MAKING THE RED ONE GREEN – RENEWABLE HEAT FROM ABANDONED FLOODED MINES

David Banks
School of Engineering, James Watt Building (South), University of Glasgow. Glasgow, G12 8QQ, UK
Holymoor Consultancy Ltd., 360 Ashgate Road, Chesterfield, Derbyshire, S40 4BW, UK

Abandoned mines are often allowed to flood, sometimes overflowing at the surface to form discharges of potentially contaminated (often ochreous, acidic or metal-rich) mine water. Other such mines are actively pumped and managed to prevent contaminated water overspilling at the surface. They are usually regarded as environmental or economic liabilities. At increasing numbers of locations throughout the world, the huge reservoir of warm(ish) water contained in these mines is being utilised as a thermal resource or store, providing "green" space heating or cooling. The underground network of tunnels and shafts provides a heat exchange interface with the rocks in the mined area. In this way, it is possible to convert an ochreous reddish-orange environmental liability into a green renewable energy asset. Five main factors hinder the adoption of mine water as a thermal resource: (i) the lack of proven heating and cooling demand in the vicinity of some mines; (ii) the major investment required in district heating/cooling systems to optimally utilise the resource; (iii) legislative and licensing uncertainty; (iv) the perceived risk of ochre/metal precipitate clogging of heat exchangers and injection wells; (v) the perceived risk of rapid thermal breakthrough of re-injected thermally spent water at the production well. This paper examines how these issues have been tackled at a number of European mine water sites.

"Will all great Neptune's ocean wash this blood
clean from my hand? No; this my hand will rather
the multitudinous seas incarnadine,
making the green one red."

William Shakespeare, Macbeth, Act II, Scene 2

MINE WATER AS A THERMAL RESOURCE

MINE WATER - AN INTRODUCTION

When working, almost any mine that penetrates below the regional water table will require active dewatering to keep it dry. While working, water and air freely circulate throughout the mine, accelerating many of the geochemical reactions which would otherwise be limited by lack of access to oxygen in undisturbed ground. Many mineral deposits (including coal, oil shales and many metals) contain sulphide minerals, which tend to oxidise in a mining environment to release sulphate and dissolved metals. Some of these (e.g. pyrite) also release acid:

$$2FeS_2 + 7O_2 + 2H_2O \leftrightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+$$

When a mine is abandoned (as many coal mines were in the UK in the 1980s and 1990s), the pumps may be switched off and the mine water gradually refills the mine, possibly overflowing at the surface as a contaminated mine water discharge (Banks et al. 1997a,b).

On further exposure to oxygen, the ferrous (Fe^{2+}) iron oxidises to ferric (Fe^{3+}), and hydrolyses, to precipitate as iron oxyhydroxide or "ochre".

$4FeS_2 + 15O_2 + 14H_2O \leftrightarrow 4Fe(OH)_3\downarrow + 16H^+ + 8SO_4^{2-}$

Thus, coal mine water discharges in the UK are often characterised by an "apron" of ochre at the discharge point and ochre staining of river beds downstream of the discharge. The discharge may be treated to remove the dissolved iron (or manganese), either by active methods or by a range of passive methods (typically involving aeration, sedimentation and polishing wetlands - Banks & Banks 2001, PIRAMID 2003).

In some cases, the consequences of uncontrolled discharges of mine water are deemed unacceptable, and an agency (such as the UK's Coal Authority) continues to dewater the mine complex by pumping, in order to prevent such outbreaks. The pumped water typically requires treatment. The management of minewater is often at a regional scale (Younger & Harbourne 1995), given that collieries in UK coalfields often interconnect over many tens of km (Burke & Younger 2000).

MINE WATER - A THERMAL RESOURCE

Thermogeologists and hydrogeologists are increasingly recognising that flooded mines represent a thermal resource. They contain enormous reserves of groundwater at or (in deep mines) somewhat above the annual average air temperature. Flooded mines thus have the potential to provide space heating (via heat pumps) in winter and space cooling in summer. The network of tunnels and shafts represents an enormous heat exchange interface with the rocks contained in the mined area. If a shaft or borehole penetrates a mine roadway, the water yields available can be very high. For example, if a heat pump extracts 5°C worth of heat from a stream of groundwater, the heat available is:

5°C x 4180 J/L/°C x 1 L/s = 20900 J/s or 20.9 kW, from 1 L/s of water.

If 100 L/s mine water are available, the amount of extractable heat is 2.1 MW.

Such mine water-based heating and cooling systems occur throughout the world, and reviews are provided by Banks et al. 2003, 2004; Watzlaf & Ackman 2006; Hall et al. 2011; Preene & Younger 2014; Ramos et al. 2015 and Bracke & Bussmann, 2015. In the UK, mine water heating schemes are operational or have been trialled at Shettleston, Glasgow; Lumphinnans, Fife (Banks et al. 2009); Markham, near Bolsover, Derbyshire (Athresh et al. 2015); Caphouse, near Wakefield, Yorkshire (Burnside et al. *in press*), Dawdon, Co. Durham (Watson 2012), Crynant, South Wales (Farr & Tucker 2015) and Florence Mine, Egremont, Cumbria.

BARRIERS TO CONCEPT

Despite the technology having been demonstrated at numerous sites worldwide, there are several key hurdles which act as obstacles to implementation of the mine water heating / cooling concept.

LACK OF LOCAL DEMAND

Heating and cooling are not readily transferable over large distances; thus, for the mine water heating and cooling concept to be viable, proven demands for heating and cooling need to exist in the immediate vicinity of the flooded mine (or, more specifically, of the access point to the mine water - shaft or borehole - JHI 2016).

In some cases, open mine shafts, providing access to warm mine water, may exist in an urban centre. A good example of this is Katowice, Poland, where open pumped mine shafts in the city centre yield warm mine water (Figure 1; Janson et al. 2009). In other cases, a colliery or mine site provides an ideal location for redevelopment as commercial and industrial space (or even housing developments), with its own heating and cooling demands. This scenario has occurred at several sites in the UK and elsewhere, but the potential of minewater to provide heating and cooling was not "sold" to the developer at an early enough stage, before conventional heating and cooling systems had been locked in (Figure 2).

Figure 1. Katowice mine shaft (with dewatering pumps) in an urban environment in Poland (photo by © David Banks).

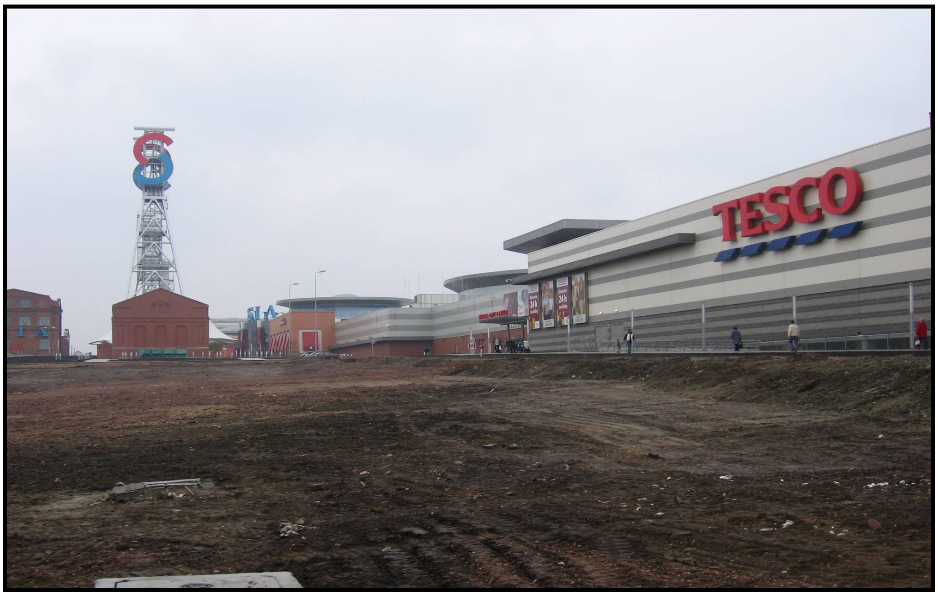

Figure 2. Redevelopment of the Kleofas mine site, Katowice, Poland (photo by © David Banks).

In yet other cases, flooded mine workings underlie a development site with proven heating and cooling demands, but no open shafts exist. Thus, accessing the mine water demands a potentially costly drilling operation, maybe to encounter a 5 m diameter roadway at several hundred m depth. The expense and potential risk of such an operation can prove off-putting to investors.

NEED FOR INFRASTRUCTURAL INVESTMENT

For a large-scale mine water heating / cooling scheme, a significant infrastructural investment may be required before the thermal resource can be utilised by surrounding residents and businesses. A *centralised* heat pump plant room may be constructed, from which hot (for space heating) or cold (for air conditioning) fluids can be distributed to nearby users. Alternatively, the mine water (or a heat transfer fluid thermally coupled to the mine water) can be distributed to users via flow and return pipes, and individual users' heat pumps extract heat from or reject heat to this fluid flow (a *distributed system*). In either case, the cost of laying mine water or district heating and cooling pipes, especially in urban areas, can be a dominant capital cost in the total development. Additionally, where retrofitting heating to existing properties, it may be necessary to invest capital in installing the modern, low-temperature radiators / underfloor circuits that function efficiently with heat pumps.

LEGISLATION - WHAT TO DO WITH THE THERMALLY SPENT WATER?

Another set of obstacles is potentially legal: will an operator be granted an abstraction licence for the mine water? And how long will that licence last? For the size of capital investment in a large-scale mine water heating and cooling project, the investor must be sure that the legal right to abstract water can be guaranteed over at least several decades. And, if an operator extracts mine water from the ground, do they accrue liability for any contamination arising from that water, and how long might that liability last?

It is not enough to pump mine water from the ground and extract heat or "coolth" from it. One must also be able to dispose of the thermally "spent" mine water legally and cost-effectively. The mine water can be rejected to a surface water recipient. However, this will typically require that the water be treated to remove potential contaminants before discharge (another cost). Will temperature changes in the water affect the efficiency of water treatment? Alternatively, the mine water can be reinjected to the mine following usage, but this often incurs the cost of drilling and maintaining one or more injection boreholes. There is also the thermal risk that the cool, reinjected mine water will find its way back to the production well within the mine system (a phenomenon known as thermal feedback).

Of course, not all mines yield contaminated water. The water pumped through a heat pump of nominal 123 kW capacity at Florence ironstone (Fe_2O_3) mine, in Cumbria, UK, during a trial was of rather good quality and was able to be discharged directly to the local stream. Similarly, the water from Barredo colliery at Mieres, Asturias, Spain, is discharged after heat exchange, to the local river.

THERMAL FEEDBACK WITHIN THE MINE

Where thermally spent water (e.g. cool water from a space heating operation) is reinjected to the mine, there is a risk that it will find its way back to the abstraction well. Of course, the walls of the mine tunnels and shafts act as heat exchange surfaces, and the cool water reacquires heat from the surrounding rocks during its passage. If the flow pathway is too short or too direct, however, the cool water enters the production well before it has had a chance to reacquire its initial temperature, cooling the production water and lowering the efficiency of the heating operation.

Thus, a detailed mapping of subsurface pathways, coupled to a thermal modelling exercise, needs to be undertaken to prove the heat exchange capacity of the main flow pathways. The predominant models for this are the Lauwerier-Pruess-Bodvarsson model (Lauwerier 1955, Pruess & Bodvarsson 1983) and the Rodríguez-Díaz model (Rodríguez & Díaz 2009). Loredo et al. (*in preparation*) have reviewed these models and concluded that the Rodríguez-Díaz model, possibly with some minor modifications, is the preferred approach for quasi-circular tunnels. Authors such as Ferket et al. (2011) have taken this approach further by coupling such heat exchange algorithms to pipeline network models such as EPANET, to simulate heat flow and transfer within a network of mine passages.

Numerical modelling can, of course, also be brought to bear on this problem (Renz et al. 2009).

OCHRE CLOGGING AND HYDROGEOCHEMICAL RISKS

The perceived risk that iron or manganese oxyhydroxides may precipitate in pumps, pipes, heat exchangers or injection wells has also deterred several potential investors from mine water based heating / cooling schemes. This is, for most coal mine waters, a real risk - the waters typically have a circum-neutral or slightly acidic pH and concentrations of several mg/L or even tens of mg/L Fe, which will oxidise, hydrolyse and precipitate if allowed in contact with oxygen. Several studies lead us to conclude that, if iron is reduced (Fe^{2+}) and dissolved at the point of abstraction, and if contact with oxygen can be prevented during the abstraction-heat exchange-reinjection process, then iron can be kept in solution and ochre clogging will not occur in significant amounts.

The Dawdon mine water heat pump scheme (Watson 2012) in County Durham, UK initially passed mine water (pumped from Dawdon Colliery) through a heat pump system after it had been treated by aerobic methods. Significant clogging problems were experienced and the scheme was thus altered to pass the raw, untreated mine water (prior to access to oxygen) through the heat exchanger, which greatly reduced the clogging issues.

At Shettleston, Glasgow and Lumphinnans, near Cowdenbeath in Fife, Scotland, two modest heat pump schemes have been running off mine water from shallow flooded colliery workings since around 1999. There have been relatively few clogging problems in the heat pumps themselves - such issues as have arisen have been connected with the re-injection borehole, especially following vandalism at the Lumphinnans site, which resulted in the thermally spent water coming into contact with oxygen prior to reinjection and thus significant ochre clogging of the reinjection borehole (Banks et al. 2009).

Modelling also suggests that many mine waters have a significant partial pressure of CO_2, which can degas if it is exposed to the atmosphere. This brings about a rise in pH which promotes precipitation of metal oxyhydroxides and carbonates.

The message thus appears to be: keep the abstraction-heat exchange-reinjection circuit pressurised and sealed, without atmospheric contact.

The EU-funded LoCAL (Low Carbon AfterLife) project (see Acknowledgements) has tentatively found that some mine waters have already apparently been exposed to oxidising conditions in the subsurface, such that ferrous iron oxidation and hydrolysis have commenced prior to abstraction (e.g. Caphouse mine, Yorkshire). Thus, the water may already contain small particles of ochre which can cause clogging issues regardless of the recommended precautions suggested above. The LoCAL project plans to trial the use of environmentally benign reducing additives (sodium bisulphite and sodium dithionite) to assist in keeping iron in its dissolved, ferrous state, during heat exchange and/or reinjection.

LoCAL CASE STUDY SITES

The LoCAL project specifically seeks to overcome some of the barriers discussed in this paper. It is monitoring a range of case study sites in the UK, Poland and Spain, all of which have differing heat exchange configurations.

OPEN-LOOP SITES

An “open loop” system actively abstracts groundwater (or mine water) and passes it through a surface heat exchanger or heat pump, where heat is extracted from or rejected to the flow.

Caphouse: A Pilot-Scale Open Loop Scheme with Discharge to Surface Water

The National Coal Mining Museum of England at Caphouse, near Wakefield, Yorkshire, UK, hosts a pilot-scale scheme to heat an audio-visual display room by means of a Vaillant 10 kW heat pump. The heat pump can be coupled either (a) via shell-and-tube heat exchangers, to the flow of mine water pumped each night from the 197 m deep Hope Shaft (“open loop”), or (b) to a closed loop “Energy Blade” heat exchanger submerged in a mine water treatment pond (Burnside et al. *in press* - see below).

The Hope Shaft at Caphouse is pumped every night and early morning from a submersible pump at c. 170 m bgl to keep regional mine water levels low enough to prevent (a) regional break out of uncontrolled mine water discharges, and (b) the museum’s underground “show gallery” from being flooded. The pumped water is treated passively via a system of aeration cascade, settlement basins and polishing wetlands before being discharged to the local stream. The open loop option has been operated by passing a small fraction of the pumped flow through a shell and tube heat exchanger coupled to the heat pump. The museum staff have found, however, that this option requires quite a lot of routine maintenance to keep filters on the mine water line free from ochre clogging. It appears that the iron in the pumped water may have started to oxidise and form ochre prior to abstraction from the Hope Shaft. Hitherto, however, provided routine de-clogging of filters has been performed, the system runs satisfactorily.

Mieres: A Large Open Loop Scheme with Discharge to Surface Water

The Barredo colliery at Mieres, Asturias, Northern Spain (Loredo et al. 2011, Ordóñez et al. 2012, Jardón et al. 2013) is also an open loop scheme. The shaft is no longer actively mined but is pumped in order to control mine water levels in a regionally interconnected network of collieries. Mine water, of rather good quality and temperature c. 23°C, is pumped from the 362 m deep Barredo shaft. A system of heat pumps and heat exchangers delivers several MW of heating and cooling effect to nearby University and Hospital buildings before the thermally spent water is discharged to the local river.

Shettleston: A Modest Open Loop Scheme with Reinjection Borehole

The mine water scheme at Shettleston has also volunteered to take part in the LoCAL project, being based on a c. 100 m deep borehole to coal workings beneath eastern Glasgow. The abstracted mine water is pumped directly through the evaporators of two Danfoss BW10-025 heat pumps, which provide heating to 16 social housing apartments. The water is thereafter directed to a reinjection borehole to a shallower depth (Banks et al. 2009). This arrangement is termed “open loop with reinjection”.

STANDING COLUMN SYSTEM - MARKHAM NO. 3 SHAFT

Markham No. 3 is a c. 490 m deep, 4.6 m diameter colliery shaft near Bolsover, Derbyshire, UK. It was closed in 1993-94 and mine water levels are still rising in the interconnected mine water complex associated with it.

The site is owned by the LoCAL Partner, Alkane Ltd. In around 2012, Alkane installed a submersible pump at 235 m bgl. Some 2 L/s of rather saline mine water was pumped from this depth, and passed through a shell-and-tube heat exchanger, thermally coupled to a Danfoss DHP-R 20 kW heat pump (Athresh et al. 2015). The cooler, thermally spent water was then returned to the same (No. 3 shaft) at

250 m bgl (15 m deeper than the pump). This is termed a “standing column” arrangement. Hitherto, no major problems with ochre precipitation in the heat exchanger, nor with thermal feedback of cool water, have been observed. This is ascribed to the highly reducing, methane-rich nature of the water keeping the iron dissolved, and to the large volume of water in the shaft section relative to the very modest heat extraction and pumped water circulation.

In January 2015, the pump was raised to 170 m bgl, and the reinjection diffuser repositioned at 153 m bgl (17 m *above* the pump). This was possible due to the mine water levels having recovered (risen) regionally. Under this new standing column regime, it was found that the pumped water was much fresher, indicating that the water in the shaft is hydrochemically stratified. The system continues to be monitored to ascertain if the new water chemistry will have any adverse effect on the clogging potential.

CLOSED LOOP SYSTEM - CAPHOUSE

Finally, at the Caphouse site described above, an “Energy Blade” (a radiator-like steel heat exchanger) has been submerged in the uppermost minewater treatment pond (aeration pond No. 1) and connected, via a closed loop of propylene glycol heat transfer fluid, to the heat pump. This has operated very successfully and the museum staff find it much more user-friendly and lower-maintenance than the “open loop” option (see above). This is because no mine water is actively pumped through the heat pump in the closed loop option, negating any clogging issues inside pipes and heat exchangers. Also, the treatment pond is full 24 hrs per day, allowing the heat pump to run whenever there is a demand. As noted above, mine water is only pumped through the aeration pond at night time and early morning. Thermal response testing has demonstrated that, while the closed loop system performs adequately without the need for mine water throughflow, its performance is enhanced when mine water is actively flowing through the aeration pond past the heat exchanger.

ACKNOWLEDGEMENT

Much of the work described in the paper is funded by the European Research Fund for Coal and Steel’s LoCAL project (Low Carbon After Life - sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure environmental risks), reference UE-14-RFCR-CT-2014-00001.

REFERENCES

Athresh AP, Al-Habaibeh A, Parker K (2015) Innovative Approach for Heating of Buildings Using Water from a Flooded Coal Mine Through an Open Loop Based Single Shaft GSHP System. *Energy Procedia* 75: 1221–1228. doi:10.1016/j.egypro.2015.07.162

Banks D, Burke SP, Gray CG (1997a) Hydrogeochemistry of coal mine drainage and other ferruginous waters in north Derbyshire and south Yorkshire, UK. *Quarterly Journal of Engineering Geology* 30: 257-280. doi: 10.1144/GSL.QJEG.1997.030.P3.07.

Banks D, Younger PL, Arnesen RT, Iversen ER, Banks SB (1997b) Mine water chemistry: the good, the bad and the ugly. E*nvironmental Geology* 32: 157-174. doi: 10.1007/s002540050204

Banks SB, Banks D (2001) Abandoned mines drainage: impact assessment and mitigation of discharges from coal mines in the UK. Eng*ineering Geology* 60: 31-37. doi: 10.1016/S0013-7952(00)00086-7

Banks D, Skarphagen H, Wiltshire R, Jessop C (2003) Mine water as a resource: space heating and cooling via use of heat pumps. *Land Contamination and Reclamation* 11(2): 191-198. doi: 10.2462/09670513.814

Banks D, Skarphagen H, Wiltshire R, Jessop C (2004) Heat pumps as a tool for energy recovery from mining wastes. *In* Gieré R & Stille P (eds.), "Energy, Waste and the Environment: a Geochemical

Perspective". *Geological Society Special Publication* 236: 499-513. doi: 10.1144/GSL.SP.2004.236.01.27

Banks D, Fraga Pumar A, Watson I (2009) The operational performance of Scottish minewater-based ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology* 42: 347-357. doi: 10.1144/1470-9236/08-081

Bracke R, Bussmann G (2015) Heat-storage in deep hard coal mining infrastructures. *Proceedings World Geothermal Congress 2015*, Melbourne, Australia, 19th-25th April 2015.

Burke SP, Younger PL (2000) Groundwater rebound in the South Yorkshire coalfield: A first approximation using the GRAM model. *Quarterly Journal of Engineering Geology* 33: 149-160. doi: 10.1144/qjegh.33.2.149

Burnside NM, Banks D, Boyce AJ (*in press*). Sustainability of thermal energy production at the flooded mine workings of the former Caphouse Colliery, Yorkshire, United Kingdom. *International Journal of Coal Geology* (*in press*). doi: 10.1016/j.coal.2016.03.006

Farr G, Tucker D (2015) Mine water as an energy source for heat pumps: a case study from the South Wales Coalfield. Meeting of the South West Regional Group of the Geological Society. 21st April 2015, Bristol. http://nora.nerc.ac.uk/510965/1/FarrTucker%20SEREN%20for%20NORA.pdf

Ferket HLW, Laenen BJM, Van Tongeren PCH (2011). Transforming flooded coal mines to large-scale geothermal and heat storage reservoirs: what can we expect? *In* Rüde RT, Freund A & Wolkersdorfer C (eds.), "Mine Water – Managing the Challenges". *Proc. IMWA Congress 2011 (Aachen, Germany)*: 171-175.

Hall A, Scott JA, Shang H (2011) Geothermal energy recovery from underground mines. *Renewable and Sustainable Energy Reviews15*: 916–924. doi:10.1016/j.rser.2010.11.007

Janson E, Gzyl G, Banks D (2009) The occurrence and quality of mine water in the Upper Silesian Coal Basin, Poland. *Mine Water and the Environment* 28: 232--244. doi: 10.1007/s10230-009-0079-3.

Jardón S, Ordóñez MA, Alvarez R, Cienfuegos P, Loredo J (2013) Mine water for energy and water supply in the Central Coal Basin of Asturias (Spain). *Mine Water and the Environment* 32: 139-151. doi: 10.1007/s10230-013-0224-x

JHI (2016) Fortissat community minewater geothermal energy district heating network. The James Hutton Institute, February 2016. Available at http://www.gov.scot/Publications/2016/03/8520.

Lauwerier HA (1955) The transport of heat in an oil layer caused by the injection of hot fluid. *Applied Scientific Research, Section A,* 5(2): 145-150. doi: 10.1007/BF03184614

Loredo C, Banks D, Roqueñí Gutiérrez MN (*in preparation*) Evaluation of analytical models for heat transfer in mine tunnels. *In preparation* for submission to *Renewable Energy.*

Loredo J, Ordóñez A, Jardón S, Álvarez R (2011) Mine water as geothermal resource in Asturian coal mining basins (NW Spain). *In* Rüde RT, Freund A & Wolkersdorfer C (eds.), "Mine Water – Managing the Challenges". *Proc. IMWA Congress 2011 (Aachen, Germany)*: 177-181.

Ordóñez A, Jardón S, Álvarez R, Andrés C, Pendás F (2012) Hydrogeological definition and applicability of abandoned coal mines as water reservoirs. *Journal of Environmental Monitoring* 14: 2127-2136. doi:10.1039/c2em11036a

PIRAMID Consortium (2003) Engineering guidelines for the passive remediation of acidic and/or metalliferous mine drainage and similar wastewaters. European Commission 5th Framework RTD Project no. EVK1-CT-1999-000021 "Passive *in-situ* remediation of acidic mine / industrial drainage" (PIRAMID). University of Newcastle Upon Tyne, Newcastle Upon Tyne UK. http://www.imwa.info/piramid/files/PIRAMIDGuidelinesv10.pdf

Preene M, Younger PL (2014) Can you take the heat? – Geothermal energy in mining. *Mining Technology* 123: 107–118. doi:10.1179/1743286314Y.0000000058

Pruess K, Bodvarsson GS (1983) Thermal effects of reinjection in geothermal reservoirs with major vertical fractures. *In* Society of Petroleum Engineers 58th Annual Technical Conference and Exhibition, San Francisco, CA, 5th-8th October 1983. pp. 1567–1578. doi:10.2118/12099-PA

Ramos EP, Breede K, Falcone G (2015) Geothermal heat recovery from abandoned mines: a systematic review of projects implemented worldwide and a methodology for screening new projects. *Environmental Earth Sciences* 73: 6783-95. doi: 10.1007/s12665-015-4285-y

Renz A, Rühaak W, Schätzl P, Diersch HJG (2009). Numerical modeling of geothermal use of mine water: Challenges and examples. *Mine Water and the Environment* 28: 2–14. doi:10.1007/s10230-008-0063-3

Rodríguez R, Díaz MB (2009) Analysis of the utilization of mine galleries as geothermal heat exchangers by means a semi-empirical prediction method. *Renewable Energy* 34: 1716–1725. doi:10.1016/j.renene.2008.12.036.

Watson I (2012) Dawdon mine water heat pump trial. Proc. IEA Heat Pump Programme Workshop, London 13th November 2012. Available at http://web.ornl.gov/sci/ees/etsd/btric/usnt/03IWatson.pdf

Watzlaf GR, Ackman TE (2006) Underground mine water for heating and cooling using geothermal heat pump systems. *Mine Water and the Environment* 25: 1–14. doi: 10.1007/s10230-006-0103-9

Younger PL, Banwart SA, Hedin RS (2002) Mine water: hydrology, pollution, remediation. Kluwer Academic Publishers, Dordrecht.

Younger PL, Harbourne KJ (1995). To pump or not to pump: cost benefit analysis of future environmental management options for the abandoned Durham Coalfield. *Journal of the Chartered Institution of Water and Environmental Management* 9(4): 405-415. doi: 10.1111/j.1747-6593.1995.tb00958.x