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The Treatment of Ferruginous Ground Water from an Abandoned Colliery

By G. A. Best, Ph.D., C.Chem., M.R.S.C. (Member), and
D. I. Aikman, B.Sc., M.Sc., C.Eng., M.I.C.E., M.I.W.E.S., M.A.S.A.E.
Freshwater Survey Officer, Clyde River Purification Board, and Engineer, Babtie Shaw and Morton, respectively

Introduction

Ferruginous waters from coal mining activities originate from three sources: (a) underground mine workings, (b) opencast workings, and (c) spoil heaps. The mechanism of the formation of the orange-yellow precipitate has been described by Williamson[1]. It results from the oxidation of subterranean pyrites when the mine is first opened and its subsequent dissolution in ground-water.

Not all minewater discharges are ferruginous; some are of the highest quality and can be used for potable supply, but the ferruginous discharges can give rise to disastrous conditions in receiving streams and can affect many kilometres of otherwise good quality water[2,3].

Drainage water from coal mines in the UK can be divided into the following chemical groupings[4]:

(i) Hard;

(ii) alkaline;

(iii) moderately saline;

(iv) highly saline;

(v) alkaline and ferruginous; and

(vi) acidic and ferruginous.

The term alkaline needs some qualification as the pH of the discharge can be slightly less than 7. The term is used to differentiate these discharges from acidic ones which have pH values of 5 or less.

The ferruginous discharges constitute about 8% of the total, of which 7% are regarded as alkaline and ferruginous.

This paper describes the investigations into the treatment of an alkaline and ferruginous type of discharge, namely that from the abandoned Kames colliery at Muirkirk in Ayrshire, Scotland.

The principle chemical characteristic of alkaline and ferruginous discharges is that, after aeration, all the ferrous salts are converted into the insoluble ferric form which precipitates as hydrated ferric oxide. The treatability of this type of mine water has been studied elsewhere. Clark and Crawshaw[5] reported on pilot-plant studies to treat a minewater discharge in the Burnley area. The Kames plant differs in that the main objectives were to study the aeration of the anoxic mine water, and the effect on settlement of various methods of improving floc formation in the oxidized water. In addition, work was carried out to investigate the characteristics of the resultant sludge.

Background

The colliery at Kames (Fig. 1) was closed by the National Coal Board in 1969. After the closure, the mining equipment was removed, the former being levelled and the area landscaped in preparation for returning the land to grazing. The 200 m deep main access shaft was filled with rubble, but the pumping main which was used for draining the mine was left in position. With the removal of the pumping equipment, the mine workings filled with water and overflowed via the pumping main. The mine water flowed along a channel and then cascaded down an embankment of the Garpel Water, a tributary of the River Ayr (Fig. 2).

The water emanating from the mine shaft is characterized by the absence of dissolved oxygen, having a near neutral pH and containing ferrous iron in solution (Table 1).

As the discharge flows to the Garpel Water and mixes with the river water, the iron is oxidized by oxygen absorbed from the air, and is precipitated on the river bed. This process has continued since the start of the discharge and has affected the quality of the Garpel Water and the River Ayr for about 10 km. The rate of discharge is influenced by rainfall and in the autumn of 1974 and spring of 1975 varied between 0·022 m^3/s and 0·047 m^3/s. During the course of the pilot-plant experiments in the summer of 1980, the flow ranged 0·003–0·026 m^3/s. There is no river gauging station close to the Kames colliery, but the River Ayr is gauged further downstream. These records have been used

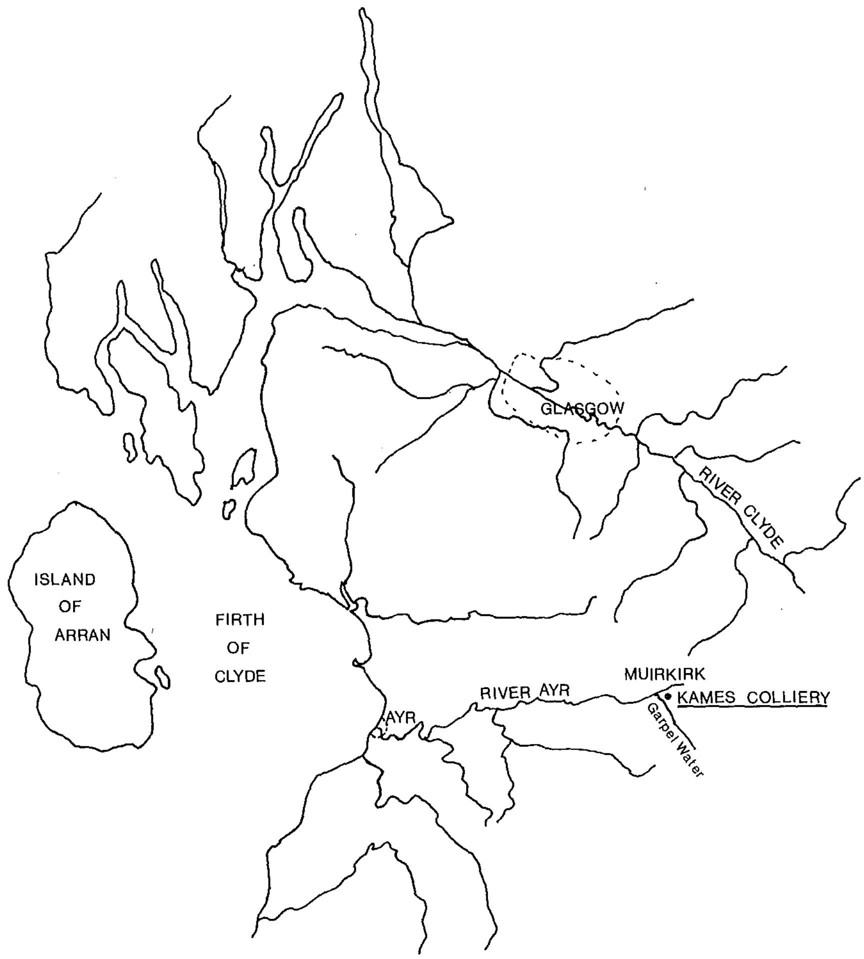

Fig. 1. Location of Kames Colliery, Muirkirk

to estimate the Q_{95} (the flow rate which is equalled or exceeded for 95% of the time) of the Garpel Water as 0·03 m^3/s and in the River Ayr below the Garpel confluence as 0·11 m^3/s.

Initially, the concentration of iron in the discharge was nearly 70 mg/l, but over the years the concentration has decreased to a present-day value of about 25 mg/l.

TABLE 1. CHEMICAL ANALYSIS OF MINE-WATER DISCHARGE
(24 samples taken during period 13/6/80 to 20/10/80

Determinand	Average	Range
Total iron (mg/l)	26	18–32
Soluble iron (mg/l)	26	18–32
Dissolved oxygen (% sat.)	nil	–
pH	6·35	6·2–6·6
Conductivity (μ S/cm)	1350	1100–1500

The effects of the discharge are demonstrated by biological surveys of the receiving waters[6]. The iron oxide precipitate blankets the river bed and reduces the habitats for invertebrate life and the spawning areas for fish. The fine particles also block the gills of the fauna, and few species survive in the waters immediately downstream from the ferruginous discharge. The results of three biological surveys taken over a period of eight years (Table 2) demonstrate how long the effects have persisted.

INITIAL INVESTIGATIONS

On-site surveys of the effect of the discharge on the receiving stream show that the water emanating from the mine has a pH value of just above 6·0, is devoid of oxygen and contains only soluble iron. As the discharge flows towards the Garpel Water it becomes slightly aerated and, as a result, the pH value increases and some of the iron precipitates (Table 3).

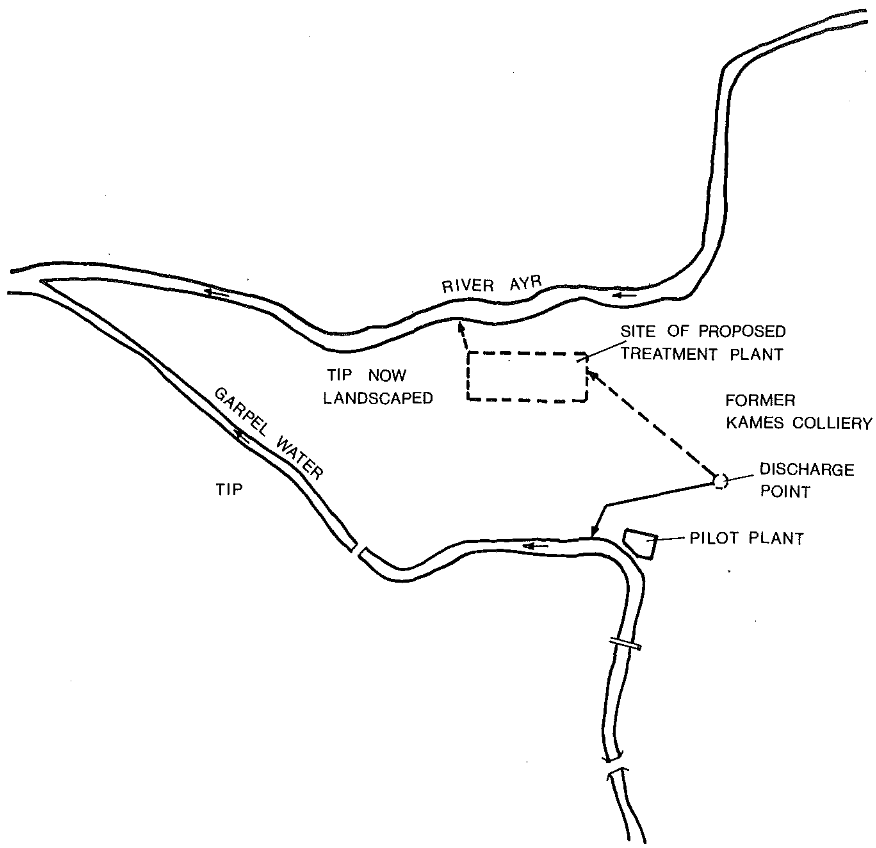

Fig. 2. Site of Kames treatment plant

TABLE 2. BENTHOS SURVEY OF GARPEL WATER AND RIVER AYR.

Sampling point	1974		1978		1982	
	No. of organisms	BMWP[x] score	No. of organisms	BMWP score	No. of organisms	BMWP score
Garpel Water above Kames discharge.	420	77	N.D.†	80	343	102
Garpel Water below Kames discharge.	1	1	18	52	27	26
River Ayr 100 m below Garpel conf.	163	44	486	68	415	111

[x]BMWP Score = Biological Monitoring Working Party Score Index
†N.D. = Not determined.

Laboratory experiments confirmed the relationship between oxygen saturation, pH and the precipitation of iron as shown in Table 4.

TABLE 3. EFFECT OF AERATION IN DRAINAGE CHANNEL

	pH	Dissolved oxygen (% saturation)
At wellhead	6·25	nil
At top of cascade to river	6·30	trace
Half way down cascade	6·65	33

TABLE 4. EFFECT OF AERATION ON KAMES MINEWATER

Dissolved oxygen (% saturation)	pH	Insoluble iron (% of total)
30	6·4	17
87	6·9	44
100	7·0	64
104[x]	7·2	89

[x]Prolonged aeration

Work reported by Harvard University[7] showed that the minimum solubility of ferric hydroxide occurred at a pH value of 8·0, whilst Glover[8] reported that, because of the rate of oxidation in minewater at pH values in the range 6·2–6·5, 90% of the iron was oxidized in 8 h.

The settling rate of the particles in the Kames minewater was measured by aerating portions of the water for different periods to obtain a gradation of DO concentrations and then measuring the settling rate in a 2-l cylinder. From these simple experiments it was found that 50% of the iron had settled in 1 h for 100% saturation, 2 h for 84% saturation, and 3·8 h for 37% saturation.

These investigations established that by making use of the natural process of oxidation and settlement, the quality of the minewater could be improved sufficient to substantially alleviate the pollution in the Garpel Water and the River Ayr.

Pilot-Plant Experiments

In 1979 the Clyde River Purification Board asked the Scottish Development Agency to fund an experimental pilot plant. The Scottish Development Agency agreed and engaged the Water Research Centre to outline methods of treatment which might be investigated. Based on the results of the laboratory experiments and site visits, the main features of a pilot plant were established by Borne[8]. The Scottish Development Agency appointed Babtie, Shaw and Morton as the engineering consultants to carry out his recommendations and to report on the design and cost of a full-scale treatment plant.

Design Criteria

The criteria for the treatment system were that (i) there should be no moving parts so that maintenance required would be minimal; and (ii) no chemicals were to be used so that continuing costs would be minimal after the initial outlay.

The pilot plant was designed to test the effectiveness of three alternative systems and, from these, to determine the design of a full-scale plant:

(a) the oxidation of ferrous iron and settlement of the ferric oxide precipitate, after aeration of the minewater by cascading over weirs of total height 3 m;

(b) the effect on settlement of precipitated iron after the retention of aerated water for 1 h in an upward-flow flocculation tank; and

(c) the effect on settlement of precipitated iron after passing the aerated minewater over a brushwood filter.

In addition to the removal of the iron from the water, experiments were carried out on drying the sludge from the various treatment systems.

Treatment Systems

The plant was designed for an inflow of about 3 m^3/h (about 2·4% of the total mine discharge) and allowed three treatment processes to be tested with a range of flows either singly or in parallel. The treatment systems are shown diagrammatically in Fig. 3 and the processes are described below.

A portion of the flow was diverted from the mine outflow to the pilot plant via a submerged orifice to give a constant flow, and was then passed down a 1·0 m high cascade. The individual steps of the cascade were dimensioned according to the method of Essery and Horner[10]. The flow was then passed to a distribution box which provided a regulated supply to each of three individual treatment systems:

System 1. Following the 1-m cascade, water was distributed evenly over the surface of the 2-m deep brushwood-filled biological filter (2 m^3 capacity). Water was collected from the base of the filter and passed into an upward flow settlement tank (18 m^3 capacity) prior to being discharged to the river.

System 2. From the base of the 1-m cascade, water was passed down a second 2-m high cascade to be further aerated; from there it was transferred to a distribution box for metering to systems 2 and 3. In the case of system 2 the water passed to an upward-flow settlement tank (volume 18 m^3) from which the effluent was discharged to the river.

System 3. Similarly to system 2 the water passed down the 1- and 2-m cascades for aeration. At the base of the 2-m cascade the flow was diverted into an upward-flow flocculation tank having a volume of 5 m^3, from where it was transferred to an upward-flow settlement tank (volume 18 m^3), and again the effluent was discharged to the river.

The cascades and biological filter box were constructed of timber, but the settling tanks were made of reinforced concrete.

When the systems were operational, sludge accumulated in the bottom of the settlement tanks. For the purpose of evaluating the sludge dewatering characteristics, a sand filter bed was provided which allowed sludges from the three different experiments to be dried at the same time. This consisted of a wooden box containing a layer of gravel covered by a layer of sand.

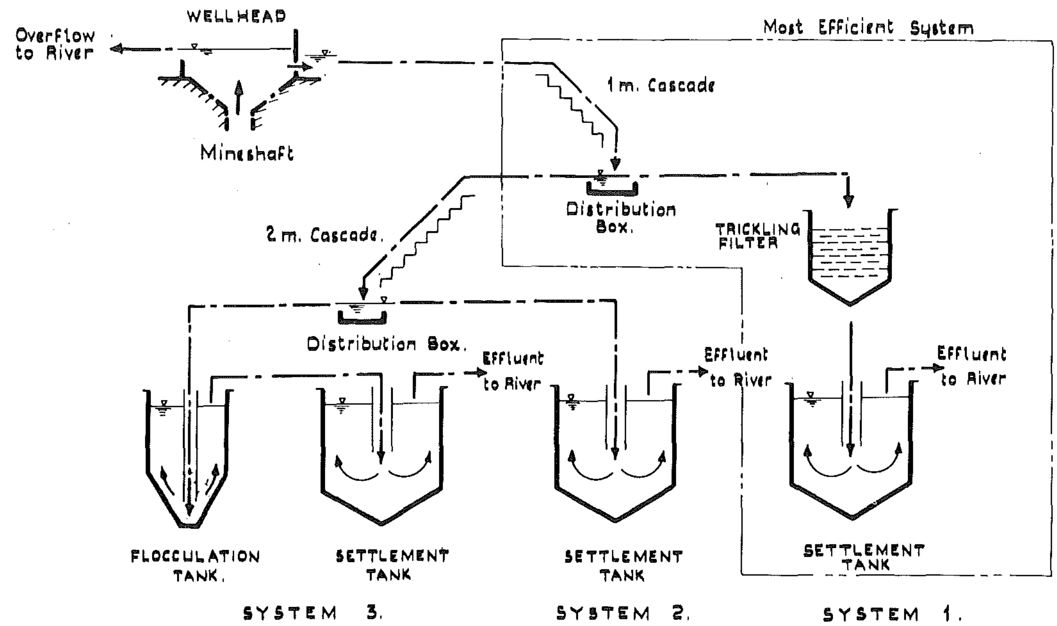

Fig. 3. Flow diagram for pilot-plant treatment systems

Operation and Maintenance

Once the flows were decided upon and the weirs had been set, the system was able to operate unattended except for the removal of iron deposits within the distribution system. Early in the trial it was noted that iron was deposited throughout the system, and narrow orifices and channels had to be cleaned on a weekly basis to prevent blockages occurring.

After about three months' operation, the settlement and flocculation tanks were pumped out and the sludge was removed to the drying beds. Concurrently, the filter box was dismantled and the brushwood was replaced. No further cleaning of the settlement tanks, flocculation tanks or the filter was carried out until the completion of the experiments.

Results

The pilot plant was commissioned early in April 1980, and the results of the first series of experiments are summarized in Table 5.

On 10 June, 1980, because the feed pipes and distribution boxes were becoming choked with ferruginous growths and granular deposits the treatment plant was temporarily shut down and given a thorough clean. The settling tanks were emptied to assess the level of accumulated sludge.

Table 5. Mean Results for First Two Months Operation

	At well head		Top of cascade		Settling tank after filter
Total iron (mg/l)	26·2	all → flow	23·7	⅓ → flow	8·3
pH	6·45		6·6		7·02
DO (% satn.)	Nil		32		81
			↓	⅔ flow	

	Bottom of cascade
Total iron (mg/l)	21·8
pH	6·86
DO (% satn.)	⅓ flow ← 59 → ⅓ flow

	Upward-flow tank	Settling tank	Settling tank
Total iron (mg/l)	18·3	11·5	14·0
pH	6·9 →	7·02	7·0
DO (% satn.)	63	72	72

N.B. The average flow for the period 1-4-80 to 11-6-80 was 3·8 m^3/h.

However, this was not successful because the sludge consisted of fine particles and was fairly mobile. When the pumping level was close to the sludge level, the sludge was readily drawn into the pump.

A (repeat) second series of experiments was carried out, and the results are summarized in Table 6. With this series, the experiments were allowed to proceed for a month longer and more frequent sampling was undertaken.

TABLE 6. MEAN RESULTS FOR FIRST TWO MONTHS OPERATION

	At well head		Top of cascade		Settling tank after filter
Total iron (mg/l)	28·0		22·5		5·0
Soluble iron (mg/l)	28·0	all → flow	9·0	⅓ → flow	0·05
pH	6·37		6·6		7·07
DO (%)	Nil		27	⅔ flow ↓	83

	Bottom of cascade
Total iron (mg/l)	22·2
Soluble iron (mg/l)	1·8
pH	6·8
DO (%)	60

	Upward-flow tank (⅓ flow)		Settling tank	Settling tank (⅓ flow)
Total iron (mg/l)	12·6		7·7	9·9
Soluble iron (mg/l)	0·9	→	0·05	0·3
pH	6·9		7·0	7·0
DO (%)	63		69	70

N.B. The average flow for the period 11-6-80 to 1-9-80 was 2·9 m^3/h.

Finally, a series of three fortnightly experiments was conducted in which all the flow to the treatment plant was diverted to each treatment method in turn. The results of these experiments are summarized in Tables 7,8 and 9. Average flow to the pilot plant during this series of experiments was 3·0 m^3/h.

In the first experiments, the greater treatment capacity of the filter was established compared with the aeration and settlement. The total concentration of iron was reduced by 68% (26 mg/l to 8 mg/l) compared to 56% for the upward-flow settlement and 46% for single settlement stage. The filter also tended to be more efficient at increasing the pH and DO levels of the mine water than the other experimental methods.

Similar results were obtained for the second set of experiments using the same conditions, namely one third of the flow of 3 m^3/h passing to each of the treatment facilities. Additional analysis was performed to determine the proportion of the iron which was soluble and insoluble.

During the three-month survey, the filter followed by settlement reduced the iron concentration by 82% and converted it all into the insoluble form. By contrast the upward-flow followed by settlement reduced the iron content by 72% whilst single settlement gave a 65% reduction in iron.

TABLE 7. MEAN RESULTS FOR TWO WEEKS INCREASED LOADING ON FILTER

	At wellhead	Top of cascade	Settling tank after filter
Total iron (mg/l)	24·1	21·2	11·4
Soluble iron (mg/l)	24·1	–	1·4
pH	6·4	6·7	6·7
DO (% satn.)	Nil	32	67

TABLE 8. MEAN RESULTS FOR TWO WEEKS INCREASED LOADING ON SINGLE SETTLEMENT TANK

	At wellhead	At top of cascade	Bottom of cascade	Settling tank
Total iron (mg/l)	25·0	20·8	20·1	15·8
Soluble iron (mg/l)	25·0	11·3	3·8	1·8
pH	6·4	6·6	6·3	6·8
DO (% satn.)	Nil	30	61	66

TABLE 9. MEAN RESULTS FOR INCREASED LOADING ON UPWARD-FLOW FOLLOWED BY SETTLEMENT TANK

	At wellhead	Top of cascade	Bottom of cascade	Upward-flow tank	Settling tank
Total iron (mg/l)	24·0	21·0	22·5	23·5	15·0
Soluble iron (mg/l)	24·0	12·8	8·8	6·7	2·6
pH	6·35	6·65	6·8	6·9	7·0
DO (% satn.)	Nil	30	63	63	68

The increase in pH value and DO concentrations by the different treatment were similar to the first experiments.

In the final set of experiments, all the flow (about 2·9 m^3/h) was passed through each of the treatment systems in turn for two weeks, to test the treatment capacity under an increased loading.

The increased loading reduced the treatment efficiency of each part of the plant as shown in Tables 7, 8 and 9. However, from all these experiments it is clear that the biological filter followed by settlement was the best method of increasing the DO content of the mine water and reducing the iron concentration even under conditions of high loading.

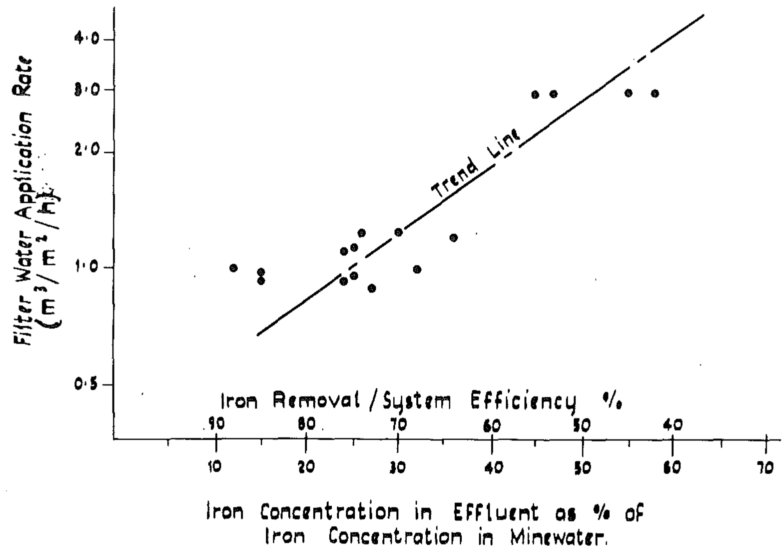

Fig. 4. Effluent iron concentration versus water application rate

The efficiency of the pilot-plant filter system was assessed for the range of flows applied by comparing the iron concentration of the effluent from the settling tank after the filter with that in the water emerging from the mine. A wide scatter of points resulted from an analysis of the data, and some extreme values were excluded where they occurred when the flow controls were probably blocked by accumulated sludge. From the results shown in Fig. 4 and the trend line through the plotted points, efficiencies were calculated (Table 10).

TABLE 10. TREATMENT EFFICIENCY OF FILTER SYSTEM

Water application rate[x] ($m^3/m^2/h$)	Iron removal (%)	% effluent iron to iron in mine water
3	48	52
2	58	42
1	75	25
0·67	86	14

[x]This refers to the rate at which water was applied to the filter.

These data were then used as the basis for the design of a full-scale treatment plant.

SLUDGE DEPOSITION AND DRAINAGE

The most difficult aspect of treatment processes is the collection and disposal of the accumulated sludge, and this applied to the Kames plant.

Iron started to precipitate out of the water as soon as it left the mine and started to absorb oxygen. Deposits of iron accumulated wherever the flow was slow or 'pockets' of dead water were formed.

Where the minewater impinged on a surface such as on the cascade or on the brushwood in the filter, hard deposits formed to a thickness of at least 4 mm. However, when the brushwood was removed from the filter and was allowed to weather, these encrustations dried out and fell off.

It was observed that the iron precipitate differed in its consistency depending on the settlement conditions (Table 11). Therefore the iron precipitate which was deposited under shallow turbulent conditions after aeration, such as in the distribution boxes (water depth 0·3 m), formed a dense sludge (12–23% DS content) which was granular in appearance. The granules were up to 2 mm across and did not lose their form on being disturbed. This material can be expected to drain rapidly without provision of a special drainage bed. By contrast, the iron precipitate at the bottom of the deep settlement tanks (water depth 3·0 m) was less dense and formed a slightly thixotropic liquid (3–8% DS).

From the above it is apparent that precipitated iron particles will readily "grow" under aerobic conditions on suitable surfaces to form a robust sludge of relatively high density, which should have

TABLE 11. ANALYSIS OF SLUDGE SAMPLES

Origin of sludge sample	DS content (%)	Iron content of wet sludge (%)	Sludge density
Settling tank after filter	7·6	2·6	–
Settling tank after 2 m cascade	3·3	1·5	–
Flocculation tank	7·7	3·3	–
Settling tank after flocculation tank	2·9	1·6	–
Distribution box at top of 2 m cascade	12	6·1	1·1
Distribution box at base of 2 m cascade	23	11·3	1·2
Drying bed after 1 month	53	10·2	–
Drying bed after 11 months	71	9·8	–
Dump of drained sludge, 1 year old	65	16·3	1·7

good dewatering properties. In order to achieve maximum sludge density and a rapidly draining material, deep tanks should therefore be avoided (to avoid anaerobic conditions) and the sludge should be settled in shallow lagoons. The use of filters prior to the lagoons should also encourage the formation of a dense sludge.

The sludge which was pumped from the base of the settling tanks onto the sand drying beds of the pilot plant was found to drain in about one month to a handleable cake containing a DS content of about 50%. Table 11 gives details of the analysis of different types of sludges collected from the pilot plant.

FULL-SCALE TREATMENT PLANT DESIGN

Based on the results of the pilot-plant experiments, the filter system was selected for the full-scale plant. However, before a full-scale plant could be designed, the required effluent standard had to be determined, based upon the water quality objective of the receiving stream.

Glover[6] has tabulated the effect of iron on biological systems (Table 12).

TABLE 12. EFFECTS OF IRON ON AQUATIC BIOLOGICAL SYSTEM

Total iron (mg/l)	Appearance in stream	Effect on aquatic life
0·5	Normal	None
1·0	Deposit just visible.	Minimal
5·0	Severe discolouration.	Severe – food chain destroyed.

The observations are partly borne out by a recent biological and chemical survey of the Garpel Water and the River Ayr taken under low flow conditions. The Garpel Water downstream from the discharge contained 4·9 mg/l total iron and the river bed yielded only 27 organisms (BMWP score 26) on the standard 3-min 'Kick' sampling[6]. The River Ayr, below the Garpel confluence, contained 1·8 mg/l total iron and the biological sample contained 415 organisms (BMWP score 111). In addition there were shoals of minnows and sticklebacks swimming about without any obvious signs of distress. Accordingly, it was decided that the water quality objective was that the good salmonid fishery of the River Ayr should not be jeopardized, and the iron content should not be greater than 1 mg/l.

It was necessary to decide which flow conditions the quality objective should be applied to, and the following options were identified:

(i) extreme flow – river flow of 95% exceedence, but normal flow rate of mine water;

(ii) low flow – river flow of 95% exceedence, and low flow rate of mine water;

(iii) normal flow – river flow of 50% exceedence and normal flow rate of mine water.

From the treatment efficiency results in Table 10, data obtained on the flow rate of the Garpel Water and the River Ayr, and the background iron concentration, the iron concentrations for the receiving water shown in Table 13 were calculated.

TABLE 13. FINAL IRON CONCENTRATION OF RECEIVING WATER

Hydraulic loading from[x] full-scale plant ($m^3/m^2/h$)	Iron in receiving water (mg/l)		
	Normal flow	Low flow	Extreme flow
0·67	0·5	0·7	1·1
1·0	0·7	0·7	1·7
1·5	0·9	0·9	2·3

[x]This is based on the rate at which water was applied to the filter.

From consideration of these various conditions, the design of the full-scale plant was based on a filter hydraulic loading rate of 1 m^3/m^2 h which coincides with the design of the pilot plant. Under the extreme flows at this loading, the iron content would reach 1·7 mg/l which was shown, by biological surveys, not to have a significant effect on the stream life.

Full-Scale Treatment Plant Layout and Operation

The proposed full-scale plant comprises a 1·5 m high pre-aeration cascade feeding a 2·0 m deep biological filter, from the base of which the aerated water passes to a shallow settling lagoon in which the iron precipitate settles out. The wet sludge may be dried either within the settlement lagoon or on separate drying beds. In either case it is proposed to dispose of the resulting cake by earthing over with inert material on site. Figs. 5 and 6 show a diagrammatic layout of the two alternative systems.

In order to avoid malfunction of the system due to premature settling out of iron, all the pipework taking water between the mineshaft and the top of the cascade is designed to operate in a surcharged condition with minimum access to oxygen. From the top of the cascade onwards, water is transferred and treated in open units, which give easy access for inspection and cleaning, and areas of dead water are avoided.

In order to allow part of the filter to be taken out of service and the media to be cleaned (by exposure to wind and rain, etc.), the filters are sized to provide 25% excess capacity above the design loading rate.

Under design conditons, it is estimated that about 550 m^3/annum of sludge would be deposited in the settlement lagoon. Drainage of this material to a handleable consistency takes approximately one month.

If material is to be dried within the settlement lagoon it is proposed that the lagoon is divided into

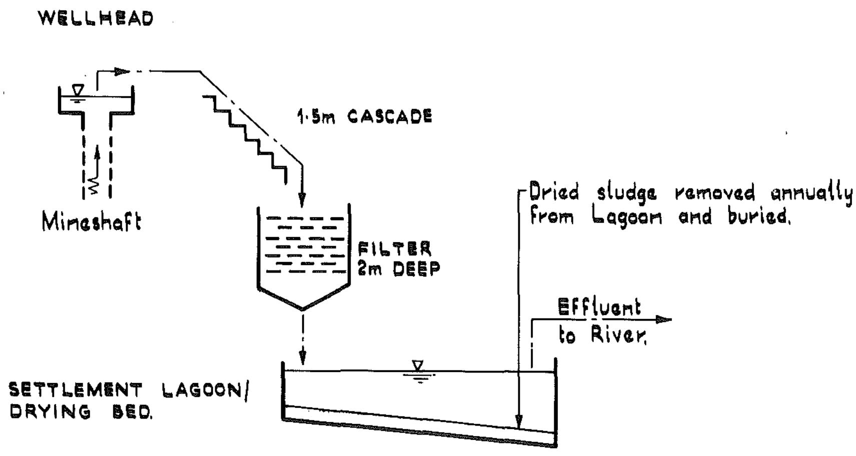

Fig. 5. Treatment system with combined settlement lagoon and drying bed

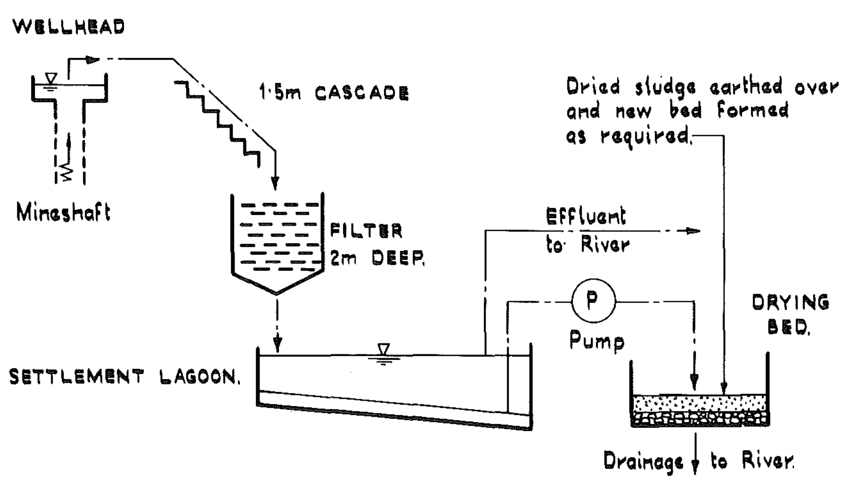

Fig. 6. Treatment system with separate settlement lagoon and drying bed

five compartments with a total of 25% excess capacity. One compartment, rotated over the five, is then always in use for drainage purposes, without affecting the operation of the system. Several layers of dried sludge, each about 10-mm thick, may be built up before the accumulated material is removed on an annual or biannual basis, to an adjacent area for earthing over. For the purpose of sludge drying and removal, it is desirable to have a smooth, hard-bottomed lagoon, with an entrance ramp at one end.

If separate drying beds are used, the settlement lagoon may be divided and one half may be drained at a time, and the sludge removed within one day; therefore, it is not considered necessary to provide any excess lagoon capacity. It is envisaged that sludge would be removed to the drying beds on a bimonthly or longer basis.

Prior to removal of sludge, the supernatant liquor may be discharged from the settlement lagoon to the river under gravity. The bed of the lagoon would be V-shaped in cross section to ensure that the sludge settles to a single point, from which it could be pumped out. Pumping sludge out of the lagoon rather than excavating it, means that a flexible lining membrane can, if necessary, be used.

The drying bed may be in the form of an unlined pond with a sloping bed and a granular drainage layer. Drained sludge may be built up in layers not exceeding 10 mm thick and earthing over would take place when the total thickness is in the region of 200–300 mm.

The use of a combined settlement lagoon and drying bed is attractive for its simplicity and lack of mechanical plant, but the estimated capital cost of the alternative system is lower. Operating costs are small in both cases.

Conclusions

The method of treatment involves aeration by a stepped cascade followed by a biological filter and then settlement of the insoluble iron for 18 h in shallow lagoons. The drainage of the sludge to a handleable consistency takes about 1 month, and could be carried out either in the lagoons or on separate drying beds. This treatment process will reduce the iron content of the 125 m^3/h discharge by approximately 75% from the original 28 mg/l and will produce an effluent which will not jeopardize the good quality fishery in the receiving River Ayr.

The capital cost for a full-scale plant incorporating separate drying beds is estimated at £170 000, with annual operation and maintenance costs of £1250. If the option of drying the sludge within the settlement lagoons is preferred, the capital costs will be greater because of the increased lagoon volume and the higher standard of construction required.

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