Reducing life-cycle costs of passive mine water treatment by recovery of metals from treatment wastes

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Abstract

In compost bioreactor systems, a commonly deployed technology at passive mine water treatment sites, metals accumulate in the treatment system substrate. Ultimately, this substrate becomes exhausted and requires disposal. An assessment was undertaken using a case study site in northern England, investigating how metal recovery might be used to reduce the whole life-cycle cost of treatment. The large-scale system at Force Crag mine harnesses bacterial sulphate reduction, primarily to remove zinc within a compost substrate.

Calculations of the rate of accumulation of zinc within the treatment system suggest that the value of zinc (as a pure metal) may amount to approximately €7600 after 10 years of operation, at current market prices. More significantly, the compost would be classified under UK legislation as hazardous waste because of the elevated zinc concentration. The cost of disposal of the 840 m^3 of compost in the treatment system would consequently be in excess of €0.8M. Such a high waste disposal cost would have a major influence on whole life-cycle cost of the treatment system, irrespective of exactly how long the system operates before the substrate becomes exhausted. The cost of removal of the zinc from the treatment substrate by washing has been calculated at approximately €155,000. This would reduce the volume, and therefore cost, of disposal by more than 10 times. Furthermore, it may be possible to re-use the decontaminated compost substrate, although this is an area of further investigation.

Data presented in this paper suggest that recovery of metals from treatment system substrates might offer substantial passive treatment system life-cycle cost reductions. At Force Crag, it is estimated that discounted life-cycle costs can be reduced from €1.63M to €1.12M over 10 years. Allowances for substrate decontamination processes should therefore be considered by treatment system operators from project inception, in order that these savings can be realised.

Key words: Passive treatment, metal recovery, life-cycle costs

Introduction

Passive mine water treatment has been widely adopted as a low-cost and low-impact means of tackling polluting discharges from abandoned mines (Younger, 2000). Bioreactors, harnessing microbial sulphate reduction in an organic substrate, offer advantages over other systems for installation at metal mine sites, as they simultaneously remove a range of metals and generate alkalinity (ITRC, 2013; Neculita et al., 2007; Rose, 2006). Inevitably, however, metals will accumulate within the substrates of bioreactors and eventually need to be disposed of. The costs associated with these materials can be high, particularly if they are classified as hazardous wastes (Gusek et al., 2006). Indeed, testing of a waste compost substrate from a system treating a zinciferous discharge at an abandoned metal mine for just 2 years was determined as hazardous waste under UK regulations due to its zinc content (unpublished data, Newcastle University 2013). The cost implications associated with disposal of these metalliferous, organic materials has been determined as € 495 - € 2170/t (Atkins, 2014). For context, the costs of disposing of hydrous ferric oxide wastes from aerobic treatment systems operating at coal mine sites is € 98 - € 160/t (Sapsford et al., 2015).

It has been suggested that metals might be recoverable from passive bioreactor wastes (Gray et al., 2012; Gusek et al., 2006; Gusek and Clarke-Whistler, 2005) and preliminary experimentation has been conducted to explore this (Bailey et al., 2015). Data suggest that metals are recoverable by particle size separation and leaching with dilute sulphuric acid (Bailey et al., 2015). These approaches are used by mining and contaminated land remediation systems (CL:AIRE, 2007; Wills, 2006; Tichy et al., 1996). By processing passive bioreactor wastes to recover metals, the costs associated with waste disposal might be substantially reduced, and an income stream may be generated.

This paper explores how recovery of metals from passive bioreactor wastes may be used to offset the life-cycle costs of mine water treatment. Financial and geochemical information have been collected from the Force Crag site in Northern England, UK, which has been operational since April 2014. The system at Force Crag Mine treats 6L/s of water draining from an abandoned Pb-Zn mine complex using two parallel Vertical Flow Pond (VFP) compost bioreactors of equal size, followed by a small polishing wetland (Figure 1). The total substrate volume of the system is 840m^3, consisting of a mix of 45% wood chip, 45% municipal waste compost and 10% digested sewage sludge. Further details of the treatment system can be found in Jarvis et al. (2015).

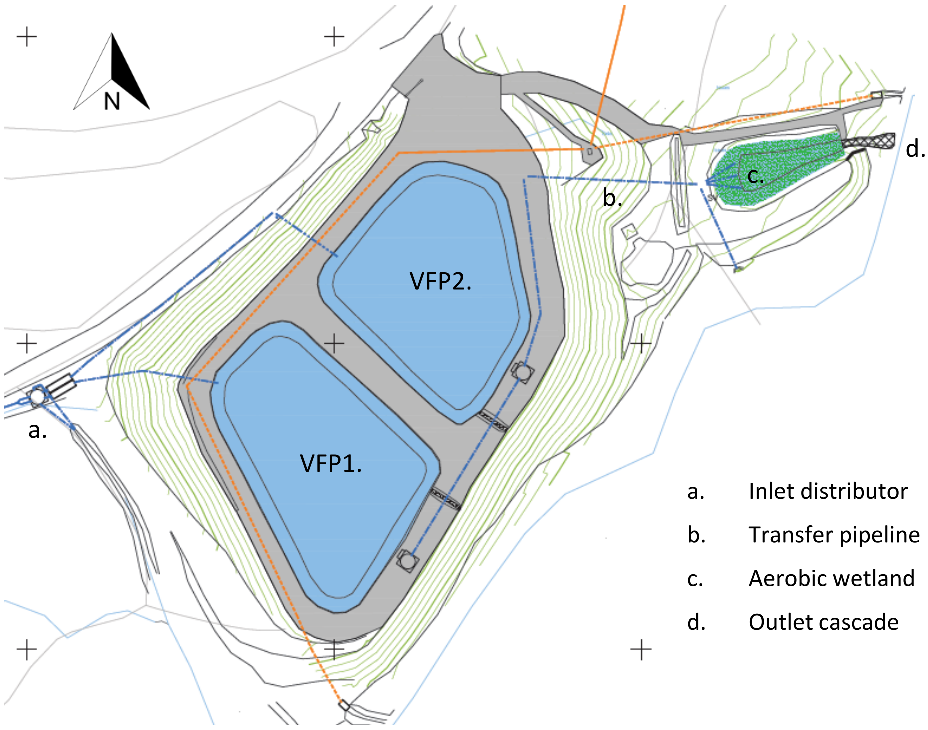

Figure 1 Force Crag mine water treatment system general arrangement, drawing courtesy of the Coal Authority. 50m grid intervals for approximate scale

Methods

Performance data for the Force Crag treatment system were collected between April 2014 and March 2015 to determine the removal of zinc within the compost substrate. Sampling was typically conducted on a weekly basis. Flow rates were measured using sharp crested v-notch weirs and bucket and stopwatch methods at locations where weirs were unavailable. Metals analysis was conducted at Newcastle University, UK, using ICP-OES.

Life-cycle cost assessments were undertaken using actual outturn figures for construction, and operational cost items based upon estimates from operational costings for more than 50 pre-existing passive treatment systems operating in the UK. Waste disposal costs were determined by obtaining quotes from 3 specialist waste carriers, with the lowest cost option of combined disposal and haulage used in forecasts. Additional financial information was obtained to determine the costs of substrate de-contamination by consultation with industrial specialists (Acumen Waste Ltd.). For this a detailed costed proposal was developed, assuming procurement of a bespoke washing rig receiving reasonable use against investment, by frequent deployment across a portfolio of treatment sites. The soil washing process was designed to separate coarse, uncontaminated substrate fractions from a metal rich fine grained fraction with a <63µm particle size, using a combination of acid leaching/neutralization and particle size separation. Costs for active treatment (as a comparator to passive treatment costs) was obtained from a detailed costed proposal for a High Density Sludge lime based system developed by Helix Projects Ltd (Schade, 2015). This active treatment approach was chosen because it is proven technology, which has previously been determined as more than 50% lower cost than alternative technologies such as biochemical sulphide precipitation and ion exchange (Younger et al., 2005). It should be noted that although latter two techniques claim to offer the ability to recover metals directly from mine waters for recycling, at the Wheal Jane study site, the quantities recoverable were not considered economically viable (Younger et al., 2005). All financial assessments have been discounted at 3.5% according to HM Treasury (2011).

Zinc removal and accumulation rate

The Force Crag treatment system was monitored in detail from commissioning in April 2014 until the end of March 2015. Data indicate that treatment performance was high: on average 95% to 99% removal of zinc (see Figure 2). Given the loading and system size, this equates to a volumetric removal rate for zinc of $1.90 g/m^3/d$. When considered together, these metrics situate the system within the upper-middle of a ranking of the known systems of this kind globally (Table 1).

On the basis of projections, the Force Crag treatment system will have accumulated 21,520mg/kg of zinc within its substrate after 10 years, if current performance is maintained. However, it has been found that accumulation of metals within treatment system substrates can inhibit the sulphate reduction process and thus treatment performance (Utgikar et al., 2002). Data presented by Rutkowski (2013) implies that sustained performance can result in very high zinc concentrations within substrates of compost based treatment systems (22,940mg/kg calculated based upon performance data for the Standard Mine bioreactor, Colorado – refer to Table 1, Figure 3).

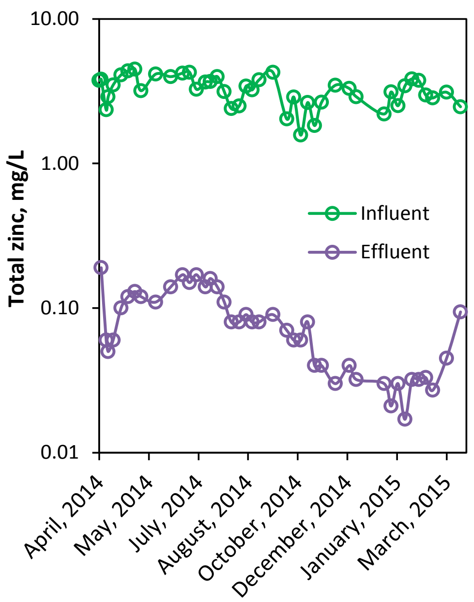

Figure 3 Zinc removal by the Force Crag mine water treatment system between April 2014 and March 2015.

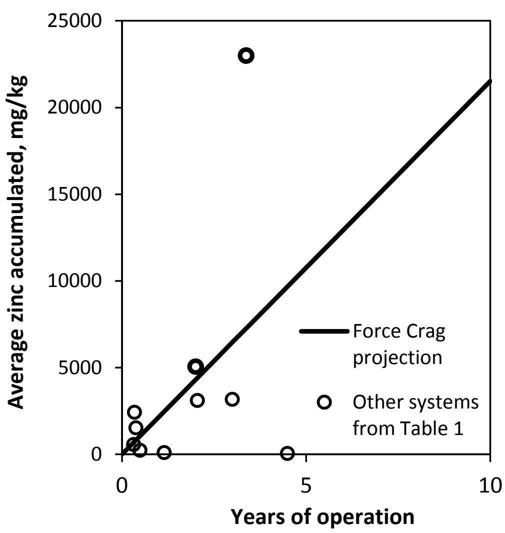

Figure 2 Zinc accumulation rate at Force Crag assuming current removal rates are maintained and, zinc content of substrate at sites in Table 1 (calculated from available data).

After 3.4 years of operation, the passive bioreactor at Standard Mine was decommissioned, yet its performance had shown no noticeable decline by this time (Rutkowski, 2013). Zinc concentrations in the Standard Mine system are estimated to be greater than forecast for Force Crag after 10 years of operation (21,520mg/kg), based upon calculations made by these authors. This implies that, after 10 years, the Force Crag system may still have not accumulated a quantity of zinc which might adversely affect its performance. Although, it is known that other factors limit the lifetime of substrates in these systems, such as plugging of substrates (Rose, 2006), depletion of substrate carbon sources required by sulphate reducing bacteria (Cheong et al., 2012; Logan et al., 2005). On the basis of these factors and examples from elsewhere, a nominal substrate lifetime of 10 years has been attributed to the Force Crag system by its operators.

Table 1 Comparative mean zinc removal rates and efficiencies from a range of bioreactor systems harnessing bacterial sulphate reduction

System name/ description, Reference	Location	Influent zinc	Study period	Efficiency and removal rate (zinc)	
		mg/L	*d*	*%*	*g/m^3/d*
Nenthead, field based pilot bioreactor(Jarvis et al., 2014)	Cumbria, UK	2.2	730	68	0.9
Luttrell system, single cell bioreactor (ITRC, 2013; Hiibel et al., 2008)	Montana, USA	205	1095	99	1.45
West Fork Unit, settling / anaerobic ponds active lead mine (Gusek et al., 1998)	Missouri, USA	0.36	180	80	0.63
Burleigh Mine, up-flow bioreactor (USEPA, 2002)	Colorado, USA	57	1460	56	3.40
Burleigh Mine, down-flow bioreactor (USEPA, 2002)	Colorado, USA	57	1460	65	3.93
Cadillac Molybdenite bioreactor / oxidation pond & ALD (Kuyucak, 2006)	Quebec, Canada	1.35	420	99	0.11
Cwm Rheidol field based pilot bioreactor. Unpublished data, Newcastle University	Wales, UK	12.75	750	63	2.07
Palmerton pilot unit, smelter drainage bioreactors (Dvorak et al., 1992)	Pennsylvania, USA	317	126	100	9.58
Dalsung Tungsten Mine pilot bioreactor (Cheong et al., 1998)	South Korea	11.4	118	84	2.40
Standard Mine superfund site, Biochemical reactor (Rutkowski, 2013; Reisman et al., 2008)	Colorado, USA	24.7	1230	100	11.20
Haile Mine bioreactors (2no.) / wetland (ITRC, 2013)	S. Carolina, USA	1.8	1642.5	95	0.02
Lady Leith bioreactor and wetland (ITRC, 2013)	Montana, USA	0.75	3 visits in 2007	72	0.54
Active coal mine site, pilot bioreactor (Trumm and Ball, 2014)	New Zealand	6.3	141	100	5.40
Galkeno adit, United Keno Hill Mines wetland http://technology.infomine.com	Yukon, Canada	25		72	0.64
Force Crag bioreactors (this study).	Cumbria, UK	3.26	365	95-99	1.90

Life cycle costs

Passive treatment systems, while typically entailing relatively low initial outlay costs, have been shown to form wastes which are costly to dispose of. It has been suggested that active bio-chemical approaches, where chemicals and/or power are required in the treatment process, are preferable due to their ability to recover metals, rather than generate wastes (Johnson et al., 2006). At Force Crag, however, just 5.8t of zinc would be recoverable from mine water over 10 years, worth a modest € 7600 at current prices (LME, 2015). Considering the cost differential between a relatively low-cost active treatment system and a passive system over 10 years is € 1.8M, the financial case for passive treatment remains strong for sites such as this.

Regardless of the low-cost nature of passive treatment compared to active, waste disposal costs are still expected to be substantial, amounting to € 0.85M every 10 years at Force Crag, at current prices. De-contamination of substrates so that they can be re-used either in the treatment system or elsewhere, with disposal of a low-volume of contaminated material would therefore be preferable. Typical costs for a soil washing system (using acid leach and particle size separation as determined by Bailey et al. (2015)) have been determined as € 56/t, equating to € 58,810 for 1055t substrate at Force Crag. Additional costs which are associated with plant mobilization (estimated at € 9910) and disposal of residue (€ 85,030 - assumed to be 10% of initial substrate mass, as hazardous waste) brings the total cost to € 0.16M, at current prices. The costs in Table 2 have been discounted at 3.5% to determine the 10 year life-cycle cost, including substrate washing and replacement at the end of this period. Over 10 years, the life-cycle costs of treatment are reduced from € 1.63M to € 1.12M, substantially outweighing the 10 year cost of active treatment by HDS of € 3.41M.

Table 2 Construction and operational costs of active and passive and passive with waste reduction by soil washing at the Force Crag site

	Active treatment by HDS	Passive bioreactor treatment	Passive bioreactor with waste reduction
Capital construction	€ 1,922,000	€ 873,300	€ 873,300
Operation (labour/power/maintenance)	*€ 134,370	*€ 12,400	*€ 12,400
Substrate washing	n/a	n/a	**€ 68,720
Sludge disposal	*€ 13,240	**€ 850,330	**€ 85,030
Substrate replenishment	n/a	**€ 36,200	**€ 36,200
Chemical reagent cost	*€ 25,360	n/a	n/a
10 year 3.5% DCF life cycle cost	€ 3,410,900	€ 1,630,500	€ 1,119,400

(*annual cost; **one off cost at 10yr)

In this financial forecast, provision is given to dispose of a metal rich filter cake, derived from the substrate washing process. Recovery of metals would, however, be a reasonable proposition, given that they would be in a concentrated form. At Force Crag, it has been estimated that substrates would contain 2.19% w/w zinc after 10 years. Metal recovery tests from a similar substrate to that used at Force Crag found that >95% recovery of zinc was achievable within 100 hours using 0.5M sulphuric acid (Bailey et al., 2015). Accordingly, if metals were concentrated into a filter cake ~10% of the mass of the starting substrate, it may be reasonable to expect a zinc content of >20% w/w. At these levels, the filter cake would be far more amenable to re-cycling than the waste substrate, provided that facilities are available to receive the material.

Conclusions

Data obtained from the Force Crag compost bioreactor treatment system show high performance, achieving 95-99% zinc removal across the system. Projections suggest that at current rates of removal, 21,520mg/kg of zinc will have accumulated after 10 years, although it is known that there are a number of mechanisms constraining system longevity. Inevitably, substrate disposal and replacement will be required; however costs can be high due to hazardous waste classification of these metal rich materials.

Analysis conducted in this case study shows that despite high waste disposal costs, passive treatment still offers value for money compared to active HDS treatment over a 10 year period. Nevertheless, substrate washing to concentrate metals into a filter cake could offer substantial life-cycle cost savings of € 0.51M on a € 1.63M project. Furthermore, additional savings may be achieved if the filter cake could be re-cycled to recover metals. Provision for substrate washing at passive treatment sites should be made accordingly, in order that operators are able to achieve these life-cycle cost savings.

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References

Atkins, W. S. (2014) 'Technical note: Compost Wetland Medium - Force Crag and Gate Gill. Unpublished report to The Coal Authority'.

Bailey, M. T., Jarvis, A. P. and Gandy, C. J. (2015) 'Characterization of Passive Treatment System Substrates and Potential for Zinc Recovery', *10th International Conference on Acid Rock Drainage.* Santiago, Chile, 21 - 24 April 2015. Gecamin, pp. 1 - 11.

Cheong, Y.-W., Hur, W., Yim, G.-J., Ji, S.-W., Yang, J.-E., Baek, H.-J. and Shim, Y.-S. (2012) 'Longevity of Organic Layers of Vertical Flow Ponds for Sulfate Reduction in Treating Mine Drainages in South Korea', *Environmental Geochemistry and Health,* 34, (1), pp. 115-121.

Cheong, Y.-W., Min, J.-S. and Kwon, K.-S. (1998) 'Metal Removal Efficiencies of Substrates for Treating Acid Mine Drainage of the Dalsung Mine, South Korea', *Journal of Geochemical Exploration,* 64, (1–3), pp. 147-152.

CL:AIRE. (2007) 'Technical Bulletin 13: Understanding Soil Washing', in Contaminated Land: Applications in Real Environments(ed).

Dvorak, D. H., Hedin, R. S., Edenborn, H. M. and McIntire, P. E. (1992) 'Treatment of Metal-Contaminated Water using Bacterial Sulfate Reduction: Results from Pilot-Scale Reactors', *Biotechnology and Bioengineering,* 40, (5), pp. 609-616.

Gray, N. D., Gandy, C. J. and Jarvis, A. P. (2012) 'Mitigation of Pollution from Abandoned Metal Mines. Part 2, Review of Resource Recovery Options from the Passive Remediation of Metal Rich Mine Waters', *Environment Agency Publication, Project SC090024/1.*

Gusek, J. and Clarke-Whistler, K. (2005) 'Where Does the Recovery of Metal Resources from Passive Treatment Systems Fit in with Sustainable Development Initiatives Associated with Large Mining Projects?', *National Meeting of the American Society for Mining and Reclamation.* Breckenridge, CO, USA, 19 - 23 June 2005. American Society for Mining and Reclamation, pp. 454 - 469.

Gusek, J., Wildeman, T. R. and Conroy, K. W. (2006) 'Conceptual Methods for Recovering Metal Resources from Passive Treatment Systems', *7th International Conference on Acid Rock Drainage.* St. Louis MO, 26 - 30 March 2006. American Society of Mining and Reclamation, pp. 690 - 702.

Gusek, J. J., Wildeman, T., Miller, A. and Fricke, J. (1998) 'The Challenges of Designing, Permitting and Building a 1200 GPM Passive Bioreactor for Metal Mine Drainage, West Fork Mine Missouri', *15th National meeting of the American Association of Surface Mining and Reclamation.* St Louis, Montana, pp. 203 - 212.

Hiibel, S. R., Pereyra, L. P., Inman, L. Y., Tischer, A., Reisman, D. J., Reardon, K. F. and Pruden, A. (2008) 'Microbial Community Analysis of Two Field-Scale Sulfate-Reducing Bioreactors Treating Mine Drainage', *Environmental Microbiology,* 10, (8), pp. 2087-2097.

HM Treasury. (2011) *The Green Book.* London: TSO.

ITRC. (2013) *Biochemical Reactors for Mining-Influenced Water.* Interstate Technology and Regulatory Council.

Jarvis, A. P., Davis, J., Gray, N. D., Orme, P. H. A. and Gandy, C. J. (2014) *Mitigation of Pollution from Abandoned Metal Mines: Investigation of Passive Compost Bioreactor Systems for Treatment of Abandoned Metal Mine Discharges.* Bristol: Environment Agency.

Jarvis, A. P., Gandy, C. J., Bailey, M. T., Davis, J. E. and Orme, P. H. A. (2015) 'Metal Removal and Secondary Contamination in a Passive Metal Mine Drainage Treatment System', *10th International Conference on Acid Rock Drainage* Santiago, Chile, 21 - 24 April 2015. Gecamin, pp. 1 - 9.

Johnson, D. B., Sen, A. M., Kimura, S., Rowe, O. F. and Hallberg, K. B. (2006) 'Novel Biosulfidogenic System for Selective Recovery of Metals from Acidic Leach Liquors and Waste Streams', *Mineral Processing and Extractive Metallurgy,* 115, (1), pp. 19-24.

Kuyucak, N. (2006) 'Selecting Suitable Methods for Treating Mining Effluents', *PerCan Mine Closure Course*.

LME (2015) *London Metal Exchange*. Available at: http://www.lme.com/ (Accessed: 29-9-2015).

Logan, M. V., Reardon, K. F., Figueroa, L. A., McLain, J. E. T. and Ahmann, D. M. (2005) 'Microbial Community Activities During Establishment, Performance, and Decline of Bench-Scale Passive Treatment Systems for Mine Drainage', *Water Research,* 39, (18), pp. 4537-4551.

Neculita, C. M., Zagury, G. J. and Bussière, B. (2007) 'Passive Treatment of Acid Mine Drainage in Bioreactors using Sulfate-Reducing Bacteria', *Journal of Environmental Quality,* 36, (1), pp. 1-16.

Reisman, D., Rutkowski, T., Smart, P. and Guskek, J. (2008) 'The Construction and Instrumentation of a Pilot Treatment System at the Standard Mine Superfund Site, Crested Butte, CO ', *National Meeting of the American Society of Mining and Reclamation.* Richmond, VA, USA, 14 - 19 June 2008. American Society of Mining and Reclamation, pp. 892 - 909.

Rose, A. W. (2006) 'Long-Term Performance of Vertical Flow Ponds - An Update', *7th International Conference on Acid Rock Drainage.* St Louis, MO, 26 - 30 March 2006. American Society of Mining and Reclamation, pp. 1704 - 1716.

Rutkowski, T. (2013) 'Passive Treatment of Mining Influenced Wastewater at the Standard Mine Superfund Site, Crested Butte, Colorado, USA', *Mine Water Solutions.* Lima, Peru, April 15 - 17 2013. InfoMine, pp. n/a.

Sapsford, D. J., Santonastaso, M., Thorn, P. and Kershaw, S. (2015) 'Conversion of Coal Mine Drainage Ochre to Water Treatment Reagent: Production, Characterisation and Application for P and Zn Removal', *Journal of Environmental Management,* 160, (0), pp. 7-15.

Schade, H. (2015) 'Desk Study - Active Treatment Review (Force Cragg - Mine Water Treatment Plant)', *unpublished report*.

Tichy, R., Grotenhuis, J. T. C., Rulkens, W. H. and Nydl, V. (1996) 'Strategy for Leaching of Zinc from Artificially Contaminated Soil', *Environmental Technology,* 17, (11), pp. 1181-1192.

Trumm, D. and Ball, J. (2014) 'Use of Sulfate-Reducing Mussel Shell Reactors in New Zealand for Treatment of Acid Mine Drainage', *West Virginia Mine Drainage Task Force.* Morgantown, WV, USA, 25 - 26 March 2014. pp. 9.

USEPA. (2002) 'Anaerobic Compost Constructed Wetlands System (CWS) Technology: Innovation Technology Report', *U.S. Environmental Protection Agency*.

Utgikar, V. P., Harmon, S. M., Chaudhary, N., Tabak, H. H., Govind, R. and Haines, J. R. (2002) 'Inhibition of Sulfate-Reducing Bacteria by Metal Sulfide Formation in Bioremediation of Acid Mine Drainage', *Environmental Toxicology,* 17, (1), pp. 40-48.

Wills, B. A. (2006) *Wills' Mineral Processing Technology.* Oxford: Butterworth-Heinemann.

Younger, P. L. (2000) 'The Adoption and Adaptation of Passive Treatment Technologies for Mine Waters in the United Kingdom', *Mine Water and the Environment,* 19, pp. 85-97.

Younger, P. L., Coulton, R. H. and Froggatt, E. C. (2005) 'The Contribution of Science to Risk-Based Decision-Making: Lessons from the Development of Full-Scale Treatment Measures for Acidic Mine Waters at Wheal Jane, UK', *Science of the Total Environment,* 338, (1–2), pp. 137-154.