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Wheal Jane mine water active treatment plant – design, construction and operation

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Abstract

The Wheal Jane tin mine was abandoned in March 1991 and the water level allowed to rebound to the surface in November 1991, at which stage an emergency treatment system was implemented. Treatment operations were temporarily suspended in January 1992, and this resulted in the failure of an adit plug and the uncontrolled release of mine water into the surrounding environment. Following the release, temporary treatment recommenced and studies were undertaken to assess the environmental impact and determine the most appropriate long-term treatment option. These studies concluded that active treatment using lime dosing and a design based on sludge recirculation was preferable.

The Environment Agency procured a contractor to design, build and operate a plant for an initial period of 10 years using a Partnering Contract. The contract was won by United Utilities Industrial Ltd. using technology provided by Unipure Environmental Inc. The treatment plant comprised a high density sludge facility designed on the basis of pilot trials undertaken at the pre-tender stage. These trials revealed that installation of a tertiary filter to ensure effluent quality and the provision of a sludge press to dewater the sludge to 50% solids (on a weight by weight basis) was unlikely to be necessary. Construction of the plant was undertaken in two phases with the installation of tertiary treatment and the filter press delayed until after the performance of the Phase I plant had been assessed. The performance of the Phase I plant demonstrated that tertiary treatment and a sludge press were not required and as a result a saving of £1.7m was made.

In the first 22 months of operation in excess of 12 310 000 m^3 of water were treated, at an average rate of 17 265 m^3/day (200 L/s), removing over 3200 tonnes of metals with an overall removal efficiency of 99.2%.

Key words: dissolved metals, high density sludge, hydroxide precipitation, mine water, Unipure process, Wheal Jane

INTRODUCTION AND BACKGROUND

The abandoned Wheal Jane tin mine is located in south-west Cornwall, England. Mining on the site was first recorded in 1740, although it is thought to have started in pre-Roman times. Mining recommenced in the early 1960s with the development of a new mine on the site. The ownership of the mine subsequently changed hands three times, until 1991 when the tin price plummeted to just over £2,000/tonne, making the mine unviable. Underground operations ceased on 6 March 1991, and the mine was formally abandoned on 9 September 1991. Following the cessation of pumping in March 1991, the mine water level rebounded until on 17 November 1991 water started to issue from the Jane's Adit. The adit was plugged on 20 November 1991 and

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an emergency treatment system set up to pump and treat mine water from an abandoned mine shaft into the Clemows Valley Tailings Dam (CVTD), where lime was added to precipitate the dissolved metals. Treatment was suspended on 4 January 1992 due to turbidity problems and the mine water was allowed to accumulate in the abandoned workings. On 13 January 1992 the Nangiles Adit plug failed, causing an uncontrolled release of approximately 50 000 m^3 of metal laden, acidic mine water into the Carnon River and the Fal Estuary. The released water contained in excess of 3500 mg/L of dissolved metals (principally iron, zinc, cadmium, arsenic, aluminium, plus other traces of toxic metals). As a result, the zinc and cadmium Environmental Quality Standards (EQS) for the Carnon River (500 μg/L Zn^T and 1 μg/L Cd^T) were exceeded by 900 times and 600 times respectively.

Emergency treatment was immediately recommenced and the pumping capacity increased to maintain the mine water level below the invert of the Nangiles Adit. Lime was added to the pumped water to neutralise the acidity and remove the dissolved metals as a gelatinous precipitate. The treated mine water was discharged into the Clemows Valley Tailings Dam (CVTD), which was used to both settle and store the precipitated solid. Supernatant water was discharged from the dam to the River Carnon via a polishing lagoon.

During 1992/93, the Environment Agency, with the assistance of the mine owners, progressively upgraded the emergency treatment system by replacing the original mine water pumps with six Grundfos pumps, each capable of pumping 55 L/s, and with the installation of a new lime dosing plant.

PROJECT DEVELOPMENT

The emergency treatment plant gave the Environment Agency time to commission consultants, Knight Piésold (Cambridge 1997; Hallett 1999), to undertake studies on the impact of the discharge and to assess long-term treatment options. These studies showed that passive treatment was not appropriate as there is insufficient suitable land available within the Carnon Valley to reliably treat the Wheal Jane mine water.

The studies reviewed a variety of technologies and concluded that conventional oxidation and chemical neutralisation (OCN), biochemical sulphidisation (BCS) and ion exchange (IEX) were the most appropriate. The project team identified that the disposal of sludge was a significant component of the project cost and therefore it was crucial to minimise the volume of sludge generated. Preference was therefore given to either a lime-based high-density sludge (HDS) process or sulphide precipitation (although concerns were raised about the long-term storage of sulphide rich sludge).

PROJECT PROCUREMENT

In collaboration with the Environment Agency and the Department of Environment, Transport and the Regions, Knight Piésold developed a procurement strategy for the appointment of a contractor to design, build and operate (DBO) the plant for a period of ten years. To achieve these objectives within the EU Procurement Procedure, framework contractors were prequalified and invited to tender on the basis of either an illustrative design prepared by the EA consultants or their own preferred treatment technology. The tenders were evaluated on the basis of the technology offered, project costs and risk. A preferred contractor was selected to take the project forward in an 'open book' contractual arrangement that used the tender prices as the basis for developing the final scheme cost.

The contract was tendered between November 1998 and March 1999. As part of its tender bid, United Utilities Industrial (UUI), engaged Camborne School of Mines (CSM) to identify technologies capable of meeting the Agency's requirements for the Wheal Jane mine water treatment plant. CSM identified five suitable technologies, of which the Unipure process was deemed most appropriate.

Following a visit to two Unipure installations in the US, UUI assembled a project team comprising:

- lead contractor and plant operator, United Utilities Industrial Ltd.;
- process installation contractor, Salcon Invent Ltd.;
- civil engineering contractor, Dean and Dyball Ltd.;
- process technology provider, Unipure Environmental Inc.

UUI was appointed as the preferred contractor in May 1999, and a finalised project target cost was agreed in September 1999.

DESIGN SPECIFICATION

The flow from the mine varies seasonally, typically peaking in excess of 330 L/s during January to March and declining to about 110 L/s during August to September. To accommodate this range it was decided to install two identical treatment streams, each with a rated capacity of 230 L/s (with the ability to treat the mine water delivered by four pumps, together with the seepage water recovered from the toe of the CVTD

Table 1. Wheal Jane MWTP water quality requirements

Parameter	Unit	Influent		Consent	
		Ave	Max	Short-term	Long-term
pH		3.50	3.85	6–10	6.5–10
Total As	mg/L	3.0	16.0	0.5	0.1
Total Al	mg/L	23.0	40.0	13.0	10.0
Total Cd	mg/L	0.056	0.149	0.04	0.04
Total Cu	mg/L	0.80	7.65	0.3	0.08
Total Fe	mg/L	206	402	5.0	5.0
Total Mn	mg/L	6.0	19.2	7.0	1.0
Total Ni	mg/L	0.55	1.2	1.0	1.0
Total Zn	mg/L	51.0	176.0	20	2.5
Total Pb	mg/L	0.15	0.60	–	–

(where the downstream slope of the dam meets the surrounding ground level)). In an average year, both streams are only expected to operate for around seven months, allowing essential maintenance to be carried out during the remainder of the year.

The predicted ten-year mine water quality is tabulated in Table 1, together with the short-term (Phase I) and long-term (Phase II, post 1 March 2002) discharge consents.

THE PROCESS

The conventional hydroxide precipitation process can be modified to produce a metalliferous sludge that settles to greater densities. The high-density sludge (HDS) produced from this process typically allows sludge concentrations of 15 to 25% (w/w) to be achieved on clarification/thickening, and values of between 50 and 80% from filter presses. Critical to the formation of HDS is the adoption of multistage neutralisation and the recirculation of a proportion of the sludge. HDS can be formed by mixing the recirculated sludge with either the lime prior to introducing the mine water, or the mine water prior to adding the lime. The Unipure process uses iron as the basis for forming HDS, and therefore, given the high dissolved iron concentration in the mine water, was ideally suited to the Wheal Jane project.

PILOT PLANT TRIALS

To assess the performance of the Unipure process, it was decided to mobilise a pilot plant from the US as part of UUI's tender preparation. Although it is possible to demonstrate the process chemistry using bench scale equipment, a 1 m^3/hr pilot unit (Figure 1) was selected to ensure that the sludge produced by the pilot unit was fully representative of that produced by the full-scale plant, thereby minimising the risks associated with scaling the design up. The pilot plant was set up on 30 December 1998 and two sets of trials were undertaken. The first campaign was undertaken in January 1999 to demonstrate the suitability of the process to the EA, prior to tender submission, and to provide basic design and operating cost parameters. The results from this trial formed the basis of the successful UUI tender. A second set of trials was undertaken in August 1999, following nomination of UUI as the preferred bidder, to allow optimisation of the tender design by the project team.

The compliant design required the installation of tertiary sand filters to ensure satisfactory final effluent suspended solids and manganese concentrations, together with a filter press to dewater the sludge to at least 50% solids. The Unipure pilot trials indicated that a satisfactory final effluent quality could be achieved without the use of sand filters, and that the sludge settled rapidly to about 35% solids within 8 hours. Filter press trials demonstrated that solids concentrations in excess of 70% by weight could be achieved using either conventional or membrane presses. Based on these results, potential savings of up to £2m were identified by not installing the tertiary sand filters or the sludge press. The project partnership therefore recommended that the plant should be built in two phases, comprising:

- Phase I – neutralisation vessels and sludge clarifier/thickeners, with the direct discharge of treated effluent to river, and surplus sludge pumped to the CVTD for settlement and storage;
- Phase II – tertiary filters and sludge press.

Figure 1. Unipure pilot plant

Figure 2. Photograph showing the general layout of the plant

To confirm whether the tertiary filters and the sludge press were needed, it was decided to delay the Phase II works for twelve months to allow the performance of the full-scale Phase I plant to be assessed. To allow UUI to operate the plant during this period, the EA granted a less onerous short-term effluent consent (Table 1).

DESIGN PARAMETERS

The pilot-plant trials established the following design parameters:

Reactors	*Stage 1 reactor*	*Stage II reactor*
Minimum retention time	30 min	30 min
Sludge recirculation ratio	25:1 to 50:1	
Operating pH	6.5– 7.5	9.25

Thickener/clarifier	
Clarifier rise rate	1.2 m^3/m^2.hr
Clarifier loading rate	2 m^2/tph
Flocculant dosing rate	3 mg/L
Sludge density	20% w/w

PLANT LAYOUT

The plant layout is shown in Figure 2 and is illustrated schematically in Figure 3. Each stream is identical and consists of a Stage I reaction chamber, a Stage II reaction chamber and two lamella clarifiers. Both streams

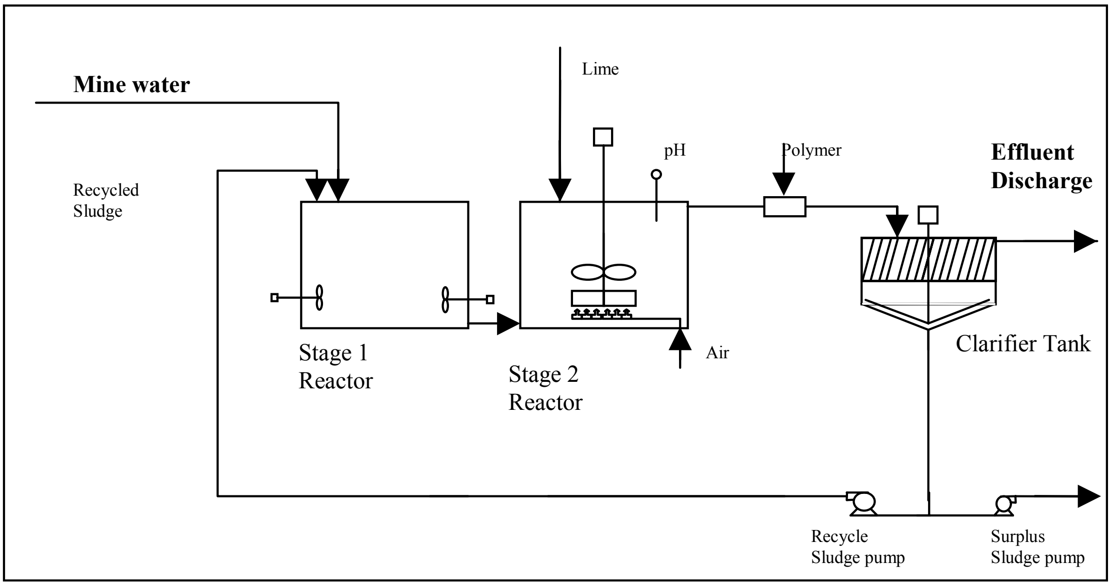

Figure 3. Process stream schematic arrangement

are served by common equipment, comprising lime and flocculant make-up systems, air blowers, a sludge holding tank, transfer pumps and final effluent discharge monitoring equipment.

Plant principal components

No. 2 Shaft borehole pumps
Raw mine water is lifted some 65 m from No 2 Shaft into the plant, by six three-stage Grundfos (SP215) submersible pumps, each delivering up to 55 L/s. A standby pump is permanently installed in the shaft for immediate use with an eighth pump held in store. The pumps (and associated power cable) are supported by the 150 mm diameter wellmaster pipe connecting the pumps to a flow distribution manifold located at surface level.

Figure 4. Stage I reactor

Stage 1 Reaction chamber
The raw mine water is neutralised by the recycled sludge in the Stage I reactor (Figure 4). To comply with the Environment Agency's design life of at least 60 years, both the reactors and the clarifier tanks are constructed from concrete. The Stage I (and Stage II) reactors comprise 10 m square tanks with a working depth of about 5.5 m and working capacity of 550 m^3. The Stage I reactor raises the influent mine water pH from 3.5, to a pH of between 6 and 8, and precipitates most of the dissolved metals. The pH in the Stage I reaction chamber is not directly controlled, but can be altered by varying the recirculation rate. Provision was made in the original design to also control the pH by the introduction of lime via a manually operated valve. This system has never been used. Two 4 kW Landia POPR-I mixers are installed in opposite corners of the reaction vessel to mix the raw mine water with the recycled sludge and stop any settlement occurring.

Figure 5. Stage II reactor mixer bridge

Stage 2 Reaction chamber
The neutralised mine water passes beneath the common dividing wall between the Stage I and II reaction vessels into the 550 m^3 Stage II reactor where the pH is raised to about 9.25 by the addition of lime-slurry at approximately 6% solids (weight/weight). The operational pH is controlled between 9.15 and 9.35 to ensure that the total manganese concentration of the final effluent complies with the discharge consent. Air blowers are used to introduce oxygen to ensure complete oxidation of ferrous iron to ferric. A Mixertech type 1163 mixer, driven by a 75 kW motor via a Flender B3BV09, is used to ensure satisfactory oxygen transfer and adequate mixing (Figures 5 and 6). The mixers are fitted with a bottom mounted vertical blade turbine and a propeller type impeller. The vertical blade turbine provides sufficient shearing energy to break up any weak sludge particles and to enhance the rate of oxygen transfer from air introduced by the sparge system. The impeller breaks up the coarse air bubbles produced by the sparge pipe into much smaller bubbles, which due to greater surface area increase the oxygen transfer rate by at least 300%. To ensure adequate mixing a propeller type impeller is located about one third of the way up the submerged length of the shaft.

The pH and solids concentrations within the Stage II reactor are monitored by Endress & Hauser probes which are used via the PLC to control the Stage II reaction tank pH.

In-line static mixer
The treated mine water passes from the reaction chamber through an in-line static mixer (Statiflo series 600

Figure 6. Stage II reaction vessel mixer

Figure 7. Clarifier overflow

motionless mixer), where a slightly anionic flocculant is added to assist solid/liquid separation. The dosed mixture then flows through a launder into each of the clarifiers.

Lamella clarifier/thickener units

Solids/liquid separation is achieved in two 7 m square lamella clarifier/thickener units operated in parallel. Thickened solids from the clarifier are either recirculated to the Stage I reactor or are surplused from the system at a solids concentration of between 15 and 25% (weight by weight). Particular attention was paid during the design process to meeting the area requirements for both supernatant water clarification and sludge thickening. To achieve these requirements lamella packs were installed in each unit to increase the effective clarification area of each unit from 49 m^2 to about 400 m^2. Thickened sludge is recovered from the base of the tank via a 150 mm diameter underflow pipe connected to the sludge recirculation and surplusing pumps (4 kW Warman 100 C-GP and 1.5 kW Warman GP75B-CCC-A1 respectively). Sludge is directed to the centrally positioned underflow pipe by a rake mechanism driven by 1.1 kW motors. The volume of sludge returned to the Stage I Reactor is automatically varied in response to changes in the mine water flow rate. A magnetic flowmeter (Danfoss Magflow type 5000) located on the sludge return line is used to control the speed of the variable speed recirculation pump, thereby ensuring that the required flow rate is pumped irrespective of the sludge viscosity. An Endress & Hauser Probfit CUA461 sludge density meter is fitted to each sludge recirculation line to monitor the underflow solids concentration. These are used to automatically surplus excess sludge once the solids content exceeds a predetermined value.

Sludge surplusing

Excess sludge from the plant is pumped to a 368 m^3 holding tank designed to provide at least five days sludge storage capacity, to avoid sludge disposal during bank holidays. Two Landia mixers prevent settlement within the tank. Warman centrifugal pumps automatically pump the sludge from the tank to the CVTD, where the solids settle and consolidate to about 50% w/w.

Final effluent monitoring

The volume of treated water discharged from the plant is measured using an ultrasonic level meter (Pulsar Flow Oracle) and vee notch weir. In addition, the final effluent suspended solids content is recorded using an Endress & Hauser turbidity meter and the pH is triple validated by three Endress & Hauser probes. All the final effluent validation data are automatically recorded and used for discharge compliance and process control.

Lime make-up system

The original lime make-up system installed in 1993 is used to supply lime to the new plant. The system is capable of storing 80 tonnes of calcium hydroxide in two 40 tonne silos. Lime slurry was originally supplied alternately from two batch tanks. However, as part of the new plant, this was modified to transfer the batched lime-slurry to a holding tank from where it is pumped by a Warman centrifugal pump, around the plant. The lime dosing into the Stage II reaction vessel is controlled by means of a PID controller, using an Endress & Hauser pH meter and Rotork actuated valves.

Polymer make-up system

A Ciba Specialist Chemicals Ltd. polymer preparation unit is used to make up powder polymer into a 0.035% solution for flocculation purposes. The polymer preparation plant is common to both streams, but feeds two sets of dosing equipment, with one set-up per stream. Following a number of jar and plant optimisation trials, a slightly anionic polymer has been selected (Magnafloc 155). This was originally being dosed at 3 mg/L, but has subsequently been reduced to 1.8 mg/L without adversely effecting water quality.

Air blower system

Each process stream has two Hick Hargreaves air blowers (rated at 30 kW and 25 kW) providing up to 2664 m^3 of air per hour. A third 30 kW unit is installed as a common standby.

Instrumentation, control and automation (ICA)

The plant is automatically controlled by an Allen Bradley PLC (programmable logic controller). All levels, flows and meter readings are recorded, together with the operational state of every major component. Access is gained to the PLC by the SCADA system, which also records all historical activities. The plant is monitored 24 hours per day, 365 days a year, by the United Utilities Industrial off site remote telemetry system. Any alarms recorded by the telemetry system are immediately passed to the on-call standby operator, who will attend the site within two hours.

Data from the final effluent flow and quality monitors are also sent to the Environment Agency's regional control centre, from where the performance of the plant can be independently verified.

OPERATIONAL PERFORMANCE OF PHASE I PLANT

Commissioning of the Phase I plant took place in October 2000. High-density sludge was formed within two days of flows being turned on, and effluent was discharged directly to the environment, without using the tailings dam as polishing facility, within four days. Throughout the month of December 2000, 344 L/s of mine water were being treated by the plant. The average effluent quality over the first 22 months was 0.81 mg/L iron, 0.19 mg/L zinc and 0.31 mg/L manganese, demonstrating that tertiary treatment was not required. The progressive optimisation of the plant has resulted in a reduction in the flocculant dose rate from 3 mg/L to 1.6 mg/L in September 2002 and a reduction in power consumption. The sludge produced by the plant settles to in excess of 30% (w/w) in four hours on deposition in the tailings dam consolidates to about 50% (w/w).

PHASE II PLANT UPGRADE

A performance review of the plant was undertaken after a period of twelve months operation. This confirmed that the plant performance had exceeded expectations, with very low residual metal and solids concentrations in the effluent. In addition, the consolidation characteristics of the sludge were such that the target density of 50% solids could be achieved in the dam without the use of sludge dewatering. Following this review, the project team agreed that the installation of the tertiary filters was not necessary to meet the required solids concentrations in the effluent, but that the robustness of the operation would benefit from the installation of a new lime plant control panel, the installation of a large lime-slurry storage tank and the provi-

Table 2. Wheal Jane MWTP project economics

Item	Cost (£)
Total budget for consultancy, design, build and ten-year operating contract	16.9m
Target costs for the construction of the Phase I plant	3.9m
Actual cost of the Phase I plant	3.4m
Actual cost of Phase II works	0.3m
Saving on Phase II works	1.7m
Annual operating cost	1.0m
Predicted operating cost (predicted to vary with declining concentration)	0.16 to £0.20/m^3
Predicted average operating cost for the ten-year contract period	0.17/m^3
Actual operating cost over the first two years per m^3 of water treated	0.18/m^3
Actual operating cost over the first two years per kg of metal removed	0.64/kg

sion of a standby polymer system. In addition, to minimise the risk to the environment in the event of plant failure, provision has been made to use the CVTD as an emergency storage facility.

The net saving achieved as a result of not installing the tertiary filtration and the sludge filter press is estimated to be £1.7m.

PROJECT ECONOMICS

The principal economics of the project are shown in Table 2.

The predicted average operating cost at £0.17/m^3 was based on the average metal concentration projected for the ten-year operating contract, taking into account the ongoing decline in metal concentrations. Consequently treatment costs were anticipated to decrease throughout the contact period as the metal concentration declined, between £0.20/m^3 and £0.16/m^3, as shown in Table 2. The actual average operating cost achieved over the first two years (£0.18/m^3) is comparable with the predicted long-term average, and therefore represents a reduction in the anticipated unit cost for this period.

To encourage all parties involved with the long-term operation of the plant to strive for further reductions in operating costs, the project team are exploring the introduction of an incentivisation clause into the operating contract. The objectives of this incentivisation clause are to strive for a continued reduction in operating costs, through focusing on key improvements to the technical performance of the plant and appropriate risk allocation. The contractor would be awarded a financial incentive for achieving key technical improvements and cost reductions.

SUMMARY AND CONCLUSIONS

The procurement of the Wheal Jane mine water plant was the first major partnering project undertaken by the Environment Agency. The adoption of this approach has enabled a significant reduction in the cost, and was considered to be a contractual success by all parties involved. Further cost reductions are anticipated by continuing the partnering approach throughout the operating period of the contract.

The use of a 1 m^3/hr pilot plant enabled the performance of the process to be demonstrated at an early stage, and provided meaningful data on the physical behaviour of the sludge for full-scale plant design. The performance of the full-scale plant has exceeded the client's expectations, and has resulted in a £1.7m saving by avoiding the necessity for installing a tertiary sand filter and sludge dewatering filter press.

In the first 22 months of operation, in excess of 12 310 000 m^3 of water were treated, at an average rate 17 265 m^3/day (200 L/s), removing over 3200 tonnes of metal with an overall removal efficiency of 99.2%.

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