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USING HELIUM AS A TRACER GAS TO MEASURE VERTICAL OVERBURDEN CONDUCTIVITY ABOVE EXTRACTION PANELS

Yvette Heritage[1] and Winton Gale[1]

ABSTRACT: The potential of helium injection into goaf and overburden strata as a tool to determine and measure goaf to surface connectivity is discussed. Laboratory studies investigated the flow mechanics and flow velocities of injecting helium through fractures by goaf injection technique and applied the laboratory findings to the field. From the laboratory studies, it was found that the mechanics of helium flow through fractures is by bubble flow. A relationship between gas velocity and fracture aperture was found allowing the determination of fracture conductivity through helium injection, which was comparable with previous works. Field trials of helium injection into the goaf were successfully conducted to determine whether a connection exists between the surface and the goaf. Helium injection process was carried out in two stages; the measurement of background helium, and injected helium. The average fracture aperture was determined from the arrival time of the first injected helium pulse, which takes the most direct path to the surface. The equivalent average conductivity was calculated from the average fracture aperture. Another technique of borehole helium injection was used to determine connection in the fracture network of the overburden. The borehole helium injection technique is a more direct approach of injecting helium into the fracture network of the overburden. With a borehole drilled into the highly permeable caved zone of the goaf, then borehole helium injection can demonstrate more quickly if a connection to the surface exists.

A repeatable technique of helium injection into the goaf or borehole has successfully been developed and demonstrated to prove connectivity between the goaf and surface of a longwall coal mine. These techniques will prove an effective tool for monitoring of environmental and hydrological problems.

INTRODUCTION

Longwall coal mining at shallow depths has many mining and environmental issues related to subsidence. The issues range from mining impacts caused by ventilation and spontaneous combustion to environmental impacts created from the release of goaf gas and hydrological issues. A primary cause of these impacts is subsidence which can form a connection between the goaf and surface, initiating these impacts. Determining the magnitude and extent of surface to goaf connection can assist in reducing the impact mining has on the environment and improve mining efficiency.

A connection is formed when the overburden subsides and new joints are created in addition to the reactivation of old joints. This opening up of joints creates a connected fracture network from the goaf to the surface which varies in tortuosity and conductivity. Creating a tool and method of determining connectivity and conductivity from surface to goaf would be invaluable to the coal mining industry.

This study aimed to assess the potential of helium injection into goaf and overburden strata as a tool to determine goaf to surface connectivity. Laboratory studies investigated the flow mechanics and flow velocities of helium through fractures. Field experiments trialled the helium goaf injection technique and applied the laboratory findings to the field.

BACKGROUND

The flow mechanics of gas and liquids has been extensively researched (Fourar and Bories, 1995; Viana et al, 2003; Odling et al, 1999; Liefer, Patro and Bowyer 2000; Sarkar, Toksoz and Burns, 2004; Ranjith, Choi and Fourar, 2006). Gas flow is described as laminar or bubble flow.

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Darcy flow only describes laminar flow however flow is not always laminar due to flow structures, pressure gradients and gas concentrations (Fourar and Bories, 1995). Non laminar flow, such as bubble flow, follows a different set of parameters. Bubble flow is traditionally discussed as gas flow in a liquid or solid in a liquid, but rarely gas flow in gas. Characteristics of this study however indicate bubble flow of gas in gas, helium in air.

The literature looks at helium and radon (which migrates similarly to helium) detection in soil gas samples in a variety of fields (Kristiansson and Malmqvist, 1982; Reddy et al, 2006; Ciotoli et al, 1999; Agarwal et al, 2006; Gascoyne and Wuschke, 1997; Lineham et al, 1996). This study is unlike the other studies as it involves the detection of helium directly from surface cracks formed from subsidence in longwall coal mining. The helium injection technique also differs from previous techniques as the helium is injected into the goaf and rises up under its own buoyancy through primary and secondary fracture networks to the surface.

HELIUM INJECTION INTO FRACTURED ROCK

To investigate the mechanics of helium flow to see whether helium flows through fractures as bubble or Darcy flow a laboratory experiment was constructed. The nature of the flow mechanics will affect the interpretation of the results.

The set up of the experiment involves an enclosed system including a helium injection chamber at the base, a vertically fractured core sample in the middle, and a helium collection chamber at the top. Core samples were cut and set at various apertures and placed in a mould. The mould is open at the base and the top of the core sample, sealed at the sides, with the fracture set on the vertical plane. The helium is injected into the basal chamber, where it rises with the same pressure differential each time and measured at the top of the sample.

Helium was detected at the top of the sample in intermittent bursts or pulses. The first pulse was smaller in concentration than the following pulses indicating the shortest travel distance, while the larger pulses that follow indicate the average travelling distance. The large pulses continue until the helium diminishes. This pulsed style of flow indicates bubble flow. Bubble flow for helium is supported by the literature. Subsequent analyses and calculations will be based on bubble flow mechanics.

The calculation of fracture aperture from the helium rise velocity provides a link between gas flow and water flow, as conductivity is calculated from the fracture aperture. Cored sandstone samples were cut vertically in half and separators were placed between the cored halves at different thicknesses. These artificially fractured rock samples represent natural vertical joints in which helium is to be injected into. The joint surface is not completely flat as the samples were not perfectly cut. Therefore the spaced apertures may not necessarily be represented by the separated thickness and may be larger than expected.

The experiment was set up to time how long it took the first pulse to travel the shortest distance through the sample. The average fracture aperture of the shortest path can then be calculated using both Stoke's Law and Davies and Taylor's rise velocity formula. Six samples, each with set apertures of approximately 0.05 mm, 0.1 mm, 0.15 mm, 0.2 mm, 0.25 mm and 0.5 mm, were injected with helium and the time of the first pulse recorded. This was repeated as many times as possible for each sample. All the samples yielded reasonably within the expected range.

The samples were also subjected to water flow tests where water flowed through the fractured samples under constant head. The aperture of the samples was calculated using the cubic law. The water tests were used to verify the set apertures and form a comparison for the helium results. The results are tabulated in Table 1.

The water tests show the aperture to be larger than the set aperture as expected. This is due to the extra space created between the rough fracture surface and the spacers. The helium method yielded smaller apertures than the water test results. This may be due to a factor of surface tension or static between the helium and the rock wall of the fracture that was not accounted for.

The set apertures calculated from the results of helium and water flow are plotted in Figure 1. For smaller apertures, Stoke's Law fits more closely with the set and water derived apertures, while the

Davies and Taylor equation fits more closely for larger apertures above 0.15 mm. This is supported by the literature where Stoke's Law is used for smaller apertures and Davies and Taylor is used for larger apertures.

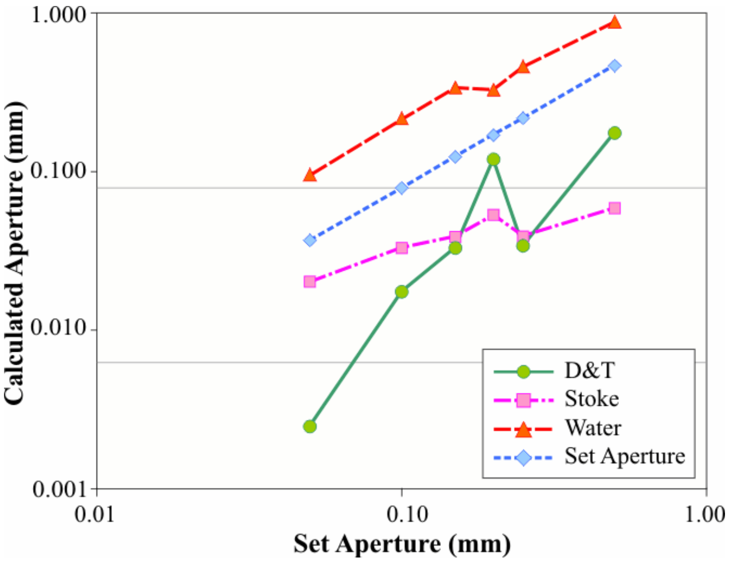

Figure 1 - Comparison of calculated apertures for Stoke's and Davies & Taylor's and water test methods.

The conductivity (*K*) of a fracture is calculated from the fracture aperture (*e*) using the cubic law. The kinematic viscosity (*v*) is $1.01\text{x}10^{-6}$ m^2/s for water as follows (Indraratna and Ranjith, 2001):

$$K = \frac{ge^3}{12vb}$$

The calculated apertures, from the helium bubble flow and Darcy water flow, have been used to calculate the equivalent conductivities (Table 1). These calculations will be useful when injecting into the goaf to determine average conductivities of the overburden.

There are limited experiments worldwide that illustrate the flow rates of helium through fractured rock. Etiope and Martinelli (2002) have summarised examples of bubble flow through fractured rock which are represented in Figure 2. The examples include radon in igneous rocks (1) and helium bubble flow through low-permeability saturated faulted clays (2), medium-permeability clays (3) and high-permeability saturated faulted granite (4).

The flow per aperture has an upper boundary of Stoke's Law for small apertures, Davies and Taylor's equation for larger apertures and the terminal velocity of helium in air, as determined in this study. Factors that reduce the flow rate from the theoretical results include surface roughness, aperture variability, external stress and infill (Ranjith, 2000), which explains the trend of the experimental data. The data is also closer to the theoretical gas velocity for the larger apertures as the surface effects reduce with the increase in aperture width.

HELIUM GOAF INJECTION

This section looks at the injection of helium into the goaf of a longwall and the helium detection methods in surface cracks for the purpose of determining surface to goaf connectivity and characterising the overburden conductivity. It follows our chronology of determining the best technique for helium goaf injection and surface detection through field trials at Beltana and Ashton Mines.

Table 1 - Experimental results with aperture and conductivity calculations

Set Aperture mm	Sample Length m	Mean Time s	Rate m/s	Calculated Aperture mm			Calculated Conductivity m/s		
				Davies & Taylor	Stokes's Law	Water	Davies & Taylor	Stoke's Law	Water
air	1.14	7.5	0.152						
0.5	0.655	33.33	0.02	0.206	0.076	0.889	7.0E-06	3.6E-07	5.7E-04
0.25	0.58	62	0.009	0.047	0.053	0.495	8.2E-08	1.2E-07	9.8E-05
0.20	0.185	11.2	0.017	0.145	0.070	0.364	2.5E-06	2.8E-07	3.9E-05
0.15	0.245	26.6	0.009	0.045	0.052	0.375	7.5E-08	1.2E-07	4.3E-05
0.10	0.235	34	0.007	0.025	0.045	0.250	1.3E-08	7.5E-08	1.3E-05
0.05	0.205	72	0.003	0.004	0.029	0.119	6.5E-11	2.0E-08	1.4E-06

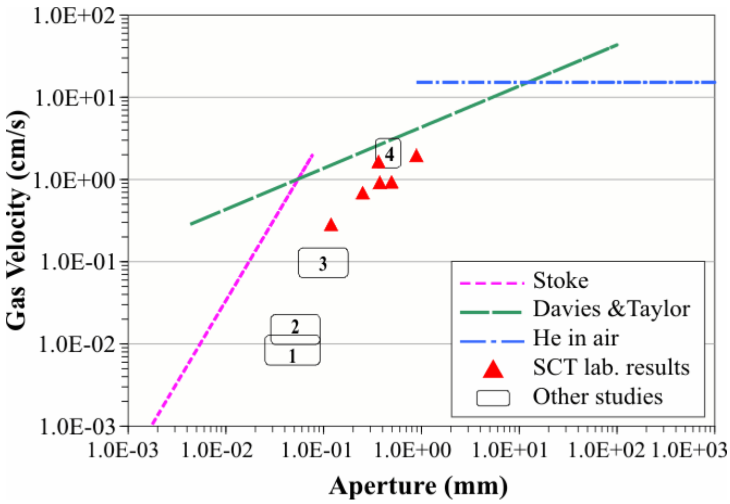

Figure 2 - Gas velocity versus aperture

Realistically, for helium to migrate from the goaf to the surface, the helium will travel through a network of fractures. The shallower the depth of cover over a mined seam, the more direct the fracture path is to the surface. Therefore the thicker the depth of cover, the more tortuous the flow path will be. There are other local factors that influence the tortuosity and aperture of the fractures, one of them being lithology.

The methodology for helium injection into the goaf is a follows. The goaf helium injection stage requires one person underground to release the gas and another person on the surface to monitor the surface cracks. To inject the helium into the goaf, tubing must be installed in the cut-through seal to the edge of the goaf, otherwise the helium may pocket in the cut-through. The helium is then released and the time of the release recorded. On the surface, the cracks are monitored for the injected helium. The time and concentration is recorded for each helium pulse. Detected helium results are compared with background helium results. A Uson Qualichek 1210 Leak Locator was used to detect the concentrations of helium. The detector has a remote sensor with a long nozzle to detect the helium emerging from the surface cracks.

Beltana Trial

Trials were conducted at Beltana No. 1 Mine in Singleton, where helium injections were carried out in the Whybrow Seam goaf in longwall Panels 6 and 7. The seam ranges in depth from approximately 50 m to 220 m. Subsidence cracks at Beltana form an arc from the maingate to the tailgate. This trial involved the injection of high purity helium into the goaf of the longwall panel where it would be monitored in surface subsidence cracks.

The geological section of the site consists of an interbedded sedimentary sequence of sandstone, siltstone, mudstone and coal with part of the sedimentary sequence overlain with sill. The current working seam is the Lower Whybrow.

Trials were conducted at three sites with depths of cover of 50 m, 105 m, and 220 m. During preliminary trials background helium was also observed emerging from the surface cracks. This created another element to determining whether a surface to goaf connection exists. The need for background helium to be characterised was now necessary to isolate injected helium from background helium. The background helium may not come from the mined seam but may come from smaller coal seams higher up in the sequence. The variability of whether there is background helium can also change daily with the change in air pressure. For this reason, background tests must be conducted on the day of the injection.

In the subsequent trial, the background and injected helium was detected from the surface cracks in pulses. The pulses indicated bubble flow while the variability of the pulses indicated a tortuous path. The flow mechanism resembled laboratory results.

50 m site - The surface cracks at this site were large and continuous and could be traced for at least 20 m, up to and over 50 m. The 50 m site was not tested for background helium. However large quantities of helium were detected 5 minutes after the injection. Background readings were not measured at this site; however, as the site is only 50m deep there are no major coal seams above the mined seam which would imply that any reading of background or injected helium would be sourced from the goaf.

105 m site - The subsidence cracks at the 105 m site were smaller than the 50 m site and less continuous on the surface. After helium injection, small pulses of helium were detected in a number of cracks which did and did not exhibit background helium. The cracks with no background helium and a helium injected result indicated a connection between the surface and the goaf. This situation is ideal as no background comparisons are needed. The low intensity of the peaks indicates that the average aperture is very small and only a small amount of helium migrated along this path.

The other scenario was cracks that had background helium results that needed to be compared with the injected helium results. As the background helium has the same pulse flow characteristics as the injected helium, a comparison of the rate and peak intensity is needed. The magnitude of background peaks was generally less than 30 sccm. After 12:58:40 pm a definite increase in intensity of helium concentration is observed with average peaks increasing to approximately 50 sccm. The helium was injected at approximately 12:30 pm indicating the injected helium reached the surface approximately 30 minutes after injection. The variability of average peak height two hours after injection indicates the migration path is a tortuous fracture network.

220 m site - The 220 m site showed cracks similar in size to those at the 105 m site. The crack continuity is about 1-10 m. The surface continuity at this site was reduced by surface features such as vineyards and roads. Background helium levels were observed at the 220 m site early on in the trial process and reduced dramatically over the period of the trial. In the final injection at this site most cracks monitored did not show a helium response except for one crack which noticeably showed a helium response with no measured background helium. This may indicate a surface to goaf connection. The peak intensity and frequency similarly to the 105m site again indicating a small average fracture aperture with a finite volume of helium injected into the fracture system. Other cracks showed a small helium response during background monitoring but did not show any response after helium goaf injection. This shows the variability of helium detection at this site and may indicate that the measured post injection helium response described above may not be indicative of a surface to goaf connection.

The 105 m site was used to determine fracture aperture and conductivity. The time taken for the injected helium to reach the surface at the 105 m overburden site was 30 minutes. At this overburden thickness the caved zone is approximately 50 m, resulting in 55 m of upper strata with reduced flow velocities. Subtracting the time and distance of free helium flow allows the calculation of average velocity which in turn determines the average aperture. For this instance, the helium flowed at 150 mm/s for 50 m which equates to 5.5 minutes. The remaining time (30-5.5 minutes) of 24.5 minutes is the time it takes to travel the last 55m. This equates to a flow rate of 4cm/s assuming a direct path. Extrapolating the gas velocity to the aperture in the bubble migration graph illustrated in Figure 2 we get an aperture of approximately 1mm. It is unlikely that the flow path is direct so an element of tortuosity would increase the distance of flow and the flow rate. Therefore the calculated aperture is a minimum aperture.

Conductivity is calculated from the aperture of a fracture. The calculated conductivity is an average conductivity throughout the overburden. For the 105 m site above, the aperture was calculated at a minimum of 1mm for the non caved zone. The conductivity formula for an individual fracture using the cubic law is as follows (Indraratna & Ranjith, 2001):

$$K_f = \frac{ge^3}{12vb}$$

Where the hydraulic conductivity of a single fracture is K (m/s), *g* is gravity (m^2/s), aperture is *e* (m), kinematic viscosity (*v*) is 1.01×10^{-6} m^2/s for water and *b* is the spacing between fractures (m). An aperture of 1mm, using this formula and assuming 1 fracture in a 1m cube, equates to a hydraulic conductivity of 8×10^{-4} m/s (assuming water as the fluid). Therefore the average hydraulic conductivity of the non caved zone above the goaf at 105 m overburden is greater than 8×10^{-4} m/s.

The advantage of using the helium injection technique to estimate hydraulic conductivity is that it focuses on the vertical conductivity as opposed to other methods, such as borehole packer testing, that focus on horizontal conductivity.

From the Beltana helium injection trials, a technique for injecting helium into the goaf and detecting the helium in surface cracks was developed. The trials revealed a limitation where background helium from both the working seam and seams in the overburden was emerging from the surface cracks. To overcome this background helium detection, both pre and post helium injection levels were required to be monitored. If the background levels are too high then it is difficult to distinguish the injected helium from the background helium.

Ashton Trial

After field trials at Beltana, the technique was tested at another site. Further injections took place at Ashton Underground Mine to determine whether a surface to goaf connection existed in Longwall 1. Injections were conducted at 95 m and 75 m overburden thicknesses.

The geological section at Ashton consists of an interbedded sedimentary sequence with numerous coal seams. The current working seam is the Pikes Gully Seam which in Longwall 1 ranges from 40 m to 95 m deep. The surface cracks at the 95m overburden site were up to 0.3 m wide with vertical continuity of at least 5-7 metres. The cracks at this site were large due to the influence of the sloping topography. After performing background checks, helium was injected into the goaf at 21 Cut-through. No helium was detected in surface cracks at this site. The cracks at the 75 m overburden site were much smaller with a maximum of only approximately 0.05 m wide. After performing background helium checks, helium was injected into the goaf at 17 Cut-through. No helium was detected in surface cracks at this site.

Helium may not have reached the surface for two reasons: i) the gas may have risen into a pocket with no surface connection, and not reached the cracks that do have a connection, or ii) there is no surface to goaf connection. Therefore, this method of helium injection does not confirm that there is a surface to goaf connection however it does not mean that a connection does not exist.

In the two trials, a method of helium injection and detection has successfully been used to determine whether a surface to goaf connection exists. A repeatable technique of helium injection into longwall goaf was developed to determine whether a surface to goaf connection exists (See ACARP Report C15010).

BOREHOLE HELIUM INJECTION

Borehole helium injection was trialled in addition to helium injection into the goaf. This method was created to reduce the limiting factors found using goaf injection, such as the inability to direct the helium into the continuous vertical cracks in the goaf. This method using borehole helium injection was trialled at Ashton Mine after goaf helium injection observed a null result. A borehole was drilled into the goaf of a longwall panel. Subsidence cracks on the surface adjacent to the borehole were the targets for detecting the helium.

The lithology of the overburden consisted of interbedded sandstone, siltstone and coal. The mined Pikes Gully Seam sat approximately 90m below the surface. The 50 m borehole was drilled to approximately 40 m above the mined seam. Difficulty in retaining water return during drilling in addition to attempted packer testing indicated a highly conductive fracture network around the borehole.

The method for borehole helium injection is as follows. The intervals were defined with inflatable packers at the top and the base of the borehole. Helium was injected into the strata at 500 kPa. The helium was injected into the packed off interval and injected horizontally into the strata. The injected pressure quickly decays from the borehole centre. Then due to its buoyant nature, the helium rises up to the surface via the interconnected fracture network.

Background tests conducted on the two tested surface cracks detected zero helium. All three tests at 20 m, 30 m, and 50 m recorded a connection with pulses of helium observed up to 6 minutes apart however mostly about 1 minute apart (Table 2).

Table 2 - Ashton borehole helium injection results

Depth (m)		Time Between Pulses (mins)		
From	To	Min.	Max.	Mean
18.32	**21.56**	**~1**	**~1**	**~1**
30.00	**31.31**	**1**	**6**	**~1**
49.4	**50.6**	**0.2**	**1.7**	**~0.5**

The conductivity calculated from the rate of helium injected into the borehole was found to be at least $1x10^{-5}$m/s, similar to that of the packer testing results. However, once the applied pressure was turned off, the pressure down the borehole dropped off immediately indicating that the down-hole pressure was much less than the injection pressure. This is due to the helium in the hole discharging faster than it was recharging, due to resistance in the inflation tube. This may indicate a much higher conductivity than calculated.

The rate of helium flow to the surface indicates a much higher conductivity than the volume injected into the strata. At the 50 m deep site, helium took 75 s to reach the surface, which equates to a rate of approximately 650 mm/s. Referring to the gas velocity vs. aperture graph of other test results (Figure 2), the gas velocity in this study corresponds to free flowing gas with apertures greater than 5mm. The conductivity of a fracture with 5 mm aperture equates to $1x10^{-1}$ m/s, which is much higher than the conductivities calculated from the water and helium volume flow rates due to not measuring the exact down hole pressure.

The results of the borehole injection test indicated that the overburden above the test locations was conductive and indicated that the helium injected into the goaf at the two underground sites may not have had a clear pathway to the fractured overburden above the monitoring sites. The borehole injection method did not preclude the presence of an impermeable layer below the borehole that could explain the lack of helium migration from the goaf injection to the surface.

The borehole helium injection technique is a more direct approach of injecting helium into the fracture network of the overburden. With a borehole drilled into the highly permeable caved zone of the goaf, then borehole helium injection can demonstrate more quickly if a connection to the surface exists.

An advantage of the borehole helium injection is that the helium is injected directly into the fracture network as opposed to the injection of helium into the goaf which does not guarantee that the helium will rise into the fractures that have a connection to the surface. Another advantage is the time taken to monitor the cracks during borehole injection is only a matter of minutes rather than the hours it takes to monitor the goaf injection.

The borehole helium injection can be used in conjunction with packer testing to parallel the results. Packer testing shows the characteristics of lateral conductivity around the borehole while helium injection shows the characteristics of vertical conductivity adjacent to the borehole.

LIMITING FACTORS

A few limiting factors were found during this study. The limiting factors may affect the results of the test by inhibiting flow or detection of the helium.

Helium is found in goaf gas at some mines and can be detected prior to helium injection. If the background helium levels are too high then it is difficult to differentiate the injected helium from the background helium. However, as helium dissipates with time, the test can be delayed until the background helium levels are low enough.

Rain can cause a direct problem by increasing the moisture content in the soil which in turn expands the soil resulting in the reduction of crack aperture. Rain can indirectly restrict flow through small cracks by silting them up. Therefore, if the test cracks are small, it is ideal to test before rain events if possible. However if this is the case, then it is advantageous for the mine.

CONCLUSION

From laboratory experiments it was found that the mechanics of helium flow through fractures is by bubble flow. A relationship between gas velocity and fracture aperture was found allowing the determination of fracture conductivity through helium injection, which was comparable with previous works.

Field trials of helium injection into the goaf were successfully conducted to determine whether a connection exists between the surface and the goaf. The determination of whether a surface to goaf connection exists requires a two stage process consisting of the measurement of background helium and injected helium. The average fracture aperture is determined from the arrival time of the first injected helium pulse which takes the most direct path to the surface. From the average aperture an equivalent average conductivity can be calculated.

Another technique of borehole helium injection was used to determine connection in the fracture network of the overburden. The borehole helium injection technique is a more direct approach of injecting helium into the fracture network of the overburden. With a borehole drilled into the highly permeable caved zone of the goaf, then borehole helium injection can demonstrate more quickly if a connection to the surface exists.

A repeatable technique of helium injection into the goaf or borehole has successfully been developed and demonstrated to prove connectivity between the goaf and surface of a longwall coal mine. These techniques will prove an effective tool for monitoring of environmental and hydrological problems.

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REFERENCES

Agarwal, M, Gupta, S K, Deshpande, R D and Yadava, M G, 2006. Helium, radon and radiocarbon studies on a regional aquifer system of the North Gujarat-Cambay region, India, *Chemical Geology*, 228:209-232.

Ciotoli, G, Etiope, G, Guerra, M and Lombardi, S, 1999. The detection of concealed faults in the Ofanto Basin using the correlation between soil-gas fracture surveys, *Tectonophysics*, 301:321-332.

Etiope, G and Martinelli, G, 2002. Migration of carrier and trace gases in the geosphere: An overview, *Physics of the Earth and Planetary Interiors*, 129:185-204.

Fourar, M and Bories, S, 1995. Experimental study of air-water two-phase flow through a fracture (narrow channel), *Int. J. Multiphase Flow*, 21(4):621-637.

Gascoyne, M and Wuschke, D M, 1997. Gas migration through water-saturated, fractured rock: results of a gas injection test, *Journal of Hydrology*, 196:76-98.

Indraratna, B and Ranjith, P, 2001. Hydromechanical Aspects and Unsaturated Flow in Jointed Rock, 30p (A.A. Balkema Publishers: Lisse).

Kristiansson, K and Malmqvist, L, 1982. Evidence for nondiffusive transport of $^{222}_{86}Rn$ in the ground and a new physical model for the transport, *Geophysics*, 47(10):1444-1452.

Liefer, I, Patro, RAKI and Bowyer, P, 2000. A Study on the Temperature Variation of Rise Velocity for Large Clean Bubbles, *Journal of Atmospheric and Oceanic Technology*, 17(10):1392-1402.

Lineham, T R, Nash, P J, Rodwell, W R, Bolt, J, Watkins, V M B, Grainger, P, Heath, M J and Merefield, J R, 1996. Gas migration in fractured rock: results and modelling of a helium gas injection experiment at the Reskajeage Farm Test Site, SW England, United Kingdom, *Journal of Contaminant Hydrology*, 21:101-113.

Odling, N E , Gillespie, P , Bourgeon, B , Castaing, C , Chiles, J-P, Christensen, N P, Fillion, E, Genter, A, Olsen, C, Thrane, L, Trice, R, Aarseth, E, Walsh, J J and Watterson, J, 1999. Variations in fracture system geometry and their implications for fluid flow in fractured hydrocarbon reservoirs, *Petroleum Geoscience*, 5:373-384.

Ranjith, P G, 2000. *Analytical and Experimental Modelling of Coupled Water and Air Flow through Rock Joints*, PhD thesis (unpublished), University of Wollongong, Wollongong.

Ranjith, P G, Choi, S K and Fourar, M, 2006. Characterization of two-phase flow in a single rock joint, *International Journal of Rock Mechanics and Mining Sciences*, 43:216-223.

Reddy, D V, Sukhija, B S, Nagabhushanam, P, Reddy, G K, Kumar, D and Lachassagne, P, 2006. Soil gas radon emanometry: A tool for delineation of fractures for groundwater in granitic terrains, *Journal of Hydrology*, 329:186-195.

Sarkar, S, Toksoz, M N and Burns, D R, 2004. Fluid Flow Modeling in Fractures [online], *MIT Earth Resources Laboratory Industry Consortium Meeting*, Available from:< www-eaps.mit.edu/erl/research/report1/pdf2004/sarkar.pdf> [Accessed: 19 November 2008].

Viana, F, Pardo, R, Yanez, R, Trallero, J L and Joseph, D D, 2003. Universal correlation for the rise velocity of long gas bubbles in round pipes, *J. Fluid Mech.*, 494: 379-39