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Influence of Mine Layout, Mining Method, and Geology on Down-Dip Coal Barrier Performance at the Solar No. 7 Mine

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ABSTRACT

The Solar No. 7 and Solar No. 10 mines were designed to prevent mine waters from directly discharging to the surface. In January of 2004, a discharge occurred as the Solar No. 7 mine was in its final stage of flooding through a barrier averaging 456-ft in width over a 1,600-ft length (No. 1). Another barrier (No. 2) was designed to protect four municipal water wells operating 1,800-ft away and producing from within or slightly below the Upper Kittanning coalbed from the adjacent Solar No. 7 and No. 10 mine pools. These two barriers were selected for this study because of varied mine layouts, mining methods, and geology factors affecting their performance. Analysis was aided by the collection and geo-referencing of 6-month mining maps from the Pennsylvania Department of Environmental Protection (PA DEP). A structure contour map of the Upper Kittanning coalbed was constructed from mine map elevation points. These data and 2-ft surface contour maps were used to measure the precise location of the coal outcrop. The actual discharge point was as little as 425-ft away from a thin-pillar section and 475-ft away from a pillar recovery section. The discharge point was found to be located slightly above the coal, indicating that the drainage path was at least partially through the strata directly above the Upper Kittanning coalbed. Hydraulic conductivities and potential discharge pathways are analyzed and discussed. The possible factors influencing the performance of the down-dip barriers at Solar No. 7 and Solar No. 10 are: a) the width of the barrier, b) the applied hydraulic gradient, c) the type of mining adjacent to the barrier, d) the overburden, e) the pattern and characteristics of fractures, and f) the quality of waters contained within the mine pools. This study, part of a larger effort funded by the Appalachian Research Initiative for Environmental Sciences (ARIES), is tasked to determine the key factors responsible for the successful design of down-dip coal barriers.

INTRODUCTION

Most legacy drift mines (mines operated prior to the 1970s) entered the coal reserve from outcrop and developed up-dip. This was the preferred mining method because water entering the mine would move away from the working faces, minimizing problems during production (Figure 1a). Unfortunately, this mining technique can negatively impact the quality of water moving through it. When mine water comes in contact with strata rich in iron,

aluminum, manganese and other metals, it can produce a range of pH and sulfate-rich drainage.

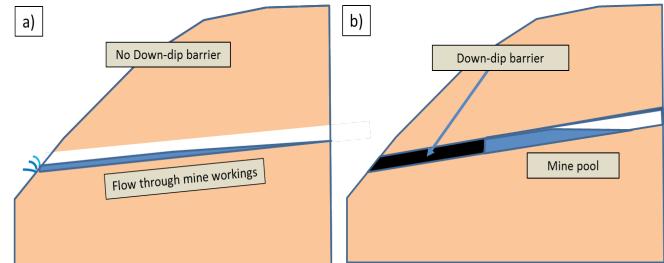


Figure 1. a) Typical scenarios for legacy underground coal mines where mining developed from the drift area and moved up-dip allowing water to move away from the working faces. b) Post-SMCRA, where mining established a down-dip coal barrier to contain the mine pool and eliminate drainage.

Section 516(b)(12) [30 USC 1266(b)(12)] of the Surface Mining Control and Reclamation Act (SMCRA) of 1977 changed this way of mining, requiring all new mines with acid- or iron-producing coal seams to locate openings to prevent a gravity discharge of water from the mine. This statute has successfully led to the development of mine pools that are contained by a down dip barrier that prevents mine waters from discharging to the surface (Figure 1b). In general, these mine pools contain reduced oxygen levels, which lowers the potential for pyrite and other minerals to produce waters rich in metals and sulfates. Currently, mine layout designs focus primarily on the size and hydraulic characteristics of the un-mined coalbed between the up-dip mine pool and areas where down-dip surface discharge is possible. This paper focuses on a detailed analysis of the mine layout, mining method, and geology of the Solar No. 7 and No.10 mines in Somerset County, Pennsylvania, where coal barriers have been both successful and ineffective in preventing discharges.

BACKGROUND

The Solar No.7 and Solar No. 10 room-and-pillar underground coal mines are located in northern Somerset County, Pennsylvania, near U.S. Route 30 (Figure 2). The Upper Kittanning coalbed in this area is 4 to 5-ft thick and overlain by shales and sandstones.

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The coalbed is underlain by claystones and the Johnstown limestone. Thick sandstone overlies the main entries near the Solar No. 7 portals (Figure 3). The Solar No. 7 mine was opened in 1975 by Lunar Mining, Inc. followed by Solar No. 10 in 1976 by Solar Fuel Company Inc. Both mines were purchased and sold to a number of different companies during their working lives. The Solar No. 7 mine was operated by Genesis Inc. at the time of its closing in 2002. Currently, Rosebud Mining Co. owns the mine property. The Solar No. 10 was owned by Solar Fuel Company Inc. at the time of its closing in 2002 and is the current owner of the mine property.

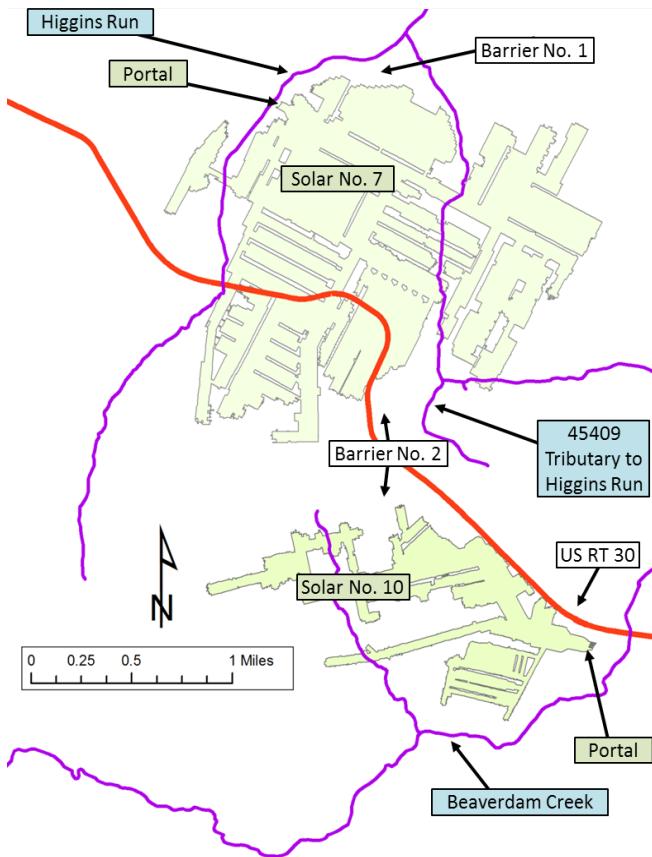


Figure 2. a) Locations of the Solar No. 7 and Solar No. 10 mines. The positions of the major streams, U.S. Route 30, mine portals, and down-dip barriers (No. 1 and No. 2) are also shown.

MINING METHOD

Solar No. 7 and Solar No. 10 are room-and-pillar mines. Development panels were sometimes subjected to either full or partial pillar recovery. Figure 4 shows the mine layout of the Solar No. 7 mine with the outlines of full and partial pillar recovery areas. Pillars within full extraction sections are recovered, leaving only remnants of coal acting as a temporary roof support. The immediate roof in these areas was allowed to fail, filling the sections with broken rock and forming gob. In areas where partial pillar recovery occurred, portions of the pillars were left in place. Lastly, a significant amount of the production sections in the southeastern portion of the mine were developed using thin pillars (Figure 4). Most of the pillars in these sections are less than 30-

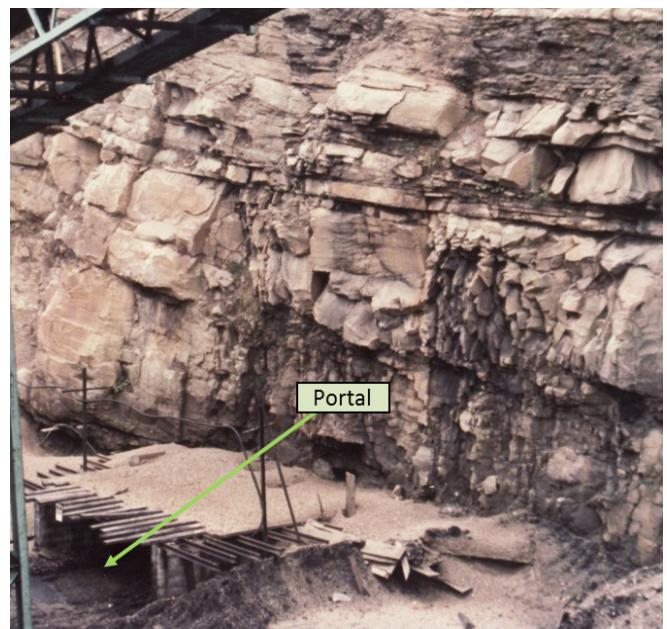


Figure 3. Photograph of the Solar No. 7 portal area showing the thick, massive sandstone roof rock.

ft wide and their long-term strength characteristics are unknown. Similar mining methods were used at the Solar No. 10 mine.

GEOLOGY

In a report by Iannacchione, et. al. (1981), the stratigraphy above the Upper Kittanning coalbed was analyzed using data from over 70 exploration core holes that covered the Solar No. 7 and Solar No. 10 mine properties. Three basic roof-rock types were identified: a thick sandstone (Freeport sandstone); a thick, dark-gray laminated shale; and a lateral transition zone between the sandstone and shale units. The transition zone is generally comprised of slickensided shale and a few thin sandstone stringers.

The Upper Kittanning coalbed at the Solar No. 7 and Solar No. 10 mines lies within the Somerset Syncline where the structure contour elevations are approximately 1,600-ft and gently rise 2° to 4° to the Boswell Dome in the northwest and the Negro Mountain Anticline in the southeast. A detailed structure contour map was constructed from the hundreds of survey contained on the mine's official maps (Figure 5). The locations of Barrier No. 1, along Higgins Run, and Barrier No. 2, protecting the Stoystown municipal water supply wells, are also shown.

ACCURATELY DETERMINING THE UPPER KITTANNING COALBED OUTCROP

A precise understanding of the structure contours for the Upper Kittanning coalbed is needed to accurately determine the coal outcrop along the Higgins Run down-dip barrier (Figure 6). The authors developed information on three different Upper Kittanning coalbed outcrop lines:

- Dashed line: Outcrop line drawn on the mine's 6-month mining map.

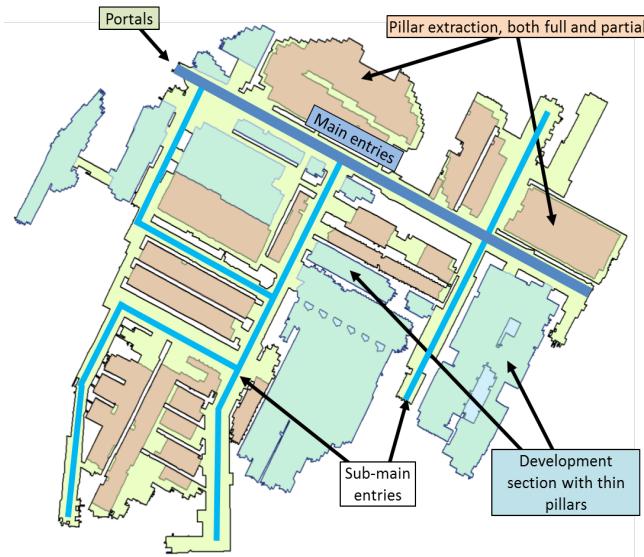


Figure 4. Mining methods used at the Solar No. 7 mine included multiple entry room-and-pillar main and sub-main entries with attached production panels.



Figure 6. Three examples of the Upper Kittanning coalbed outcrop lines along Higgins Run, each dependent on a unique structure contour map.

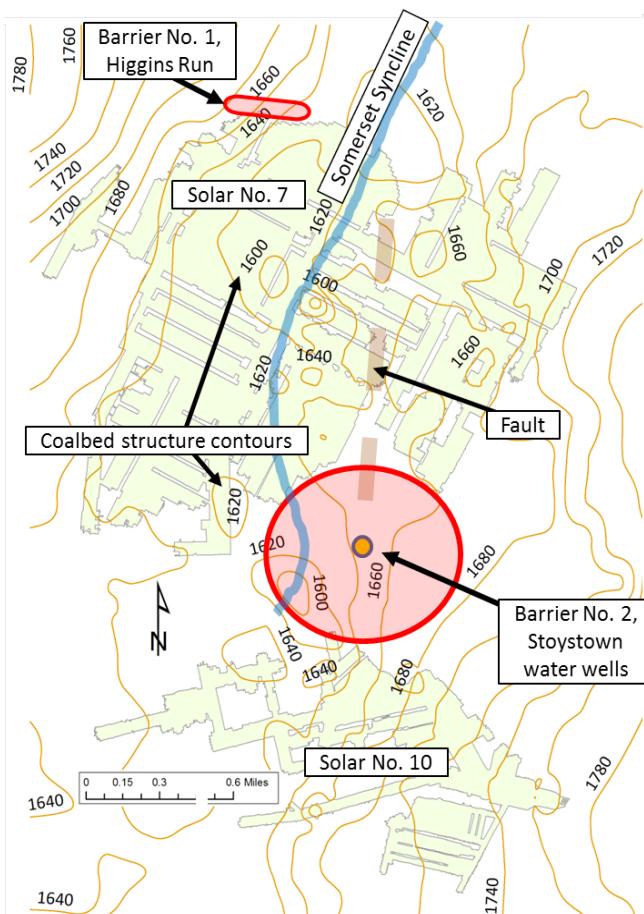


Figure 5. Upper Kittanning coalbed structure contour map constructed from numerous in-mine survey points. Also shown are the location of the down-dip barriers studied in this report. (No. 1 and No. 2).

- Dots: Outcrop line drawn from intersection of the structure contours from the Pennsylvania (PA) Geological Survey data with their equivalent surface lines (from the LIDAR 2-ft surface contour maps provided by the PA Geological Survey).
- Solid line: Outcrop line drawn from the intersection of the structure contours from the in-mine survey points with their equivalent surface lines (again from LIDAR 2-ft surface contours).

These three outcrop lines each present a slightly different view of the barrier size along Higgins Run. The most accurate outcrop line comes from the in-mine survey data and is used throughout the remainder of the report. The authors wanted to present this analysis to illustrate the complexity of establishing the position of the coal outcrop. This position can affect the barrier width estimates.

DISCHARGE ALONG HIGGINS RUN (BARRIER NO. 1)

In the winter of 2004, PA DEP agents first noted a ‘yellow’ discharge indicative of iron rich waters from the hillside along Higgins Run (Figure 7a). The surface discharge occurred when the mine pool reached its highest elevation of 1,681-ft. The discharge occurred in a relatively narrow zone ranging between 10 and 40-ft in width. The length of the down-dip barrier from the 1,680-ft contour (maximum pool elevation) to the eastern end of the projected Upper Kittanning coalbed outcrop is measured to be approximately 1,400-ft. The average width of the barrier was calculated from 16 line segments, and it averages 456-ft (Figure 7). The elevation at the discharge point is approximately 1,660-ft, producing a hydraulic head of approximately 20-ft. The estimated discharge rate was 30 to 75-gpm.

All of the reported discharges occurred within a narrow area (Figure 7b). It is interesting to note that a wetlands, approximately 100-yards to the west of the discharge point, did not show any signs of contamination from mine water (Figure 7c). At this point in time, the mine operator began to pump and treat water from

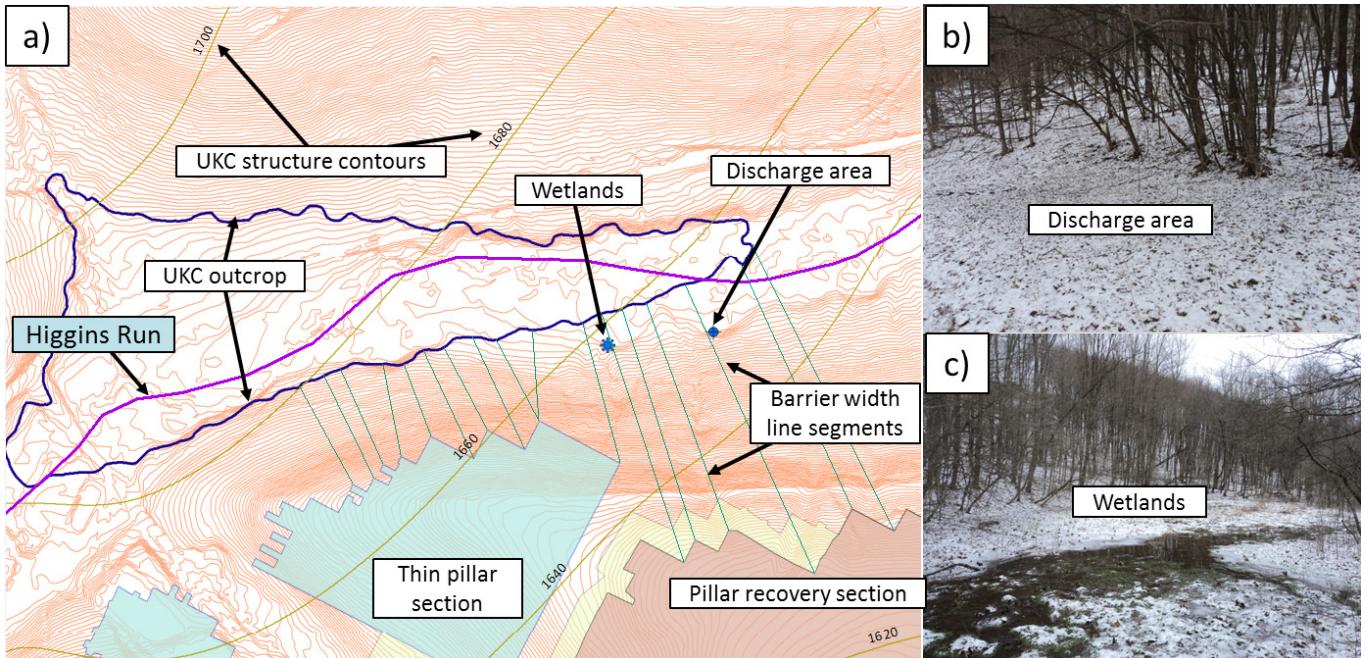


Figure 7. a) Plan view showing the mine layout, Upper Kittanning coalbed outcrop line and structure contours, Higgins Run, discharge area, and adjacent wetlands. b) Photograph of the discharge area. c) Photograph of the adjacent wetlands.

the mine pool. Over the next several months the mine pool was lowered to approximately 1,655-ft. Discharge conditions ceased at that elevation. On February 26, 2004 raw discharge from the Solar No. 7 borehole indicated the water pooled in the mine had become significantly impaired (Table 1).

Table 1. Samples of raw water from a borehole into the Solar No. 7 on February 26, 2004.

Parameter	Values
Flow, gpm	1,000
Iron, mg/l	190
Suspended Solids, mg/l	74
Manganese, mg/l	4.08
Aluminum, mg/l	0.46
Sulfates, mg/l	560
Specific Conductance, umho	1,753
Alkalinity, mg/l	59.3
Acidity, mg/l	138.3
Field pH (S.U.)	6.5
Laboratory pH (S.U.)	5.85

HYDRAULIC CONDUCTIVITY OF THE HIGGINS RUN BARRIER

As previously stated, down-dip coal barriers are important in preventing the discharge of mine water from an abandoned coal mine. The low hydraulic conductivity of the coal barrier restricts the flow between the mine pool and potential discharge points. The distance between these points can play a major role in the

effectiveness of the barrier to retard the mine pool water from reaching the surface through the coalbed. By modeling a coal barrier's hydraulic properties, accurate predictions regarding mine pool discharge are possible. Darcy's Law utilizes the principal properties of an isotropic system to provide an accurate "barrier K" value,

$$Q = K_h b L_b \left(\frac{dH}{w_b} \right) \rightarrow K_h = \frac{Q}{t L_b \left(\frac{dH}{w_b} \right)}$$

where

Q = flow out of the aquifer (ft^3/d),

K_h = horizontal hydraulic conductivity (ft^2/d),

w_b = width of barrier (ft),

L_b = length of the barrier (ft),

dH = difference in hydraulic head, discharge point to the top of the mine pool (ft), and

t = thickness of the barrier (ft).

The 'barrier K' value for coal in two bituminous coal mines of northern West Virginia was estimated using this method (McCoy et al., 2006). The McCoy study assumes that all of the water seeping through the barrier is homogeneous and is not flowing through any open and dominant fractures. An important assumption is that

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Table 2. Range of properties used to estimate the hydraulic conductivity of the portion of the Higgins Run coal barrier that discharged during 2004.

Barrier name	Coal thickness (<i>t</i>), ft	Barrier width (<i>w_b</i>), ft	Barrier length (<i>L_p</i>), ft	Hydraulic head, ft	Flow rate, gpm	K _h , ft/d
Higgins Run	4.5	456	1,400	21	30–75	20–50

vertical infiltration through the overburden and into the coal barrier is negligible. This means that the actual *K_h* value would be lower due to mass balance. In studies by McCoy, et al (2006) and Islam, et al. (2013), barrier K values were estimated to range from 0.03 to 14-ft²/d. The wide range of values could be due to varying site conditions.

The authors used the data collected during this investigation to estimate the hydraulic conductivity for the Higgins Run barrier (Table 2). The ‘barrier K’ values attained in this study were calculated under the assumption that groundwater travels strictly through an unaltered coalbed (no fractures). The minimum and maximum values of hydraulic conductivity were found to be 20 and 50-ft/d. These values are much larger than those discussed in the McCoy study, indicating that a fracture flow path is possible.

FRACTURE FLOW ABOVE THE HIGGINS RUN BARRIER

An estimated discharge rate of 30 to 75-gpm occurred at one location (Figure 7) along the 1,400-ft barrier (Barrier No.1). Potential causes for the high hydraulic conductivity values could be due to the presence of fractures and bedding planes surrounding the coal barrier. These features are mainly geologic in origin, although full extraction mining can deform, or even induce, their occurrence. Iannacchione, et al. (1981) found that joints, coal cleat, and slickensided planes all had prominent clustering of N 17° W, N 72° W, N 48° E, N 62° E, and N 74° E. The latter three orientations are sub-parallel to the shortest distance from the yield pillar and full extraction pillar sections to the discharge point along Higgins Run.

Open fractures are more common in shallow rocks because the weight of the overburden in deeper rocks can potentially close the fractures (Pigati et al., 2006). The highest concentration of weathered fractures and bedding planes are typically found near the outcrop. The down-dip barrier along Higgins Run is very close to the surface, ranging in depth from zero to 100-ft. In this area, weathered fractures are possible and their orientation is likely to be sub-parallel to the width of the barrier.

The most general case to consider is a single weathered fracture extending vertically from the coalbed to the surface (range of 10 to 100-ft) and connecting the Solar No. 7 mine pool with the discharge point (Figure 7) along a N 60° E trendline. This case can be modeled using an approach developed by Romm (1966).

$$Q = \frac{\rho_w g b^2}{12\mu} (bh_f) \frac{\partial H}{\partial w_f}$$

Where:

$$Q = \text{volumetric flow rate (ft}^3/\text{d}) [448.8 \text{ gpm} = 1 \text{ ft}^3/\text{s}]$$

$$h_f = \text{saturated fracture height (ft)}$$

$$w_f = \text{length of the fracture through the barrier (ft)}$$

$$\partial H = \text{difference in hydraulic head, discharge point to the top of the mine pool (ft)}$$

$$b = \text{fracture aperture (ft)}$$

$$\rho_w = \text{density of water (1.94-slugs/ft}^3)$$

$$g = \text{gravitational constant (32.17-ft/s}^2)$$

$$\mu = \text{viscosity of water}$$

$$\frac{\partial H}{\partial w_f} = \text{hydraulic gradient (We assume 21-ft/500-ft)}$$

Under these conditions, the 30 to 75 gpm discharge along Higgins Run could be produced from a single water filled fracture with a height (*h_f*) of 21-ft and an estimated aperture (*w_f*) ranging from 0.08 to 0.11-in.

STOYSTOWN WATER SUPPLY BARRIER

The Solar No. 7 and Solar No. 10 mines are adjacent to the Stoystown municipal water supply. Stoystown, Pennsylvania, has four water wells producing directly from the Upper Kittanning coalbed and the underlying Johnstown limestone and Kittanning sandstone (Figure 8). These water wells were drilled in a valley and average approximately 200-ft in depth. The overburden above Barrier No. 2 ranges from slightly less than 200-ft to greater than 400-ft. Under these conditions, fractures should be relatively narrow (low aperture width). A potential source of this water reservoir is thought to be a fault that crosses the Solar No. 7 mine from north-to-south (Iannacchione, et al., 1981) and intersects the area containing the Stoystown water wells (Figure 5). This fault was observed underground to contain numerous open fractures and bedding planes (Figure 9).

The no-mining coal reserve had a radius of 1,800-ft and, in this location, constitutes a down-dip barrier (Barrier No. 2). Most of themine sections around the perimeter of this reserve are filled with water. The elevation of the Upper Kittanning coalbed at the water wells is approximately 1,645-ft. If the Solar No. 7 mine pool was at 1,655-ft, only a 10-ft hydraulic head would have been present. When the Solar No. 10 mine is flooded to its portal, an elevation of approximately 1,765-ft is achieved. This would produce a maximum hydraulic head of approximately 120-ft. It should be

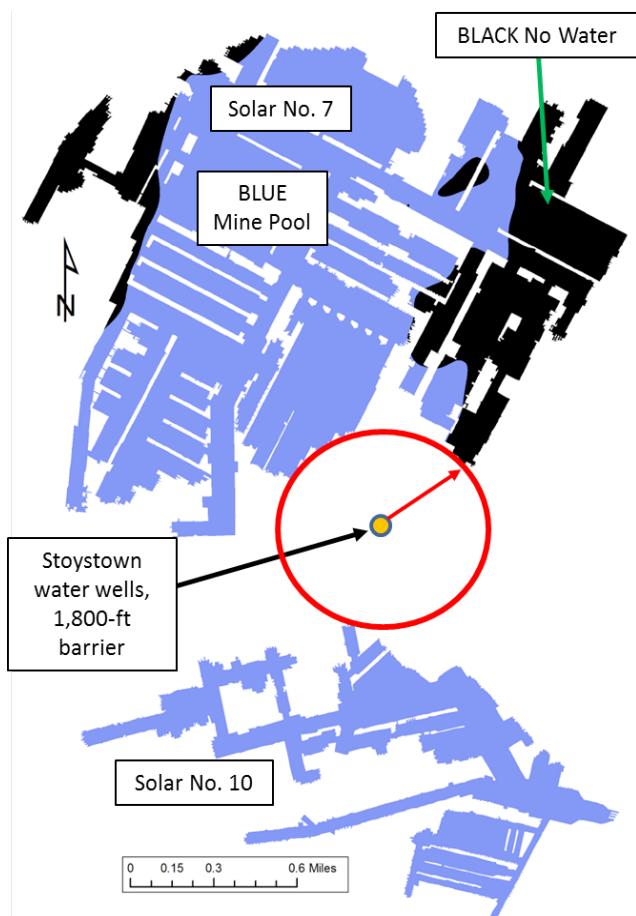


Figure 8. Location of the Stoystown municipal water wells with the 1,800-ft coal barrier. The water level for the Solar No. 7 mine pool is 1,655-ft and 1,765-ft for the Solar No. 10 mine pool. Also note the location of the fault that could be partially responsible for the productivity of these wells.



Figure 9. Photographs of faults observed within the Solar No. 7 mine. These faults are projected to intercept the Stoystown water supply wells.

noted that mining sections within the Solar No. 7 and Solar No. 10 mines near this Stoystown coal barrier were developed with a combination of thin pillars and full pillar extraction mining methods (Figure 4).

Mining by Solar No. 7 on the north side of Barrier No. 2 has seemingly done little to affect the quality of water located in the strata associated with Upper Kittanning coalbed and produced from the Stoystown water supply wells. If it had affected this

water supply, elevated levels of iron, manganese, sulfates and other products found in the Solar No. 7 mine pool would be present. One reason for this could be the relatively low hydraulic head (~10-ft) produced when the mine is maintained at 1,655-ft.

The influence of mining by Solar No. 10 on the south side of Barrier No. 2 on the Stoystown water supply is more difficult to determine. It is more likely that Solar No. 10 mine pool water would impact the water supply since a 120-ft hydraulic head is being applied to this side of the barrier. There seems to be two possibilities for non-impairment of the Stoystown water wells through Barrier No. 2 from the Solar No. 10 mine:

1. The down-dip barrier is large enough that it retarded the amount of flow due to resistance of flow in the coal (Darcy's law), or
2. Flow through the barrier is occurring under the 120-ft hydraulic head, but the water quality in the Solar No. 10 mine pool is not impaired.

This second point was explored in more detail by the authors. The Solar No. 10 discharge is generally low (0 to 60 gpm) and contains low concentrations of iron, manganese, and sulfates. This discharge is located at the reclaimed portal and is most likely caused by a leaking mine seal or water flow through the strata surrounding the seals. Table 3 shows the parameters of raw water collected from the Solar No. 10 mine. From these samples, it is indicative that the water is net alkaline and contains significantly less iron, manganese, and sulfate than the Solar No. 7 mine pool. These data suggest that it is not possible to definitively determine the effectiveness of Barrier No. 2.

CONCLUSION

The discharge at the Solar No. 7 mine occurred in a relatively narrow zone within a down-dip barrier along Higgins Run (Barrier No.1). The average width of the barrier is 456-ft and the length is 1,400-ft. The hydraulic head on this barrier at the maximum mine pool was calculated to be approximately 21-ft. The discharge to Higgins Run occurred in an area where pillar recovery and thin pillars were used. The discharge was relatively low, ranging from 30 to 75-gpm. The hydraulic conductivity of the Higgins Run coal barrier is calculated to be between 20 and 50-ft/d. This relatively high value may be influenced by intense fracturing, some with large apertures due to weathering near the surface outcrop or adjacent to the pillar recovery area. Using a method derived from Romm (1966), this same discharge could be produced from a single water filled fracture with a height (h_f) of 21-ft and an estimated aperture (w_f) ranging from 0.08 to 0.11-in. Both of these conditions are possible. However, at this point, neither can be proven. The relevant point is that each condition would require a different design consideration. Does the barrier need to be wider or do weathered fractures need to be identified and sealed to prevent a discharge under these specific conditions?

In the second case study, an 1,800-ft no-mining coal barrier (Barrier No. 2) may have successfully protected four highly productive municipal water wells. The hydraulic head on this barrier ranged from 10-ft on the north to as much as 120-ft on the south. The mine pool on the north side of the barrier contains impaired water that is high in iron, manganese, and sulfates; while the mine pool on the south side consist of non-impaired water. It is possible that the hydraulic conductivity of the coal barrier is

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Table 3. Samples of raw water from the CWPD monitoring point at the Solar No. 10 mine from March 2011 to November of 2012.

Parameter	Monitoring dates							
Date sampled	29-Mar-11	10-May-11	16-Aug-11	24-Oct-11	21-Feb-12	13-Jun-12	28-Sep-12	7-Nov-12
Flow, gpm	0.072	0.072	0.072	60	50	50	50	50
Iron, mg/l	2.95	3.19	9.41	4.83	5.5	5.3	10.5	0.75
Suspended Solids, mg/l	5	<5	21	9	15	6	15	<5
Manganese, mg/l	0.57	0.59	0.68	0.55	0.48	0.64	0.6	0.1
Aluminum, mg/l	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.1
Surfates, mg/l	94	99	98	96	79	80	77	56
Specific Conductance, umho	698	633	647	657	621	682	622	289
Alkalinity, mg/l	153	147	164	163	160	162	159	43
Acidity, mg/l	-135	-135	-156	-151	-142	-132	-149	-33
Field pH (S.U.)	7.5	8	7.5	7.5	7	7.5	7.5	7.5
Laboratory pH (S.U.)	7.58	8.14	7.25	7.45	7.19	7.49	7.44	7.71

low enough to prevent measureable water infiltration. It is equally possible that flow through the barrier has occurred but has not contaminated the Stoystown water supply because the Solar No. 10 mine pool is relatively low in iron, manganese, and sulfates.

Down-dip coal barriers need to be designed to protect surface and groundwater resources (Barriers No. 1 and No. 2) from mine pool discharges. The ability of coal barriers to resist flow caused by hydraulic gradients from mine pools can be greatly affected by the potential presence of fractures close to outcrop. It is interesting to note that Kendorski, et al. (2007) stated that most empirical design methods for barrier width are a function of depth; yet, current barrier conductivity empirical design methods use only hydraulic head and coalbed thickness. In the future, when conditions are similar to those encountered in this study, the design should be as much focused on the potential flow pathways caused by fractures adjacent to the coalbed as the thickness of the coal barrier. Lastly, it may be advisable to restrict pillar recovery adjacent to the down-dip barrier.

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