consider them explicitly at each step. By using the heuristic within this environment, the engineer can use this summary data to help guide the decision to override the recommendation of the heuristic toward blending and strip ratio goals.

Finally, the control window is essentially the input window with prompts. The program displays the ranked block priorities in this window and accepts responses concerning which block is to be mined. Upon receiving the command to mine a given block, all of the other windows are updated. The summaries are recalculated, and the graphics windows convert the block just mined to its new status, generally by a change of color in the display. Through the control window, it is also possible to put the block back and choose another.

Summary

This paper has presented a new approach aimed at improving the mine production scheduling process. Based on the traditional approaches, the new method adds an ability to look ahead and analyze how important it is to mine in any area at the current time. The purpose is to approximate the results that could be achieved by using a mathematical optimization without leaving the logical context of traditional production scheduling procedures followed by most mining engineers. This approach also proves to be valuable for mine planning.

A computer program has been developed that incorporates the approach and system design described here. The paper, however, describes what a program of this nature should accomplish in general terms only. There are many alternative forms that a program based on this paper can take in addition to the one developed by the author. ■

References

Gershon, M.E., 1983, "Optimal Mine Production Scheduling: Evaluation of Large Scale Mathematical Programming Approaches," *International Journal of Mining Engineering*, Vol. 1, pp. 315-329, December.

Helgeson, W.B., and D.P. Birnie, 1961, "Assembly Line Balancing Using the Ranked Positional Weight Technique," *The Journal of Industrial Engineering*, Vol. XII, No. 4.

Canonical diagram as a graph representation of a mine ventilation network

A.M. Wala and T. Altman

Abstract – *Using theory of network planning together with graph theory, an algorithm is presented that creates canonical diagrams for mine ventilation networks (MVN). The data generated by the algorithm is used in the construction and plotting phases of a program that automatically plots the canonical diagrams, which can then be used for further studies of a given MVN.*

Introduction

The structure of a mine ventilation network (MVN) can be represented graphically using either the mine plan (map) itself or a number of other types of diagrams. In the US, the two most common approaches are line and schematic diagrams (Figs. 1 and 2).

The purpose of this paper is to introduce another type of diagram, called the canonical diagram (Wala and Kim, 1985). The method of MVN representation that uses canonical diagrams is used extensively in Europe, especially in Poland, where it was developed.

The canonical diagram is a noncalibrated topological image of a ventilation system. It gives a simple representation of the ventilation network, allows for the classification of airflows within it, and enables rapid computer analysis and computation, as well as the representation of results. It is especially useful in studying and controlling airflow, and it may be a lifesaving tool in conducting rescue operations during and after mine fires (e.g., Czeczott, 1925).

The concept of using the canonical diagram to represent ventilation systems was introduced by H. Czeczott in 1925. His terminology describing the topology of connections in MVN was later adopted by mathematicians working in graph theory. In 1956, H. Bystron extended the original concept, introducing the method for plotting canonical and potential diagrams (Fig. 3). Using state-of-the-art computer techniques, these ideas and concepts can now be implemented and used in practice.

Mine ventilation network as a graph

The flow model of a physical flow system, such as a mine ventilation system, can be represented using a graph that consists of a set of branches, which will correspond to the airways of a mine, and a set of nodes, which are the interconnection points between the airways. It may be said that a branch, e_{ij}, connects nodes v_i and v_j. Hence, the set of branches is a collec-

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tion of ordered pairs of node indices (i, j) that denote the start and end points of a given branch. Such a collection of nodes and branches is called a linear graph or a canonical diagram (Figs. 4a and 4b). By assuming one of the two directions as a reference direction of a branch, indicated by the arrows in Fig. 4b, a directed graph is created.

A graph can be *open* with the beginning node v_1 and end node v_5 (Fig. 4a), or *closed* if it has an additional (closing) branch through the atmosphere (Fig. 4b). In practice, the majority of mines have more than one intake and return shaft. To create a graph representation of these mines, new beginning and end nodes are added to the graph and are connected to all of the intake and return nodes, respectively (Fig. 4c).

To construct a graph of the ventilation network as a canonical diagram using the ventilation plan, line diagram, schematic diagram, or three-dimensional (isometric) diagram (Fig. 5) requires experience and, sometimes, even knowledge about the physical nature of the underground system. The majority of mistakes that could be made while plotting canonical diagrams will be eliminated when the theory of network planning and graph theory are applied to simplify the problem. Moreover, computers can be used to further speed the process of analyzing and preparing the data needed for these diagrams.

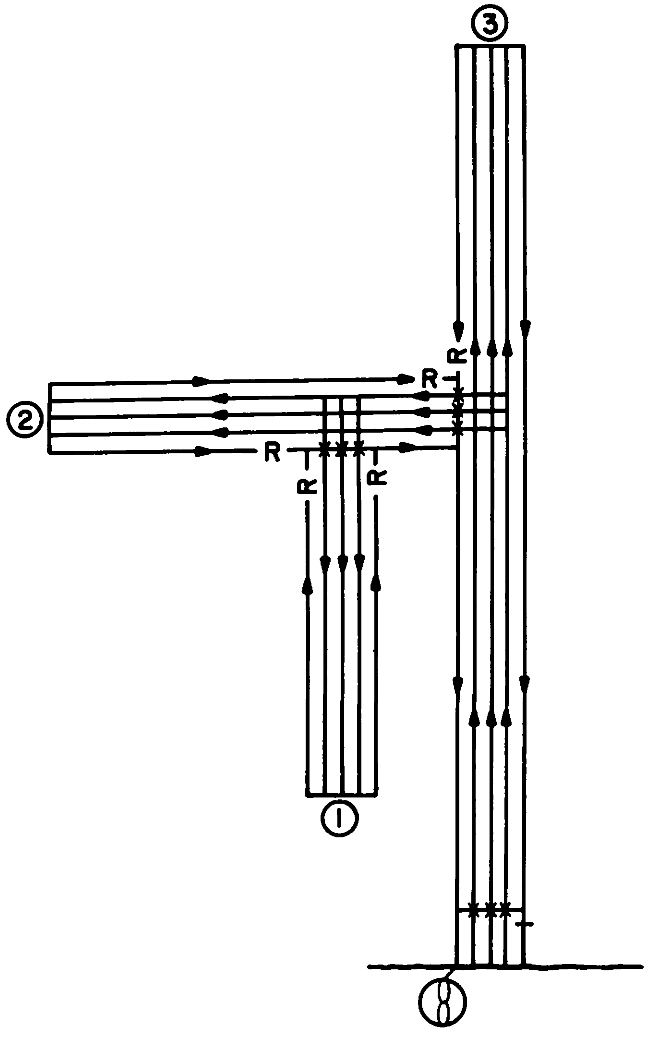

Fig. 1 — Line diagram of MVN

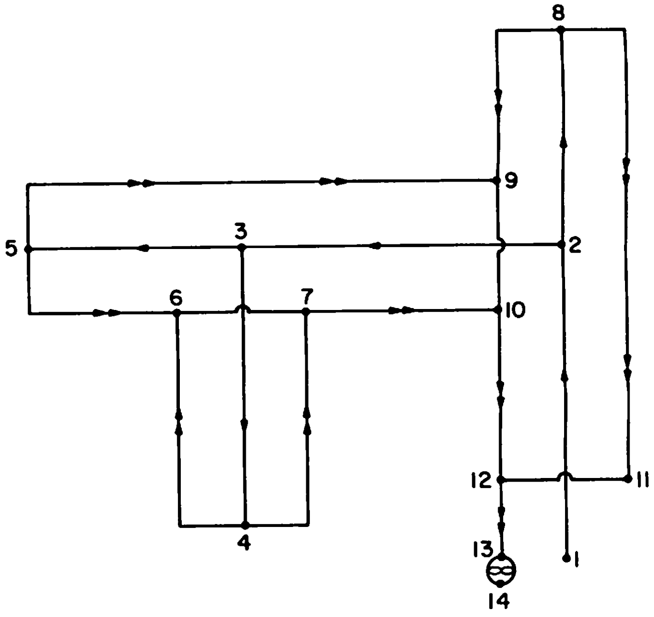

Fig. 2 — Schematic diagram of the MVN shown in Fig. 1

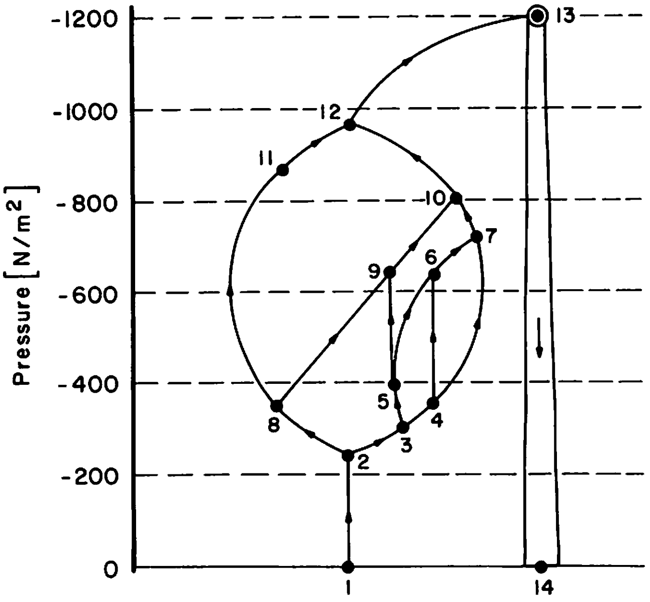

Fig. 3 — Potential diagram of the MVN shown in Figs. 1 and 2

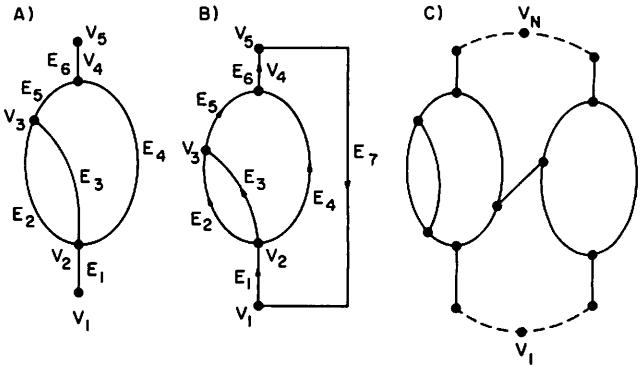

Fig. 4 — Mine ventilation network: (a) as an open graph; (b) as a closed and directed graph; (c) graph for a multishaft (multiopening) MVN

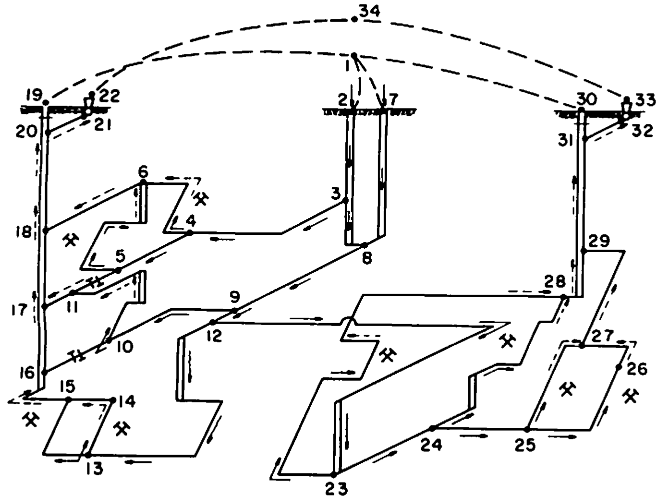

Fig. 5 — Three-dimensional (isometric) diagram of a multishaft mine ventilation system

Node labeling algorithm for MVN

Theory of network planning, together with graph theory, may be used to develop an algorithm that will create a (systematic) enumerated graph of a ventilation network. Enumeration of such a graph requires that the set of nodes be grouped into levels (and given appropriate labels), according to their relative distance from the start node.

Let $G = (V, E)$ be an acyclic directed graph representing the airflow network of a given mine. The branches, $e_{ij} \in E$, represent the airways, and the nodes, $v_i \in V$, correspond to their intersections. With each node, $v_i \in V$, associate a *level* function defined recursively as follows:

- $\text{level}(v_1) = 1$, where v_1 is the node corresponding to the main intake vent of the mine.
- $\text{level}(v_i) = 1 + \underset{e_{hi} \in E}{\text{Max}}\, \text{level}(v_h) \quad h = 1, 2, \ldots,$.

Now partition V into equivalence classes $V_1, V_2, \ldots, V_m$, according to the level function (i.e., $v_k^i \in V_k$ if $\text{level}(v_k^i) = k$).

Labeling the nodes in V is a relatively straightforward procedure. First, set $V_1 = v_1$. Next, for all nodes v_i, if $e_{1i} \in E$, then each v_i is relabeled as $v_1^1, v_1^2, \ldots, v_1^f$, where f is the number of nodes at the first level. The procedure is iterative in that we first label all of the nodes on the first level (i.e., level = 1), the second level, ..., the m-th level, where m is the diameter of the graph G. Obviously, once a node v_k^i has been assigned an index k, that index will never change (since it could only increase in value during the next iterations, which would imply that the graph was cyclic to start with, or that the level function was not evaluated properly).

The i index of v_k^i will indicate the order in which the given node has been assigned to the set V_k. Using a modified version of Dijkstra's algorithm (Aho, Hopcroft, and Ullman, 1974), it is possible to implement the abovementioned labeling algorithm to run in time proportional to the number of branches in the graph.

The graph labeling procedure described above is used by the construction and plotting routines, which actually generate the canonical diagram of the ventilation network.

Canonical diagrams created by the developed method

The proposed method will be examined, by example, for two different ventilation networks. First, given a simple ventilation system, whose line and schematic diagrams are shown in Figs. 1 and 2, respectively (e.g., Hartman, Mutmansky, and Wang, 1982), we will create the canonical diagrams (generate the subsets $V_1, V_2, \ldots, V_m$, of V) manually, and then by a computer. To avoid problems later, the nodes of the graph should be carefully numbered. The following procedure was used to assign the initial node labels:

> The nodes were numbered so that all branches have the property that $i < j$. This will always be possible because the directed graph in question is (by definition) acyclic.* To accomplish this, 1 is assigned to the entrance (main intake) node; then the next (unused) label is assigned for any unlabeled node, all of whose predecessors have already been labeled. This procedure is repeated until all nodes have been labeled (Fig. 2).

The procedure is based on the idea of breath-first traversal of graphs (e.g., Aho, Hopcroft, and Ullman, 1974), which accesses the nodes in level order and, hence, for all branches e_{ij}, ensures the property that $i < j$. It should be noted that the foregoing labeling of nodes is by no means unique.

The set V_1 consists of the node that corresponds to the main intake point from which the air enters the mine. The set V_2 contains all nodes that are directly connected to $v_1^1 = V_1$ and have no other predecessors. In V_3, all nodes that have at least one predecessor node in V_2 are included, but no others (unassigned ones). Observe that it is possible for a node in V_3 to be directly connected to $v_1^1 = V_1$, but if that node also has a predecessor in V_2, then it could not have been included in V_2 during the previous step. The procedure will terminate when all the nodes have been assigned a label. It is obvious that the nodes that belong to the same set V_i cannot be connected.

For the ventilation system shown in Fig. 2, the partition of the set V into levels can be displayed as follows:

V_1 (level 1) — 1
V_2 (level 2) — 2
V_3 (level 3) — 3, 8
V_4 (level 4) — 4, 5, 11
V_5 (level 5) — 6, 9
V_6 (level 6) — 7
V_7 (level 7) — 10
V_8 (level 8) — 12
V_9 (level 9) — 13
V_{10} (level 10) — 14

or it can be seen graphically in Fig. 6.

Let us evaluate $\text{level}(v_{12})$. One approach is to list all paths from v_1 to v_{12} and then choose the longest one (in terms of the number of nodes in it). Clearly the length of this path will indicate the lowest possible level that can be assigned to v_{12}. There are six unique paths from v_1 to v_{12}:

(a) $v_1 - v_2 - v_8 - v_{11} - v_{12}$
(b) $v_1 - v_2 - v_8 - v_9 - v_{10} - v_{12}$
(c) $v_1 - v_2 - v_3 - v_5 - v_9 - v_{10} - v_{12}$
(d) $v_1 - v_2 - v_3 - v_5 - v_6 - v_7 - v_{10} - v_{12}$
(e) $v_1 - v_2 - v_3 - v_4 - v_6 - v_7 - v_{10} - v_{12}$
(f) $v_1 - v_2 - v_3 - v_4 - v_7 - v_{10} - v_{12}$

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*For closed graphs, a special label name is assigned to the closing branch.

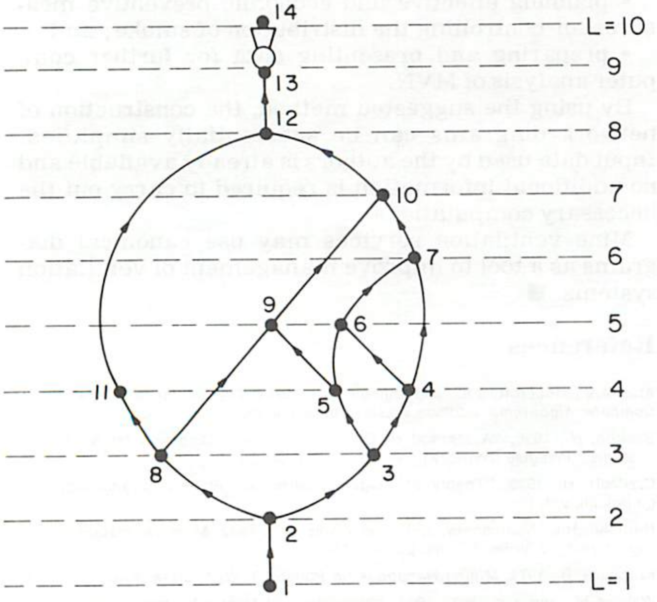

Fig. 6 — Canonical diagram of the MVN from Fig. 1, constructed by utilizing data created using the suggested procedure

Table 1

```
ENTERED NUMBER OF BRANCHES      18
- - - - - - - - - - - - - - - - - - - - - - -
STRUCTURE OF THE MINE VENTILATION NETWORK
BRANCH #        START NODE          END NODE
- - - - - - - - - - - - - - - - - - - - - - -

   1                1                  2
   2                2                  3
   3                2                  8
   4                8                  11
   5                11                 12
   6                12                 13
   7                3                  5
   8                3                  4
   9                4                  6
   10               5                  9
   11               9                  10
   12               5                  6
   13               6                  7
   14               7                  10
   15               10                 12
   16               4                  7
   17               13                 14
   18               8                  9
- - - - - - - - - - - - - - - - - - - - - - -
J2 AND J3 ARE INTERCONNECTED NODES,
J2 AT LEVEL L, J3 AT LEVEL N2
   J2               J3                 N2
- - - - - - - - - - - - - - - - - - - - - - -

             LEVEL NUMBER L= 2
   2                1                  1
             LEVEL NUMBER L= 3
   3                2                  2
   8                2                  2
             LEVEL NUMBER L= 4
   11               8                  3
   5                3                  3
   4                3                  3
             LEVEL NUMBER L= 5
   6                4                  4
   6                5                  4
   9                5                  4
   9                8                  3
   6                4                  4
   6                5                  4
             LEVEL NUMBER L= 6
   7                6                  5
   7                4                  4
             LEVEL NUMBER L= 7
   10               9                  5
   10               7                  6
             LEVEL NUMBER L= 8
   12               11                 4
   12               10                 7
             LEVEL NUMBER L= 9
   13               12                 8
             LEVEL NUMBER L= 10
   14               13                 9
```

Paths (d) and (e) are both of length 8, which is the level assigned to v_{12}. Even with the help of a computer, the method of enumerating all paths would quickly become unmanageable as the number of nodes (and branches) increases. Fortunately, the authors' node labeling algorithm for MVN eliminates the need for generating these paths.

The computer-generated solution is presented in Table 1. There, information is found about the levels of individual nodes as well as their critical connections (i.e., the labels of their immediate predecessors in the adjoining level). This information also proves to be useful during further studies.

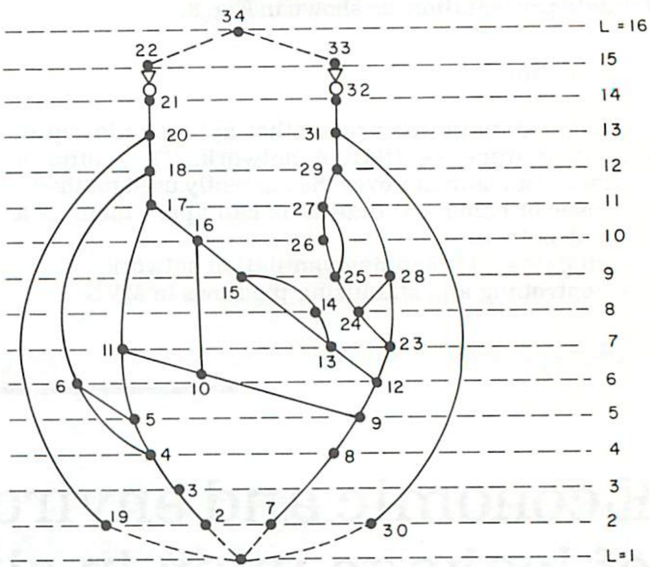

Fig. 7 — Canonical diagram of the MVN shown in Fig. 5, created with computer assistance

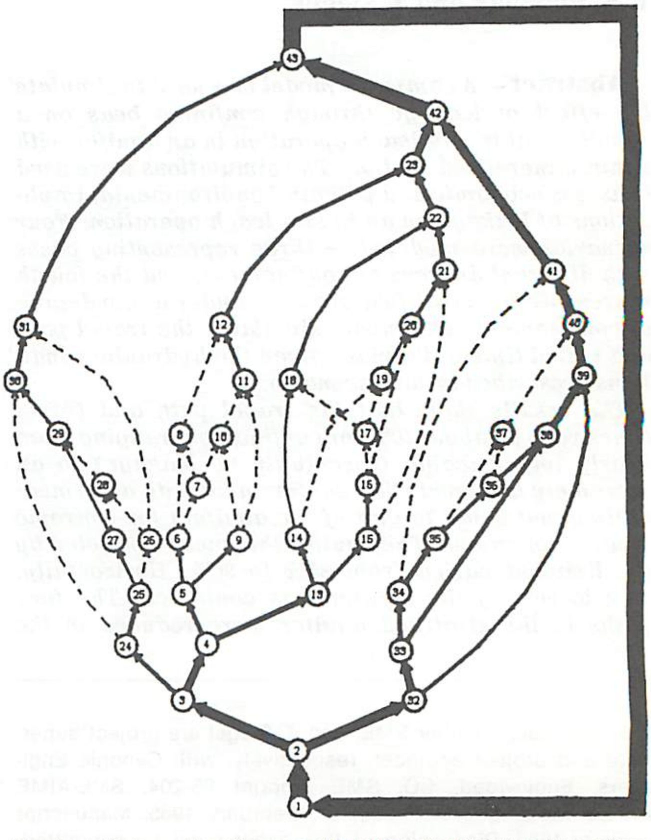

Fig. 8 — Schematic diagram of airflow distribution in a mine, plotted based on the canonical diagram

Figure 5 shows the representation of a more complicated ventilation system (Krupinski, 1974) by isometric diagram. The system is a multishaft (multiopening) one, so nodes #1 and #34 were added. The canonical diagram for this ventilation network (created with computer assistance) is presented in Fig. 7.

As was mentioned previously, when the nodes have their coordinates assigned according to the pressure distribution in the mine, a canonical diagram can be used to plot the potential diagram of a given ventilation network. Figure 3 shows the potential diagram of the mine ventilation system in Fig. 1.

Using the techniques described here, together with an intelligent plotter, canonical diagrams can be used for data presentation, as shown in Fig. 8.

Conclusion

Canonical diagrams are another approach to representing a mine ventilation network. They offer a number of advantages over the currently used methods. The user of canonical diagrams can apply them as a starting point in:

- studying and planning ventilation networks;
- controlling and stabilizing the flows in MVN;
- planning effective and economic preventive measures for controlling the distribution of smoke; and
- preparing and presenting data for further computer analysis of MVN.

By using the suggested method, the construction of network diagrams can be substantially simplified. Input data used by the authors is already available and no additional information is required to carry out the necessary computations.

Mine ventilation services may use canonical diagrams as a tool to improve management of ventilation systems. ■

References

Aho, A.V., Hopcroft, J.E., and Ullman, J.D., 1974, *The Design and Analysis of Computer Algorithms*, Addison-Wesley Publishing Co.

Bystron, H., 1956, "A Method of Drawing Canonical Diagrams for Ventilation Systems," *Przeglad Gorniczy* (in Polish), Vol. 3, pp. 86-100.

Czeczott, H., 1925, "Theory of Diagonal Currents," *Prace Akademii Gorniczej* (in Polish), Vol. 1.

Hartman, H.L., Mutmansky, J.M., and Wang, Y.J., 1982, *Mine Ventilation and Air Conditioning*, J. Wiley & Sons, pp. 443-444.

Krupinski, B., 1974, *Mining Handbook* (in Polish), 3, Wyd. Slask, Katowice, p. 43.

Wala, A.M., and Kim, B.J., 1985, "Simulation of Unsteady-state of Airflow and Methane Concentration Process in Mine Ventilation Systems Caused by Disturbances in Main Fan Operation," *Proceedings*, 2nd US Mine Ventilation Symposium, Reno, NV, pp. 85-93.

Economic and environmental implications of leakage upon in situ uranium mining

R.S. Popielak and J. Siegel

Abstract – *A computer model was used to simulate the effect of leakage through confining beds on a hypothetical in situ leach operation in an aquifer with a thin mineralized section. The simulations were used to assess economic and potential environmental implications of leakage on an in situ leach operation. Four scenarios were modeled — three representing cases with different degrees of confinement, and the fourth representing a stratified ore zone under a low degree of confinement. The model simulated the travel path and travel time of lixiviant given the hydraulic conditions prescribed in each scenario.*

The results show that the travel path and travel times vary by about 10% for confinement ranging from nearly impermeable (essentially no leakage) to an extremely low level (thin confinement with a permeability about equal to that of the aquifer) for isotropic aquifer conditions. The aquifer thickness contacted by the lixiviant varied from 85% to 90%. Horizontally, 55% to 60% of the aquifer was contacted. The flow paths in the stratified aquifer were reduced in the vertical direction and expanded horizontally. Forty-five percent of the aquifer thickness was contacted vertically with 88% contacted horizontally. Breakthrough time for lixiviant traveling at mid-depth of the aquifer increased two times when the leakage was increased from nearly zero to a value representative of thin and highly permeable confinement.

Leakage affects the economics of in situ mining by (1) increasing the time required to leach out the ore, and (2) increasing the thickness of the ore zone aquifer to be restored. The potential for environmental impacts appears to be minor. In all four simulations, the lixiviant did not contact the confining strata. Restoration would be limited to cleanup of the ore zone aquifer within the thickness contacted by lixiviant and within the radius of the lixiviant that traveled farthest away from the production cell.

Introduction

One condition that should be addressed in designing an in situ uranium mine is the degree of confinement of the ore zone aquifer by upper and lower strata of low permeability known as aquitards. If an aquifer is bound by aquitards that offer a low level of confinement, then the steady-state drawdown due to pumping a single well will be less than would be expected in a totally confined aquifer. This is because leakage through the aquitards is an additional source of water to the well (Freeze and Cherry, 1979).

R.S. Popielak, member SME, and **J. Siegel** are project supervisor and project engineer, respectively, with Canonie Engineers, Englewood, CO. SME preprint 85-204, SME-AIME Annual Meeting, New York, NY, February 1985. Manuscript January 1985. Discussion of this paper must be submitted, in duplicate, prior to Oct. 31, 1987.