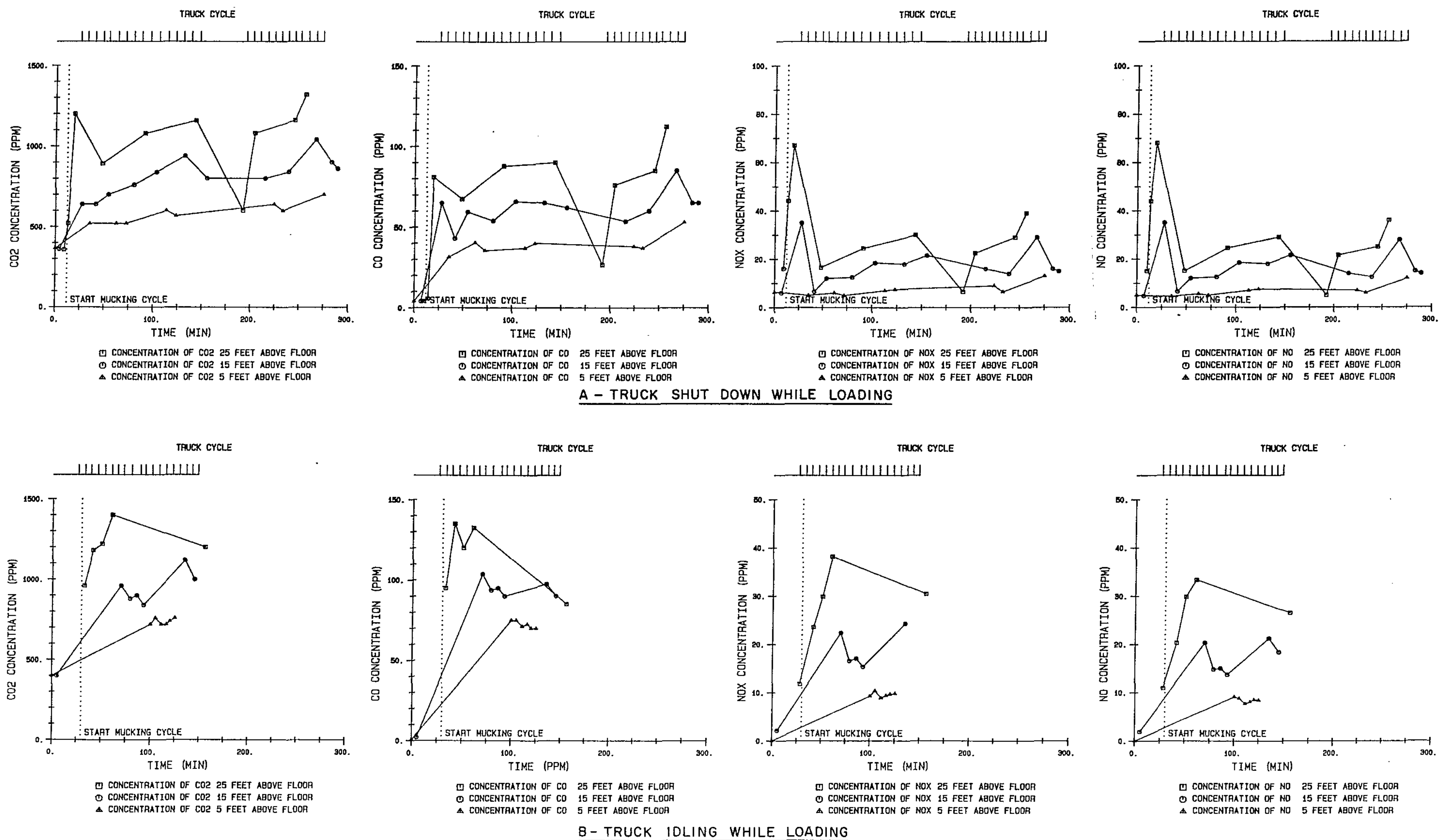

FIGURE A-4. - Concentration of various gaseous pollutants versus time during simulated mucking operations.

TABLE A-2. - Time weighted average pollutant concentrations measured in mucking simulations

Pollutant	Height above floor (ft)	TLV (vppm)	Pollutant concentration (ppm)[2]: Loading cycle with truck shut down	Pollutant concentration (ppm)[2]: Loading cycle with truck idling
CO_2[1]	25	5000	628[1]	877[1]
	15		423[1]	565[1]
	5		191[1]	366[1]
CO	25	50	76	112
	15		62	94
	5		40	72
NO_x	25	25	25.4	33.7
	15		17.4	19.1
	5		7.6	9.6
NO	25	25	24.2	29.7
	15		16.8	17.3
	5		7.0	8.4

[1] Corrected for ambient background - 400 ppm

[2] Density = 0.062 lbs/ft^3

truck idling, while the other three pollutants increased between 15 and 23 percent.

The mining equipment used in these tests was old. Although its exact history is not known, the equipment was used in the original mining at the Colony Pilot Mine in the middle 1960's and early 1970's. It was retired shortly after this study. It is apparent that the engine was not as clean burning as the new engines currently available.

A3.0 DUST AND DIESEL PARTICULATE SAMPLING

Cascade impactors were used to collect dust samples in the face area after the blast. The impactor at station D-1 was destroyed by blast debris. The results of the impactor at station D-2 are listed in Table A-3.

Dust samples were collected during loading tests using cascade impactors located at station D-3 and D-4 in Figure A-3. A dichotomous sample was located at station 140-C to provide measurements of quartz dust content. Additional samples were collected using filters located adjacent to the loader on the south wall of Crosscut 7. Results of the Cascade impactors samples are listed in Table A-4.

Dust collected during loading had a different size distribution than that collected during blasting. The amount of dust smaller than the smallest filter (< 0.72-0.79 micrometers) averaged 68 percent of the total mass during loading, as compared to 1.6 percent during blasting. The color of the fine fraction was black for loading, as compared to light brown for blasting. This reflects the large amount of diesel particulates whose median aerodynamic diameter is between 0.3 and 0.5 micrometers present during loading. The fraction increased during the test with the truck left idling. The dust concentration was approximately twice as high at 12 ft above the floor, as compared to 5 ft during loading.

Quartz analysis was performed on three samples collected during loading. This data is listed in Table A-5. Quartz content averaged 12.4 percent of the coarse portion of the dust

TABLE A-3. - Particle size and mass concentration of dust generated by face blasting

Stage No.	Aerodynamic[1] particle diameter (10^{-6}m)	Mass concentration of particulate matter (mg/m^3)
1	> 14.4	4.70
2	7.06-14.4	5.76
3	2.68-7.06	1.98
4	1.18-2.68	0.38
5	0.68-1.18	0.12
Filter	< 0.68	0.21
TOTAL	- -	13.15

[1] Aerodynamic particle diameter = diameter of a particle of unit density ($1g/cm^2$) that behaves in the same way aerodynamically

TABLE A-4. - Dust particle size distribution during loading

Test	Sample location	Aerodynamic particle diameter[1] (10^{-6})	Mass concentration of particulate matter	Total Mass (mg/m^3)
Loading cycle with truck shutdown while loading	D-4, 12 ft above floor	> 15.9	0.63	
		7.84-15.9	0.73	
		2.94-7.84	0.43	
		1.31-2.94	0.25	
		0.74-1.31	0.24	
		< 0.74	2.60	4.88
	D-3, 12 ft above floor	> 16.7	0.29	
		8.27-16.7	0.71	
		3.09-8.27	0.49	
		1.39-3.09	0.25	
		0.79-1.39	0.24	
		< 0.79	3.33	5.31
	D-4, 5 ft above floor	> 14.9	0.07	
		7.32-14.9	0.12	
		2.77-7.32	0.15	
		1.22-2.77	0.16	
		0.69-1.22	0.29	
		< 0.69	1.77	2.56
	D-3, 5 ft above floor	> 15.1	0.06	
		7.66-15.1	0.11	
		2.87-7.66	0.15	
		1.27-2.87	0.16	
		0.73-1.27	0.32	
		< 0.73	2.17	2.97
Loading cycle with truck idling	D-4, 12 ft above floor	> 15.9	0.12	
		7.84-15.9	0.25	
		2.94-7.84	0.31	
		1.31-2.94	0.34	
		0.74-1.31	0.38	
		< 0.74	4.11	5.51
	D-3, 12 ft above floor	> 16.0	0.13	
		7.92-16.0	0.32	
		2.96-7.92	0.36	
		1.32-2.96	0.35	
		0.72-1.32	0.46	
		< 0.72	4.45	6.07

[1] Aerodynamically diameter = diameter of particle of unit density ($1g/cm^2$) which behaves in the same way as the actual particle

TABLE A-5. - Quartz content of dust sample collected during loading

Test	Sample type	Mass concentration (mg/m^3)	Quartz content (mg/m^3) (% of total mass)	Cristobalite (mg/m^3) (% of total mass)
Loading with truck shut down	Filter cartridge	4.63	0.296 (6.4)	<0.04 (<0.9)
	Dichotomous coarse*	0.72	0.085 (11.8)	<0.02 (<2.8)
	Dichotomous fine*	2.34	0.03 (<1.3)	<0.03 (<1.3)
Loading with truck idling	Dichotomous coarse*	0.58	0.075 (12.9)	<0.02 (<3.4)
	Dichotomous fine*	3.16	0.04 (<1.3)	<0.04 (<1.3)

* Coarse fraction 2.5 - 15.0 micrometers; fine fraction <2.5 micrometers

(2.5 - 15.0 micrometers) and was less than 1.3 percent in the fine fraction (< 2.5 micrometers). This supports the conclusion that the majority of the fine particles in the Cascade impactor samples were diesel particulates.

A3.1 TEMPERATURE STRATIFICATION

Temperature measurements were made during the loading cycle to determine the magnitude of temperature stratification that could develop. Temperature versus time data is presented in Figure A-5 for all measurements at sections 90, 140 and 190. The curves show the buildup of temperature to a steady-state and illustrate the difference between floor and roof locations. The time of the truck cycle is shown above the plot. Time weighted averages of the data are listed in Table A-6. The data indicates an average peak temperature difference of 4.7°F between 10 ft and 25 ft above the floor. This stratification is due to the buoyancy of hot exhaust gases from the diesel equipment.

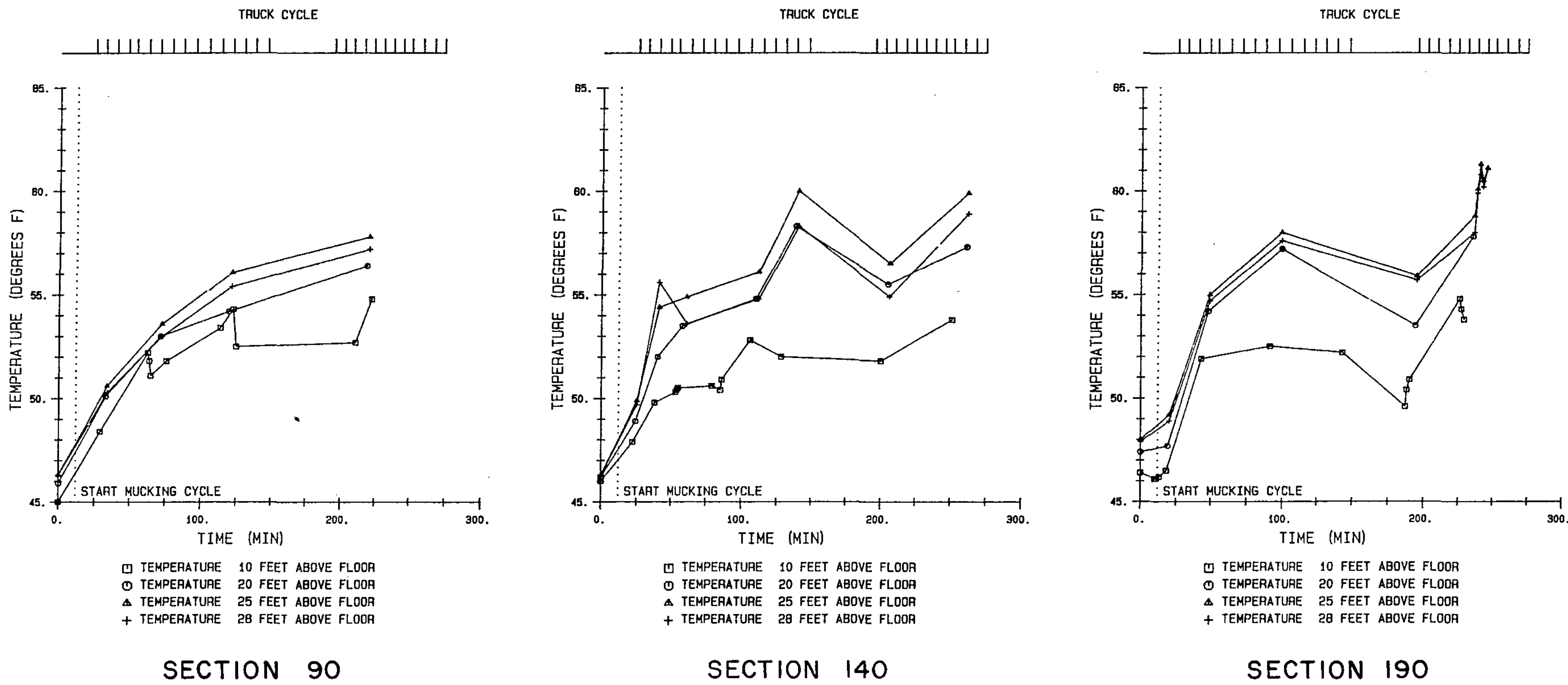

FIGURE A-5. - Temperature versus time measured during the mucking simulation.

TABLE A-6. - Time weighted average temperatures during loading

Height above floor (ft)	Time weighted average temperature (°F)		
	Section 90	Section 140	Section 190
10	52.7	52.0	52.0
20	54.7	56.0	55.0
25	56.3	57.5	57.1
28	55.6	56.0	56.7

APPENDIX B

Tracer Gas Test Layouts

and Sampler Locations

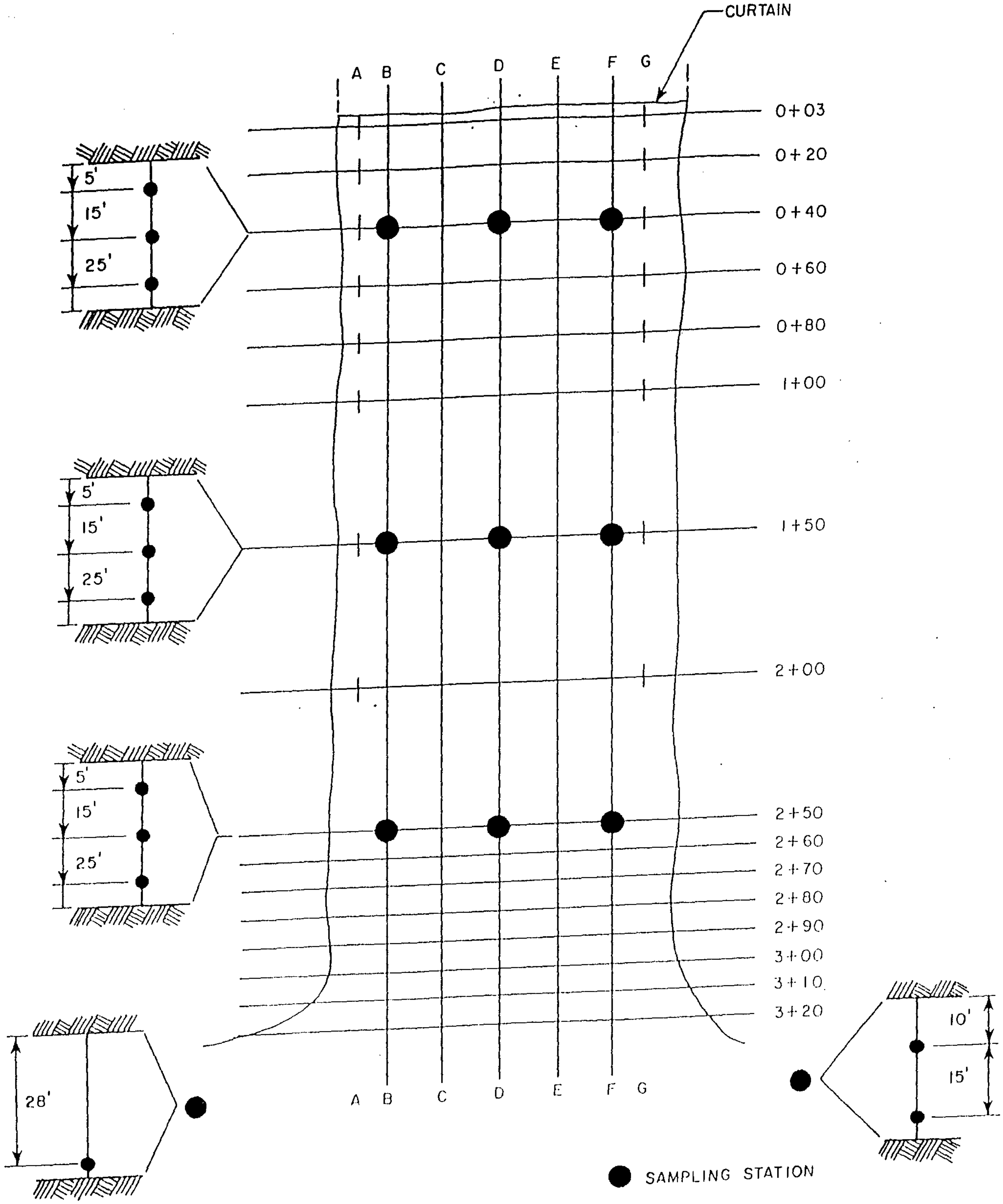

FIGURE B-1. - Sampler locations for simulation of clearing a heading after blasting.

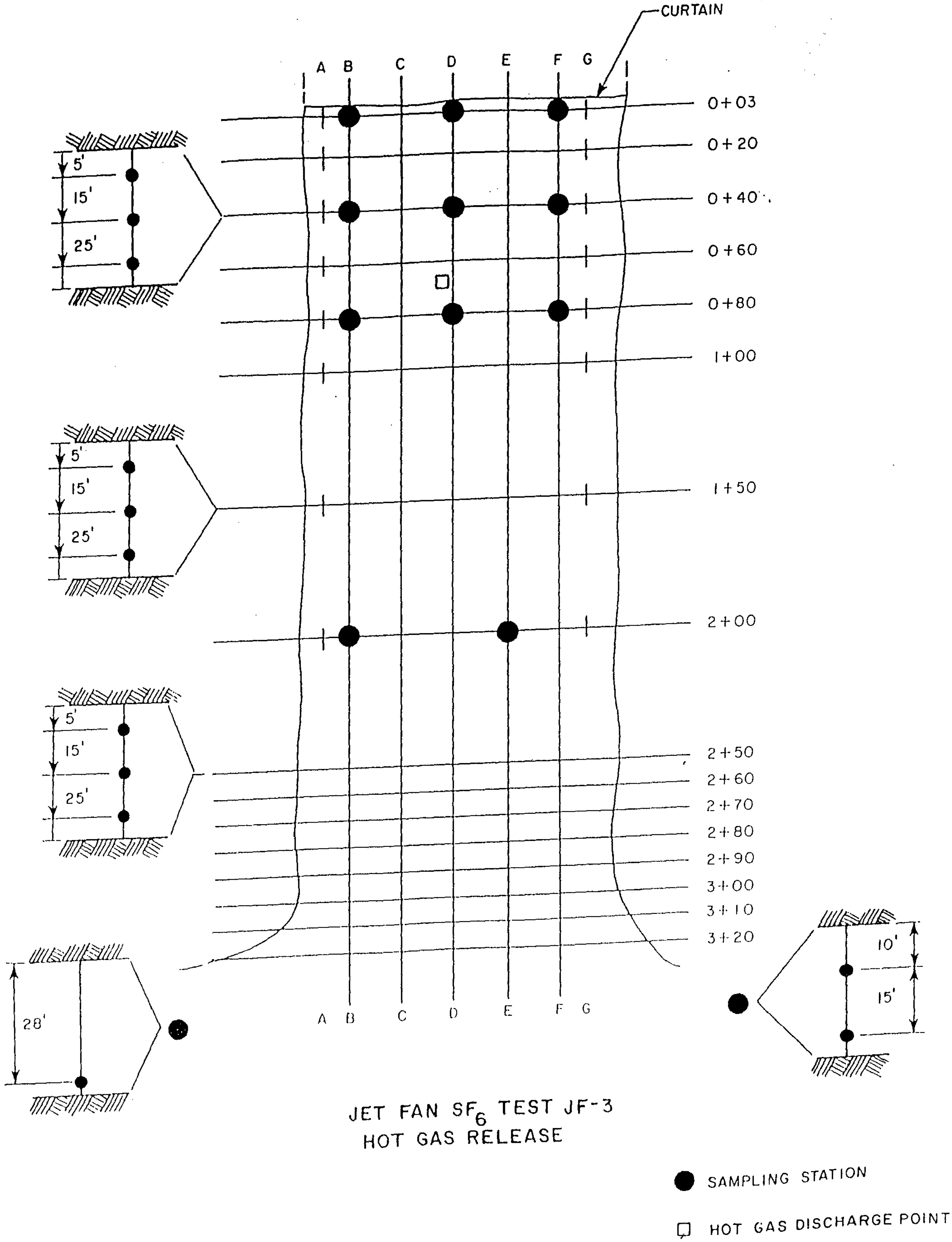

FIGURE B-2. - Sampler locations for simulation of hot diesel exhaust.

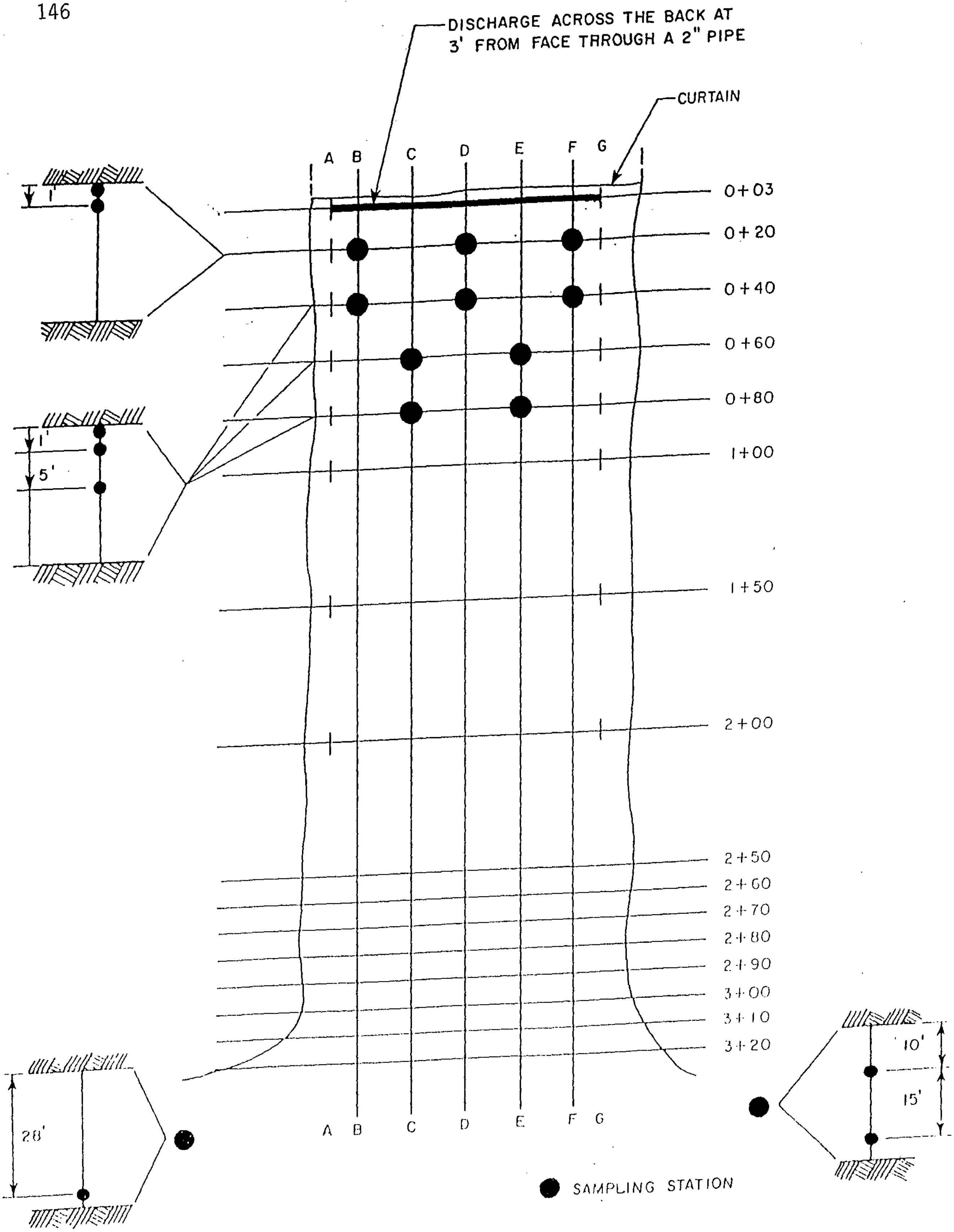

FIGURE B-3. - Sampler locations for methane layering test simulation.

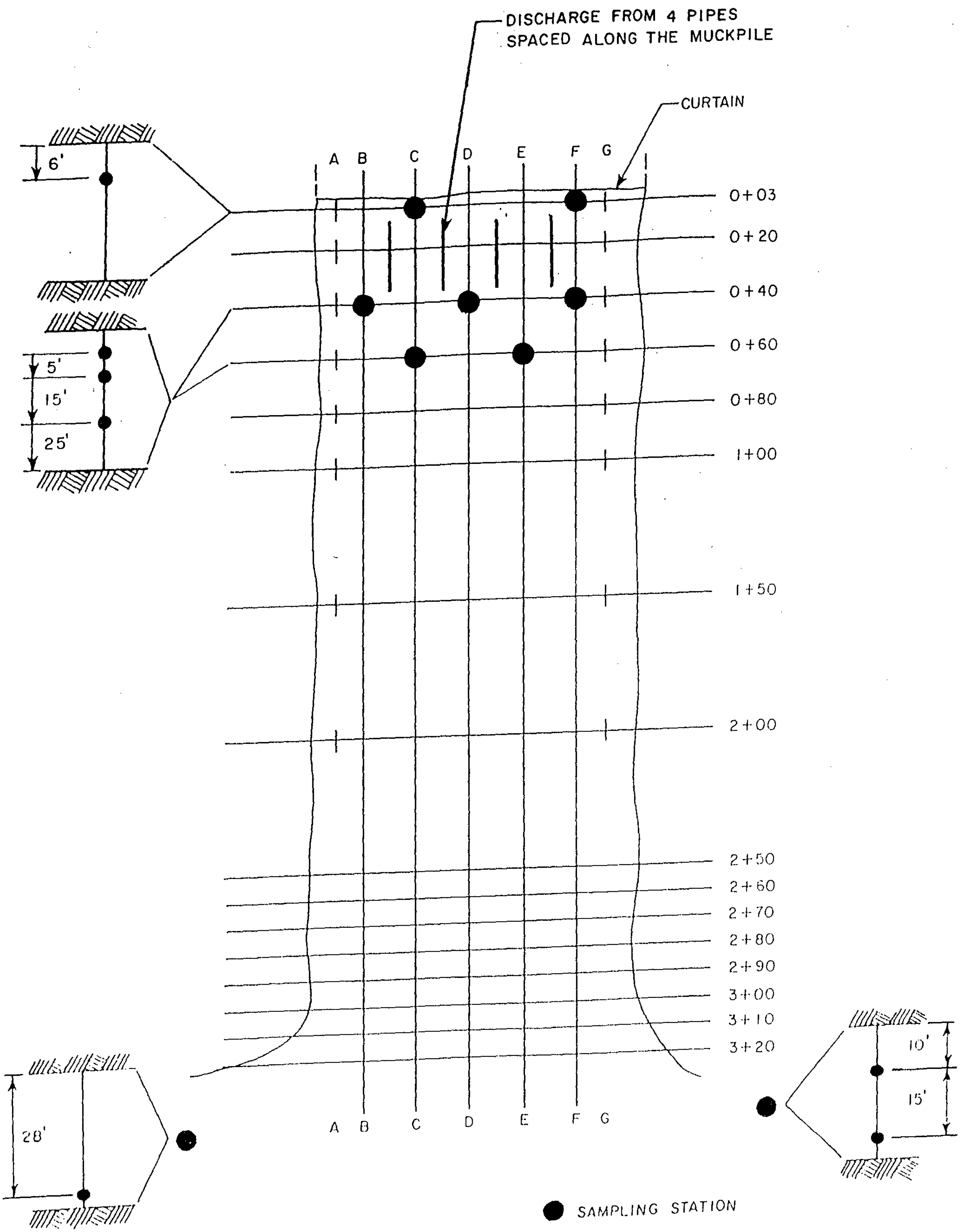

FIGURE B-4. - Sampler locations for simulation of methane from muckpile.

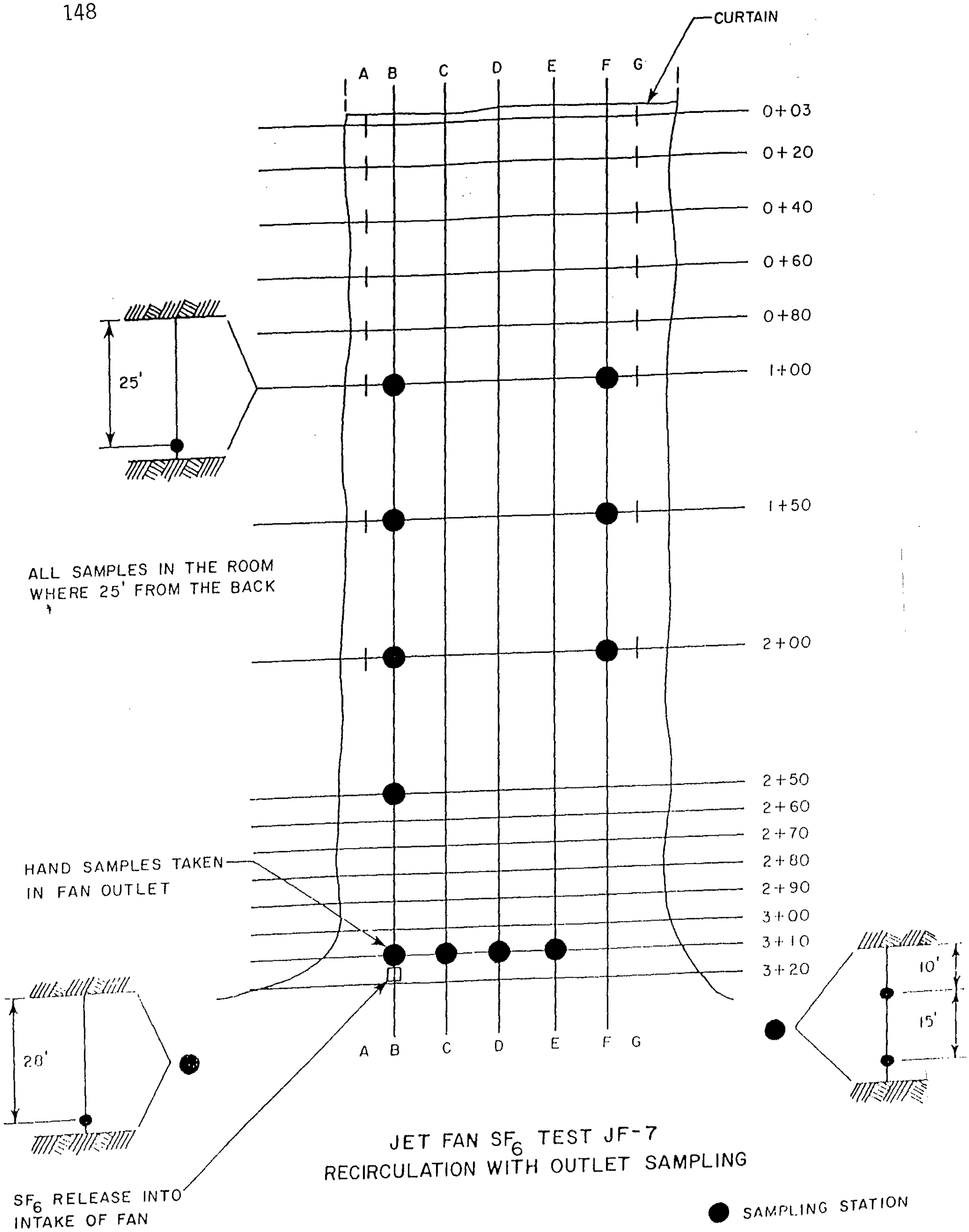

FIGURE B-5. - Sampler location for inlet recirculation measurements.

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