FIRE DIAGNOSTIC SIMULATION FOR BURNING COAL WASTE BANKS [1]

by

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and

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Abstract. Past research has shown that extinguishing abandoned underground mine fires has not been successful because of the inability to locate fire zones accurately. The U.S. Bureau of Mines has developed a mine fire diagnostic technique which determines gas signatures and pressure flows in the mine atmosphere from a two-dimensional array of boreholes which intersect the strata of an abandoned mine. This technique has worked well in delineating both heated and non-heated subsurface zones at several abandoned mine fire sites. To apply this same technology to fire zones in burning coal waste piles requires a three-dimensional array of boreholes in the pile. Utilizing a scale model of a coal waste pile, the Bureau is currently studying the flow fields that would be induced by a three-dimensional array of boreholes. This report describes some initial results of these physical modeling studies.

Additional key words: Ventilation analysis, waste banks, AML Fires, fire diagnostics.

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Introduction

Uncontrolled fires in abandoned coal mines and coal refuse piles can cause devastating results to both life and property. Although it has been estimated that more than 500 coal waste bank or coal strata fires exist in the United States, it is reasonable to assume that additional fires have gone undetected and will likely remain so until surface anomalies become visible, i.e., subsidence, noxious fumes, or spoiled vegetation (Johnson and Miller 1979). It is known that elevated coal temperatures can be sustained for long periods with little oxygen supply and little or no noticeable surface disturbances. Therefore, the development of physical models of dynamic coal fire environments are necessary to assure more accurate diagnosis.

Previous surface induced ventilation tests of underground coal strata at Bureau of Mines field projects at Renton and Carbondale, Pa suggest that the presence of heated zones significantly changes the gas flow and stoichiometry of the region enough to create a signature for those zones (Kim, et. al. 1989; Dalverny and Chaiken, in prep.). When underground flow patterns were induced by a surface exhaust fan, it was found - through ventilation network analysis - that the effective underground resistance to gas flow was not uniform across suspected fire zones, and that calculated resistance values could indicate the presence or absence of a fire zone. In these projects, it was not possible to fully verify the results of the ventilation network analyses, since ground truth is unobtainable without detailed excavation. While proof of the concept that fires can be located by the analysis of borehole pressure measurements will eventually lie in actual field studies, calibration and evaluation of the derived network algorithm can be accomplished through laboratory modeling studies involving flow dynamics within a scale-model of coal waste material. An analysis of the induced flow patterns within a scale model waste bank material should enable prediction of the fluid dynamics that are involved with *in situ* abandoned mined-land fires which occur in unconsolidated waste banks.

Methodology

Materials

The coal waste material used for analysis was collected from the preparation plant of an active underground mine. The material was unweathered. The results of the proximate and ultimate analysis of the waste material are presented in Table 1. The particle size distribution and porosity of the waste material were determined according to standard testing methods (Lambe 1968). The porosity is 28.5% and the general size distribution of the material is illustrated in Figure 1. Using data collected from a constant head permeameter (6 ft in length, 8 in in diameter) with Darcy's Flow Law Equation, the permeability of the waste material was found to average 10^{-2} Darcy's or 0.02in/sec. The physical characteristics of this material are consistent with those of other types of coarse-grained coal waste materials.

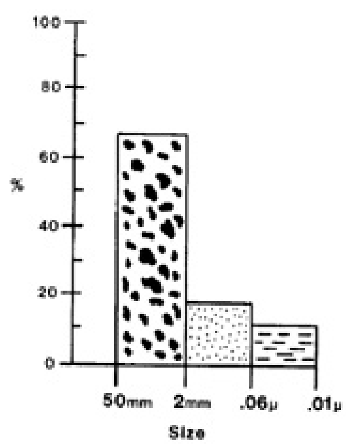
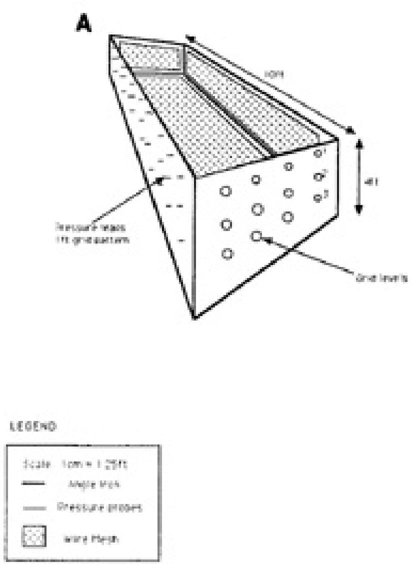


Figure 1. Histogram of sediments size-distribution of coal waste material.

Waste Bank Scale Model

The waste bank scale model consists of a 10 x 5 x 4 foot (200 cubic feet) porous side steel-grated frame box containing coal waste (Fig. 2). Two vertical boreholes of 4 in and 2 in diameter were placed within the box 30 in from the top surface of the pile. These boreholes can be alternatively used to change the borehole suction diameter. The vacuum suction pressure through the waste material is maintained by an exhaust fan. A series of 120 stainless steel pressure probe rods were inserted into the waste material by drilling through the sides of the box at 1, 2, and 3 ft depths beneath the pile surface at I ft centers (Fig. 2). After suction was applied to the respective boreholes, probe vacuum changes were monitored with a series of magnehelic gauges.

Sixteen suction ventilation tests were completed in order to access the flow patterns of air under vacuum through the waste bank material for suction at both boreholes and by varying the rate of fan suction through the system. Reduction in the rate of fan suction was accomplished by a controlling baffle placed near the source of suction. The controlled fan suction pressures used within the pipe averaged 36, 26, and 17 inches of water or 100%, 75%, and 50% capacity of maximum suction. A 50% reduction in flow velocity did, however, affect the vacuum pressure diffusion pattern by about a factor of two when compared with the 100% and 75% flow rates, i.e., the probes recorded approximately 50% less vacuum at each monitoring port.



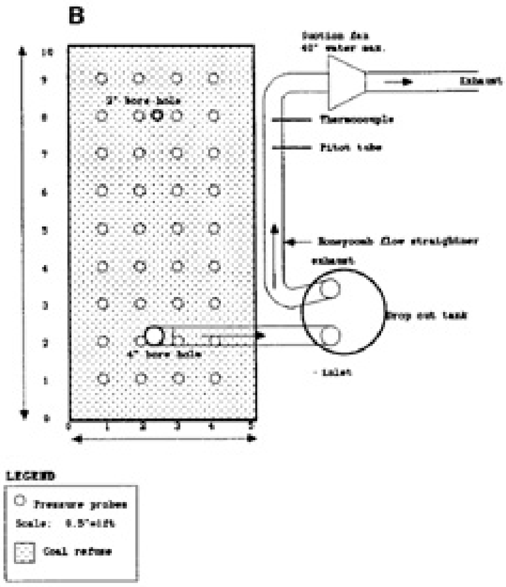


Figure 2. Perspective view of size-dimensions of waste bank scale model (A). Planar view of waste bank scale model (B).

To model the diffusion of air through the waste material under vacuum, suction was applied to both borehole diameters at 100% suction capacity of the fan. Eight separate tests were completed for each borehole to test the reproducibility of the flow patterns.

Table 1. Refuse Characteristics.

Proximate Analysis	As-received	Dry	Dry Ash-free
Moisture	2.78	--	---
Ash	67.37	69.29	---
Volatile Matter	12.49	12.85	41.85
Fixed Carbon	17.36	17.86	58.15
Ultimate Analysis	**As-received**	**Dry**	**Dry Ash-free**
Hydrogen	1.84	1.57	5.11
Carbon	19.23	19.78	64.42
Nitrogen	0.27	0.28	0.91
Sulfur	5.29	5.44	17.72
Oxygen	6.00	3.64	11.84
Ash	67.37	69.29	---
Heating Valve (BTU/LB)	3344	3440	11203

Two sets of mathematical equations were fit to the vacuum data: 1) a four- dimensional surface where vacuum pressure patterns were tested as a function of the three orientation co-ordinates (x,y,z) of the monitoring ports within the waste bank and 2) a three-dimensional surface for each depth level where vacuum pressure patterns were tested as a function of the x-and y- co-ordinates of the monitoring ports within the box.

Analysis

An analysis of variance model was used to test the differences between the three fan suction rates. For the 4 inch borehole tests vacuum rates at the monitoring ports were not significantly different between 100% and 75% fan capacities. For suction at the 4 inch borehole, differences were found between the 50% fan capacity, and both 100% and 75% fan capacities. Similar results were also found between the monitoring ports at respective fan capacity tests for suctions at the 2 inch borehole. Differences in vacuum flows within the waste bank were not observed between the 4 inch and 2 inch diameter boreholes at either 100% or 75% fan capacity.

Since gas flowing toward a borehole under suction should follow a radial flow pattern, it was assumed that second-order polynomial equations would best model and predict vacuum flow patterns toward both the 2 inch and 4 inch diameter boreholes. Results of the four-dimensional analysis for the sixteen tests gave predictive surface R^2 values between 0.75 and 0.83 for the respective 2 inch and 4 inch diameter borehole suction tests. The result of the 3-dimensional analysis for the sixteen tests gave predictive surface R^2 values between 0.76 and 0.98 for the respective 2 inch and 4 inch diameter borehole tests. These high values for R^2 (explained variance) predict very well the experiment flow patterns.

A three-dimensional plot comparison between the test data and predicted surfaces for the 3 levels for a four inch borehole diameter test is presented in Figure 3. There is good correspondence between the test data and the predicted values at each monitoring level. Level 3, which occurs at a depth of 3 feet beneath the top of the coal waste material provided the least predictive surface with a R2 value of 0.76. The other two levels have considerably better fits with respective R^2 values of 0.87 and 0.98.

An analysis of the residuals associated with the respective predictive surfaces did not show any secondary surfaces or patterns that might suggest either an uneven size distribution of the waste material or irregular vacuum flow rates through the material toward the borehole. Analysis of the pressure flow characteristics between the monitoring probes flowing toward the bottom of the borehole show that flows were within the regime of Darcy conditions for each of the tests. Thus it appears appropriate to model the flows within the constraints of Darcy's Law.

Conclusions and Technical Evaluations

Flows toward the boreholes generally follow a radial pattern and can be well predicted with a series of polynomial equations. The least predictive surfaces were found to occur within the lower (3 ft) levels of the waste bank box. It is believed that the effect of the impermeable steel bottom of the waste bank box is causing vacuum flows to follow a non radial pattern at this level, i.e. flows are not radial distributed throughout the coal waste material. The vacuum distance of borehole suction within the waste material radiates about 6 feet at level 3 and about 4 feet at levels 1 and 2 (Fig. 3). For monitoring ports beyond these distances for the respective tests suction pressures were undetectable.

These tests have revealed promising results which should enable modeling of vacuum flows within in situ waste banks:

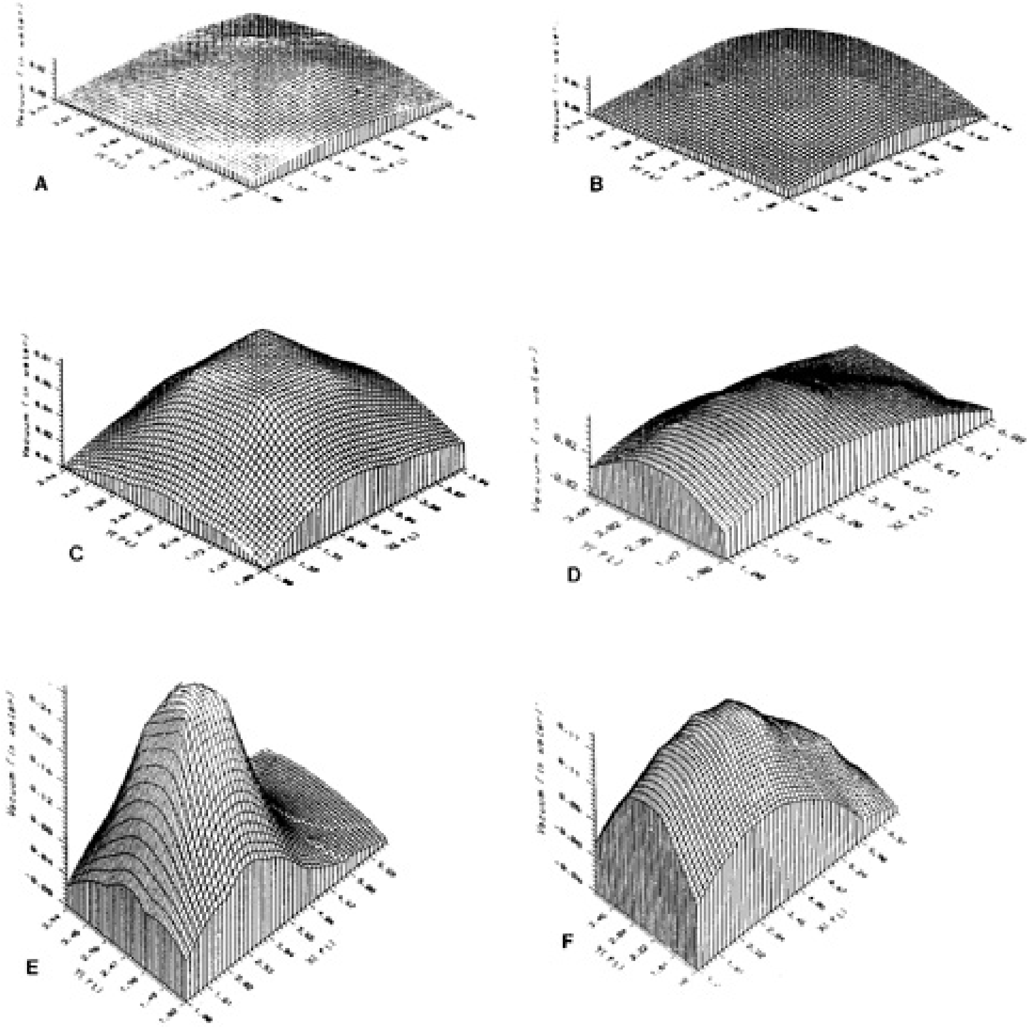


Figure 3. Comparison between three-dimensional experimental and predicted surfaces for vacuum flows by levels. Experimental Level 1 (A), Predicted Level 1 (B), Experimental Level 2 (C), Predicted Level 2 (D), Experimental Level 3 (E), Predicted Level (F).

1. Flow patterns through coal waste material generally follow a radial pattern.
2. These flows follow Darcy's Law and as such their fluid dynamics can be modeled with Darcy's Flow Equations.
3. The flows can be predicted with a series of second-order polynomial equations with a high degree of statistical reliability.
4. For borehole suctions within the range of 36 to 25 inches of water at the fan source either a 2 inch or 4 inch borehole can be used without significantly altering the flow patterns within the waste material.

The results of these experiments combined with the existing fire diagnostic technology suggest that field tests at an in situ burning waste bank are warranted. Field testing will include the initial placement of boreholes within a pattern that will provide optimum coverage of the waste bank. The pattern will be dictated by the physical characteristics of the waste material (size, porosity, permeability, etc.) as well as the geometric dimensions of the waste bank. Two inch diameter boreholes appear to be adequate as long as flow pressures at the suction source can be maintained above 25 inches of water. Fan suctions will be applied with vacuum pressures monitored with the magnehelic gauges. Comparison will be made between the field-collected data and the prediction model. This will enable verification with the four-dimensional and three-dimensional predictive surfaces determined from the waste bank model experiments.

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