# Up-Scaling from Trial to Operation: Practicalities of Construction and Permitting, Force Crag Mine

**Arabella Moorhouse[1], Rachel Harris[1], Lee Wyatt[1], Stephen Hill[1] and Hugh Potter[2]**

1. *Environment Department, The Coal Authority, United Kingdom*
2. *Land Contamination Management, Environment Agency, United Kingdom*

## ABSTRACT

Following successful small-scale compost-based bioreactor (tank size 3.75 $m^3$; flow rate 1.1 L/min) metal mine treatability trials undertaken by Newcastle University, a full-scale vertical flow pond treatment system was constructed in 2014 at the abandoned Force Crag Mine (Cumbria, UK). Metal concentrations in the mine water are sufficiently high to cause the receiving water course, the Coledale Beck, to fail UK environmental quality standards. The innovative system remediates the baseflow of mine water (6 L/s), which contains elevated concentrations of zinc (3.8 mg/L) in a treatment area of 1250 $m^2$ with a target residence time of ~14 hours.

Force Crag is a remote site located within a National Park that is popular with tourists and walkers. The mine site, including the underground workings, buildings and mine surface, are owned and managed by the National Trust (a UK historical conservation charity). Construction of a treatment system in this isolated, open access, rugged area resulted in challenges that needed to be considered in the design process. The novel nature of the treatment technology deployed at the site required any scheme to be designed to enable rigorous scientific investigation of the system to prove the design concept. Furthermore, operational issues (*e.g.* quantities of gas release) that could result from the full-scale system also needed to be addressed.

All of these challenges were overcome, resulting in the successful delivery of a new treatment technology. This paper highlights the engineering and permitting aspects of up-scaling from a trial system to a full-scale novel treatment methodology.

**Keywords:** mine water, treatment, construction, full-scale, metal mines

## INTRODUCTION

Novel mine water treatment technologies are continually being developed in both the academic and commercial sectors to tackle the problem of removing dissolved divalent metals from base metal mine discharges. Although well-established methods exist for the passive removal of iron, *i.e.* aeration cascades, settlement lagoons, aerobic reed beds and reducing alkalinity producing systems (RAPS) as described in the PIRAMID Guidelines (2000); passive techniques designed to remove other common contaminant metals such as zinc, cadmium, copper, lead etc., which are more difficult to precipitate from mine waters than iron, are less common. Active treatment methods, such as the lime dosing plant currently operating at Wheal Jane Mine in Cornwall, UK (Wyatt *et al.*, 2013), add an alkali to the water to increase the pH sufficiently to allow the formation of carbonate and/or oxy-hydroxide mineral species to precipitate, producing an ochre sludge. Systems such as these are expensive to operate however, requiring continuous staffing levels with high electricity consumption, in addition to the use of large quantities of chemical products. Furthermore, active systems often generate significant volumes of metal-rich sludge, which not only contain the metals themselves, but also the supplementary component of the chemical additions; which in the case of lime dosing, can be considerable. Consequently, active treatment systems, although a very successful option, often have both high capital and operational costs; the typical operational costs for the Wheal Jane mine water treatment facility for example, are £1.5M per year. For schemes that are in effect required for perpetuity, such systems are far from ideal. The desire to reduce high capital investment and high operational costs are two of the main drivers for researchers to develop alternative, more passive and accordingly more cost effective, treatment methodologies.

Laboratory scale trials are the first stage in the development process of any passive mine water treatment technology, which if proven successful, progress forwards to pilot-scale trials. However, for the often small-scale nature of pilot trials, important issues such as supply of materials, size of treatment areas, construction requirements, operational needs, variable or flashy flow rates, regulatory permits and local climatic variations are generally readily overcome. When attempts are made to scale-up a pilot-sized system to a full sized operational site however, these are factors that must be considered and addressed. Subsequently, although many successful pilot-sized treatment systems are described in the literature, the practicalities of the 'real world' can result in relatively few of these methodologies being successfully deployed in the field at the full-scale.

This paper discusses the challenges that can occur when a successful small trial passive system is up-scaled to a full sized, operational system situated in the natural environment.

### Dealing with abandoned metal mining pollution in England

Throughout England, there has been historic mining of metals across many regions. However, in contrast to the legacy resulting from the coal mining industry, which is subject to legislation in the UK, there is no one single body responsible for metal mining pollution.

Following the transposition of the European Water Framework Directive (WFD) (2000/60/EC) in to UK national law in 2003, the Department of Environment, Food and Rural Affairs (Defra) has taken measures to establish a remediation program for water pollution from non-coal (predominantly metal) mines which affect up to 2 500 km of rivers in England. In 2012, a consortium published a report (NoCAM) identifying and prioritizing the principle non-coal mine water impacts present in England (and Wales) (Jarvis and Mayes, 2012). In 2011, Defra allocated funds to the Coal Authority (CA), based on the organization's *c.* 20 years experience in mine water remediation, in conjunction with the Environment Agency (EA), to deal with pollution from abandoned non-coal mines.

**Force Crag Mine, Cumbria, UK**

Force Crag Mine is an abandoned lead-zinc-barites mine located in the Lake District National Park in Cumbria (North West England), near the village of Braithwaite (Figure 1). Situated 7 km West of Keswick, in the headwaters of the Coledale Valley, the mine site covers an extent of approximately 1.2 km long from the banks of the Coledale Beck westwards towards the ridge of Grisedale Pike. Hosted in Ordovician siliciclastic sediments (Kirk Stile Formation), the east-west trending, vein-hosted mineralization present at Force Crag is a zoned ore body dominated by galena (lead-ore) and sphalerite (zinc-ore) with barite and quartz gangue (Tyler, 2005).

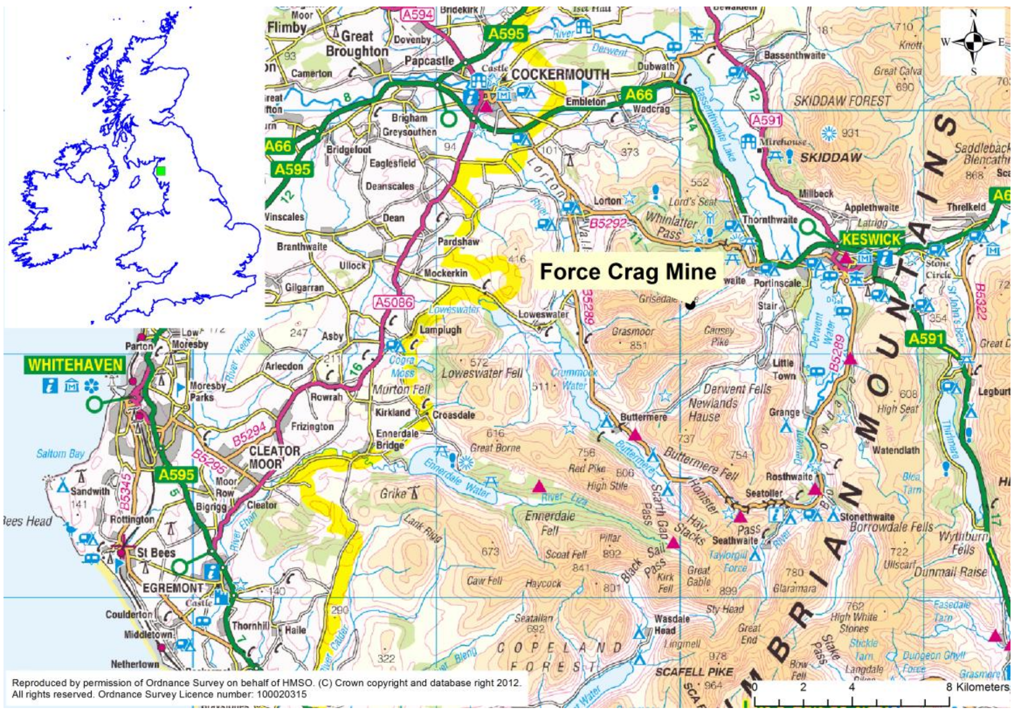


**Figure 1** Location map for Force Crag mine and surrounding area

Mining has occurred at Force Crag since at least the 15th Century, although the most intensive period was during the 19th Century when the mine was worked intermittently for lead-ore and barite; operations finally ceased at the site when the mine closed in 1992 (Tyler, 2005).

Force Crag mine workings comprise of a series of nine individual levels driven into the mountainside. Level Zero forms the lowest level near the valley floor, and the workings are currently drained from both Level One and Level Zero. Despite the occurrence of some diffuse contamination originating from the processing and mining waste at the site, the Level One discharge has been have identified as the main point source of metal contamination in the Coledale Beck at Force Crag. The Coledale Beck is one of the main tributaries to the Newlands Beck and the impact of the pollution resulted in the Newlands Beck being ranked at number 16 in England and Wales (Jarvis and Mayes, 2012) on a priority list; in 2013, the EA raised Newlands Beck to rank 1 in England after collection of further data.

### *Mine Water Chemistry*

The mine water at Force Crag is circum-neutral with elevated concentrations of zinc and cadmium, combined with relatively low concentrations of iron. Consequently, the receiving watercourses, the Coledale Beck and Newlands Beck, fail the UK environmental quality standards (currently classified as failing with moderate status under the WFD) for zinc (~12 μg/L) and cadmium (0.08 μg/L) for a reach of at least 10 km. A summary of the chemical characteristics of the mine water from Level One is provided in Table 1. The flow from Level One is relatively flashy in nature; on average, the flow rate is 8-10 L/s, although flow rates of >40 L/s have been recorded after storm events in 2014.

**Table 1** Typical mine water chemistry (total metals) of the Level One discharge, Force Crag Mine (n=11 samples, data collected in 2014)

| | pH | EC μs/cm | Alkalinity mg/L | Calcium mg/L | Magnesium mg/L | Iron mg/L | Zinc mg/L | Cadmium μg/L | Lead μg/L | Sulfate mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 7.1 | 150 | 25 | 13 | 5 | 0.63 | 3.8 | 18 | 40 | 31 |
| Min | 6.9 | 119 | 13 | 7 | 3 | 0.34 | 2.1 | 11 | 27 | 18 |
| Max | 7.4 | 270 | 56 | 15 | 5 | 0.80 | 4.9 | 22 | 66 | 38 |

## Stakeholders

To facilitate the successful deployment of a novel mine water treatment system at the Force Crag mine site, a large number of stakeholders were required to work together. A group comprising of four organizations (CA, EA, Newcastle University and National Trust), formed the main body of stakeholders that collaborated closely to deliver the mine water treatment scheme. Overall however, a total of eleven different organizations (including 3 regulatory bodies) were involved in the project to differing extents. For further information on the methodology adopted by the CA on stakeholder management for this site, the authors direct the reader to Harris *et al.* (2014).

## TREATMENT METHODOLOGY

The passive treatment methodology that has been deployed at Force Crag has been developed from laboratory and pilot scale trials undertaken by Newcastle University (NU) funded by Defra and published by the EA (Jarvis *et al.*, 2014). This technique employs an anaerobic compost bio-reactor where sulfate reducing bacteria are exploited to remove metals from circum-neutral mine waters. A key component of this methodology is to ensure that there is sufficient carbon present in the media to sustain the desired microbial community, without promoting competing methanogenic communities which would not attenuate the metals. Over a period of 40 months, the Newcastle team executed a series of simultaneous laboratory column experiments, laboratory-style field column experiments and pilot-scale reactors. One pilot-scale reactor which operated for 24 months, was deployed at Nenthead Mine; an abandoned lead-zinc mine in the North Pennines (Cumbria), located 7 km SE of Alston, with a circum-neutral mine water typically containing ~2 mg/L of zinc.

Pilot-scale systems installed in the field, particularly those which harness biological processes, often require time to allow the system to establish and reach a steady state. In addition, they must also be small enough to provide information on when the system reaches saturation, resulting in breakthrough of the metal contaminant. Important factors which require consideration when building full scale treatment systems is the longevity of the system, in addition to the size of treatment area required. Consequently, it is crucial that pilot-scale systems provide the necessary data to address these important issues; the system deployed at Nenthead fulfilled these criteria.

Using a down-flow system, the Nenthead reactor treated an average flow of 1.1 L/min for a period of 24 months, successfully removing on average *c.* 70 % of the total zinc concentration, with a mean residence time of ~14 hours. Containing 2.25 $m^3$ of media mix, comprising of compost (PAS100 British Standards Institution), woodchips and activated digested sewage sludge with a limestone chip under drain, the Nenthead reactor was 2.5 m long, 1.5 m wide and 1.0 m deep (Jarvis *et al.*, 2014). Mixing of the four components, which were sourced locally, occurred on site to reduce heterogeneity in the media. Based on the success of the Nenthead reactor, and particularly the excellent zinc removal rates observed despite the short residence time, the full-scale vertical flow pond (VFP) system at Force Crag was proposed; however, the complexity of building a full-scale system presented a different set of challenges than those typically faced in small-scale systems.

## DISCUSSION

Force Crag Mine site has a number of designations, including Site of Special Scientific Interest (SSSI), Special Area of Conservation (SAC) and Scheduled Monument; the site is also a popular tourist region in an area of open access (an area where free access is granted to the public). Furthermore, the Coledale Beck, which flows through the site, is a tributary of the Newlands Beck, which contributes to Bassenthwaite Lake and subsequently, the River Derwent; areas designated as SSSI, SAC and a National Nature Reserve. Contamination from abandoned metal mines has a negative impact on these environmentally sensitive areas; consequently, the remediation of the mine water discharge at Force Crag was identified as being able to deliver significant benefits to the whole catchment. Many of the challenges associated with constructing the system were related to the designations assigned to the site, in addition to the requirements for environmental permitting. This paper focuses on the issues pertaining to the construction and permitting of the scheme.

### Construction

Some of the key challenges associated with the up-scaling from a pilot to a full-scale system are related to the construction, engineering and operational considerations for the scheme. This section focuses on some of these issues that occurred at the Force Crag site, and how they were addressed.

#### *Mine water collection and scheme layout: the precursors to construction*

Extensive investigations were undertaken by the EA, in conjunction with NU (funded by Defra), prior to construction of the treatment scheme, examining the point sources and diffuse pollution of the Force Crag site and the environmental impact on the Coledale Beck and Newlands Beck. This unpublished work identified the Level One discharge as the main point source of metal pollution at the site and concluded that remediation efforts should be focused on this primary source of cadmium and zinc. In 2013, a system of buried pipework was installed to take the Level One mine water from its original discharge point to the Coledale Beck; a flow measurement weir was also installed with the ability to allow diversion of water to the proposed treatment site.

Discussions with the National Trust and English Heritage were also ongoing during this period to finalize an agreement for the siting of the scheme within the site. Following negotiations between the CA, EA, National Trust and English Heritage, the area of the former tailings pond, located between the old mine workings and the Coledale Beck, was chosen. This agreement was reached with the understanding that the remediation of the mine water discharge from Level One was part of the 'evolution' of the site from an area of active mining to one of environmental remediation.

Once the scheme location was established, plans were submitted to the local administrative authorities to obtain planning approval. When assessing the impact of a new development, planning officers need to understand the scale of the development and what the visual impact will be, especially in a sensitive region such as a National Park. At this point in time however, the trial at Nenthead was still ongoing; concept designs were therefore produced to provide the authorities with a high level plan using the layout and performance of the Nenthead reactor as a guide. Figure 2 shows the final layout of the scheme, which is not dissimilar from the plans originally submitted to the local planning authorities. The original plan envisaged a single treatment pond; however, a decision was subsequently taken to have two VFPs in parallel, to enable future variations in flow rates in each pond to investigate the influence of residence time on metal removal performance. At the time of engaging the local authority, some uncertainty still remained about the size of the new scheme and the amount of flow to be treated. Nominal guidelines were therefore provided to the CA by NU to size the scheme based on the results their team had obtained from the Nenthead trial. Furthermore, using the results obtained from the catchment monitoring undertaken by NU, a baseflow rate (6 L/s) for the scheme was also agreed that would result in a measureable improvement to the Coledale Beck while ensuring a consistent flow to the VFP. Further details of the Force Crag treatment scheme are provided in Jarvis *et al.* (2015).

### *Treatment Media*

An important component of the VFP system is the treatment media. Following finalization of the system design, it was initially assumed by the design consultants that placement of the media (a mixture of PAS100 compost, woodchips and activated sewage sludge) into the ponds would be achieved by driving heavy plant machinery directly into the cells, using the media as a traversable surface. However, it became clear that this would have a detrimental impact on the material, reducing the porosity and permeability of the media by compaction and potentially damaging the under drain network. A key part of this system is the even down flow of water; any damage to the under drain or reduction in the porosity and permeability of the media, could result in water short circuiting, thereby decreasing residence times and reducing system performance. Discussions onsite with the contractor, design consultants and NU, resulted in the layout of the ponds being amended; the road way between the ponds was widened to facilitate the use of a long-reach excavator that could work from the pond edges.

### *Under drain*

A complex under drain system, briefly mentioned above, is another key component of the system. This network of pipes divides each pond into four quadrants (each of which can be sampled individually at the discharge point), to facilitate the assessment of metal removal in each sector of the pond. The original under drain design drafted by NU included specific sizes for limestone chips and the number of perforations in the pipework. In preference to using customized products, it was decided to use commercially available pipes combined with larger limestone chips to achieve the same levels of permeability, whilst minimizing costs. Comprising of 770 m of standardized perforated drain pipes, the resulting network is encased in limestone gravel (20-40 mm), which protects the pipework and reduces the potential for the compost material to obstruct the system.

Initially it was proposed that the scree and spoil material readily available on site could be used for the gravel layer in lieu of limestone, as the only function of the drain was to facilitate the drainage of the treated water out of the system. However, this option was dismissed as this material would have introduced fresh metal contamination into the system following the removal of metals in the mine water by the media. It was therefore agreed that a limestone under drain would be installed. A local source of limestone was identified by the contractor, however on sampling by NU, it was found to contain slightly elevated concentrations of water-soluble sulfate. As some limestone dissolution is expected to occur, and it was important to be able to measure the amount of sulfate being removed by the system, a calcium carbonate limestone that contains fewer impurities was therefore imported from further afield.

### *Wetland*

An aerobic wetland for the purpose of aerating the water exiting the anaerobic ponds and filtering any fine particulates that may remain in the water was required for the scheme. In preference to *Phragmites sp.* reeds that are typically used by the CA in constructed wetlands, it was decided to use metal-tolerant rushes (*Juncus sp.*) already established in the area to reduce the visual impact of the wetland. During construction, the plants were temporarily relocated before being placed in their final position in the wetland. There was some concern that although these plants prefer water-logged conditions, they would not survive submerged in a water depth of 300 mm; water levels were therefore lowered to 100 mm and to date, the plants are thriving in their new environment. It is intended to use similar wetland systems at future schemes employing this technology, although such wetlands will need to be larger in size compared to the small unit installed at Force Crag.

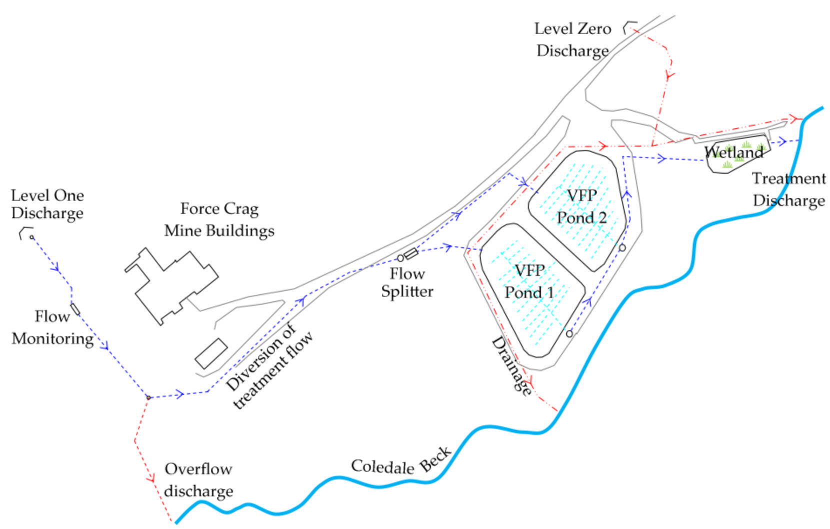


**Figure 2** Schematic diagram of the treatment system at Force Crag mine (not to scale)

### *Flow rates*

Low flow rates (typically L/min) in small scale systems are easily controlled and manipulated. In a full scale-system however, flow rates are less easy to regulate, yet in a trial setting it is vital to accurately control them to rigorously assess the performance of a system. The CA standard designs, although adequate for coal mine water treatment schemes, do not provide sufficient control to accurately regulate flow rates through the ponds installed at Force Crag. A new system was therefore devised which can accurately capture a designated baseline flow from the Level One discharge, dividing the flow equally between the two ponds. This system also provides the ability to investigate effects on performance of increased flow rates and thus reduced residence times.

### *Gas*

A potential by-product of harnessing sulfate reducing bacteria (SRB) is the generation of hydrogen sulfide ($H_2S$) gas. Although it was expected that some $H_2S$ gas would be produced by the system ($H_2S$ could be smelled at the Nenthead reactor and can also be smelt at the CA's RAPS unit installed at Tan y Garn in South Wales), it was unclear what the exact impact at the site would be. Force Crag is situated in a remote, upland, un-inhabited area, and although ramblers and walkers are frequently in the vicinity of the treatment system, it was decided that to install a cover would be prohibitively expensive and would not be aesthetically acceptable in the National Park. To mitigate the problem the following measures were taken; the water depth of the ponds was increased to ~400 mm (from 300 mm); open manhole covers were installed to limit gas build up in any confined spaces which require regular access; a rigorous gas monitoring regime has been instigated to examine gas production and where the 'hot-spots' are located; continuous gas monitors have been installed to assess the risk posed to maintenance operators and the public. Future treatment systems may be required to be sited in populated areas; the data collected from this pilot system will therefore be used to demonstrate the impact of $H_2S$ gas and inform planning authorities about the risks associated with this type of system and the measures that can be taken to mitigate them.

## Permitting

A second key challenge associated with the up-scaling from a pilot to a full-scale system in addition to the construction is the environmental permitting of a scheme. This section focuses on some of the permitting solutions that were implemented at the Force Crag site.

### *Treatment Media*

In contrast to the small-scale reactor trial at Nenthead, where the bulk of the treatment media components were purchased from the local garden center and mixed on site in a bucket (A. Jarvis, 2013, *pers. comm.*), the importation and mixing of the media for the full-scale system deployed at Force Crag, caused obstacles which the CA needed to address. It quickly became apparent that in order to use a media containing activated sewage sludge, a waste permit would be required from the EA. Although PAS100 compost and woodchips are not individually classified as waste materials, the inclusion of activated sewage sludge within the mix results in the treatment media being classified as a waste material under EU law; and is therefore subject to the Environmental Permitting (England and Wales) Regulations 2010, which legislates for the movement, importation and placement of waste material(s).

To successfully achieve a homogenous mix of ~650 tonnes of media, large machinery were required to manage the volumes involved; as a suitable mixing area was not present at Force Crag, the materials were mixed off-site. Using a contractor with an existing waste permit to accept the sewage sludge (and willing to apply for the necessary extensions to their license to undertake the media mixing), removed the requirement to apply for these permits directly; saving both time and reducing costs. Ultimately, the only regulatory requirements the CA were obliged to fulfill was to obtain the necessary permits to import and position the media into the VFP cells.

The long term placement of the media within the treatment ponds was an issue that the regulator was required to consider carefully, to ascertain under what conditions the CA could surrender the waste permit necessary for the placement of the media. It was desirable to surrender the permit upon completion of the construction work to ensure that the ongoing yearly obligations associated with holding waste permit were not incurred, thereby minimizing costs to the UK government. In order to accept the surrender of the permit, the EA had to be confident that the waste placement was a 'low' risk. Under normal circumstances this requires the waste material to be capped to prevent water ingress. At Force Crag, it was agreed that by preventing any mine water ingress into the surrounding ground from the ponds (through the use of impermeable liners), the capping of the treatment media by the overlying layer of water combined with the requirement for the water discharging from the treatment system being subject to monitoring under an environmental permit, the regulator agreed that the waste permit could be surrendered.

In addition to the waste permit requirements, the long term disposal of the spent metal-rich compost media also needed to be considered. Although some measures have been suggested which may increase the longevity of the system (*e.g.* 1. increase the working head of the water in the system to encourage the down flow of water if the permeability of the media reduces; 2. introduce a fresh carbon supply to replenish the food source for the bacteria), it is inevitable that eventually, the media will no longer be effective and require replacement. At some point in the future, the ~650 tonnes of material in the Force Crag VFPs will require permanent disposal, almost certainly off-site. At present, the precise chemical composition of the spent media is unknown. To compensate for this lack of knowledge, the material used in the Nenthead reactor has been used as a proxy to determine the most probable disposal route for the media used at Force Crag. The regulations pertaining to the disposal of waste requires that such material is categorized within a classification system that limits the disposal routes for certain types of wastes. Due to the high concentration of metals in the media, the material is likely to be classified as hazardous waste. However, the high organic content of the compost-based media limits the avenues for disposal; hazardous waste landfill sites within Europe are not permitted to accept wastes with an organic content in excess of 6 %. While there may be options to pre-treat the media prior to disposal the practicalities (both technical and financial) remain uncertain. Consequently, it was decided that a 'worst case' disposal option would be included in the whole-life cost of the system to ensure that future funds were available to dispose of the media at the end of its operational life should they be required.

### *Discharge Permit*

It is recognized by the EA that there is a low risk of pollution from short-term pilot treatment systems at abandoned metal mines. Small-scale experimental mine water treatment plants can therefore be operated without an environmental permit provided the system is carefully monitored, the EA is notified of the trial and its duration and no pollution occurs. For full scale-systems however, environmental permits are required. In the UK, owners or operators of mines abandoned before 2000 cannot be held liable for permitting water pollution, and so public funds are being used to build and operate treatment systems at prioritized long-abandoned mines. Passive systems do not provide the same certainty of effluent quality as active systems, but should lead to significant improvements in river water quality. The EA has therefore decided that in specific circumstances, the numeric emission limits normally applied to effluents may not be appropriate for passive treatment systems at abandoned metal mines. For the Force Crag system, the EA agreed to issue a permit that requires the CA to carry out detailed monitoring to demonstrate the performance of the VFP and to ensure that there is no increase in pollution, without numerical targets for metals.

**CONCLUSION**

This paper has focused on some of the construction and permitting issues that can result when taking a small-scale pilot system into the 'real world' as a full-scale operating scheme. Although challenging, these issues can often be overcome by being flexible with design and the sourcing of raw materials, in addition to engaging with numerous stakeholders to ensure a pragmatic approach is taken. In summary, the main challenges identified in this example are as follows:

- Provide local planning authorities with outline plans for designs whilst communicating the message that some modifications to the system may be required.
- Being flexible in the design process, as unforeseen problems will occur during the construction process.
- Clearly specify the materials and methods required and determine the detailed layout of the treatment system before construction commences.
- An adaptable operational monitoring program is required that can change to monitor unexpected issues (*e.g.* $H_2S$ gas) that may arise in the first years of operation.
- Detailed discussions and agreement with the environmental regulator are required in the early stages of the project to ensure the correct permits can be attained.

**REFERENCES**


Environmental Permitting (England and Wales) Regulations 2010, No. 675.

Harris, R.A., Moorhouse, A.M.L., Hill, S. and Wyatt, L.M. (2014) Stakeholder Management: the key to successful metal mine discharge remediation. In "An interdisciplinary response to mine water challenges - Proceedings of the 12th Congress of International Mine Water Association 2014". Wanghau Sui, Yajun Sun and Changshen Wang (Eds.) pp 781-785.

Jarvis, A.P. and Mayes, W. (2012) *Prioritisation of abandoned non-coal mine impacts on the environment – The national picture.* SC03136/R2 Environment Agency, Bristol, UK. Available from https://www.gov.uk/government/publications/prioritisation-of-abandoned-non-coal-mine-impacts-on-the-environment (accessed 30 Sept 2014).

Jarvis A.P., Davis, J.E., 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.* Available from https://www.gov.uk/government/publications/treatment-of-pollution-from-abandoned-metal-mines (accessed 24 October 2014)

Jarvis A.P., Gandy C.J., Bailey M.T., Davis J.E., Orme P.A.H., Malley J., Potter H.A.B, Moorhouse A.M.L. (2015) Metal removal and secondary contamination in a passive metal mine drainage treatment system. 10th IMWA-ICARD 2015, Santiago, Chile.

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, UK, pp. 166.

Tyler, I (2005) *Force Crag: The history of a Lakeland mine.* Blue Rock Publications, Keswick, pp. 130.

Wyatt L.M., Watson, I.A., Kershaw, S. and Moorhouse, A.M.L. (2013) An adaptable and dynamic management strategy for the treatment of polluted mine water from the abandoned Wheal Jane Mine, Cornwall, UK. In "Mine Closure 2013 – Proceedings for the Mine Closure Conference 2013". Eds Tibbett M., Fourie A.B. and Digby C. pp 69-78.

2000/60/EC The Water Framework Directive. (2000) *Directive of the European Parliament and of the council of 23 October 2000 establishing a framework for Community action in the field of water policy.*