Performance and Cost Implications of a New Landfill Leachate Treatment System.

S. TATTERSALL[1]
I.D. WILLIAMS[2]

[1] SITA UK, SITA Kirklees, Diamond Street, Huddersfield, West Yorkshire, HD1 6BZ, UK.
[2] Centre for Waste Management, University of Central Lancashire, PRESTON, PR1 2HE, UK.

SUMMARY: During the winter of 2001/02, SITA (Lancashire) Limited built a leachate treatment plant at its Arden Quarry Landfill Site located in the Peak District of North Derbyshire. The plant required an investment of over £500,000 and became the first full-scale leachate treatment plant at any of the company's sites. Previously all leachate from the site was removed to a suitable Wastewater Treatment Plant (WTP) via large tanker vehicles. These tanker movements raised considerable objections from local residents and consequently, the local council. In addition, the increasing cost of the tankering operations threatened the financial viability of the landfill site, and as the local sewage works was not suitable for strong effluent, a primary treatment plant was built. This study evaluates the implementation and cost-effectiveness of the new WTP, as well as impacts on stakeholder relationships.

Field tests measuring pH, temperature, conductivity, COD and ammonia were carried out biweekly on all stages of the treatment process for a six month period during July-December 2002. These data were underpinned and enhanced by regular laboratory analyses of a wide range of other potential contaminants. In addition, first year operational costs were calculated and considered, and then compared to the cost if tankers had still been utilised.

The study's results suggest that the WTP is effective at treating the landfill site's leachate to the required standard on a consistent basis. Although requiring a substantial capital outlay, the plant is very cost-effective. In addition, the success of the plant has enabled stronger working relationships with key stakeholders, including the local council and residents, and brought good publicity to the company. Problems and potential drawbacks, such as high electricity consumption, are identified and discussed.

1. INTRODUCTION

Arden Quarry landfill site is situated in the High Peak area of North Derbyshire, near New Mills. The site has been operational for five years, receiving non-hazardous, municipal, commercial and industrial wastes at a rate of around 90,000 tonnes per annum. Planning permission has been granted to landfill the entire void of Arden Quarry (around 4 million cubic metres), which is expected to take at least another twenty years.

Historically, all leachate generated by the site (over 10,000,000 litres during 2001) was removed by large road tankers to a suitable Wastewater Treatment Plant (WwTP), normally Davyhulme in Manchester. This is because the Arden Quarry site is situated in a rural location and nearby WwTPs are too small and generally unsuitable for treating strong effluent. The costs associated with tankering large volumes of effluent were high (around £14 per tonne) and this expense jeopardised the future economic viability of the site. Moreover, a local pressure group, 'Save Sett Valley', whose aim is to minimise the impacts of the landfill on the local community, were expressing serious concern about the sheer number of large, articulated tanker vehicles visiting the site to remove leachate. Given that leachate volumes are directly proportional to rainfall catchment area and deposited waste mass, it is easy to see that, as additional cells are built, leachate volumes generated would continue to increase steadily over time. A further consideration was that leachate from many landfill sites will have to undergo preliminary (on-site) treatment prior to discharge via sewer to their WwTPs in order to comply with the European Union's Urban Waste Water Directive (91/271/EEC).

A number of leachate treatment techniques have been applied with varying degrees of success, in the UK, including:

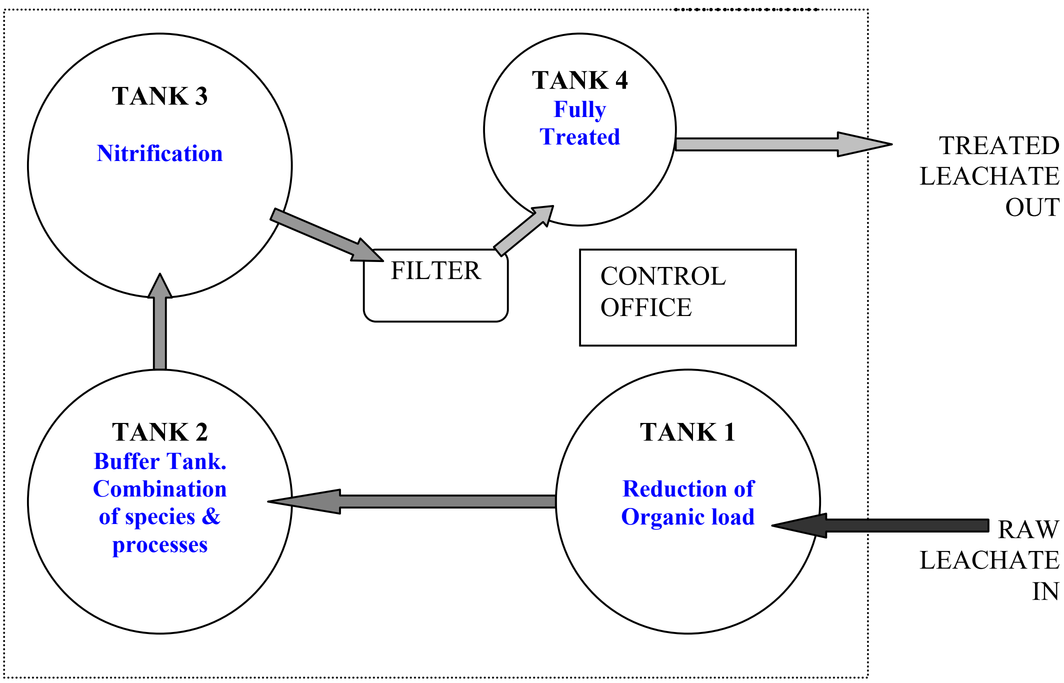
- Aerobic biological treatment (attached growth or non-attached growth);
- Anaerobic biological treatment;
- Spray irrigation to land;
- Reed bed treatment;
- Ammonia stripping;
- Reverse osmosis; and
- Ozonation.

In general, aerobic biological processes have been the most successful and reliable treatment of landfill leachate (Robinson, 1995). This type of treatment can readily reduce the high organic loading present in leachates during the early stages of waste decomposition. Nitrification of high concentrations of ammoniacal-nitrogen can be achieved by use of an extended aeration cycle during plant operation, and can be encouraged by use and conservation of heat *i.e.* energy-efficient design and utilisation of waste heat from the combustion of landfill gas (Robinson, Walsh and Carville, 2002). The most widespread experiences of successful aerobic leachate treatment have involved the use of non-attached growth processes in aerated lagoons or tanks. Aeration encourages the formation and growth of suspended biological flocs, which break down and metabolise the polluting components of the leachate. Retention periods of 10 to 50 days are capable of greater than 90 percent removal of chemical oxygen demand (COD) and ammoniacal nitrogen (Robinson, 2001).

Alternatives to aerobic biological processes have been used successfully but have failed to become established because of cost or inconsistent treatment standards. For example, although reverse osmosis systems are extremely consistent in their treatment of effluent, the huge capital expense and running cost of these systems tends to preclude their use.

After due consideration, the landfill operator decided to invest over £500,000 in an engineered leachate treatment plant (Figure 1), with the treated leachate being discharged to Whaley-Bridge WwTP, near New Mills, via a foul sewer pipe. This process is subject to a discharge consent that sets a minimum standard for effluent discharge from the leachate treatment plant. The results of a study to evaluate the operational and financial performance of this new treatment plant are reported in this paper.

Figure 1. Plan of Arden Quarry landfill leachate treatment plant, showing route of leachate.



2. ARDEN QUARRY LEACHATE TREATMENT SYSTEM

As shown in Figure 1, the treatment plant consists of three 600 m^3 capacity concrete tanks (Tanks 1, 2 and 3). These 3 tanks hold the leachate at different stages of degradation whilst it is oxygenated to allow biological treatment by aerobic bacteria. A fourth tank (Tank 4), is constructed of steel and holds 100 m^3 of fully treated leachate ready for discharge to sewer. Its main purpose is to allow control over the rate of discharge to sewer but it also provides samples of treated effluent for an automated sampling system. The relatively clean water in Tank 4 is used by the Advanced Filtration Media (AFM) filter to backflush (clean) its glass filtration media 4 times per day. The tanks are maintained at 20°C by circulating hot water provided by a water-filled heat exchanger suspended above the flame of a gas flare, which utilises gas extracted from the landfill site. To conserve heat, each tank is buried four-fifths into the ground.

The leachate is oxygenated by means of an 'extended diffused aeration system', which comprises of two industrial compressors supplying compressed air to a ring-main around each tank. From the ring-main, 40 diffusion pipes are immersed into the leachate of each tank, allowing oxygenation via fine bubble diffusion. This extended diffused aeration system depends upon the performance and concentration of the bacterial, protozoan and algal species already present in the leachate water; it is the activity of these organisms that actually treats the leachate and not the aeration system *per se*. No bacteria were brought to site during commissioning, rather the species already present in the leachate are provided with an optimal habitat for growth.

The system is as automated as possible, being operated by purpose-built software via a control panel. The dissolved oxygen (DO) content in each tank is monitored via two oxygen probes at different levels in the water column (upper and lower), and the system is dosed with 2 l of anti-foam and 2 l of phosphoric acid each day.

3. EXPERIMENTAL

3.1 Aims of the study

To evaluate the process, chemical and financial analyses were utilised. Chemical analyses of the leachate and treated effluent were obtained from both field tests and laboratory results. The financial impact of the treatment plant was considered with regard to benefit over the previous arrangement of removing leachate by road haulage. The main aims of the study were to:

- Evaluate the effectiveness of leachate treatment system (including the AFM filter) and assess compliance with the proposed discharge consent;
- Provide background monitoring data that could be used as a reference for future management of the plant;
- Assess the economic viability of the system; and
- Suggest how the system could be improved.

3.2 Methods

3.2.1 Field tests

Electrical conductivity, pH, ammonia, COD and water temperature for each treatment tank were measured regularly during the period July-December 2002, on average twice per week. Only ISO 14001 accredited methods were utilised for all field tests; details of the sampling protocols and analytical methods have been published previously (Tattersall, 2004). When available, five samples were obtained during each monitoring visit:

- Raw untreated leachate taken from the inlet pipe feeding the system.
- A sample from Tank 1; leachate in the initial stage of treatment.
- A sample from Tank 2; leachate in the intermediate stage of treatment.
- A sample from Tank 3; leachate in the final stage of treatment.
- A sample from Tank 4; discharge pipe, the treated leachate discharged to sewer.

3.2.2 Laboratory analyses

At least twice per month, samples were sent to an accredited laboratory for general wastewater analysis. The parameters monitored were pH, electrical conductivity, dissolved oxygen (DO), ammonia (NH_4-N), Cl^-, COD, biochemical oxygen demand (BOD), SO_4^{2-}, alkalinity (as $CaCO_3$), total oxidised nitrogen (TON), total organic carbon (TOC), Na, K, Ca, Mg, Fe Mn, Cd, Cr, Cu, Ni, Pb and Zn. The laboratory results allowed verification of the field test data as well as providing additional data. Further details are available in Tattersall (2004).

3.2.3 Cost analysis

In order to judge the effectiveness of the leachate treatment system against the broader financial context of the business, an evaluation was performed by adapting an established methodology (Robinson, Walsh and Carville, 2002). The costs of leachate disposal (£ m^{-3}) before and after commissioning of the treatment plant were estimated. The costs of leachate disposal by road were determined for one year by adding disposal fees to haulage and operational costs for the total leachate generated by the site during August 2002-July 2003. To enable a fair comparison, the annual costs of leachate treatment on-site were estimated over the same time period by adding capital repayments, for plant construction, to costs for electricity, leachate disposal, maintenance and repair, dosing chemicals and staffing.

4. RESULTS AND DISCUSSION

4.1 Comparison of field and laboratory analyses

Table 1 summarises the field and laboratory analyses of samples taken over the study period. The reduction in concentrations of these key chemical indicators as the leachate passes through the treatment plant is obvious. Although the field and laboratory samples were often taken on different days or at different times, the results show the same trends and are broadly comparable, except for the ammonia data, where we believe the field-testing kit over-estimated values at higher concentrations due to the turbidity of samples.

Table 1. Comparison of field test and laboratory results for Arden Quarry leachate.

	Field (12) Mean	**Field Standard deviation**	**Laboratory (10) Mean**	**Laboratory Standard deviation**
RAW LEACHATE				
pH	7.77	0.31	7.75	0.27
NH_4 (mg/l)	509	200	427	308
Conductivity (µS)	7122	1805	8923	4247
COD (mg/l)	2531	866	1323	746
TANK 1				
pH	7.83	0.56	8.1	0.39
NH_4 (mg/l)	328	164	123	117
Conductivity (µS)	5017	1263	5380	1396
COD (mg/l)	668	334	734	372
TANK 4 (effluent)				
pH	7.49	0.31	7.9	0.67
NH_4 (mg/l)	3.55	4.89	0.72	0.40
Conductivity (µS)	3150	1288	4862	851
COD (mg/l)	241	87	320	97

Number of samples taken shown in brackets ()

4.2 Raw leachate analyses

Table 2 shows a comparison between the laboratory analyses for Arden Quarry leachate collected during this study and data on landfill leachate collected by the Department of the Environment (1995). Although the Arden Quarry leachate has a relatively weak organic loading, it is broadly compatible with the municipal effluent displayed in column C. This is unsurprising because the site has never accepted hazardous wastes and approximately 50% of waste inputs to Arden Quarry are from municipal collection rounds. However, the evidence the Arden Quarry leachate is weaker than ‘average’ (municipal and methanogenic) has consequences when recommending the system for other sites.

Table 2. Comparison of data for Arden Quarry leachate with previously published data (DoE, 1995). (*The end columns express Arden Quarry mean values as a percentage of methanogenic mean and the municipal mean).

	A - Average Composition of Acetogenic Leachate			B - Average Composition of Methanogenic Leachate			C - Municipal	D - Arden Leachate			B - D Comparison	C - D Compar-ison
Parameter	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Mean**	**Min**	**Max**	**Mean**	**%**	**%**
pH	5.12	7.8	6.73	6.8	8.2	7.52	7.22	6.6	8.5	7.7	102	107
COD	2740	152000	36817	622	8000	2307	3275	40	4560	1982	86	61
BOD (5day)	2000	68000	36817	622	8000	2307	689	102	290	440	19	64
Ammoniacal-N	194	3610	922	283	2040	889	438	60	853	468	53	107
Chloride	659	4670	1805	570	4710	2074	1039	192	2140	1210	58	116
BOD (20day)	2000	125000	25108	110	1900	544		-	-	-		
Total organic carbon	1010	29000	12217	184	2270	733	733	74	459	318	43	43
Fatty acids (as C)	963	22414	8197	<5	146	18		-	-	-		
Alkalinity (as $CaCO_3$)	2720	15870	7251	3000	9130	5376		1190	4880	3728	69	
Conductivity (µs/cm)	5800	52000	16921	5990	19300	11502	6686	2130	14600	7940	69	119
Nitrate-N	<0.2	18.0	1.8	0.2	2.1	0.86		-	-	-		
Nitrite-N	0.01	1.4	0.20	<0.01	1.3	0.17		-	-	-		
Sulphate (as SO_4^{2-})	<5	1560	676	<5	322	67	144	5	32	17	25	12
Phosphate (as P)	0.6	22.6	5.0	0.3	18.4	4.3	-	-	-	-		
Sodium	474	2400	1371	474	3650	1480	725	226	1500	1015	69	140
Magnesium	25	820	384	40	1580	250	139	46	250	157	63	113
Potassium	350	3100	1143	100	1580	854	444	94	610	418	49	94
Calcium	270	6240	2241	23	501	151	293	130	270	193	128	66
Chromium	0.03	0.3	0.13	<0.03	0.56	0.09	0.07	0.07	0.012	0.1	111	143
Manganese	1.4	164.0	32.94	0.04	3.59	0.46	2.6	0.1	2.55	0.98	213	38
Iron	48.3	2300	653.8	1.6	160	27.4	71	0.8	13.24	6.56	24	9
Nickel	<0.03	1.87	0.42	<0.03	0.6	0.17	0.09	0.036	0.12	0.09	53	100
Copper	0.020	1.10	0.130	<0.02	0.62	0.17	0.03	0.014	0.1	0.06	35	200
Zinc	0.09	140.0	17.37	0.03	6.7	1.14	0.39	0.1	0.2	0.17	15	44
Cadmium	<0.01	0.10	0.02	<0.01	0.08	0.015	<0.01	0.001	0.1	0.05	333	
Lead	<0.04	0.65	0.28	<0.04	1.9	0.20	0.10	0.01	0.1	0.06	30	60
Arsenic	<0.001	0.148	0.024	<0.001	0.485	0.034	0.0065	-	-	-		
Mercury	<0.0001	0.0015	0.0004	<0.0001	0.0008	0.0002	<0.0001	-	-	-		

N.B. Units mg/l except for pH and conductivity.

4.3. Typical treatment results

The data in Table 3 shows that all the parameters determined decreased in value as the leachate progressed through the treatment system (except for sulphate and TON, which increased, as expected). The study raised a few key points to note:

- The nitrifying bacteria fully established themselves in Tank 3 in September 2002 and continued to reduce ammonia values of the final effluent even as the study came to a close.
- The recycling of the bacteria captured from the AFM filter into Tank 2 provided the biological seed for the ammonia reduction. If the leachate in Tank 2 still had a high organic loading (>1000mg l^{-1} COD), the aggressive heterotrophic bacteria from Tank 1 would have dominated Tank 2, out-competing the nitrifers, and ammonia reduction would have been significantly reduced.
- The conductivity of the raw leachate was extremely variable (in the range 2000-15,000 µs cm^{-1}). This was probably largely due to rainfall dilution, although there is a natural variability in leachate concentrations, depending on the age and type of the waste in the landfill.

Table 3. Typical treatment results for Arden Quarry Treatment Plant (July-December 2002).

Parameter	Units	Raw leachate	Tank 1	Tank 2	Tank 3	Tank 4
pH		7.8	7.9	7.5	7.5	7.6
Conductivity	uS/cm	7940	5054	3635	3116	3351
NH_4-N	mg/l	468	302	24	4	3
COD	mg/l	1982	675	369	239	254
Temperature	^{0}C		11	10	10	14
BOD	mg/l	290	93			6
Alkalinity	mg/l	3728	1193			240
Fe	mg/l	6.56	1.47			0.30
Mn	mg/l	0.98	1.12			0.18
Cd	mg/l	0.051	0.001			0.001
Cr	mg/l	0.067	0.017			0.015
Cu	mg/l	0.06	0.01			0.04
Pb	mg/l	0.06	0.01			0.02
Ni	mg/l	0.089	0.057			0.057
Zn	mg/l	0.17	0.10			0.08
Ca	mg/l	193	156			136
Mg	mg/l	157	91			101
Na	mg/l	1015	503			541
K	mg/l	418	196			209
Sulphate	mg/l	17	117			148
Nitrogen (TON)	mg/l	1	55			203
TOC	mg/l	318	123			87
Dissolved oxygen	mg/l	0.9	3.8			6.9
Chloride	mg/l	1210	810			701
Suspended solids	mg/l					49

Notes: Blank cell means no results available. Raw = Raw leachate. Tank 4 = Fully treated/discharged effluent.

4.4 Individual contaminants and the discharge consent

The full ‘discharge consent’ was still not finalized at the time of writing, although some interim limits had been set. Estimated consent limits are shown in Table 4, together with mean values for final effluent arising from the treatment plant. It is encouraging to note that all parameters are generally well within the estimated discharge consent limits.

The study raised several key points to note:

- The Arden Quarry system utilises nitrifying bacteria and oxidation to convert NH_4 to NO_3. Nitrifying bacteria are sensitive to other organisms, poisoning and temperature, and they take months to build up and acclimatise to a new environment. The results showed ammonia effluent levels to be borderline in the early weeks until the bacteria acclimatised to give consistent discharges of below 4 mg l^{-1}, well below the estimated discharge limits.
- Methane must not be discharged to a sewer because of the risk of explosion. The maximum permissible safe concentration of dissolved methane in wastewater is 1.4 mg l^{-1}, as most authorities require a factor of safety of 10 when setting the maximum permissible limit of 0.14 mg l^{-1} (CIWEM, 1998). The turbulent action of air passing through the tanks of the Arden Quarry system ensures that volatile gases are driven off entirely.
- The treatment process significantly reduces metal concentrations. Precipitation of metals into the basal sludge, particularly in Tank 1, accounts for the main reduction. The estimated discharge consent is fairly generous regarding metals given that any fugitive emissions will be subject to a similar process at the receiving WwTP. It is possible that the surprisingly low concentrations of metals in the effluent may lead (after further testing) to the effluent being down graded from a “prescribed substances discharge” to a “routine category” effluent.

Table 4. Effluent analyses in context of the proposed discharge consent.

Parameter	Units	Number of samples	Mean	Maximum	Estimated consent limit
pH	mg/l	53	7.55	8.6	6-10
NH_4-N	mg/l	51	3.2	20	20*
COD	mg/l	50	254	518	1500**
Volume	m^3				200
BOD	mg/l	3	6.0	13	250
Temperature	^0C	42	13.9	20	43
Cd	mg/l	3	0.00133	0.002	0.020
Cr	mg/l	3	0.015	0.016	
Cu	mg/l	3	0.042	0.1	TOTAL TOXIC
Pb	mg/l	3	0.018	0.04	METALS*
Ni	mg/l	3	0.17	0.059	10 mg/l
Zn	mg/l	3	0.075	0.09	
Sulphate	mg/l	2	146	158	1000
Suspended solids	mg/l	2	48.5	90	200

* Total toxic metals (not including mercury and cadmium, which have individual limits). No analyses available for arsenic, antimony, beryllium, selenium, silver, tin or vanadium. No data for mercury.

4.5 Cost analysis

Using the approach outlined in Section 3.2.3, the following results were obtained:

- The cost for leachate disposal for the period August 02 – July 03, had the treatment plant not been built, was estimated as **£13.39 m^{-3}**.
- Cost of leachate treatment for period August 2002 – July 2003 was estimated as **£4.21 m^{-3}**.

The company therefore made a 68% yearly saving on leachate disposal utilising the treatment plant as opposed to the continued use of road tankers. A key accounting ratio that examines capital investment and return is the ROCE (return on capital employed ratio). For the study period, the ROCE was estimated as **27.3%**; an excellent performance. Based upon these data, the payback time for the capital investment was estimated as **3 years, 8 months.**

It must be borne in mind that as the site develops, leachate volumes will increase and the site is expected to be open for waste for another 20 years or so, depending upon future inputs. The treatment plant has been designed to treat up to 200 m^3 of leachate each day giving a current annual capacity of 73,000 m^3. If, hypothetically, the site treated 73,000 m^3 of leachate during the next year, the operational costs would not increase significantly above Year One costs. Capital repayments would remain broadly the same and electricity costs would increase only marginally. Disposal costs would rise *pro-rata* and there would be a similar increase in maintenance, repair and staffing costs. Thus, it is anticipated that with the site running at capacity, annual running costs would not rise significantly. By comparison, the cost of haulage is estimated to increase enormously.

4.6 Summary of non-monetary issues

The investment in the treatment plant has been successful in other, non-chemical or financial ways. The new system has pleased both the local pressure group and Derbyshire County Council. A strong relationship has been built with the WwTP operator, who is impressed with the plant and keen to lend every support for future projects.

The new treatment plant has significantly reduced the impact of the landfill site and its operations on the local environmental. Tankering leachate contributed to traffic pollution and congestion, particularly in the rural area around the site. The discharge of untreated leachate onto a local WwTP would eventually have led to an overloading of the system; this was therefore prevented. In addition, the freeing-up of capacity at Davyhulme WwTP now allows that site to accept other industrial effluents. The sewerage infrastructure, from landfill site to WwTP, is all buried below ground and is therefore not visually intrusive, nor should it interfere with any local ecosystems.

There have also been operational advantages to the site. These include better control over leachate heads on site. The site is limited to 1 m maximum depth of leachate within the site; in very wet weather it was difficult to guarantee a sufficient number of tankers to remove the leachate before the limit was breached. Each load of leachate necessitated the use of a member of staff until the tanker had left site, causing problems when the site was short staffed, staff were on lunch breaks or busy on other tasks. Although the treatment plant also demands attention, routine checks can be scheduled into quiet periods, as it is not necessary to inspect at specific times.

CONCLUSIONS AND RECOMMENDATIONS

Overall this research has been successful in evaluating the new leachate treatment plant at Arden Quarry landfill site. The key findings of the study are outlined below.

- The plant is effective at treating the site's leachate to the required standard on a consistent basis.
- Although requiring a substantial capital outlay, the plant is very cost-effective. These savings will increase with time.
- The plant could have application elsewhere. It could be used as a template for similar landfill sites, although caution should be exercised because of site-specific conditions and circumstances. For example, the leachate at Arden Quarry is weaker than average and plant did not require a de-nitrification stage because of its favourable position at the head of a long sewerage network.
- The involvement of local stakeholders and associates during the planning stages has been beneficial to all parties. The success of this approach has helped the landfill company form stronger relationships with the WwTP operator, the Environment Agency and Council officials, as well as local pressure groups and the public.
- The AFM pressure filter has proved effective in its operations, although further studies are required to fully establish its efficacy.
- The plant is a heavy consumer of electricity. Although the Arden Quarry plant will soon be powered by renewable (landfill gas derived) energy, further means of reducing power consumption are necessary.

Other recommendations for further work arising from this study are outlined below.

- Continuous, real time monitoring of the discharged effluent is desirable, and appropriate equipment should be identified and installed.
- Further research is necessary into the power demands of system. The compressors used for aeration are the main power consumer - they are simply either on or off. However, the system may be under maximum load *i.e.* treating 200 m^3/day of strong leachate or under negligible load of say 10 m^3/day during drought conditions. The working population of bacteria is often given more oxygen (power) than it needs for optimum performance and this is clearly a waste. Ideally, the aeration system should be linked to the DO sensors and should maintain each tank automatically at an appropriate DO concentration. The current system is analogous to a domestic central heating system that operates without thermostatic control; the heat generated is far above the requirements of the occupants and is therefore effectively a waste.
- A pending change in legislation via the Landfill Directive means that prior to 2010 there must be a significant reduction in the amount of biodegradable wastes going into landfill sites. Many waste streams must also be pre-treated prior to final disposal at a landfill site. These changes could have a significant impact on the types and volumes of leachate generated and there is a clear need for research, although any study would require significant resources, not least a self–contained landfill cell from which to collect the leachate. Major changes to the chemistry of landfill leachate would impact on local water authorities as well as landfill operators.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of SITA, Mr Martin Craven, Dr. Howard Dryden (the designer of the treatment plant), and Mr. Geoff Ellison.

REFERENCES

Chartered Institution of Water & Environmental Management (CIWEM) (1998). *Wastewater Treatment*. CIWEM, 15 John St, London, WC1N 2EB.

Department of the Environment (DoE), (1995). A review of the composition of leachates from domestic wastes in landfill sites. *Department of Environment Research Report No. CWM 072/95*. HMSO, London.

Robinson, H.; Walsh, T. and Carville, M., (2002). Advanced leachate treatment at Buckden Landfill, Huntingdon, UK. *Institute of Waste Management (IWM) Annual Conference Proceedings*, Torbay, June 2002. IWM, Northampton.

Robinson, H., (2001). Massive investment in high-tech treatment provides the solution to leachate problem. *Local Authority Water & Environment*, October 2001.

Robinson, H., (1995). The UK: leading the way in leachate treatment. *Institute of Waste Management (IWM) Annual Conference Proceedings*, Torbay, June 1995. IWM, Northampton.

Tattersall, S., (2004). Evaluating the performance and cost implications of the leachate treatment system at Arden Quarry Landfill Site. *MSc Thesis*, May 2004. Available from: Centre for Waste Management, University of Central Lancashire, Preston, PR1 2HE.