RI 7987

Bureau of Mines Report of Investigations/1974

Statistical Analysis of Methane Concentration Fluctuations Produced by Incomplete Mixing of Methane and Air at a Model Coal Mine Working Face

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 7987

Statistical Analysis of Methane Concentration Fluctuations Produced by Incomplete Mixing of Methane and Air at a Model Coal Mine Working Face

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UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton, Secretary

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BUREAU OF MINES
Thomas V. Falkie, Director

This publication has been cataloged as follows:

Bielicki, Richard J

Statistical analysis of methane concentration fluctuations produced by incomplete mixing of methane and air at a model coal mine working face, by Richard J. Bielicki and Fred N. Kissell. [Washington] U.S. Bureau of Mines [1974]

21 p. illus., tables. (U.S. Bureau of Mines. Report of investigations 7987)

Includes bibliography.

1. Methane. 2. Mine ventilation. 3. Mine safety. I. U.S. Bureau of Mines. II. Kissell, Fred N., jt. auth. III. Title. (Series)

TN23.U7 no. 7987 622.06173

U.S. Dept. of the Int. Library

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STATISTICAL ANALYSIS OF METHANE CONCENTRATION FLUCTUATIONS PRODUCED BY INCOMPLETE MIXING OF METHANE AND AIR AT A MODEL COAL MINE WORKING FACE

by

Richard J. Bielicki[1] and Fred N. Kissell[2]

ABSTRACT

Poor mixing of methane and air at coal mine working faces causes fluctuating methane concentrations. If these fluctuations are large enough, methane levels can periodically exceed safe limits, even though the time average methane concentration may be satisfactory. Concentration fluctuations measured underground can result both from variations in methane emission rate and poor mixing. The present paper reports on a statistical analysis of fluctuations at a constant methane emission rate, that is, on fluctuations due only to poor mixing. A full-scale model of a working face was used.

Both peak heights and elapsed times between peaks were evaluated. Good mixing was indicated by normal, Poisson, and exponential distributions while poor or incomplete mixing was indicated by log-normal or gamma distributions.

INTRODUCTION

The hazards created by the presence of methane gas in coal mines are especially great in the face area where most miners work and where considerable amounts of loosely deposited and suspended coal dust particles can also be ignited. Aside from inadequate ventilation of the working face, poor mixing of methane and air also contributes to face ignitions. Poor mixing causes wide fluctuations in the methane concentration, with the result that the explosive limit may occasionally be exceeded even though the time average concentration is below explosive limits.

Baake, Leach, and Slack (1)[3] have studied circumstances surrounding methane ignitions at longwall faces in British coal mines. They concluded that the probability of an ignition was directly proportional to the square of the average methane concentration, and inversely proportional to the densimetric Froude number.

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[1] Physical scientist (now with Eastern Field Operations Center).
[2] Physical research scientist.
[3] Underlined numbers in parenthesis refer to items in the list of references at the end of this report.

The Froude number F (1) is related to the degree of mixing and is expressed by

$$F = \frac{U^2}{g \frac{\Delta\rho}{\rho} \sqrt{A}},$$

where U is the average airspeed (ventilation quantity divided by the cross-sectional area); g is the gravitational acceleration; $\Delta\rho/\rho$ is the relative density difference (difference in density between air and methane divided by the density of air); and A is the cross-sectional area. An increase in air quantity at the face naturally reduces the average methane concentration by simple dilution. However, more air means a higher airspeed which increases the Froude number, improves mixing, and decreases still further the possibility of an ignition.

Using a small Plexiglass model of a working face, Shuttleworth (6) has shown that when eddys occur they result in constantly changing flow patterns with various degrees of recirculation. This recirculation and the changing flow patterns cause fluctuations in the methane concentration as measured at any point.

In the United States, the mandatory safety standards of the 1969 Coal Mine Health and Safety Act (8) require that the maximum allowable methane concentration as measured not less than 12 inches from the roof, face, or rib of a working place must be less than 1 volume-percent. Under the proper conditions, methane gas will propagate flame at concentrations between about 5 and 15 volume-percent. If mixing of methane gas and intake air in the working place is good, methane is rapidly and completely dispersed throughout the fresh air volume and no eddy zones or zones of concentration build up can occur. This would preclude the possibility of an ignition. Unfortunately poor mixing and eddy zones are sometimes encountered in working places (2-7), and an ignition may be possible.

Kissell and others (2) have studied the variations in methane concentration at coal mine working faces under actual mining conditions. Using data obtained with continuous-recording methane monitors located on the mining machine and in the immediate return, they found that a plot of the methane concentration versus time presented a series of peaks and valleys; each peak corresponded to a cut by the mining machine (fig. 1). The statistical distribution of the peak heights was either normal or log-normal. The authors concluded that the type of distribution depends on the degree of mixing of methane and air. Normal distributions indicate good mixing whereas log-normal distributions indicate poor mixing.

Variations in the methane concentration during mining result from variations in methane emission which in turn depend on how fast coal is being cut, and/or poor mixing of the emitted methane and the ventilation air. The conclusion of Kissell and others that the type of distribution depends on the degree of mixing was surprising in view of the fact that the major source of the peaks appeared to be differences in emission rate resulting from differences in the rate at which coal was cut by the mining machine. To explore

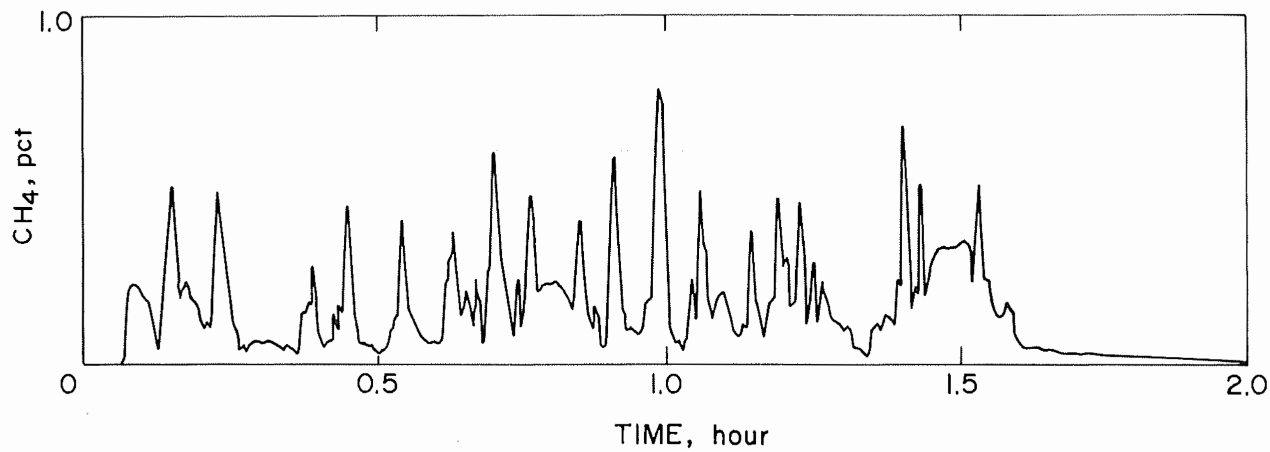

FIGURE 1. - A typical series of peaks obtained during actual mining conditions.

this further a study was made of the statistical distribution of the methane peaks obtained for constant methane emission, that is, of the peaks resulting from poor mixing only. In addition, we examined the effect of methane concentration fluctuations on the accuracy of grab samples used to determine the methane content, and we attempted to establish the factors which control the frequency with which peaks occur.

ACKNOWLEDGMENT

The authors would like to thank the Pittsburgh Technical Support Center, especially Robert Dalzell, Chief, Ventilation Group and Jack Stevenson, mining engineer, for their technical assitance and generosity in allowing us the use of their full-scale model.

EXPERIMENTAL

This study could not be performed underground because there is no simple way to cut coal and release methane at a constant rate. Accordingly, all experiments were performed in a full scale plywood model of a coal mine working face constructed by the Pittsburgh Technical Support Center of the Mine Enforcement and Safety Administration (MESA) (fig. 2.). The inner dimensions of the model are: height, 7 ft; width, 12 feet; length, 80 feet. A wooden model of a Jeffrey 120M Heliminer was placed at the face. Methane was released through flowmeters into three horizontal perforated pipes (subsequently called bottom, center, and top) which provided an even release over the face area. Fresh air was supplied by an auxiliary fan located outside the model, assisted at times by a machine-mounted diffuser fan with a 2,000-cfm capacity. With this model, one or more parameters, such as methane release rate or line brattice position, could be varied while holding the others constant.

The methane concentration and air velocity were monitored continuously with Bacharach combination methanometer-anemometer instruments, with heads located as close together as possible (fig. 3). Flow patterns were observed

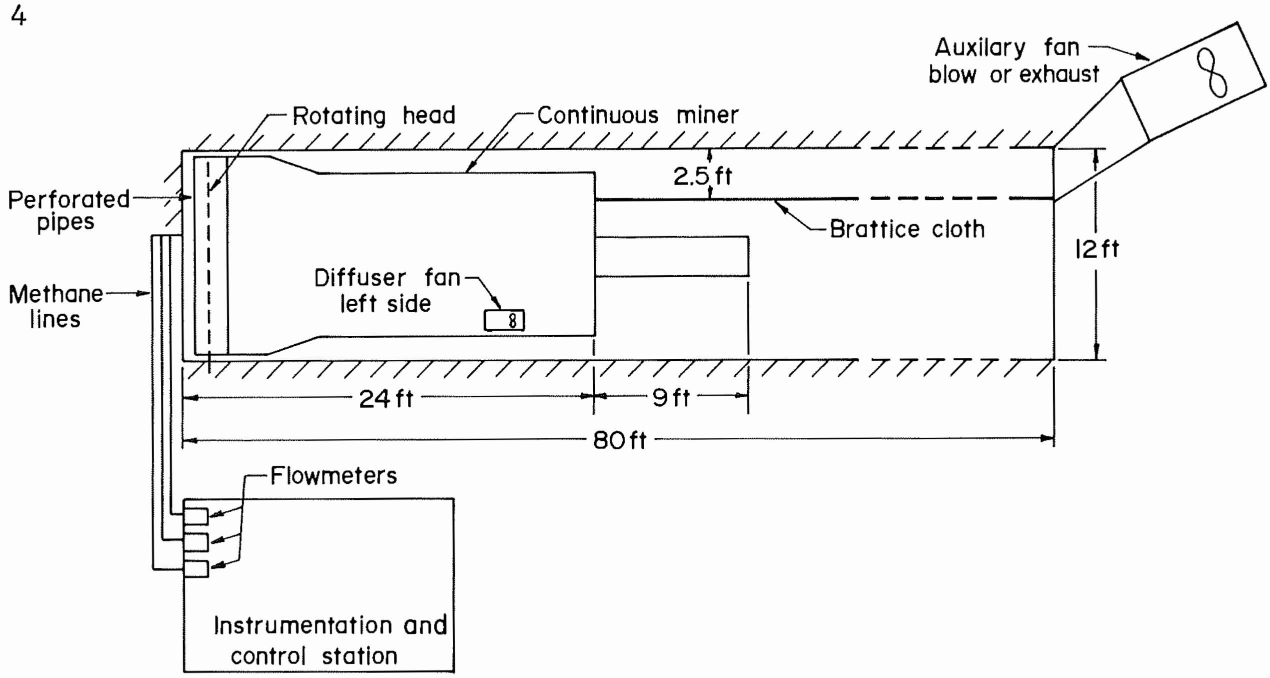

FIGURE 2. - A diagram of the plywood model.

LEGEND

▭ Anemometer

◁ Methanometer

Monitor locations			
Monitor	Distance, ft		
	Face	Side	Roof
Right	4	1.5	3.5
Center	2.5	6	1
Left	4	1.5	3.5

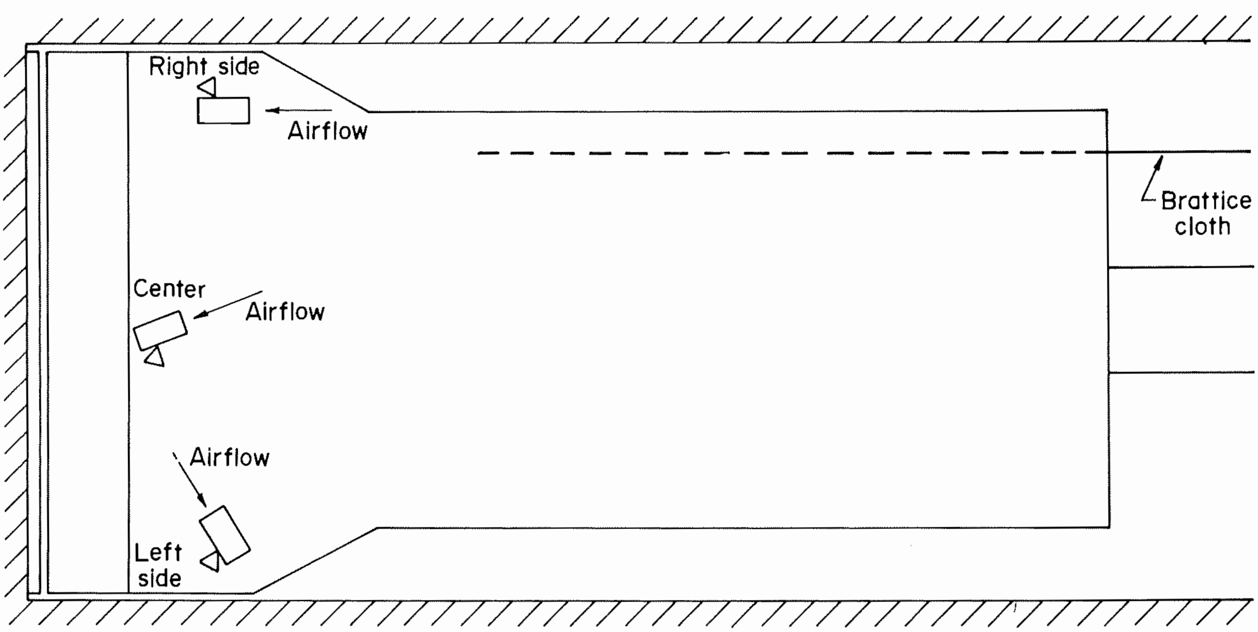

FIGURE 3. - Location of monitoring instruments.

periodically to facilitate proper "aiming" of the anemometer heads in the maximum velocity direction. Dual track recorders were used with each instrument. The time response of both the anemometer and methanometer were on the order of a few seconds.

The initial step was to measure the fluctuations of methane concentration at various points of the working face for constant methane emission. By doing this we could determine quantitatively the effect on mixing of various factors, such as line brattice position.

In the first set of experiments the blow brattice system of primary ventilation was used, varying the brattice-to-face distance from 18 to 30 ft. The brattice was located on the right side of the entry about 2 1/2 ft from the rib. Fresh air flow from behind the brattice (measured at the tight rib side between rib and brattice) varied from 6,700 to 9,000 cfm, while methane release rates varied from 15 to 65 cfm. The diffuser fan, located 18 feet from the face on the right side of the miner, was used periodically.

The second set of experiments used the exhaust brattice system of primary ventilation, with brattice-to-face distances varying from 10 to 22 ft. Fresh air flow up the entry varied from 6,500 to 7,900 cfm (measured at the tight rib side); methane release rates varied from 6 to 40 cfm. The diffuser fan was located on the left side of the machine about 20 ft from the face.

Both sets of experiments were conducted with the cutting head of the miner simulating a bottom cut and turning at a constant 60 rpm. The turning of the cutter head facilitates mixing somewhat and is therefore included as an integral part of the model.

RESULTS AND DISCUSSION

Effect of Incomplete Mixing on the Distribution of Methane Concentration Peaks

Figure 4 shows several recorder traces obtained under different experimental conditions. Methane concentration and air velocity are both given. In 4A and A' poor mixing is indicated. The methane concentration fluctuates substantially and the average air velocity is low. In 4B and B' the mixing has been improved and the velocity has been increased by moving the line brattice closer to the face. The methane concentration fluctuates less, and the average concentration is lower. In 4C and C', the methane and air are very well mixed; no distinct maxima are evident. This high degree of mixing was achieved by using a 2,000 cfm diffuser fan as shown in figure 2.

Similar recorder traces were obtained by a total of 48 separate trials, in which the following parameters were varied:

1. Type of ventilation.

2. Brattice-to-face distance.

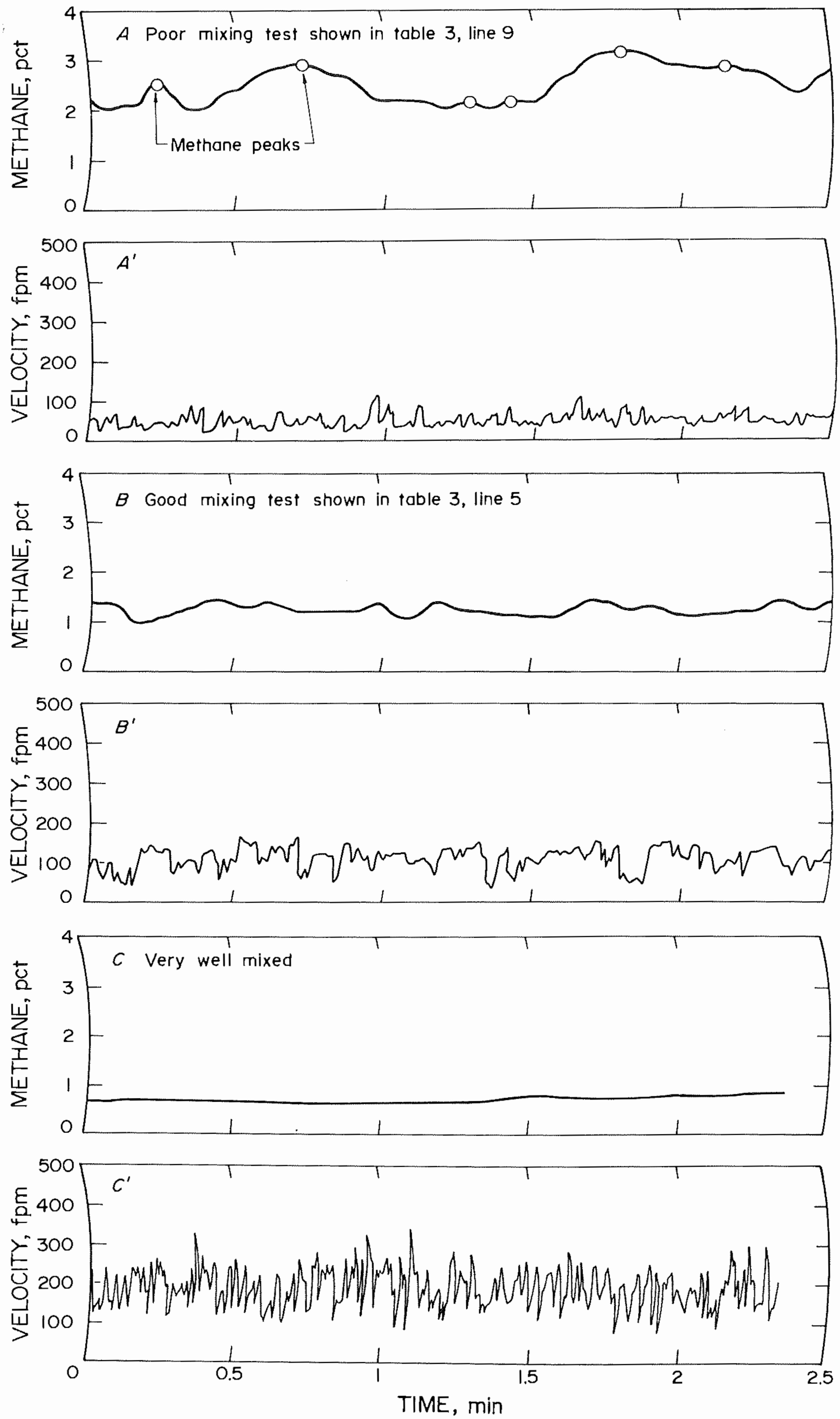

FIGURE 4. - Recorder traces obtained with constant methane flow.

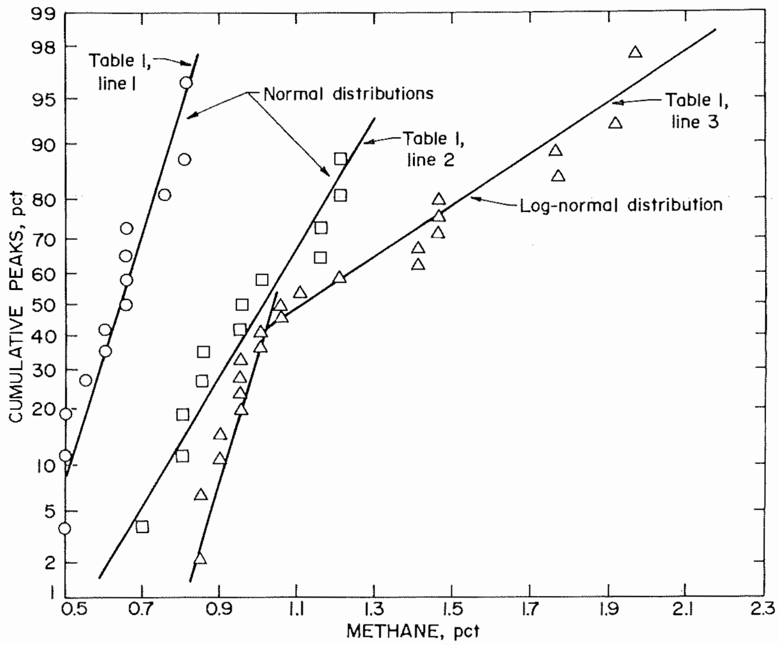

FIGURE 5. - Probability plots on normal probability paper.

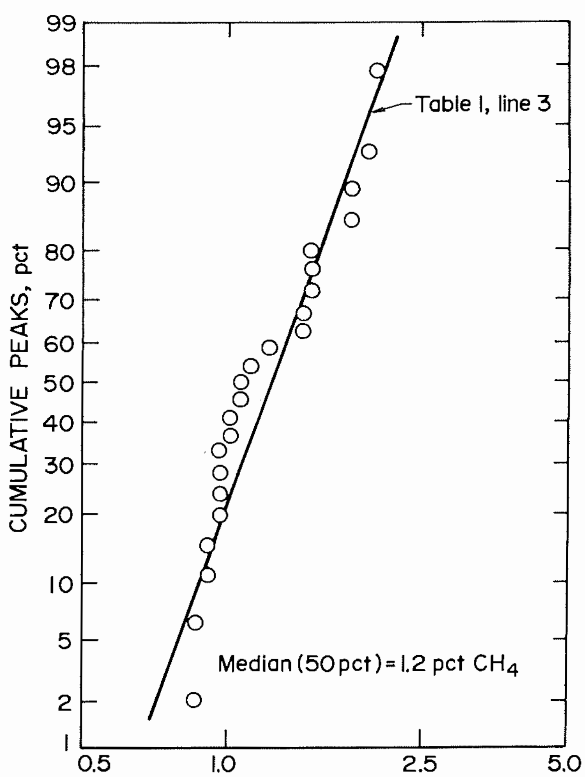

FIGURE 6. - Probability plots on log-normal probability paper.

3. Diffuser fan on or off.

4. Methane release rate.

5. Methane release position (top, middle, and/or bottom of face).

6. Fresh air quantity.

One hundred and thirty-eight recorder traces, similar to those shown in figure 4, were obtained from the three monitors during the 48 trials. A typical recorder trace was 10 minutes long and contained about 20 peaks, if peaks occurred. The average time between peaks was about 30 seconds.

The methane concentration peaks from each trial and each location were ranked statistically[4] and then plotted on probability paper. Generally the first plot was on normal-probability paper (fig. 5). If the points fitted a straight line, a normal distribution was assumed. One of the curves of figure 5 exhibits a distinct break to the right. This is the distinguishing characteristic of log-normal distributions when plotted on normal probability paper. Curves that fell into this category were re-plotted on log-normal probability paper where the points were better fitted to a straight line (see fig. 6).

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[4]To rank statistically:

1. Rank the peaks from the smallest to the largest. Thus

$$x_1 , < x_2 , < x_3 \;\ldots\; < x_n .$$

2. Plot the x's versus (i-1/2)(100/n) on probability paper. Thus, the lowest observation is plotted at (1/2)(100/n); the next lowest at (3/2)(100/n), and so on.

In general, when the methane concentration fluctuations were great (fig. 4A), a ranking of the peaks fit a log-normal distribution; when the fluctuations were small (fig. 4B), they fit a normal distribution. For the very well mixed case where no peaks were evident (fig. 4C), a statistical ranking was of course not possible. We can only assume that if the experimental data were good enough to discern maxima under these conditions, they would be normally distributed.

Such probability plots can be used to estimate the probability of occurrence of higher methane concentrations. For instance, in figure 6 the median (50 percent rank) concentration peak is at 1.2 percent methane, whereas the 98 percent rank peak is at 2 percent methane. Therefore, 2 percent of the peaks (100 minus 98) are above 2 percent methane.

The data from the first series of experiments, in which the blow brattice system was used, are summarized in table 1. Column 7 gives a measure of the scatter, S (84.13 percent value minus the median) which is actually the standard deviation for a normal distribution. Column 8 gives the value of the median peak.

Examination of table 1 shows that:

1. Increasing the methane release rate increases the likelihood of a log normal distribution. For instance, the first trial shows a 30-cfm release rate, a normal distribution, and a standard deviation of 0.09. The trial in the third line shows, under similar conditions (except for a 55-cfm release rate), a log normal distribution, and a standard deviation of 0.55. This was an unexpected result. It indicates that the higher methane flows cause some alterations in the airflow patterns, which is surprising considering that the airflow quantity is over a hundred times greater than the methane flow. However, Luxner (4) has shown that under poor ventilation conditions the primary airflow never reaches the face and so the methane is removed only with secondary eddys. These secondary eddys contain much less air, and it is easier to visualize the methane flow having some effect.

2. Increasing the brattice-to-face distance, while keeping other parameters constant, increases the scatter of the peaks indicating a deterioration in mixing. For example: Line 1, left side, 18 ft, diffuser off, 30 cfm CH_4, S = 0.09, normal. Line 12, left side, 26 ft, diffuser off, 30 cfm CH_4, S = 0.80, log normal. At brattice distances of 22 ft or greater with the diffuser fan off the median peak concentrations at the right side monitor were high indicating poor mixing in that area.

3. With all other parameters constant, mixing was improved by use of the diffuser fan. For example, examination of the third and fourth lines shows that at the left-side monitor, brattice-to-face distance of 18 ft, diffuser off, B40 + C7-1/2 + T7-1/2 (total CH_4 flow of 55 cfm), the distribution was log-normal with a standard deviation of 0.55. With the diffuser on, the distribution was normal with a standard deviation of 0.11. This improvement occurred in spite of the fact that turning on the diffuser fan raised the median peak concentration from 1.075 to 2.15 percent methane.

TABLE 1. - Results from probability plots of concentration peaks (blow brattice ventilation system)

1 Monitor location	2 Line No.	3 Brattice to face distance (ft)	4 Diffuser fan	5 Volume CH_4[1] (cfm)	6 Type of distribution	7 S (pct CH_4)	8 Peak median (pct CH_4)	9 Fresh airflow at end of brattice (cfm)
Left side	1	18	Off	B15+C7½+T7½	Normal	0.09	0.64	6,700
	2	18	Off	B30+C7½+T7½	Normal	.18	1.01	6,700
	3	18	Off	B40+C7½+T7½	Log normal	.55	1.075	6,700
	4	18	On	B40+C7½+T7½	Normal	.11	2.15	6,700
	5	22	Off	B15	Normal	.075	.525	7,500
	6	22	Off	B20	Normal	.15	.625	7,500
	7	22	Off	B25	Normal	.10	.925	7,500
	8	22	On	B30+C7½+T7½	Not clear[2]	.34	1.975	7,500
	9	22	On	B40+C7½+T7½	Normal	.10	2.35	7,500
	10	22	On	B45+C7½+T7½	Normal	.15	3.125	7,500
	11	22	On	B50+C7½+T7½	Normal	.325	3.525	7,500
	12	26	Off	B15+C7½+T7½	Log normal	.80	2.60	8,200
	13	26	On	B15+C7½+T7½	Normal	.10	1.30	8,200
	14	30	Off	B15	Normal	.15	.40	9,000
	15	30	Off	B20	Normal	.25	1.45	9,000
	16	30	Off	B25	Normal	.35	1.90	9,000
	17	30	Off	B30	Log normal	.85	2.65	9,000
	18	30	On	B45+C7½+T7½	Normal	.25	3.50	9,000
	19	22	On	B15	Very well mixed[2]	-	-	7,500
	20	22	On	B25	Very well mixed	-	-	7,500
	21	22	On	B30	Very well mixed	-	-	7,500
	22	22	On	B40+C7½+T7½	Very well mixed	-	-	7,500
	23	26	On	B25	Very well mixed	-	-	8,200
	24	26	On	B30	Very well mixed	-	-	8,200
	25	30	On	B15	Very well mixed	-	-	9,000
	26	30	On	B30	Very well mixed	-	-	9,000
Center	27	22	Off	B15	Normal	.13	.95	7,500
	28	22	Off	B20	Normal	.16	1.38	7,500
	29	22	Off	B25	Normal	.17	1.84	7,500
	30	22	On	B30+C7½+T7½	Normal	.17	.96	7,500
	31	22	On	B50+C7½+T7½	Log normal	.58	1.42	7,500
	32	22	On	B40+C7½+T7½	Normal	.425	1.20	7,500
	33	30	On	B30	Not clear	.425	1.20	9,000
	34	30	On	B45+C7½+T7½	Log normal	.675	1.15	9,000
	35	26	Off	B15+C7½+T7½	Log normal	1.15	1.45	8,200
	36	26	On	B15+C7½+T7½	Normal	.25	.70	8,200
	37	30	Off	B15	Normal	.20	.35	9,000
	38	30	Off	B20	Normal	.30	.80	9,000
	39	30	Off	B25	Normal	.30	.90	9,000
	40	30	Off	B30	Normal	.30	1.15	9,000
	41	22	On	B15	Very well mixed	-	-	7,500
	42	22	On	B25	Very well mixed	-	-	7,500
	43	22	On	B30	Very well mixed	-	-	7,500
	44	22	On	B45+C7½+T7½	Very well mixed	-	-	7,500
	45	26	On	B25	Very well mixed	-	-	8,200
	46	30	On	B15	Very well mixed	-	-	9,000

See footnotes at end of table.

TABLE 1. - Results from probability plots of concentration peaks (blow brattice ventilation system)--Continued

1 Monitor location	2 Line No.	3 Brattice to face distance (ft)	4 Diffuser fan	5 Volume CH_4[1] (cfm)	6 Type of distribution	7 S (pct CH_4)	8 Peak median (pct CH_4)	9 Fresh airflow at end of brattice (cfm)
Right	47	22	Off	B15	Normal	0.26	2.24	7,500
side	48	22	Off	B20	Not clear	.42	3.40	7,500
	49	22	Off	B25	Not clear	.46	4.36	7,500
	50	22	On	B30+C7½+T7½	Normal	.055	.48	7,500
	51	22	On	B40+C7½+T7½	Normal	.04	.70	7,500
	52	22	On	B45+C7½+T7½	Normal	.09	.77	7,500
	53	22	On	B50+C7½+T7½	Normal	.09	.91	7,500
	54	30	On	B45+C7½+T7½	Normal	.06	.67	9,000
	55	26	Off	B15+C7½+T7½	Not clear	1.40	3.60	8,200
	56	30	Off	B15	Normal	.75	1.60	9,000
	57	30	Off	B20	Not clear	.65	3.25	9,000
	58	30	Off	B25	Not clear	1.25	2.80	9,000
	59	30	Off	B30	Not clear	.75	3.40	9,000
	60	18	Off	B15+C7½+T7½	Very well mixed	-	-	6,700
	61	18	Off	B30+C7½+T7½	Very well mixed	-	-	6,700
	62	18	Off	B40+C7½+T7½	Very well mixed	-	-	6,700
	63	18	On	B40+C7½+T7½	Very well mixed	-	-	6,700
	64	22	On	B15	Very well mixed	-	-	7,500
	65	22	On	B25	Very well mixed	-	-	7,500
	66	22	On	B30	Very well mixed	-	-	7,500
	67	22	On	B40+C7½+T7½	Very well mixed	-	-	7,500
	68	26	On	B25	Very well mixed	-	-	8,200
	69	26	On	B30	Very well mixed	-	-	8,200
	70	26	On	B15+C7½+T7½	Very well mixed	-	-	8,200
	71	30	On	B15	Very well mixed	-	-	9,000
	72	30	On	B30	Very well mixed	-	-	9,000

[1] B, bottom pipe; C, center pipe; T, top pipe.
[2] It was not clear whether the distribution was normal or log-normal.
[3] The recorder trace gave practically a straight line.

4. For a given test, not all monitor locations gave the same type of distribution. For example, the left side (line 3) with brattice distance of 18 ft, the diffuser off, and a total CH_4 flow of 55 cfm showed a log-normal distribution. The right side (line 62) during the same test had only a few small fluctuations, indicating very good mixing and normal distribution. This can be partly attributed to the fact that the blow brattice was on the right side, and therefore all the methane released at the face was potentially being swept toward the left side because of the primary direction of ventilation flow. This would also explain the increase in the median peak concentration noted in 3.

5. If the standard deviation (S) was greater than about 0.4, the distribution was generally log-normal or could not easily be placed in either category ("not clear"). This is to be expected, for the standard deviation is really a measure of the scatter of the points. The greater the scatter, the poorer the mixing and the greater the fluctuations.

Kissell and others found (2) that the ratio S:median gave a good indication of the type of distribution. If this ratio was less than 0.3, the peak heights observed during mining fit a normal distribution in most cases. If the ratio was more than 0.3, in most cases a log-normal distribution fits best.

A similar division of the data in table 1 was attempted but the ratio S:median was a poor indicator of the type of distribution, and the value of S alone was a much better indicator. In table 2, the data from table 1 have been ranked in increasing order of S. A value of S less than 0.4 indicates a normal distribution and good mixing.

TABLE 2. - Ranking of data from well-mixed to poorly mixed by use of peak standard deviation(S)

1 S	2 Type of distribution	3 Monitor location	1 S	2 Type of distribution	3 Monitor location
0.040	Normal	Right	0.260	Normal	Right
.055	Normal	Right	.300	Normal	Center
.060	Normal	Right	.300	Normal	Center
.075	Normal	Left	.300	Normal	Center
.090	Normal	Right	.325	Normal	Left
.090	Normal	Right	.340	Not clear	Left
.090	Normal	Left	.350	Normal	Left
.100	Normal	Left	.420	Not clear	Right
.100	Normal	Left	.425	Normal	Center
.100	Normal	Left	.425	Not clear	Center
.110	Normal	Left	.460	Not clear	Right
.130	Normal	Center	.500	Log normal	Left
.150	Normal	Left	.580	Log normal	Center
.150	Normal	Left	.650	Not clear	Right
.150	Normal	Left	.675	Log normal	Center
.160	Normal	Center	.750	Normal	Right
.170	Normal	Center	.750	Not clear	Right
.170	Normal	Center	.800	Log normal	Left
.180	Normal	Left	.850	Log normal	Left
.200	Normal	Center	1.150	Log normal	Center
.250	Normal	Left	1.250	Not clear	Right
.250	Normal	Left	1.400	Not clear	Right
.250	Normal	Center			

The experiments with the blow brattice system were followed by a second series of experiments with the exhaust brattice system. Table 3 gives the results from the probability plots. The exhaust system does not remove methane as effectively as the blow system. To avoid dangerously high methane concentrations, the brattice-to-face distance and CH_4 flow rates had to be smaller than those in the first set of experiments. All of the trials using the diffuser fan gave very good mixing and therefore are not listed. It is again apparent that increased brattice-to-face distance and increased methane flow rates are more likely to result in poor mixing. It is also apparent that not all monitor locations gave the same type of distribution in any given trial, the right side having more log-normal or "not-clear" distributions as well as higher average methane concentrations than the left side. Since the exhaust brattice was on the right side, all the methane now released at the face was being swept toward the right side because of the direction of primary ventilation flow. In addition, if the standard deviation exceeded 0.25, the distribution was generally log normal or "not clear."

TABLE 3. - Results from probability plots of concentration peaks (exhaust brattice ventilation system)[1]

1 Monitor location	2 Line No.	3 Brattice to face distance (ft)	4 Diffuser fan	5 Volume CH_4 [2] (cfm)	6 Type of distribution	7 S (pct CH_4)	8 Peak median (pct CH_4)	9 Fresh airflow at end of brattice (cfm)
Right side	1	10	Off	B20	Normal	0.07	0.61	6,500
	2	10	Off	B15+C7½+T7½	Normal	.08	.67	6,500
	3	10	Off	B25+C7½+T7½	Normal	.14	.91	6,500
	4	14	Off	B20	Not clear	.28	1.66	7,000
	5	14	Off	B15	Normal	.13	1.38	7,000
	6	14	Off	B15+T5	Normal	.10	1.40	7,000
	7	18	Off	B15	Not clear	.30	2.65	7,400
	8	18	Off	B10	Normal	.19	1.985	7,400
	9	22	Off	B10+T5	Log normal	.38	2.65	7,900
	10	22	Off	B10	Normal	.25	2.10	7,900
	11	22	Off	B6	Normal	.14	1.60	7,900
Center	12	10	Off	B20	Not clear	.325	.80	6,500
	13	10	Off	B15+C7½+T7½	Normal	.16	1.20	6,500
	14	10	Off	B25+C7½+T7½	Not clear	.25	1.675	6,500
	15	14	Off	B20	Not clear	.425	2.65	7,000
	16	14	Off	B15	Not clear	.35	2.15	7,000
	17	14	Off	B15+T5	Log normal	.65	2.45	7,000
	18	18	Off	B15	Not clear	.40	3.00	7,400
	19	18	Off	B10	Not clear	.35	2.85	7,400
	20	22	Off	B10	Not clear	.35	3.15	7,900
	21	22	Off	B10+T5	Equipment malfunction.	-	-	-
	22	22	Off	B6	Normal	.17	2.41	7,900
Left side	23	10	Off	B20	Normal	.04	.275	6,500
	24	10	Off	B15+C7½+7½	Normal	.09	.22	6,500
	25	10	Off	B25+C7½+7½	Normal	.07	.23	6,500
	26	14	Off	B20	Normal	.065	.49	7,000
	27	14	Off	B15	Normal	.075	.475	7,000
	28	14	Off	B15+T5	Normal	.05	.28	7,000
	29	18	Off	B15	Normal	.06	.30	7,400
	30	18	Off	B10	Normal	.07	.19	7,400
	31	22	Off	B10	Equipment malfunction.	-	-	-
	32	22	Off	B10+T5	Normal	.13	.50	7,900
	33	22	Off	B6	Normal	.18	.84	7,900

[1] These same tests were run with the diffuser fan on; they all showed almost no fluctuation and indicated that the air and methane were very well mixed.
[2] B, bottom pipe; C, center pipe; T, top pipe.

Thus, comparison of these primary ventilation systems shows that better ventilation of the face area is achieved with the blow brattice system and that the better mixing observed with the blow brattice is due to a greater average velocity at the face. This in turn reduces fluctuations in the methane concentration, thus decreasing probability of an ignition. A similar increase in air velocity was obtained with the diffuser fan. This can be seen graphically in figure 7 where tests with the diffuser fan on had higher average local velocities which in turn promoted better mixing.

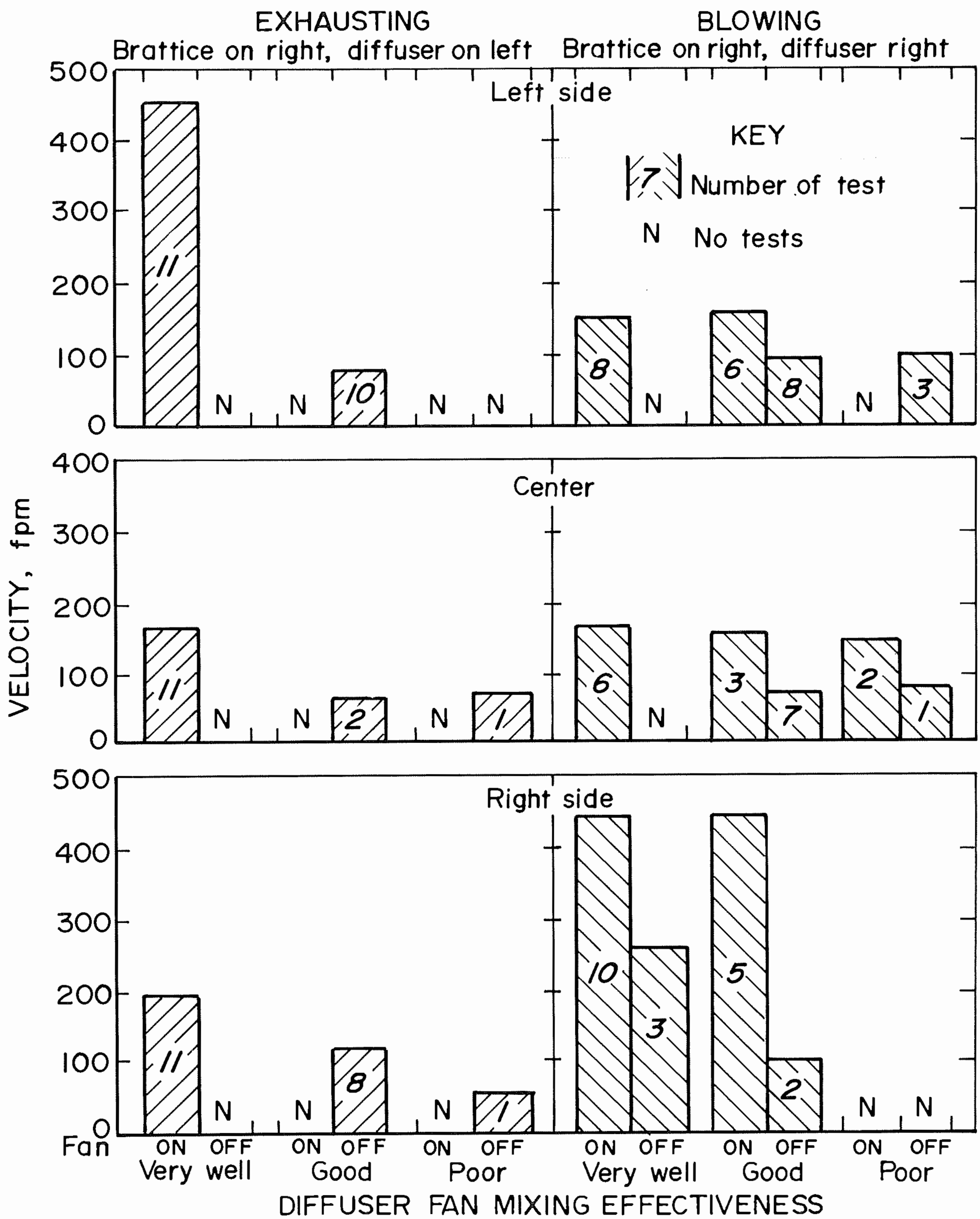

FIGURE 7. - Mixing effectiveness related to air velocity.

Effect of Concentration Fluctuations on the Accuracy of Grab Samples

Methane concentrations in coal mines are generally determined from "grab samples." When the methane and air are poorly mixed, several grab samples must be averaged to insure statistical validity (5). In the field of air pollution measurements, it is generally recognized that evaluation of a series of grab samples, under given conditions will give a log normal distribution (3).

In the preceding section methane peaks were found to be log normally distributed if the mixing of air and methane at the working face was poor. To see whether results would be similar for grab samples taken at a working face, we re-ranked the recorder traces, using the concentration at 30-second intervals (fig. 8) instead of peak values (fig. 4A). The results were similar. If a given recorder trace had peaks that were log normally distributed, then the concentration values at 30 second intervals were generally log normally distributed. Similarly, if the peaks were normally distributed, then the concentration values at 30-second intervals were normally distributed. The dividing line between normal and log-normal distributions was at a standard deviation of about 0.5. Above 0.5 the distributions tended to be log normal, and those below 0.5, normal.

Except for methane layering studies, little effort has been devoted to studying the effects of poor mixing on underground methane concentration measurements. Variations in methane concentration, even over short time

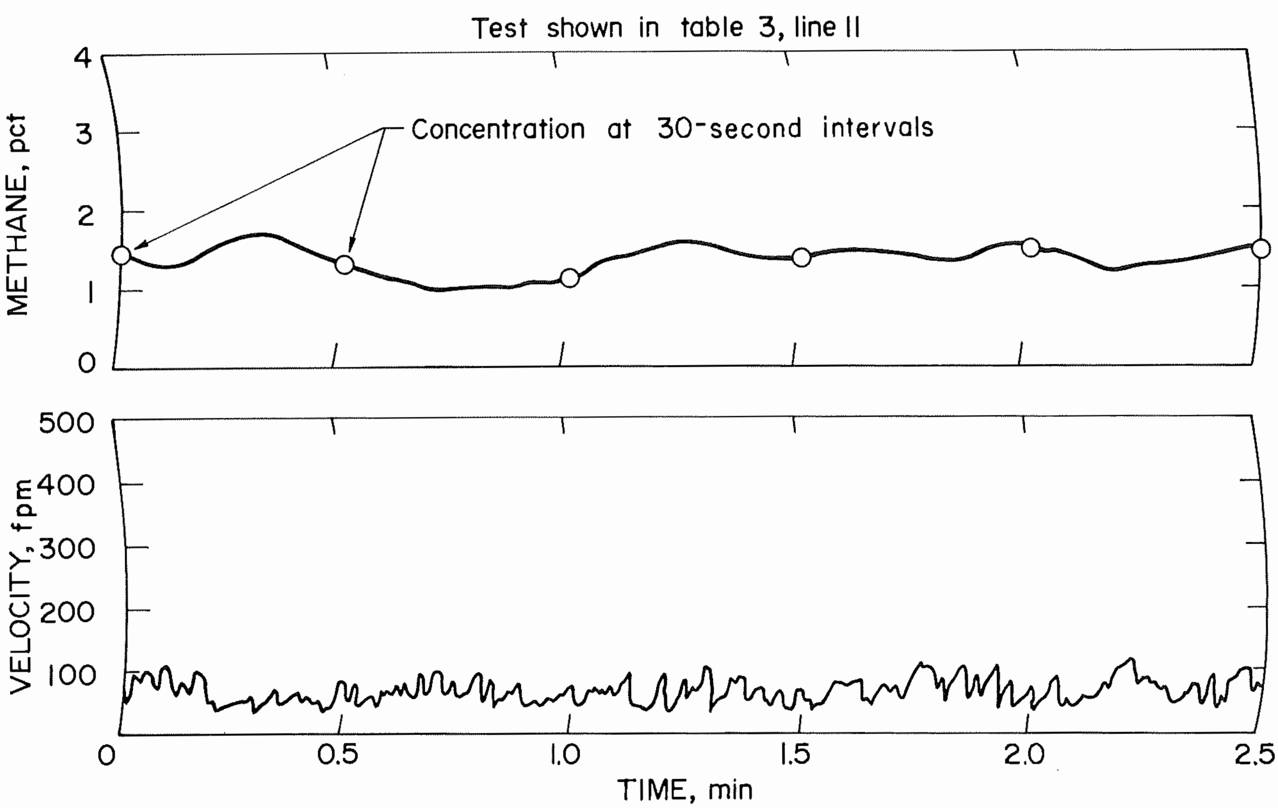

FIGURE 8. - Recorder trace obtained with constant methane flow.

intervals, have generally been attributed to variations in emission rates rather than to poor mixing. In a recent Bureau of Mines methane study, experiments were performed in which a series of air samples was taken in an entry downstream of a suspected methane emission source. Three tests were conducted at different airflows and samples were taken at 45-minute intervals:

Test	Airflow in entry (cfm)	Methane readings at 45-minute intervals (pct CH_4)					
1	6,300	0.64	0.77	0.51	0.69	0.80	-
2	4,000	.61	.76	.48	.79	.68	.79
3	3,000	.77	1.07	.94	1.17	.96	1.06

These results could be attributed to fluctuating methane emissions. However, the airflows are of the range in which we observed fluctuating methane concentrations at the model working face, and therefore it is possible that these fluctuations were also due to incomplete mixing. Probability plots for these three trials indicate that the readings are normally distributed, and that the standard deviation in each case was about 0.14. This would indicate good mixing, under the face mixing criteria developed in the previous section.

The highest airflow in these trials was 6,300 cfm (test 1). At higher air flows, one might expect much better mixing with a standard deviation below 0.14. A similar series of rib emission measurements was made by Zabetakis and others (9) to assess methane leakage into coal mines from gas and oil wells. The airflow in one air course was 26,600 cfm. The standard deviation was only 0.085, a value that could be expected from instrumentation errors alone. Thus, we may describe mixing at 26,600 cfm as very good.

Rate of Occurrence of Concentration Peaks

The distribution of methane concentration peaks has been used as an arbitrary indicator of the degree of methane-air mixing, taking a log normal distribution of peak heights as evidence of poor mixing and a normal distribution of peak heights as indicating good mixing.

Still more information about working face airflow characteristics can be obtained by considering the rate at which peaks occur, instead of the peak height itself. If the airflow at the face is fully turbulent, then one might attribute methane concentration peaks to a series of random events. If these peaks occur at a constant average rate, then the probability of k peaks occurring in any given time interval is given by the Poisson distribution function

$$Pr(k) = \frac{\mu^k e^{-\mu}}{k!},$$

where μ is the average number of peaks in a unit interval of time. To see whether our data fit a Poisson distribution we selected, for statistical accuracy, the trial corresponding to the longest time period. This was the trial in table 3, lines 11 and 33, in which the face-to-brattice distance was 22 ft, the methane flow rate was 6 cfm, and the diffuser fan was off.

For the left side location (line 33), the ranking of peaks fits a normal distribution, indicating that mixing at this location was good. To test whether the rate of peak occurrence fits a Poisson distribution we divided the recorder chart data (for the left side) into 58 30-second intervals. During the total test time of 29 minutes the methane concentration peaked 58 times. Thus, m, the average number of peaks in an interval equals 58/58 or 1.0. We then counted the number of intervals that contained zero peaks, one peak, two peaks, and so forth. The results are shown in table 4 (left side). It will be seen that 16 of the 30-second intervals had no peaks, 28 had one peak, and so forth. The correlation between f_e and f_o, the expected and observed number of intervals containing k peaks, is checked by computing χ^2. In this case

$$\chi^2 = \sum_{1}^{4} \frac{(fo_i - fe_i)^2}{fe_i} = 5.35.$$

As this is less than the tabulated value ($\chi^2_{.05,3} = 7.81$), there is no reason to reject the hypothesis that the occurrence of peaks fits a Poisson distribution and that methane peaks at the left side are random events which occur at a constant average rate.

TABLE 4. - Calculation of the Poisson distribution for the exhaust brattice system with the brattice at 22 ft from the face and CH_4 flow at 6 cfm

Left side: 58 peaks in 58 30-second intervals				
μ	Peaks (k)/unit interval	Pr (k)	Expected No. of intervals (f_e)	Observed No. of intervals (f_o)
1	0	0.368	21.34	16
	1	.368	21.34	28
	2	.184	10.67	12
	3	.061	3.54	2
	4 or more	.019	1.1	0
Calculated χ^2 = 5.35				
Tabulated χ^2 = 7.81				

Right side: 55 peaks in 60 30-second intervals:				
μ	Peaks (k)/unit interval	Pr (k)	Expected No. of intervals (f_e)	Observed No. of intervals (f_o)
0.917	0	0.400	22.0	14
	1	.367	20.19	37
	2	.168	9.24	9
	3 or more	.065	3.58	0
Calculated χ^2 = 18.39				
Tabulated χ^2 = 5.99				

For the right side, in the same trial, the situation is somewhat different. The peak distribution was normal (table 3, line 11); however, the fit with the Poisson distribution was poor (table 4, right side). Here, the calculated χ^2 is much greater than the tabulated value indicating that the peaks at the right side are not random events occurring at a constant rate.

This difference between the left and right sides becomes somewhat clearer if the "elapsed time" between peaks is considered rather than the probability of peaks occurring in a 30-second interval. For random events that take place at a constant average rate and fit the Poisson distribution, a probability density function for the elapsed times between events should fit the exponential expression

$$f(t) = E \exp(-Et),$$

where E is the expectation of a peak in a given interval (10); for example, 20 seconds. If at the left side, 58 peaks occurred in 29 minutes, then the average number of 20-second intervals, $\bar{t}$, between peaks was 1.5. Taking E to be $1/\bar{t}$, we can write

$$f(t) = 0.667 \exp(-0.667t),$$

where t is the time measured in intervals of 20 seconds. This equation is plotted in figure 9.

From the left-side experimental data, if 58 peaks occurred, then a list of the 57 elapsed times between these peaks can be generated (table 5). From this list a histogram with 20-second intervals can be constructed and compared with the exponential equation in figure 9. A χ^2 test indicated that the histogram of the elapsed times was fit by the exponential equation, as expected.

TABLE 5. - Time intervals in seconds (t) between peaks

Interval No.	t	Interval No.	t	Interval No.	t
1	17	20	18	39	28
2	12	21	22	40	11
3	15	22	16	41	9
4	7	23	15	42	34
5	14	24	72	43	41
6	15	25	18	44	45
7	19	26	23	45	16
8	16	27	13	46	16
9	16	28	18	47	51
10	9	29	17	48	93
11	14	30	9	49	15
12	99	31	18	50	48
13	18	32	38	51	88
14	17	33	13	52	18
15	21	34	69	53	39
16	76	35	30	54	15
17	15	36	18	55	65
18	45	37	19	56	34
19	41	38	56	57	33

Average Interval ($\bar{t}$) = 30 seconds

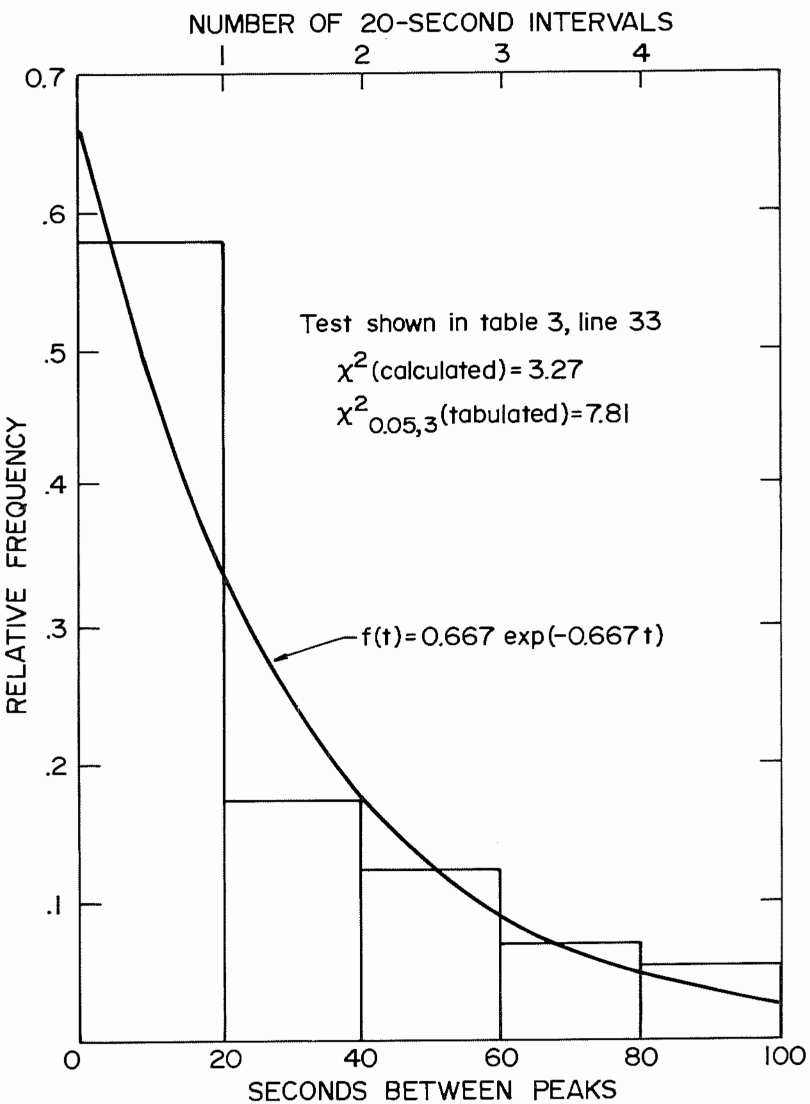

FIGURE 9. - Exponential function and histogram for the left-side data.

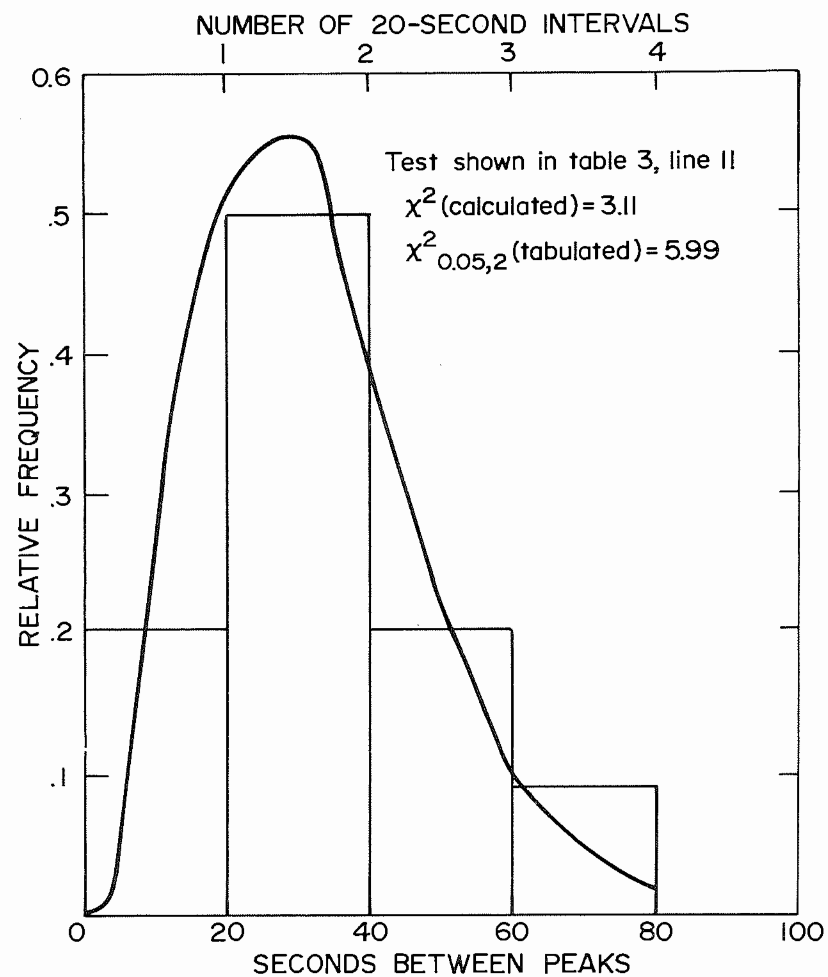

FIGURE 10. - Gamma function and histogram for the right-side data.

For the right side, where the peak occurrence does not fit a Poisson distribution, a histogram of the elapsed times did not fit an exponential expression, again as expected (fig. 10).

This histogram was best fit by a gamma distribution

$$f(x) = \frac{\lambda^{\eta}}{\Gamma(\eta)} x^{\eta-1} e^{-\lambda x},$$

where $\lambda = 2.82$, $\eta = 4.68$, and $\Gamma(\eta) = 15$.

This supports the thought that peaks at the right bit do not result from random events occurring at a constant rate. Thus, mixing at the right side appears to be less favorable than at the left, even though this difference is not apparent when considering the peak heights.

For this particular trial (table 3, lines 11 and 33), both sides have a peak height standard deviation below 0.2 and both are normally distributed. Table 3 does indicate, however, more log-normal distributions and higher peak medians occurring on the right side. This is probably due to the fact that more methane is swept towards the right side due to the direction of primary ventilation flow, as already noted in the section on effect of incomplete mixing on the distribution of methane concentration peaks.

CONCLUSIONS

Our experiments show that increasing the average air velocity in the face area improves mixing and decreases the extent of the methane concentration fluctuations. This agrees with the results of Baake, Leach, and Slack (1) which indicate that the Froude number has an important effect on the probability of a methane ignition. A statistical ranking of the concentration maxima produced results similar to those obtained by Kissell and others (2), namely, that a normal distribution corresponded to good mixing of methane and air whereas poor mixing gave a log-normal distribution.

The average velocity at the face can be increased by using a diffuser fan, decreasing the brattice-to-face distance, or using the blow brattice system of face ventilation. Not all locations in the face area were affected in the same way by changes in the ventilation system; the direction of primary airflow across the face was also an important factor.

A ranking of the methane concentrations at 30-second intervals produced results similar to those obtained with peaks. There are some indications that the effects of incomplete methane-air mixing are occassionally observed in entries if the airflow is low.

One trial, in which the peaks were normally distributed, was re-evaluated to measure the probability of occurrence of a peak in a given time interval. This probability fits a Poisson distribution on the left side, which was better ventilated and a Gamma distribution on the right side which was the less well ventilated.

It should be noted that although we make a definite distinction between normally and log normally distributed data, the distinction is not always that definite, as witnessed by the not-clear category. For the purpose of this report, however, we have simplified the analysis and have based our conclusions solely on the evaluation of empirically derived peak concentration data.

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U.S.G.P.O.—1974-605-992/537

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