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OCTOBER 1988

IMPROVED VENTILATION OF SEALED MINE GOB

Contract J0308029
Foster Miller Inc.

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

FINAL REPORT
FOR
IMPROVED VENTILATION OF
SEALED MINE GOB

BMI-7967

Contract No. JO308029

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Steven D. Wirch, D. Randolph Berry

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Abandoned underground coal mine areas must either be sealed or ventilated to comply with federal mine regulations. Ventilation of these abandoned areas is often impractical due to roof falls and inadequate primary mine ventilation. If the area is sealed, a very complex ventilation system is set up, in which the gob "breathes" in and out due to barometric pressure fluctuations. The Gob Assistant is a computer program (for use on IBM compatible personal computers) which allows the prediction of air flows into and out of a sealed mine area. Gas flows with applicable control techniques are also modeled. This information is presented to the user, who will decide which control technique, or combination of techniques, will ultimately be applied. The Gob Assistant is an intelligent gob simulator that can reduce the guesswork involved in predicting the effects of sealing and control techniques before they are applied.

This paper provides the fundamental principles upon which the Gob Assistant is based, verification of these principles, and an explanation of how these principles were integrated into the Gob Assistant.

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FOREWORD

This report was prepared by Foster-Miller, Inc., Waltham, MA under United States Bureau of Mines Contract No. JO308029. This contract was initiated under the Health and Safety Technology Program. It was administered under the technical direction of the Pittsburgh Research Center with Mr. Robert Timko acting as Technical Project Officer. Mr. Michael L. Nowicki was the contract officer for the Bureau. This report summarizes the work completed on the contract during the period September 1986 to December 1987. This report was submitted by the authors in October 1988.

The technical effort was performed by the Mining Division of the Engineering Systems Group under the direction of Mr. Terry L. Muldoon, with Mr. D. Randolph Berry as Program Manager.

The authors would like to extend their appreciation and acknowledgment to Mr. Robert Timko for the extensive technical and editorial review of the Gob Assistant. Special thanks is also forwarded to Mr. Steve Harrison, Consolidation Coal Company, for providing valuable assistance during the program development.

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1. INTRODUCTION

Sealing abandoned mine areas can reduce the primary ventilation required to maintain safe methane levels in bleeders and returns, when ventilation boreholes are used. Sealing can also reduce the potential of spontaneous combustion in abandoned mine areas by reducing barometric-induced airflow. Prediction of the benefits of sealing an area has in the past been mostly guesswork. Unsafe methane levels in returns, spontaneous combustion, and explosive gas mixtures can still occur in sealed areas.

The Gob Assistant is an intelligent gob simulator that can reduce the guesswork involved in predicting the effects of sealing and control techniques before they are applied. With the Gob Assistant a mine ventilation engineer can model an entire mine's sealed areas in less than half a day. After entering the gob constants (volume, methane concentration) and answering several pertinent questions dealing with the gob areas (elevation, pressures, and seal quality) an in-depth analysis of the gas flows into and out of the gob areas is given. Specific recommendations concerning which control techniques should be implemented and their expected effects on gas flows into and out of the sealed area are also offered.

2. ANALYTICAL MODEL

2.1 GOVERNING EQUATIONS

The flow into and out of a gob area will obey the laws of the conservation of mass (mass flow in = mass flow out). This flow has been observed to be linear with respect to change in pressure across the seal in American coal mines. This linearity is probably due to the low pressures which are observed across the seals (normally less than one inch water gauge).

Referring to figure 1, gas flow into and out of a sealed gob area will obey the laws of conservation of mass:

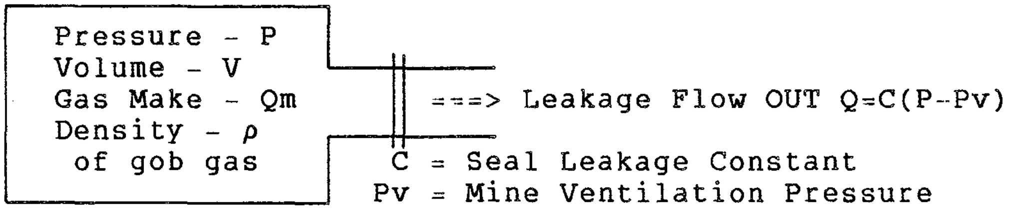

FIGURE 1. - Sketch of a simple gob area.

$$\frac{dMass}{dTime} = \rho * (Qm - Q)$$

where

Qm = gas make
Q = air flow across the seal

Given the Universal Gas Law:

$$PV = MRT \text{ or Moles } (M),\ M = \frac{PV}{RT}$$

Therefore:

$$\frac{V}{RT}\ \frac{d}{dt}\ (P) = \rho * [Qm - C(P-Pv)]$$

$$\frac{dP}{dt} = \rho * \frac{RT}{V} * [Qm - C(P-Pv)]$$

The change in pressure with respect to time may be broken down to two major variables, gas make (A1) and time constant (A2).

$$\frac{dP}{dt} = A1 - A2 * (P - Pv) \qquad (1)$$

where

$$A1 = \frac{\rho * R * T}{V} * Qm = \frac{P}{V} * Qm \qquad (1a)$$

$$A2 = \frac{\rho * R * T}{V} * C = \frac{1}{\tau} \qquad (1b)$$

Integration of the above equations for actual barometric data (Pv) results in the calculation of the gob pressure. Conversely, if the gob pressure has been measured, the seal leakage coefficient (C) may be determined. Flows into and out of the sealed area may be determined with the following flow equation during the integration process:

$$Q = \frac{A2 * (P - Pv) * V}{\text{Average Pressure}} \qquad (2)$$

where average pressure is determined from the gob's elevation.

We now have equations to determine the pressure (P) inside the gob area (equation 1) and the leakage flow (Q) into and out of the gob area (equation 2). The gas make (Qm) of a gob area is very small in relation to barometric induced flows. The primary effect of gas make (Qm) is on the gob gas methane concentration. The governing parameters in the above equations are the barometric pressures (Pv), and the time constant of the gob (τ).

The time constant of the gob (τ, as shown in equation 1b) is determined by the volume of the gob (V), the seal quality (C), and the gob pressure (P). The time constant of the gob area determines how long it takes the gob pressure (P) to respond to the driving function (barometric pressure, Pv). The greatest flows into and out of a gob area occur when the gob pressure is lagging behind the barometric pressure (delta pressure across the seals is large).

Barometric induced flows into and out of complex gob areas (several interconnected areas, openings on multiple returns, boreholes, etc.) obey the same general principles as simple gob areas, with slight modification and rearrangement of the equations.

2.2 VERIFICATION OF THE GOVERNING EQUATIONS

The preceding section presented a theoretical analysis or "model" which can be used to predict gas flow into and out of gob areas, depending on the barometric pressure (Pv) and two gob constants (A1 and A2). The gob constants in turn depend on the physical characteristics of the gob: the volume (V), gob pressure (P), gas make (Qm), and seal leakage coefficient (C). The volume and average pressure of a gob can be readily determined, but no data exists on Qm or C.[1] However, data did exist on time histories of measured barometric pressure and measured gob pressure for several mines, obtained through the Bureau of Mines, the Mine Safety and Health Administration, and industry sources. Qm and C could then be determined by fitting the calculated gob pressure curve using equation 1 to the actual data sets.

This analysis was performed on a dozen gob areas with volumes ranging from 100,000 ft^3 to over 10,000,000. One of the data sets also contained information on the methane flow out of the six gob areas in one mine system, from which it was possible to calculate the leakage flow - hour by hour - out of the gobs ("measured flow"). We then compared this measured flow to the predicted flow using equation 2. The results are shown in figure 2, where the measured flow is indicated by the square boxes, and the solid line shows the theoretical prediction. Note the strong correlation on leakage flow <u>out of</u> the gob (positive flow). Note that the theoretical model calculates both the positive flow of gas out of the gob and the negative flow into it. Since in "real life," there is no methane flow into the gob, the measured data shows a methane flow of zero when our model predicts negative flow, as you would expect. The computer model could have been easily re-programmed to set any negative

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[1] Some research has been done on determining the leakage through ventilation stoppings, but these stoppings were not directly comparable to the seals typically used for gob areas. Furthermore, the leakage coefficients for the ventilation stoppings were found to vary by more than an order of magnitude.

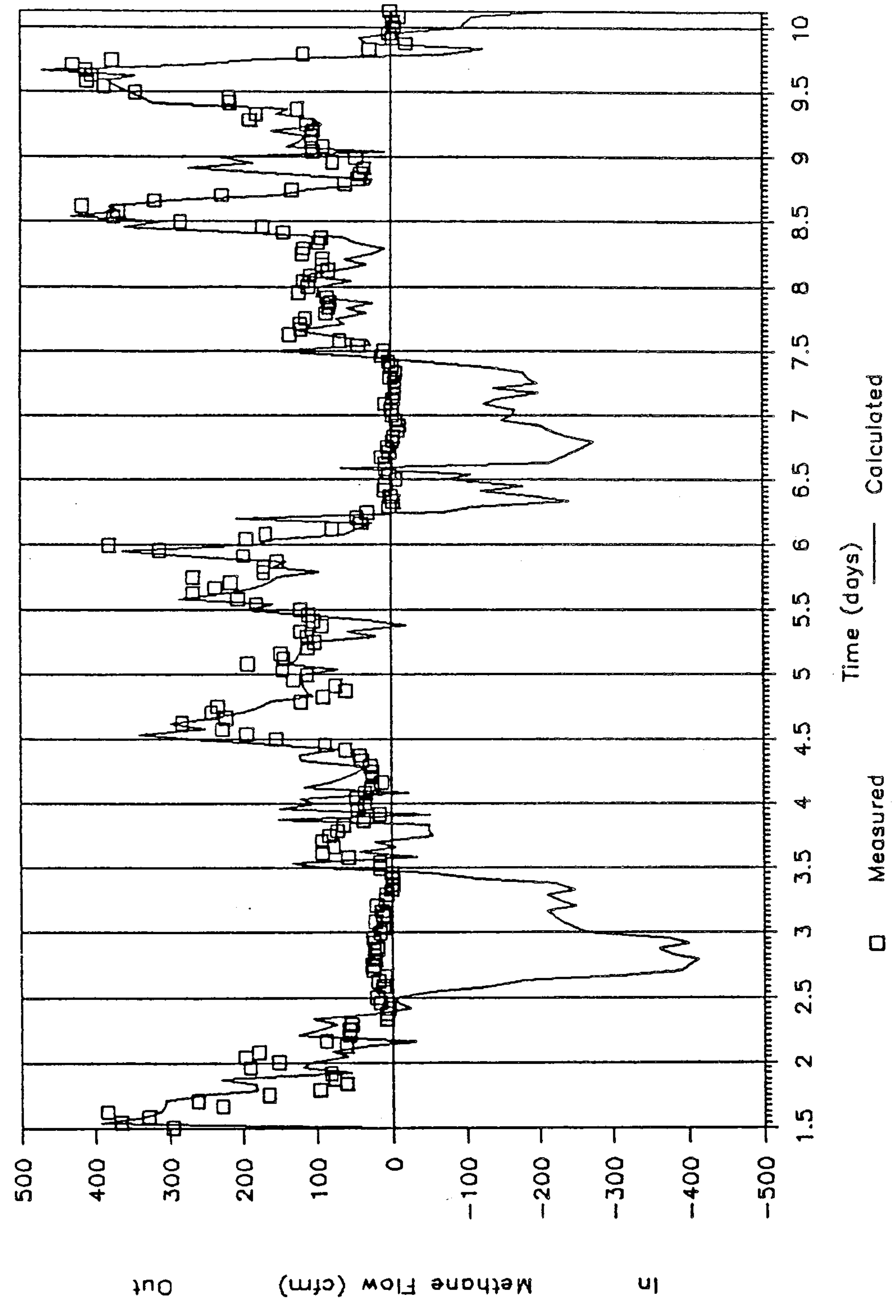

FIGURE 2. - Calculated methane flow (solid lines) versus measured methane flow (symbols).

flow to zero; however, in addition to methane flow out of the gob, we are also concerned with airflow into the gob (because of concerns about spontaneous combustion and/or creation of potentially explosive atmospheres). Thus, it was important to have the computer model predict both positive and negative flows, even though the data set (used for comparison) shows only the positive flows.

In summary, the available data sets of gob pressure enabled us to "back-calculate" values of C and Qm, and the data set on gob flow showed good correlation with the model's predictions for the hour-by-hour leakage flow out of the gob areas.

2.3 APPROXIMATION OF PEAK FLOWS AND YEARLY GAS INFLOWS

The major effort in this program was to develop a computer model which would aid a user in estimating the leakage flows into and out of gob areas - both peak flows and yearly totals. The model discussed in the previous section had shown that this could be done, provided that the barometric pressure history (Pv) and the gob constants A1 and A2 could be specified.

The previous gob analysis had been limited to the data sets for which actual gob pressures had been measured as well as the barometric pressures, for periods of 10 days or less. To expand the model to predict peak flows and yearly totals required much more comprehensive data on barometric pressure. Accordingly, a 12-year history of hourly barometric pressure in the Pittsburgh area was obtained from the National Climatic Data Center. Multiyear histories of other mining areas (Denver, Salt Lake City, etc.) were also obtained and compared to Pittsburgh. While the absolute pressure was considerably different (because of differences in altitude), the pressure <u>fluctuations</u> were comparable. The effects of altitude, and thus absolute pressure, are accounted for in the value of P in equation 1a.

Even with a powerful personal computer, running the model through 12 years of hour-by-hour data to find the peak flows and to sum up the yearly flows takes a considerable amount of time (several hours or more depending upon the machine). To analyze every combination of gobs with different gob constants would be clearly impossible. However, the analysis of several specific gobs discussed in section 2.2 had indicated that a number of simplifications might be possible:

a. Although the sizes of the gobs (V) and the tightness of the seals (C) varied widely, the resultant time constant (τ, equal to 1/A2) stayed in a fairly narrow range, typically 1/2 to 4 h.

b. For a fixed value of τ (or 1/A2), equation 2 shows that the leakage flow Q is a linear function of V, the gob volume. That is, a gob volume twice as large will have twice the leakage flow, <u>if the time constant remains the same</u>.

c. The effects of A1 (the gob constant which depends on gas make inside the gob, Qm) on leakage flow is small; furthermore it is additive. That is, increasing the gas make by 5 cfm simply increased the leakage flow in any hour by 5 cfm. The major influence of gas make is on the average methane concentration inside the gob area, which is analyzed later in this section.

Given the above observations, it becomes reasonable to analyze gob areas in terms of a few typical examples, which we will refer to as "generic" gobs. These gobs have an arbitrary volume of 1,000,000 ft^3, a gas make of zero, and time constants ranging from 0 to 8 h. Each of these "generic" gobs was then plugged into the computer model and analyzed hour-by-hour for the 12-year history of barometric pressure change. The computer calculated the changes in gob pressure and resultant leakage flow for each one-hour interval, sorted the values, and recorded the worst-flow cases (and the date and hour at which they occurred). An example of the results are shown in table 1. Examination of this data indicates that the majority of the peak flows occurred during the winter months (December to April). It was also noted that the peak gas outflows were very similar to peak gas inflows (the only difference should be due to the difference in density between the gob gas and atmosphere). Finally, note that the peak flows decrease with increasing values of τ.

In addition to the worst case peak flows, the computer recorded the number of occurrences of each flow (grouped in tens, i.e., number of hourly occurrences of flow between 0 and 10 cfm, 10^+ to 20, etc.) and the total flow in and out. These values are shown in table 2. Once again, it can be noted that increasing the time constant decreases the peak flows and also decreases the total yearly inflows and outflows.

The computer model was also used to test the effect of A1 (the gob constant relating to gas make, Qm) over the 12-year period. In this simulation, the initial gob methane concentration was set to zero, and then calculated hour-by-hour as it increased, depending on the barometric pressure change and the assigned gas make, Qm. Figure 3 shows one set of results: the methane concentration rises slowly from zero at the beginning of 1975 (the start of the barometric pressure data) and approaches a final

TABLE 1. - Peak flow data for a simple gob based upon 12-yr barometric data set

Gasmake = 0.00 cfm

Q given n cmf per million cubic feet of gob volume

Rank	Tau (hours)							
	1/2		1		2		8	
	mo/dy/yr/hr	Q	mo/dy/yr/hr	Q	mo/dy/yr/hr	Q	mo/dy/yr/hr	Q
1	1/26/78/ 1	94	1/26/78/ 1	86	1/26/78/ 3	76	1/26/78/ 3	46
2	12/ 5/77/4	84	12/ 5/77/4	65	1/10/77/ 6	51	1/10/77/ 6	31
3	1/10/77/ 6	77	1/10/77/ 6	64	12/ 5/77/4	47	3/18/77/11	27
4	1/14/83/14	72	3/21/80/ 5	59	3/21/80/ 5	47	4/ 6/82/ 2	27
5	3/21/80/ 5	71	1/14/83/14	55	1/25/75/13	44	1/25/75/13	27
6	6/ 9/85/ 9	70	2/27/84/14	52	3/ 8/84/13	43	12/ 5/77/4	27
7	2/27/84/14	60	1/25/75/13	51	4/ 2/75/23	42	1/13/76/20	27
8	1/25/75/13	57	4/ 2/75/23	51	1/13/76/19	41	4/ 3/82/ 9	27
9	1/11/75/ 3	57	3/ 8/84/13	50	3/18/77/ 5	40	4/ 3/75/ 4	27
10	4/ 2/75/23	57	12/26/75/2	49	1/14/83/15	40	3/21/80/ 7	26
11	12/26/75/2	56	6/ 9/85/ 9	48	2/27/84/14	39	12/28/83/4	24
12	6/ 2/80/20	56	2/12/77/15	47	4/ 3/82/ 7	39	2/12/85/14	23
13	2/12/77/15	55	1/13/76/15	46	12/26/75/2	39	1/ 4/82/ 6	23
14	6/11/75/14	55	12/28/83/3	46	12/28/83/4	39	3/19/86/ 5	23
15	12/28/83/3	54	4/ 3/82/ 7	45	4/ 6/82/ 2	39	1/23/82/ 5	23
16	3/ 8/84/13	54	3/18/77/ 2	44	1/ 4/82/ 5	37	12/26/75/5	22
17	12/ 1/85/4	54	1/11/75/ 3	42	2/12/77/15	37	3/16/76/ 8	21
18	3/18/77/ 2	54	1/23/76/15	42	1/23/76/15	36	1/17/85/ 6	21
19	5/ 5/85/13	52	1/ 4/82/ 5	42	12/ 1/85/6	35	4/14/80/16	21
20	12/30/76/3	51	12/ 1/85/4	41	12/ 4/83/3	35	1/21/79/ 2	21
21	5/17/77/14	51	12/ 4/83/3	41	1/31/82/15	35	1/24/79/13	21
22	1/13/76/15	51	4/ 6/82/ 2	41	3/ 7/75/12	34	4/ 4/79/15	21
23	12/26/85/5	50	1/31/82/13	41	4/ 4/79/15	34	12/ 4/83/5	20
24	6/24/79/12	50	3/12/76/15	40	3/19/86/ 4	33	1/31/82/16	20
25	4/ 3/82/ 7	50	6/ 2/80/20	40	1/23/82/ 5	33	2/ 2/83/15	20
26	9/24/78/ 6	50	3/12/75/11	40	3/12/76/15	33	3/12/85/ 4	20
27	12/ 7/84/3	50	11/ 9/79/4	40	1/21/79/ 2	33	3/22/77/ 5	20
28	2/21/80/22	49	1/21/79/ 2	40	3/ 4/77/14	33	12/ 6/83/3	20
29	5/ 1/76/ 8	49	1/11/80/14	40	3/16/76/ 8	33	3/ 8/84/13	20
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38	4/ 9/75/13	46	12/ 6/83/8	39	1/11/80/14	31	11/20/83/6	19
39	3/16/82/11	46	4/ 4/79/15	38	11/ 9/79/4	31	12/ 8/77/2	19
40	1/23/76/15	45	11/17/76/5	38	2/ 1/81/ 7	31	3/ 4/85/17	19
41	12/ 4/83/3	45	12/26/85/5	38	3/ 4/85/15	31	1/ 8/78/18	19
42	1/31/82/13	45	1/ 8/78/15	38	12/ 8/77/2	31	2/ 1/81/ 7	19
43	1/21/79/ 2	45	3/24/80/13	38	2/ 2/83/14	30	1/11/80/14	19
44	1/ 4/82/ 5	45	3/31/82/15	37	1/ 7/80/ 3	30	11/17/76/7	19
45	3/12/76/15	45	3/14/78/ 3	37	1/17/85/ 2	30	12/ 1/77/2	19
46	10/ 1/77/1	45	2/ 1/81/ 7	37	3/24/80/13	30	12/22/85/6	19
47	4/ 5/82/24	44	9/24/78/ 6	37	3/31/82/15	30	11/26/79/2	18
48	2/12/85/ 6	44	1/23/82/ 5	37	3/11/85/16	30	10/25/80/1	18
49	2/18/76/ 5	44	3/19/86/ 4	37	3/14/75/10	30	3/14/78/ 3	18
50	3/ 7/75/12	44	3/14/75/10	36	1/11/75/ 3	30	4/ 9/82/ 5	18

TABLE 2. - Yearly flow characteristics of simple gob areas

Gasmake(cfm/Mft^3)= 0.00

	Quantity (cfm/Mft^3)	Tau (hours)					
		0	1/2	1	2	4	8
	-100	0	0	0	0	0	0
I	-90	0	0	0	0	0	0
n	-80	0	0	0	0	0	0
f	-70	0	0	0	0	0	0
l	-60	2	1	0	0	0	0
o	-50	6	4	2	1	0	0
w	-40	19	14	8	4	0	0
	-30	46	51	42	23	8	1
	-20	397	375	258	198	124	39
	-10	2695	2204	1868	1676	1462	1193
	0	2556	3584	4445	4952	5590	6337
	10	2522	2042	1806	1680	1445	1134
O	20	440	411	287	206	127	60
u	30	55	63	42	24	9	3
t	40	20	12	7	3	0	0
f	50	5	3	1	0	0	0
l	60	2	1	0	0	0	0
o	70	0	0	0	0	0	0
w	80	0	0	0	0	0	0
	90	0	0	0	0	0	0
	100	0	0	0	0	0	0
Yearly inflow (cubic feet)		-2246000	-1912850	-1531350	-1295650	-1040750	-764600
Yearly outflow (cubic feet)		2234120	1902333	1560085	1344037	1080371	805075

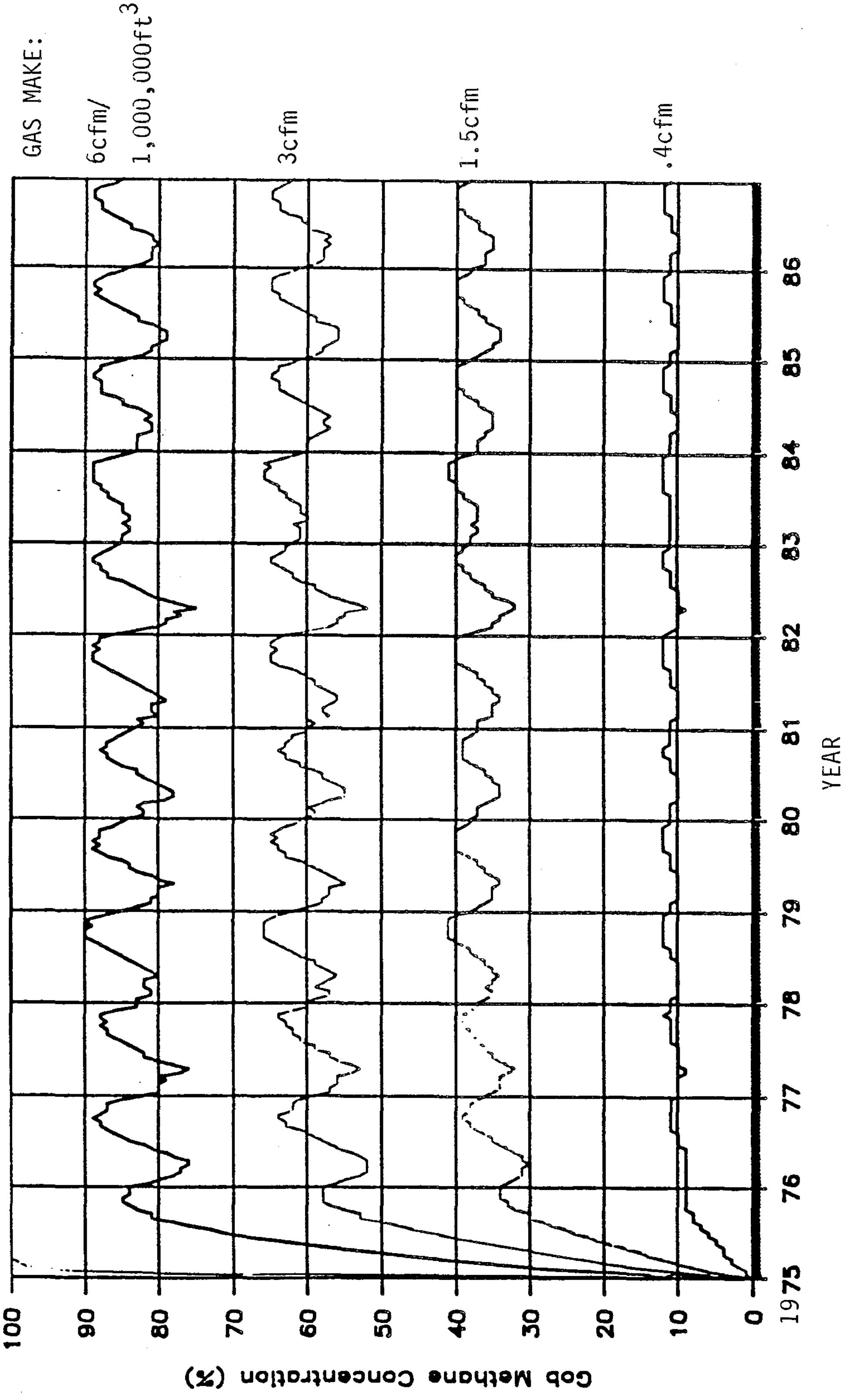


FIGURE 3. - Gob methane concentration versus time (yr) for a simple gob with a time constant (Tau) of 1 h.

"average" value after about one year. This average value depends on the gas make: a gas make of 1.5 cfm (per MMf^3 of gob volume) results in a steady-state methane concentration of about 37%, whereas 3 cfm eventually produces about a 60% methane concentration inside the gob. The length of time required to reach this "average" value depends on the time constant of the gob. Figure 3 shows only a 1 h time constant: gobs with higher time constants take longer to reach equilibrium. Note also that the methane concentration fluctuates around its steady-state value, because the higher winter-time leakage flows (observed in table 1) cause a dilution of the methane in the winter months.

The preceding tables and figures have been provided to show the methodology used in developing the computer model. How the computer then uses this information to analyze a "real" gob may best be illustrated using a simple example:

Suppose a mine operator wants to develop a bleeder ventilation plan such that a mine evacuation will be required, <u>on average</u>, no more than once a year due to excess methane in the bleeder. The following information is available:

a. Gob volume, $V = 10{,}000{,}000\ ft^3$.

b. Seal evaluation, from which the computer estimates C.

c. Mine elevation, from which the computer calculates average pressure.

d. Methane concentration in gob = 75%.

From figure 2, we see that an average methane concentration of 75% means a gas make of approximately 4 cfm per MMf^3 of gob volume.

Given V and C (and knowing p, R, and T), the time constant is calculated - assume the value is 1 h.

Since there is 12 years of barometric history, the 12th worst flow would represent the worst case, which would <u>on average</u> only be exceeded once a year. According to table 1, this flow is 47 cfm per MMf^3 of gob volume. Therefore, the 12th worst flow is:

$$\text{Design case} = \frac{(47 \text{ cfm} + 4 \text{ cfm gas make})}{1{,}000{,}000 \text{ ft}^3} * 10{,}000{,}000 \text{ ft}^3$$

$$= 510 \text{ cfm total gas outflow}$$

$$= 510 * 75\% = 383 \text{ cfm methane}$$

Thus, the mine operator should design his bleeder system to provide sufficient air to dilute 383 cfm of methane.

This answer is really just the beginning of the analysis process. The real value of the computer model lies in analyzing different techniques (improved seals, boreholes, more bleeder air, etc.) and seeing the relative amount of improvement, rather than the magnitude of a single calculation, which depends on a number of assumptions and estimates.

The preceding example was intentionally made quite simple in order to illustrate the basic principles of the operating system. In reality, the system has many features and complexities which can best be illustrated by using the system. For example, it would take an infinite number of tables to predict the performance of all possible gobs. It was, therefore, necessary to develop equations which could "extrapolate" between values of the "generic" gobs for both peak and yearly calculated flows. An error limit of less than 20% was maintained between calculated and approximated values over the entire "generic" gob range. Software was also developed so that complex, interconnected gobs - including pressure-imbalanced systems - could be modeled and analyzed. The next section describes how an operator interacts with the computer in order to provide the necessary information for analysis.

3. DEVELOPMENT OF THE GOB ASSISTANT

The above approximation methods permit calculation of flows into and out of a gob area during an average year. The unknown values are: gob pressure(yearly average), gob volume, gob methane concentration, and gob type(simple, interconnected, etc.). In the case of gob areas that have a pressure imbalance (seals on different ventilation splits or leakage to surface) the relative pressures outby the gob area also must be determined.

The Gob Assistant was designed to be self-teaching, with no need for a manual or other outside instruction. After the computer is turned on, the user follows the on-screen instructions through these steps:

a. Program installation (one-time only).

b. Demonstration program (first-time users).

c. "Construction" of the mine map (schematic).

d. Entering additional data, in response to computer-generated questions.

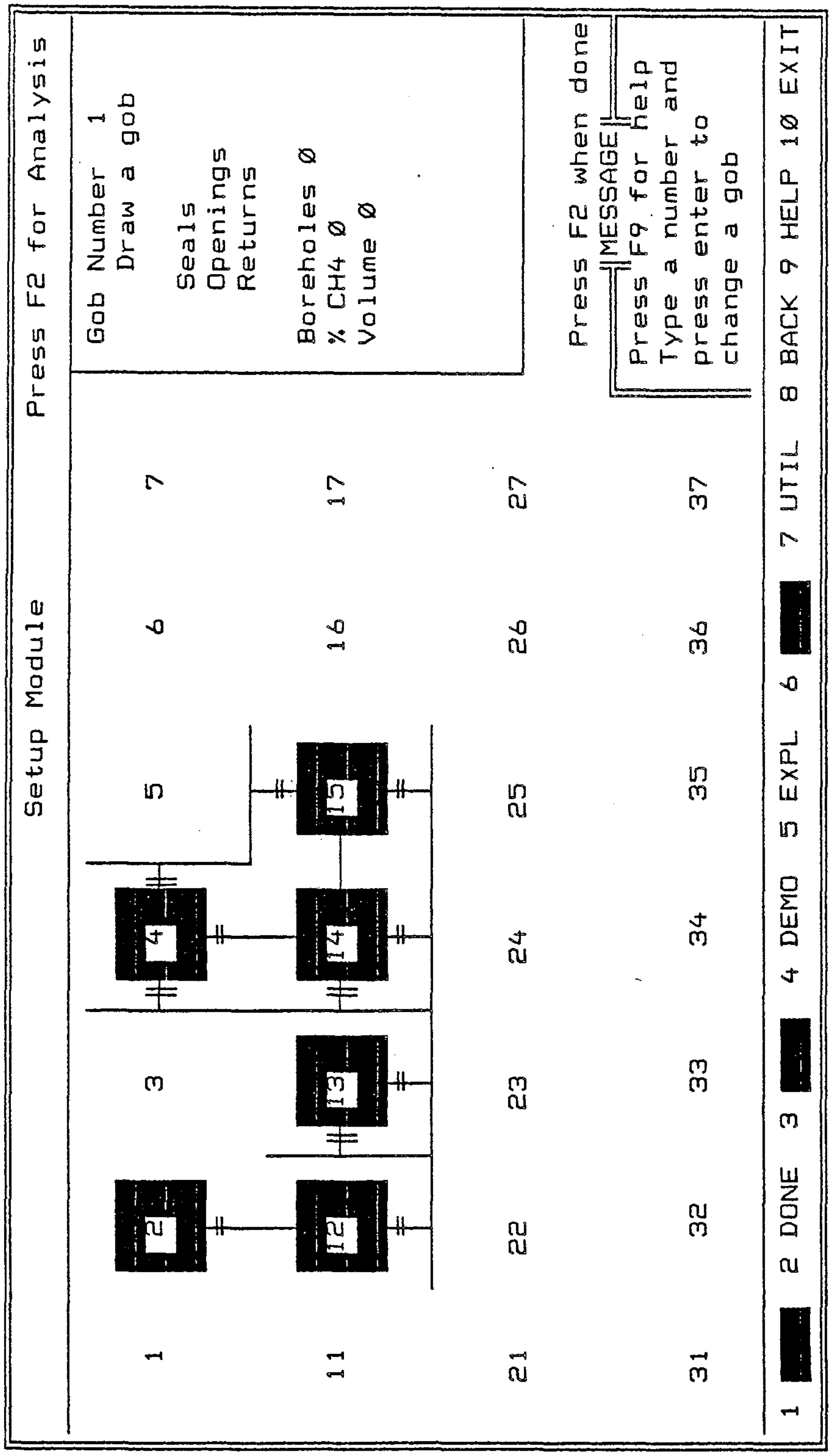
e. Computer analysis.

f. Computer-generated recommendations.

g. Return to step c or d to experiment with different layouts, seals, boreholes, etc.

The greatest user-computer interaction is seen in step c, where the user constructs a map of the desired mine layout. Figure 4 shows a typical picture of the screen during this process. On the right-side of the screen is a data entry table, where the user specifies the gob location(s), seals, etc. As each item is entered, it is automatically drawn on the map on the left side of the screen. To aid first time users, a demonstration run is included which shows how to enter the data.

When the data has been input and the user prompts the computer for data analysis, the input data is examined for validity. If errors are detected (missing volumes, seals, etc.) the user is informed of the errors, and prompted to fix them. If the data is ok, analysis begins and additional information is collected. The gob elevation is requested, and used to determine the average yearly pressure of the gob areas. The gob areas are then classified by type. Gob areas that do not connect to an



Setup Module

Press F2 for Analysis

Gob Number 1
Draw a gob

Seals
Openings
Returns

Boreholes 0
% CH4 0
Volume 0

Press F2 when done

MESSAGE
Press F9 for help
Type a number and
press enter to
change a gob

FIGURE 4. - Data input screen and table. From this screen the user draws his mine map, and inputs many of the gob constants.

airway are transformed based upon their position to gob areas that do connect to airways.

An approximation of the seal leakage coefficient is then made, based upon the answers to several seal quality questions. With subsequent uses of the program the user is asked whether or not the seal quality has been altered. This saves time and prevents unwanted alteration of seal quality.

When the seal quality is known, the user is prompted to determine the problems as he sees them, and whether or not boreholes and additonal seals may be installed. If additional boreholes can be used, and are needed, the user is asked what he expects their length to be.

Once all of the necessary data is collected, analysis of the existing gob areas is performed. If the gob area has methane problems, boreholes may be added to determine their effect on methane levels in the returns. Additional seals outby the existing seals may also be modeled to determine their effect. Depending upon the user's constraints and the results of the analysis, recommendations for each primary gob area are presented. Peak methane flows and yearly inflow are calculated. Changes in these flows are presented if control techniques are valid. If boreholes should be added, the borehole fan flow is given along with corresponding fan pressures at four different borehole diameters. With the touch of a key the user may request additional information or a hardcopy printout.

The end result is that the user has another tool to aid in analyzing and planning sealed gob areas. It must be emphasized that the major value of this program is for making comparisons - <u>not absolute calculations</u>. For example, using the computer model will enable an operator to estimate how much improvement can be expected in bleeder methane concentrations if the seals are improved or boreholes added - the comparison of "before" and "after" can be made before the first trowel of mortar is laid or the first hole drilled.

4. SUMMARY

Equations have been developed to determine peak and yearly flows into and out of a sealed gob area during an average year. These equations have been incorporated in a computer program which allows a mine ventilation engineer to model flows into and out of a gob area with various control techniques. Analysis of the flows with computer-generated control techniques permits specific recommendations which could reduce flows into and out of the gob areas.