GG156
GUIDE

ENVIRONMENTAL
TECHNOLOGY
BEST PRACTICE
PROGRAMME

COST-EFFECTIVE EFFLUENT TREATMENT IN PAPER AND BOARD MILLS

GOOD PRACTICE: Proven technology and techniques for profitable environmental improvement

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COST-EFFECTIVE EFFLUENT TREATMENT IN PAPER AND BOARD MILLS

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SUMMARY

Effluent treatment is of increasing importance for UK paper and board mills as they strive to:

- meet increasingly stringent discharge consent conditions;
- reduce operating costs.

This Good Practice Guide is intended to help mills optimise the performance of their effluent treatment plant by evaluating their existing processes and then implementing measures recognised as good practice within the industry. The Guide describes the main control parameters for each process and explains how to address common effluent treatment issues.

Before reviewing the operation of their effluent treatment plant, mills are urged to take action to minimise the amount and strength of the effluent produced by the mill. Producing less effluent in the first place will reduce the demands made on the effluent treatment plant and thus save both money and effort. Effective balancing to even out the flow and load on the effluent treatment plant is also important for cost-effective operation.

The Guide covers:

- primary treatment to remove fibre and other suspended solids from the process;
- secondary biological treatment (aerobic or anaerobic) to remove soluble organic pollutants;
- tertiary treatment, ie effluent polishing, to produce water of a quality suitable for recycling to mill processes and/or remove residual pollutants;
- sludge dewatering to reduce sludge treatment and disposal costs.

To minimise operating costs while retaining acceptable performance, it is essential to understand the different processes and to monitor key control parameters. The Guide pays particular attention to the activated sludge process, with an overview of the microbiology of this process and suggestions on how to optimise the process in terms of the food:mass ratio, sludge age and dissolved oxygen content. Ways of preventing and tackling common operational problems, eg bulking activated sludge and foaming, are described. Five Industry Examples illustrate the improvements that can be made by implementing the measures described in this Guide.

Optimising the operation of the effluent treatment plant will reduce the mill's operating costs and make it easier for the mill to comply with its discharge consent conditions. Mills discharging to sewer will also reduce their trade effluent charges.

CONTENTS

Continued overleaf

CONTENTS *(continued)*

1 INTRODUCTION

Paper mill effluent has a complex chemical character - a reflection of the wide range of possible chemicals used in the papermaking process and the variety of feedstocks (pulps and/or waste paper). Although the effluent composition varies from mill to mill, it typically contains:[1]

- 10 - 100 kg/total suspended solids (TSS)/tonne of production;
- 5 - 40 kg chemical oxygen demand (COD)/tonne of production;
- 2 - 30 kg biochemical oxygen demand (BOD)/tonne of production.

In common with other industries, effluent treatment in the paper and board industry is attracting increasing scrutiny from a number of sources. Consent conditions for discharge to controlled waters are becoming ever more stringent, with the risk of legal proceedings for continued consent failure. Where effluent is disposed of to sewer, trade effluent charges are becoming a significant proportion of a mill's running costs. The following example from a fictitious company, The Paper Company Limited, illustrates the significant cost savings that can be achieved through cost-effective effluent treatment.

Reduction in effluent plant's running costs increases profits

The Paper Company Limited, which produces newsprint, spends £1 million/year on its effluent treatment plant.

By optimising the operation of its effluent treatment plant, the Company reduced the plant's running costs by 5% - a saving of £50 000/year. This saving goes directly to the Company's bottom line as profit.

The Company currently achieves a profit of £25/tonne of newsprint sold. To increase profits by the same amount as the savings on the effluent treatment plant, The Paper Company Limited would have to sell another 2 000 tonnes/year of newsprint.

This Good Practice Guide aims to help the UK paper and board industry reduce operating costs and its impact on the environment through the effective management of on-site effluent treatment plant.

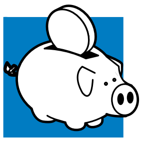
Optimising the performance of the effluent treatment plant will:

- minimise operating costs and thus increase profits;
- help to ensure compliance with all relevant legislation and consents.

[1] *Pollution Control for Paper and Pulp Processes*, Her Majesty's Inspectorate of Pollution. 1993.

1.1 THE PURPOSE OF THIS GUIDE

The Guide's primary purpose is to help those paper mills operating on-site effluent treatment plants optimise their performance by following established and sound operational techniques. Advice is given on how to reduce operating costs by optimising processes, minimising chemical use and reducing sludge production through operational changes. Measures to reduce effluent strength and/or volume - with consequent savings in trade effluent charges where applicable - are also described. Industry Examples are used to illustrate the benefits of cost-effective effluent treatment.



Significant cost savings can be achieved by avoiding the problems associated with poor operation. Photocopy and use the checklists in this Guide to help you achieve cost-effective operation of your effluent treatment plant.

This Guide is intended to be a troubleshooting manual for existing and fully operational plants. It addresses common problems encountered during effluent plant operation rather than discussing process selection. For advice on how to select the most appropriate process or effluent treatment plant, see Good Practice Guide (GG109) *Choosing Cost-effective Pollution Control*. This Guide is available free of charge through the Environment and Energy Helpline on 0800 585794. If necessary, please contact the Helpline for further advice.

The disposal of aqueous effluent should be considered as part of the mill's overall waste management strategy. For example, some techniques may reduce the strength of the effluent discharged, but in doing so generate significant amounts of solid waste. When considering its effluent treatment options, a mill should therefore take an overall view.

1.2 EFFLUENT TREATMENT OVERVIEW

Sections 2 - 4 describe the three stages of the effluent treatment process in paper mills, ie:

- **Primary treatment** (Section 2). This is the removal of insoluble material, ie suspended solids, from the effluent prior to any downstream process. Primary treatment includes fibre removal (with or without subsequent recovery) and the removal of inorganic fines and any plastics or other inert materials commonly found when waste paper is used as a source of fibre.
- **Secondary biological treatment** (Section 3). This achieves a reduction in the biological loading of the final effluent discharged into the receiving water or sewer. This stage is particularly important for optimising the plant's operation and thus achieving cost savings.
- **Tertiary treatment** (Section 4). This describes the final polishing treatment of an effluent. It is generally performed if required as a precursor to water re-use and/or to remove residual suspended solids, ammonia, colour or Schedule 5 substances (see Section 4.2.4) from the final effluent.

Fig 1 summarises the main features of primary, secondary biological and tertiary treatment of paper mill effluent. Some or all of these techniques may be applicable to a particular mill.

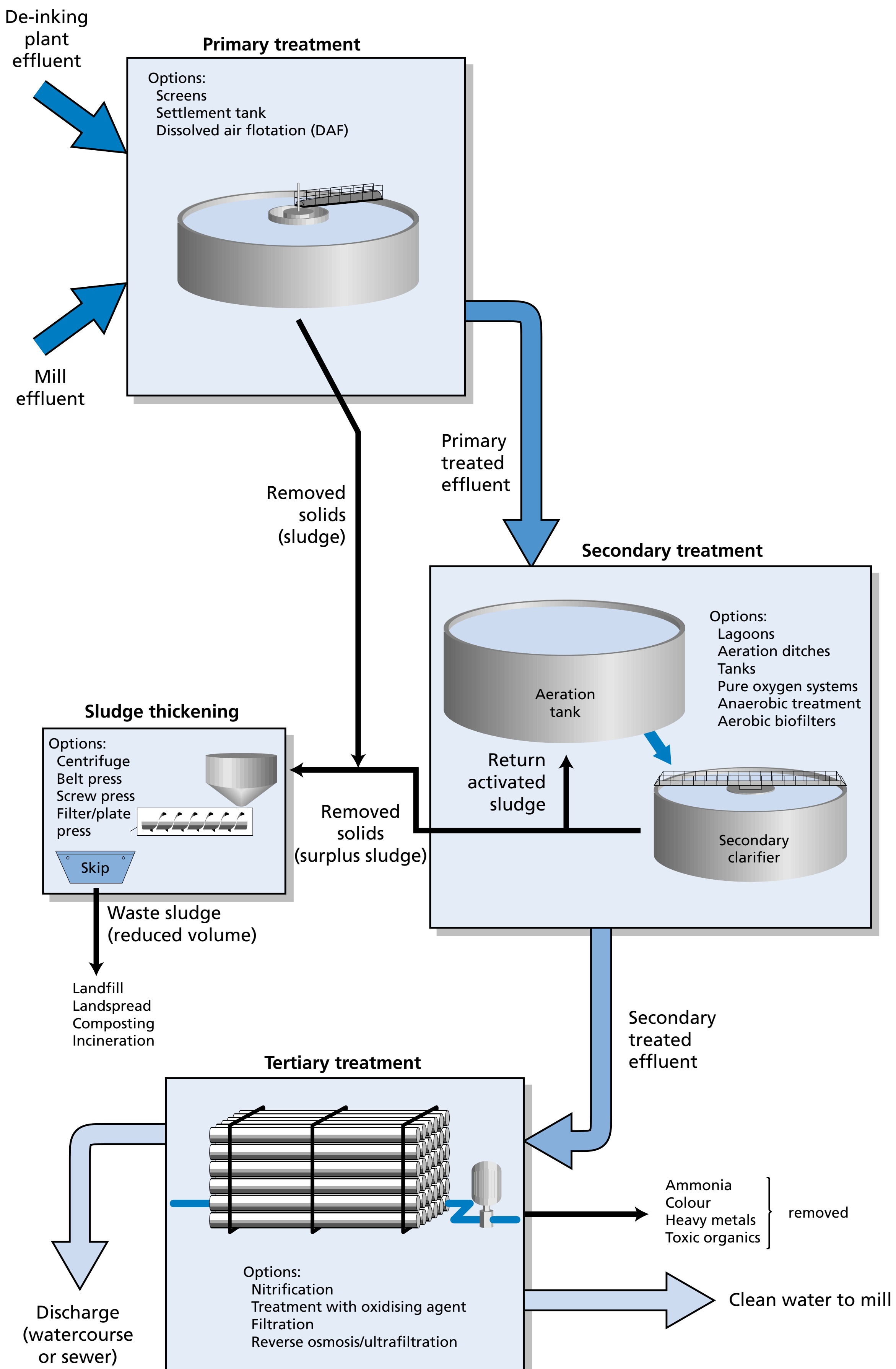


Fig 1 Effluent treatment overview

Although a mill may employ only one of the above processes, they are all areas where significant savings can be made by simple changes and improvements to working practices. It is therefore just as important for the fibre recovery screens to be working under optimum operating conditions as it is for a pure oxygen activated sludge plant.

Industry Examples in Section 6 describe how five UK paper mills achieved cost savings and other benefits by optimising the operation of their effluent treatment plants.

1.3 COST SAVINGS FROM MINIMISING EFFLUENT GENERATION

Considering the effluent treatment plant as an integral part of the mill's operations and not just as a 'bolt on' unit will help maximise savings. This approach also offers greater opportunities for fibre and water re-use within the mill.

The effluent treatment plant will cost less to run and build if the mill produces less effluent in the first place. Significant cost savings can be achieved by reducing both the amount and strength of the raw effluent entering the plant.

The first step in optimising the performance of the effluent treatment plant is to reduce the mill's water consumption. Good Practice Guide (GG111) *Practical Water Management in Paper and Board Mills* demonstrates how companies can save money by improving water management practices and reducing water consumption during the papermaking process. This Guide, which is available free of charge through the Environment and Energy Helpline on 0800 585794, describes how to:

- assess current performance;
- improve water management and system design;
- achieve savings by implementing no-cost and low-cost measures;
- make improvements through process modifications and process redesign;
- work towards achieving the concept of zero liquid effluent.

In addition to reducing the costs associated with on-site effluent treatment and off-site sludge disposal, reducing the demand for fresh water can reduce costs significantly by:

- reducing water supply costs;
- reducing the capital and/or operating costs associated with:
  - water treatment;
  - pump operation and maintenance;
  - the installation of pipework, vessels, etc.

Further information about water supplies, effluent discharges and costs in paper mills is given in Environmental Performance Guide (EG69) *Water Use in UK Paper and Board Manufacture*. Good Practice Guide (GG26) *Saving Money Through Waste Minimisation: Reducing Water Use* describes, in more general terms, the costs associated with water use and wastewater disposal and outlines a cost-effective procedure for reducing these costs. These Guides are also available free of charge through the Environment and Energy Helpline on 0800 585794.

1.4 LEGISLATIVE CONTROLS ON EFFLUENT DISCHARGE

Table 1 summarises the main environmental legislation relating to the discharge of effluent from companies in England, Wales and Scotland.[2] Mills should also be aware of the regulations and statutory guidance, eg Integrated Pollution Control Guidance Notes, applicable to their processes and operations.

section 1

Responsible body	Legislation	Pollution
Environment Agency/ Scottish Environment Protection Agency (SEPA)	Environmental Protection Act 1990, Part I: Part A processes* for Integrated Pollution Control	Discharges to controlled waters and sewers
	Water Resources Act 1991	Discharges to controlled waters
	Water Industry Act 1991	Discharges to sewers of special category effluents
Water companies/authorities	Water Industry Act 1991	Discharges to sewers

* As defined by the Environmental Protection (Prescribed Processes and Substances) Regulations 1991 and subsequent amendments.

Table 1 Key environmental legislation affecting effluent discharges from the paper industry in England, Wales and Scotland

The Integrated Pollution Control (IPC) regime was set up under the Environmental Protection Act 1990 and requires the use of the best available techniques not entailing excessive cost (BATNEEC) to prevent the release of prescribed substances, or where this is not practicable, to minimise and render harmless any other substances that might cause harm if released into any environmental medium.

In terms of effluent discharge, one effect of IPC has been to extend the consented parameters controlled under each mill's IPC authorisation or Exemption Monitoring Programme. Schedule 5 substances are those inorganic and organic compounds listed in Schedule 5 of the Environmental Protection (Prescribed Processes and Substances) Regulations 1991, and subsequent amendments, as prescribed substances for release into water. They are known to be particularly harmful to aquatic organisms, eg mercury, cadmium and pentachlorophenol. The Regulations add them to traditional consent parameters such as pH, temperature, flow rate, BOD/COD and total suspended solids (TSS).

The presence of Schedule 5 substances in paper mill effluent is generally due to trace contaminants in certain raw materials, eg wood and caustic, rather than direct additions to the process. De-inking plants are another potential source of prescribed substances owing to the composition of modern synthetic dyes and inks. Chief Inspector's Guidance Note IPR6/9 *Paper Making and Related Processes, Including Mechanical Pulping, Re-cycled Fibres and De-inking*[3] considers the potential release routes for prescribed substances from various sources in the paper mill. IPR6/9 also gives the achievable release levels for the releases of prescribed substances from paper mills to water when the best available techniques (BAT) are used. It also advises on BATNEEC. Mills now typically analyse for the presence of mercury, cadmium, hexachlorocyclohexane, organo-tin and various chlorinated organics.

[2] For information about environmental legislation applicable in Northern Ireland contact the Environment and Energy Helpline on 0800 585794.

[3] Available from The Stationery Office (PO Box 276, London SW8 5DT. Tel: 0171 873 9090. Fax: 0171 873 8200), Stationery Office bookshops, accredited agents and some larger booksellers.

IPC has a significant impact on the operation of the whole mill, including the effluent treatment plant. Technical managers should therefore be aware of their existing and future responsibilities.

For advice and information about current environmental legislation governing the paper and board industry, contact the Environment and Energy Helpline on 0800 585794.

1.4.1 IPPC Directive

The provisions of the Integrated Pollution Prevention and Control (IPPC) Directive are similar to those of IPC, but with the following significant additions:

- applies to all paper and board mills with a capacity of over 20 tonnes/day;
- covers installations rather than processes;
- includes waste disposal;
- includes energy efficiency as well as minimising process waste;
- includes energy efficiency in the use of raw materials and water.

The phased implementation of IPPC means that new, or substantially altered, installations require authorisation by October 1999. All existing installations subject to IPPC will be brought under IPPC by 2007. Because of the phasing timetable, some sectors will be brought under IPPC earlier than others. It is expected that the paper and board sector will be relatively early in this schedule, but the precise timing has yet to be defined.

1.4.2 Direct Toxicity Assessment

Direct Toxicity Assessment (DTA) is a monitoring tool which attempts to determine the actual effect of an effluent on the receiving water rather than relying on an arbitrary measurement of potential pollution such as BOD or COD. DTA is likely to have a significant impact on the management of the effluent treatment process.

The paper industry has limited experience of DTA. Paper mills ceased to be part of the Environment Agency/SEPA DTA demonstration programme at an early stage. This was because paper mill effluents were much less toxic than those of other industries taking part in the programme.

Early Environment Agency research suggests that primary treatment may remove some toxicity and that secondary treatment may be even more effective. Further research is needed to confirm these preliminary findings.

There is also some debate over the most appropriate measurement. Possible techniques range from measuring the effect of toxic materials on photo-luminescent bacteria (eg the Microtox test) to measuring the effect on Daphnia or higher vertebrates.

1.5 DISCHARGE TO CONTROLLED WATERS OR TRADE EFFLUENT?

Many mills discharge treated effluent to a controlled water - typically a river, tidal estuary or sea outfall - under the conditions of a consent granted by the Environment Agency, the Scottish Environment Protection Agency (SEPA) or the Environment and Heritage Service in Northern Ireland. The regulatory authority is responsible for maintaining the quality of the receiving waters and this consideration is reflected in the consent conditions imposed on the mill.

However, increasingly stringent consent conditions mean that the cost of achieving these limits is continually increasing - especially in terms of capital investment. A number of mills are therefore examining the possibility of discharging their effluent - perhaps after primary treatment - to sewer and paying ongoing trade effluent charges rather than investing in new effluent treatment plant.

When evaluating this option, mills should first consider the following questions.

- Is it possible to connect the mill to the local sewerage network? This will depend on the geography of an individual mill and should be discussed with the local water company.
- Does the local sewage treatment works have the capacity to accommodate the increased flows and loads from the mill?
- Can the local sewage treatment works provide adequate treatment?
- What are the potential costs associated with trade effluent discharge? Water companies calculate trade effluent charges on the basis of a standard formula known as the Mogden Formula. This formula links water company charges to the volume and strength of effluent discharged by a company to sewer. The degree of treatment provided by the water company receiving the effluent is also allowed for in the formula, which includes an element for reception and conveyance. The Mogden Formula and UK trade effluent charges are explained in more detail in Appendix 1 of Environmental Performance Guide (EG69) *Water Use in UK Paper and Board Manufacture.*[4] Mills should contact their local sewage undertaker for details of charges in their area.

Discharge to sewer does not relieve the mill of the obligation to demonstrate that this discharge method constitutes BATNEEC (or BAT in the case of IPPC) for that particular process. Chief Inspector's Guidance Note IPR6/9 *Paper Making and Related Processes, Including Mechanical Pulping, Re-cycled Fibres and De-inking*[5] provides a list of the factors to be considered when assessing the option of discharge to sewer.

> Pre-treatment to remove a major proportion of the COD and suspended solids prior to discharge to sewer can be extremely cost-effective. A significant reduction in the overall charges can be achieved for a relatively low cost.

[4] Available free of charge through the Environment and Energy Helpline on 0800 585794.

[5] Available from The Stationery Office (PO Box 276, London SW8 5DT. Tel: 0171 873 9090. Fax: 0171 873 8200), Stationery Office bookshops, accredited agents and some larger booksellers.

2 PRIMARY TREATMENT

For the purpose of this Guide, primary treatment is defined as the removal of insoluble material, ie suspended solids, from process effluent prior to its biological treatment and/or final discharge. Optimising primary treatment will help mills to either comply cost-effectively with their discharge consent or reduce their trade effluent charges.

Fibre recovery can be carried out at various points throughout the mill. It is therefore often difficult to state where the papermaking process ends and where effluent treatment begins. This boundary tends to be artificial as fibre recovery processes are essentially the same, wherever they occur. For the purpose of this Guide, fibre recovery is considered as part of the primary treatment process.

2.1 THE BENEFITS OF PRIMARY TREATMENT

Effective primary treatment produces cost savings for a number of reasons. These include:

- Waste fibre recovery.
- A reduction in the organic load (BOD/COD) entering the downstream biological treatment plant, thus improving plant performance and reducing running costs.
- Improved performance of activated sludge processes (see Section 3.5). Inert and/or inorganic solids, eg filler, occupy space in the reactor that could be utilised by biomass. Energy is required to pump this material round and operate the mixers needed to keep it in suspension.
- Less likelihood of solids, eg pieces of plastic and metal, blocking or damaging pumps and other equipment. Removing such contaminants protects plant and reduces maintenance costs.
- For those mills discharging to sewer, lower trade effluent charges.
- For those mills discharging direct to controlled waters, easier compliance with discharge consents.

The checklist in Section 2.5 is intended to be photocopied and used by mill staff to help them achieve cost savings during primary treatment. The cost savings achieved by fibre recovery and reducing the load on the secondary treatment plant are equally important.

2.2 THE IMPORTANCE OF EFFECTIVE BALANCING

The amount and properties of process effluent depend on operations in the mill and are likely to vary significantly. To achieve efficient operation of the effluent treatment plant, it is essential to remove these variations using a buffer or balancing tank. A balancing tank provides sufficient storage space to allow a non-uniform flow of effluent to be collected, mixed and pumped at a uniform rate to the effluent treatment plant. As well as increasing the efficiency of the primary treatment plant, the balancing tank protects the downstream biological treatment plant.

Although only a simple tank, the balancing tank performs the following functions:

- **Minimises flow variations.** The balancing tank provides a buffer against uneven flow of untreated effluent from the mill, thus providing a constant flow to the treatment plant.
- **Minimises variations in organic load.** Like the flow, the concentration of effluent leaving the mill can also vary. The volume of effluent held in the balancing tank allows peaks and troughs to be smoothed out, thus providing a constant organic load for treatment.
- **Provides pH control.** The balancing tank provides an opportunity to adjust the acidity or alkalinity of the effluent leaving the mill.
- **Reduces toxicity.** Should the mill release large amounts of chemicals that are toxic to the biological treatment system, their impact is reduced by dilution in the balancing tank.
- **Provides a continuous feed.** From time to time, the flow of effluent from the mill may fall dramatically - or even cease, eg during a shutdown period. The balancing tank can then be used to provide a reservoir of effluent to keep the biological system 'ticking over'.

2.3 BALANCING TANK OPERATION

A well-designed balance tank normally has some form of agitation to ensure good mixing and to keep solid material from settling out. Slight aeration of the balance tank can also be beneficial, as it prevents the untreated effluent from turning septic.

2.3.1 Normal conditions

The balancing tank receives effluent from the mill at varying rates according to mill operations. Effluent is pumped from the balancing tank at a fixed rate.

Routine or on-line testing of the organic load should be carried out. It is usually easier to measure COD rather than BOD. If the concentration of effluent leaving the tank falls, the operator may choose to gradually increase the flow to compensate. Conversely, if the concentration rises, the flow can be decreased.

The capacity of the balancing tank should allow it to be maintained at about half-full. This prevents overflows following a surge in flow and protects the treatment plant from large variations in the effluent load. Occasional requirements for increased dilution can also be met.

Under ideal conditions, 12 - 24 hours' flow should be made available. However, any form of balancing is better than none at all.

2.3.2 Abnormal conditions

Prior to a period of low flow

If the mill expects a period of low effluent flow, untreated effluent can be stockpiled to provide material to keep the plant running. By decreasing the flow from the tank and allowing the level in the balancing tank to rise, the plant can be prepared to run at a reduced level for several days.

When a toxic spillage has occurred

The standard dilution in the balancing tank is usually sufficient to reduce the toxicity of any spillages so that they have no significant effect on the biological treatment plant. In extreme cases, the flow of effluent from the balancing tank can be reduced. This will increase the volume in the balancing tank and further dilute the toxic material. If necessary, untreated effluent or recycled treated effluent can be added to achieve greater dilution. This decision, which depends on the toxic material involved, should be taken by the plant manager.

2.3.3 Common problems

Common problems associated with the operation of a balancing tank include:

- it is too small;
- it is operated as a surge tank rather than as a balancing tank;
- there is no agitation;
- untreated effluent starts to turn septic.

By following the guidance above, these problems can be avoided, with resulting cost savings.

2.4 SEPARATION TECHNIQUES

In the paper industry, primary treatment or clarification usually involves one or more of the following processes:

- screening;
- dissolved air flotation (DAF);
- settlement;
- emulsion breaking.

Advice on effective use of these techniques is given below. Screening, a purely mechanical operation, is generally the first choice technique for fibre recovery. DAF and settlement are also used to maximise fibre recovery. For the purpose of this Guide, however, these techniques are considered in terms of their effectiveness for solids removal.

> Optimisation of primary treatment processes is essential for the cost-effective performance of downstream processes.

2.4.1 Screening

The mesh size used for initial screening depends on how much fibre is present and whether recycled paper is used as a fibre source. The presence of plastics and other inert solid material also presents problems. Mesh sizes for screens are typically 0.25 - 10 mm.

Blinding of screens is a common problem. If it occurs frequently and solids losses at source (ie in the mill) cannot be reduced, an increase in the mesh size or more effective cleaning should be considered. Most screen manufacturers can supply a range of mesh sizes which are relatively easy to change. Plastic mesh screens are also more resistant to blinding than metal screens.

The screens should be examined regularly to:

- check for physical damage and blinding;
- ensure that the solids removal/backwash system is effective.

2.4.2 Dissolved air flotation

Although dissolved air flotation (DAF) is used by many mills for de-inking, its potential as a stand-alone primary treatment process is sometimes overlooked. A typical circular DAF cell used for effluent treatment is shown in Fig 2. More details about the operation of a DAF unit are given in Good Practice Guide (GG37) *Cost-effective Separation Technologies for Minimising Wastes and Effluents.*[6]

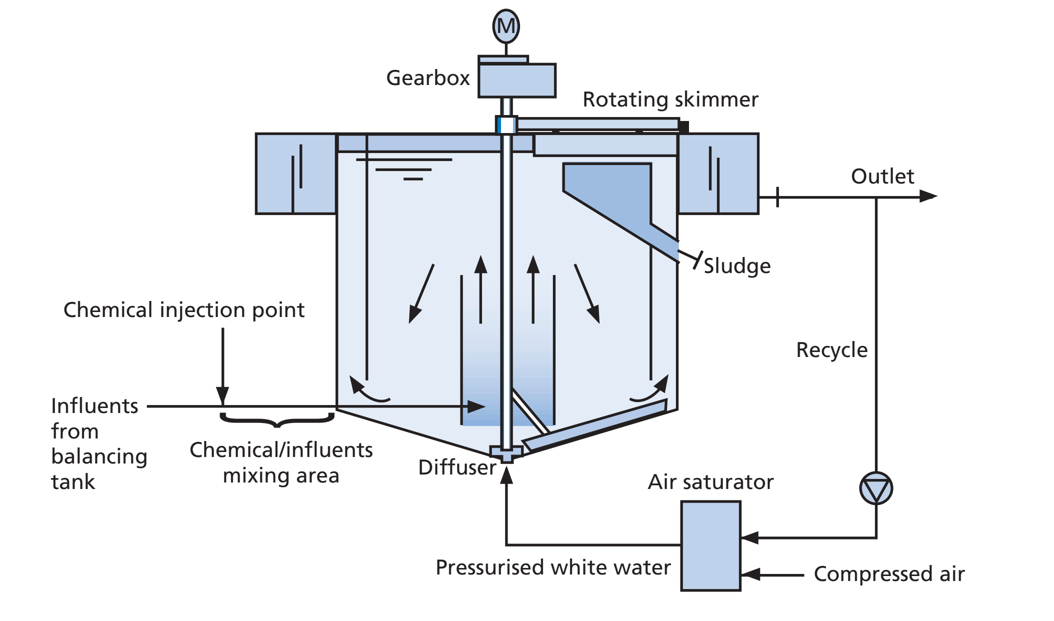


Fig 2 Typical circular DAF cell

For optimum operation of a DAF plant:

- Increase the floc size - and hence the effective surface area - by adding coagulants and/or flocculants. The increased solids removal should more than offset the cost of adding these chemicals. Perform regular jar tests (see Appendix 3) to ensure that the dose rate is appropriate and cost-effective. Such tests are often carried out free of charge by the chemical supplier.
- Ensure that the contact time and mixing of chemicals and effluent before they enter the DAF unit is adequate. This can be established by carrying out jar tests (see Appendix 3) and varying the point on the influent line at which the chemicals are injected.
- Operate the air saturators producing the pressurised white water at 400 - 700 kPa (4 - 7 bar). This should produce up to 90% air saturation. Check the gauges on the outlet of the compressed air unit and adjust accordingly.
- Ensure that, within the flotation zone, the upward flow rate (UFR) is 5 - 10 m/hour. As shown in Formula 1, the UFR is a measure of the flow rate through the tank and the surface area of the tank. It can be changed by adjusting the valves controlling the flow of effluent from the balancing tank.

Formula 1

$$\text{UFR (m/hour)} = \frac{\text{Effluent flow (m}^3\text{/hour)}}{\text{Tank surface area (m}^2\text{)}}$$

- Keep the load of the DAF unit constant (as far as is possible) by effective upstream balancing.
- Check the speed of the skimmer, this needs to be sufficient to remove the solids, but not fast enough to collect excess water, which can have an adverse effect on sludge dewatering. The correct speed will depend on the size and design of the unit, and the DAF unit supplier should be able to offer advice.

[6] Available free of charge through the Environment and Energy Helpline on 0800 585794.

section 2

2.4.3 Settlement

Settlement tanks are often used for primary treatment of paper mill effluent, either with upstream screens or as a stand-alone process.

A fibre removal rate of 50 - 70% of suspended solids is standard, with some mills achieving even higher rates. If performance is significantly less, it should be optimised by adopting the following simple measures:

- Perform regular jar tests (see Appendix 3) to check that the correct settlement characteristics are being achieved. Coagulant/flocculant use in settlement tanks is not as critical as for DAF units because the aim is to produce smaller, denser particles than the light, voluminous flocs required for DAF. However, it is still important for optimum performance. Many chemical suppliers provide information about typical settlement rates for paper mill effluents following coagulant/flocculant addition.
- Wide variations in hydraulic flow have a significant impact on the performance of settlement tanks. Ensure that adequate upstream balancing is available to produce an upward flow rate (UFR) of 1.6 m/hour ± 20% (ie ± 0.32). UFR is calculated as in Formula 1.
- If effluent flow rates are consistently higher than the tank's design specifications, consider retrofitting tilted lamella plates. These allow successful operation with a UFR of up to 5 - 10 m/hour.
- For systems with small hydraulic variations, let the outlet from the settlement tank flow out over a series of V-notch weirs around the edge of the tank. As the level in the tank rises, the available outlet area increases. This larger outlet area thus helps to 'buffer' any increases in influent flow.
- The optimum retention time (RT) for paper mill applications varies considerably as it depends on the nature of the solids/fibres present in the effluent. However, 6 - 8 hours is an acceptable time. The retention time (RT) in the settlement tank can be calculated using Formula 2.

Formula 2

$$\text{RT (hours)} = \frac{\text{Tank volume (m}^3\text{)}}{\text{Average effluent flow rate (m}^3\text{/hour)}}$$

- Do not allow sludge to build up in the bottom of the tank. Putrefying conditions may occur, leading to hydrogen sulphide production. This can lead to odour problems, corrosion of the tank base and the sludge being lifted to the surface by the gas. The desludging regime should ideally be continuous. If it is not, the sludge should not be allowed to remain stagnant for more than 2 - 3 hours.

2.4.4 Emulsion breaking

Untreated coating materials, eg emulsified polyvinyl alcohol (PVA), cause major problems at downstream biological treatment plants. Paper mills that use large quantities of coating materials should segregate emulsified effluents and treat them separately from the main effluent. Emulsions should be broken by adding acid coagulants, eg alum or ferric chloride, in a separate treatment stage prior to biological treatment.

2.5 CHECKLIST FOR PRIMARY TREATMENT

Check your system against this guidance to identify options for improvement and savings.

Checklist 1 For primary treatment

Balancing

- ☐ Ensure adequate tank capacity.
- ☐ Agitate and aerate the untreated effluent.
- ☐ Monitor flow and organic load.

Screening

- ☐ Check screens regularly for signs of physical damage and ensure efficient operation of the solids removal/backwash process.

DAF

- ☐ Add coagulants and/or flocculants to increase the floc size. Monitor chemical additions to ensure that only the amounts sufficient to do the job are used. Check the dose rate regularly by carrying out jar tests (see Appendix 3).
- ☐ Allow adequate contact time and mixing of effluent and added chemicals.
- ☐ Operate the air saturators producing the pressurised white water at 400 - 700 kPa (4 - 7 bar).
- ☐ Maintain the upward flow rate (UFR) at 5 - 10 m/hour.
- ☐ Check that the skimmers are not collecting too much water along with the solids.

Settlement

- ☐ Avoid wide variations in hydraulic flow.
- ☐ Monitor chemical additions to ensure that only the amounts sufficient to do the job are used. Check the dose rate regularly by carrying out jar tests (see Appendix 3).
- ☐ Provide adequate balancing to provide an upward flow rate (UFR) of 1.6 m/hour ± 20% (ie ± 0.32).
- ☐ If effluent flow rates are consistently high, retrofit tilted lamella plates.
- ☐ Accommodate small variations in hydraulic flow by fitting V-notch weirs to the tank outlet.
- ☐ Aim for a retention time (RT) of 6 - 8 hours.
- ☐ Avoid letting the sludge remain stagnant for more than 2 - 3 hours.

Emulsion breaking

- ☐ Segregate emulsified wastewaters and break the emulsion by adding acid coagulants, eg alum or ferric chloride.

3.1 WHY IS BIOLOGICAL TREATMENT NECESSARY?

The biological loading or biochemical oxygen demand (BOD) associated with effluent from a paper and board mill derives from a number of sources, including:

- waste fibre;
- starches and other sizes;
- process chemicals.

If these substances are discharged untreated, they act as a source of food for bacteria in the receiving water. These bacteria would break down the BOD naturally, but in doing so would use the oxygen present in the water as part of the natural respiration process, ie there would be an oxygen demand upon the receiving water. In extreme cases, all the oxygen could be used up leading to the death of fish and other aquatic organisms.

Secondary biological treatment seeks to achieve an intensification of natural processes. Aerobic processes aim to meet the effluent's demand for oxygen artificially, while anaerobic processes convert organic materials to methane.

3.2 AEROBIC PROCESSES

Aerobic effluent treatment is the biological degradation of organic material in the presence of oxygen. The provision of oxygen and control of its transfer to the bacteria are crucial to the efficient operation of the process.

Most effluent treatment plants in the UK paper and board industry have some type of aerobic treatment stage. Aerobic processes can be divided into two groups:

- **Suspended growth systems.** The biomass is maintained in suspension in an aqueous environment. Oxygen transfer occurs directly - as dissolved oxygen - from the aqueous phase to the biomass. Examples include:
  - conventional activated sludge;
  - pure oxygen activated sludge;
  - sequencing batch reactor (SBR);
  - oxidation ditch.
- **Attached growth systems** (see Section 3.9). The biomass is supported by a solid phase on which it grows. Oxygen is transferred directly to the biomass from the gaseous phase, ie the air. Examples include:
  - percolating filters;
  - biotowers;
  - rotating biological contactor (RBC).

In recent years, hybrid systems have been developed successfully, eg biological aerated flooded filter (BAFF) and the submerged biological aerated filter (SBAF).

Activated sludge is currently the commonest effluent treatment process in the UK paper industry. This Guide therefore considers the control and optimisation of this process in some detail.

3.3 BASIC AEROBIC MICROBIOLOGY

A basic understanding of the key microbiological species is essential for efficient operation and maintenance of any biological treatment plant and especially for activated sludge processes.

A wide range of micro-organisms have been identified in activated sludge solids, a flocculated mixture of mainly bacteria and protozoa. Three main groups are important, ie:

- floc-forming carbon oxidisers;
- filamentous carbon oxidisers;
- nitrifiers.

Floc-formers are needed for BOD degradation and to establish a stable flow with good settling characteristics. Filamentous species tend to be involved with bulking and foam formation - the two commonest problems associated with activated sludge plants (see Sections 3.5 and 3.6). Nitrifers convert ammoniacal nitrogen (NH_4-N) to nitrate in a two-stage process. First, *Nitrosomonas* sp. convert ammoniacal nitrogen to nitrite (NO_2^-) and then *Nitrobacter* sp. convert nitrite to nitrate (NO_3^-). Paper mill effluents tend to have a low ammoniacal nitrogen content.

The exact nature of the microbiological population is specific to each treatment plant. Operators therefore need to become familiar with what is deemed 'normal' for their particular process.

Effective monitoring and control

As part of its monitoring and control programme, Shotton Paper in Deeside carries out regular checks on the health of the biomass in its activated sludge plant (see Industry Example 3 in Section 6).

Examination of a sample of activated sludge under the microscope is an important monitoring tool. A trained eye can deduce a great deal about the overall health of the biological treatment plant.

This Guide aims to provide sufficient information to enable mills to investigate common operational problems and thus achieve optimum plant operation. For further advice and information about training in microbiological techniques, contact the Environment and Energy Helpline on 0800 585794.

Table 2 summarises the properties of the main types of micro-organisms found in an activated sludge plant and the information that can be inferred from their presence or absence.

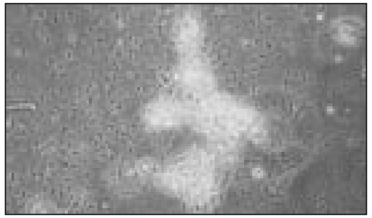
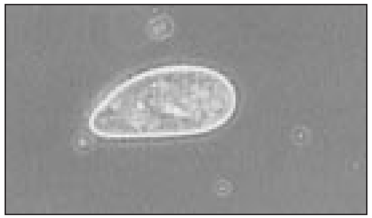
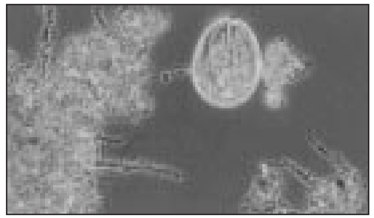
Type	Properties	Comments	
Bacteria	Single-celled organisms, either spherical (cocci), rods (bacilli) or spiral (spirilli) in shape. Often too small to be seen during a normal microscopic examination. A wide range of bacteria is involved in the degradation and stabilisation of organic matter in the activated sludge process.	Filamentous bacteria are generally symptomatic of bulking activated sludge. More easily seen under the microscope than floc-forming bacteria.	 ***Free bacteria in the liquor of a high rate activated sludge (x400)***
Protozoa	A higher life form than bacteria, although also single-celled organisms. Commonest protozoa found in the activated sludge process are ciliates (free swimming and stalked), amoebae and flagellates. Active predators that feed upon bacteria, small fungi and other protozoa. Essential to the activated sludge process as they maintain a balance between the various micro-organisms. Also considered to 'polish' effluent because they use organic particles as a food source.		
	Free swimming/crawling ciliates are the 'workhorse' of the activated sludge process.	Indicative of a relatively healthy biomass with an adequate oxygen supply.	 ***Free swimming ciliate (x400)***  ***Crawling ciliate (x400)***

Table 2 Main micro-organisms found in an activated sludge plant

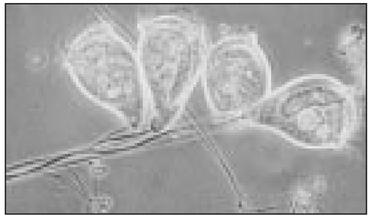
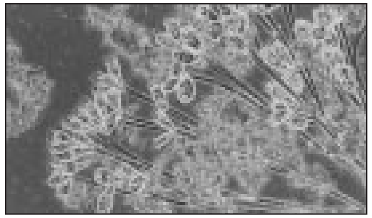
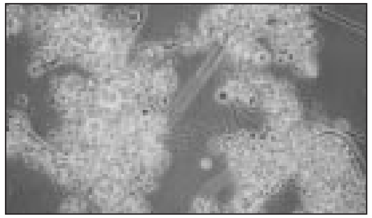
Type	Properties	Comments		
Protozoa *continued*	***Stalked ciliates*** attach themselves to flocculated material using their stalks. Efficient feeders that use the small cilia at their mouth to feed on bacteria.	Symptomatic of a healthy and well established biomass.	 ***Stalked ciliate (x400)***	 ***Abundant stalked ciliates (x100)***
	Flagellates, another type of free swimming protozoa, use their distinctive whip-like flagella for providing motive force.	Generally indicative of a young or developing biomass - commonly found immediately after seeding or in the recovery phase following a toxic shock.	 ***Flagellate (centre) (x400)***	 ***Flagellates attached to the flocs and free in the liquor (x400)***
	Amoebae are simple, single-celled organisms with an irregular and constantly changing shape. They move and feed by extending temporary structures called 'pseudopodia' from their surface. Found either naked or with shells.	Small, naked amoebae usually indicate poor operating conditions or a shock loading. Shell or testate amoebae are commonly found in activated sludge plants with a low organic loading, high level of dissolved oxygen and a long sludge age.	 ***Amoeba - naked (x400)***	 ***Shell or testate amoeba (x400)***

Table 2 Main micro-organisms found in an activated sludge plant (continued)

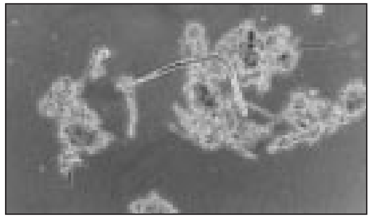
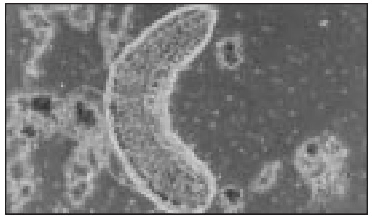
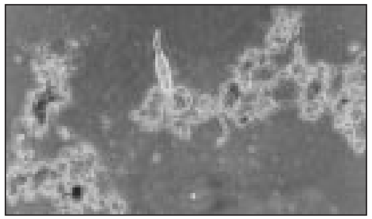
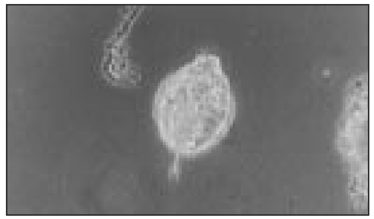
Type	Properties	Comments	
Nematode worms	Usually noticed because of their lashing, whip-like movements. 200 - 1 000 µm long. Take a relatively long time to double their numbers.	Sign of a mature sludge with a long sludge age.	 ***Nematode worm (x100)***
Naid worms	One of the largest organisms commonly found in activated sludge. Have distinctive bristles, in bundles. Can be up to 2 mm long.	Like nematodes and rotifers, their presence indicates a well-balanced, mature biomass.	 ***Naid worm (x100)***
Rotifers	Multi-cellular animals, containing specialised organs and a well-developed digestive system. Name derives from the distinctive rotating cilia around their head. Feed on protozoa, dispersed and flocculated bacteria, and smaller organic particles. Require a relatively high dissolved oxygen content of typically >2 mg/litre. Relatively slow doubling time.	Generally indicative of a well-balanced and healthy biomass. Biomass may be considered too old if they are present in greater numbers than usual.	 ***Rotifer (centre) (x100)***  ***'Shield' rotifer (x400)***

Table 2 Main micro-organisms found in an activated sludge plant (continued)

3.4 THE IMPORTANCE OF STEADY STATE CONDITIONS

Like all living organisms, the bacteria and other micro-organisms present in an activated sludge plant are extremely sensitive to their environment, ie:

- pH;
- temperature;
- dissolved oxygen;
- the presence of toxic or inhibitory materials.

It is possible for a healthy and effective biomass to grow even if conditions are not optimum. However, the biomass will be sensitive to significant changes in its environment and/or wide variations in flow and organic load. A balancing tank (see Sections 2.2 and 2.3) is therefore an important element of the effluent treatment plant.

Fig 3 shows the general appearance of firm, rounded flocs in a clear liquor. This indicates a healthy biomass.

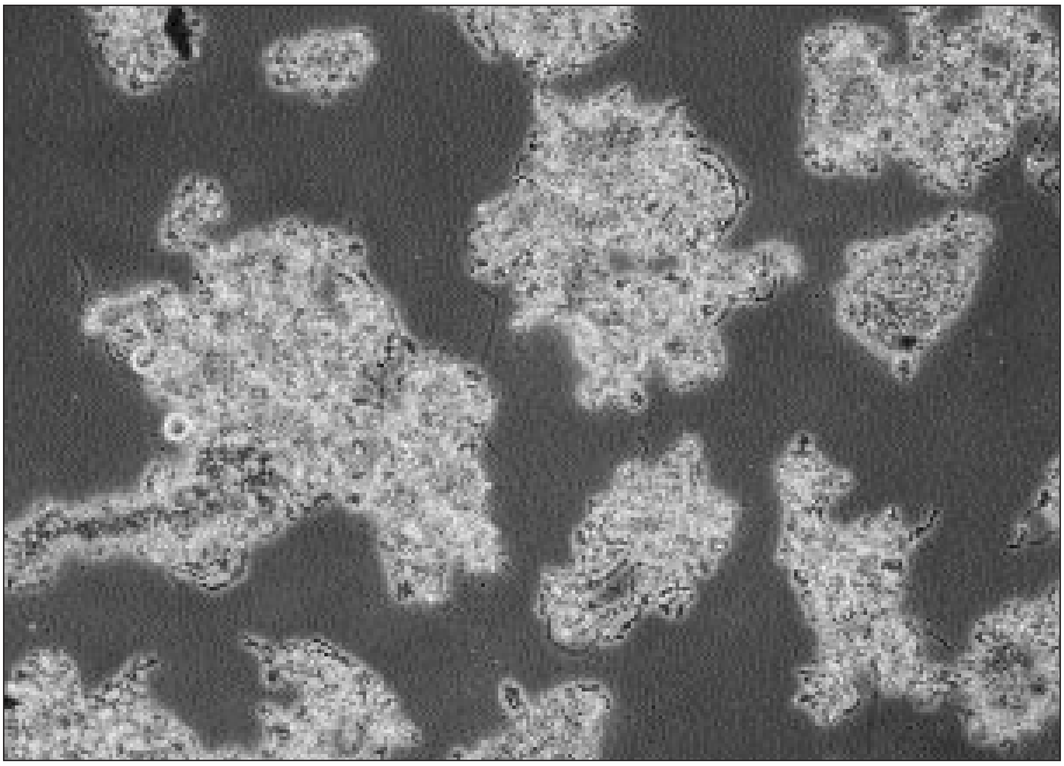


Fig 3 Healthy sludge flocs (x100)

The key to the overall health of the biomass is to keep environmental factors within optimum conditions and to maintain steady state conditions.

3.5 CONTROLLING THE ACTIVATED SLUDGE PROCESS

This process, which was developed in Manchester before the First World War for treating sewage, is used widely throughout the UK paper industry. A simple representation of the activated sludge process is shown in Fig 4.

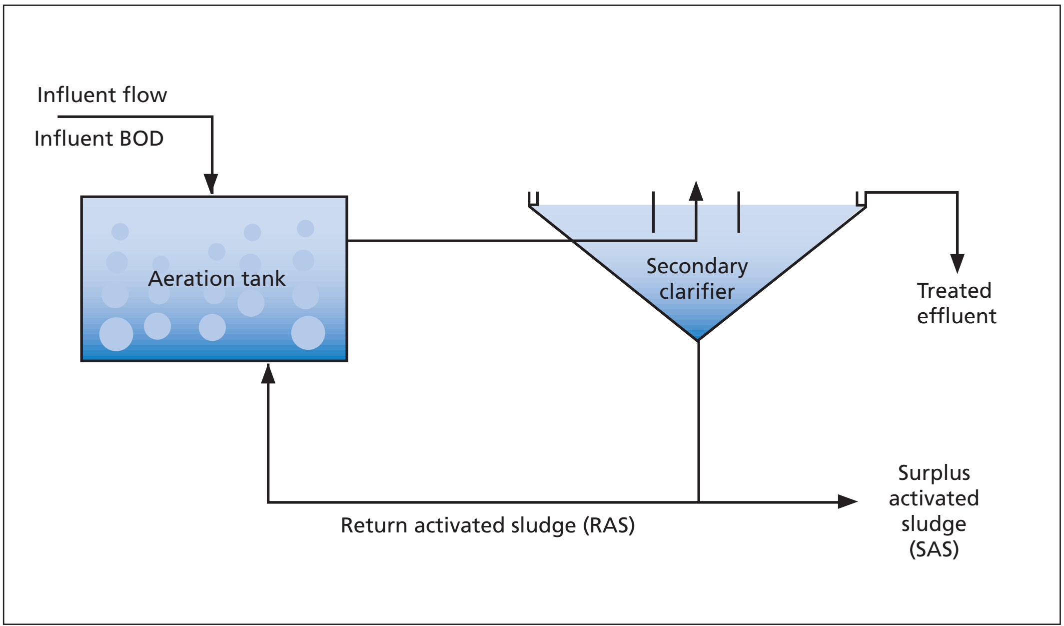


Fig 4 Activated sludge process

The three most important control parameters for optimising the operation of an activated sludge plant are:

- food:mass ratio (F:M ratio);
- sludge age;
- dissolved oxygen.

This Guide concentrates on the operation of non-nitrifying systems, but advice is given on how to operate under conditions that will encourage nitrification should it be required. A checklist for mills to photocopy and use is given in Section 3.8.

The first step is to collect data about the operation of the secondary treatment process and then take action to ensure cost-effective operation. Checklists are provided to help overcome the main operating problems encountered in the paper industry.

An effective monitoring and control programme requires an ongoing analytical testing regime. If laboratory facilities are not available at the mill, testing can be contracted out to a local laboratory specialising in water and effluent analysis.

With a basic knowledge of influent characteristics and conditions within the bioreactor, it is easy to monitor and control an activated sludge process. But, remember, do not just collect information for the sake of it - evaluate the data and respond accordingly. An example of a typical operator's log for use when managing an activated sludge plant is shown in Fig 8 (see Section 3.8).

3.5.1 Food:mass ratio

One of the main control parameters for the activated sludge process is the food:mass ratio (F:M ratio) or sludge loading rate (SLR). This is the relationship between:

- the load of BOD - or bacterial 'food' - entering the aeration plant; and
- the 'mass' of micro-organisms in the aeration tank available to treat the incoming BOD.

The amount of biomass within the reactor is known as the mixed liquor suspended solids (MLSS) or mixed liquor volatile suspended solids (MLVSS). The MLSS is established by filtering off a known volume of the biomass, eg 1 litre, and drying it in an oven at 105°C to constant weight (ie no moisture remains to be evaporated off).

The F:M ratio - possibly the single most important parameter in controlling the activated sludge process - is defined as the kg of BOD applied per kg MLSS per day. It can be calculated, as shown in the example, using Formula 3. Target ranges for F:M values in commonly used effluent treatment systems are indicated in Table 3 (Section 3.5.3).

Formula 3

$$\text{F:M} = \frac{[\text{Influent flow rate (m}^3\text{/day) x Influent BOD (g/litre)}]}{[\text{MLSS (g/litre) x Volume of aeration tank (m}^3)]}$$

The Paper Company Limited calculates the F:M ratio of its activated sludge plant

The Paper Company Limited treats the effluent from its newsprint mill in an activated sludge plant prior to discharge in a nearby river estuary. High BOD removal is demanded, but there is no ammonia element to the consent and hence no requirement for nitrification.

The plant operates with the following parameters:

Influent flow rate	250 m^3/hour, ie 6 000 m^3/day
Influent BOD	300 mg/litre, ie 0.3 g/litre
MLSS	3 000 mg/litre, ie 3.0 g/litre
Volume of aeration tank	3 000 m^3

Using Formula 3, ie:

$$\text{F:M} = \frac{[\text{Influent flow rate (m}^3\text{/day) x Influent BOD (g/litre)}]}{[\text{MLSS (g/litre) x Volume of aeration tank (m}^3)]}$$

$$= \frac{[6\,000 \times 0.3]}{[3 \times 3\,000]} = \frac{1\,800}{9\,000} = \mathbf{0.2}$$

The checklist in Section 3.8 is intended to help companies implement cost-effective measures to optimise their activated sludge process.

3.5.2 Sludge age

Sludge age is a measure of the relationship between the mass of sludge within the system and the mass of sludge lost from the system. Sludge age, which is linked to the F:M ratio, is a measure of the time the biomass is retained within the system and is referred to as the mean cell residence time or sludge retention time. It is another important plant control parameter (see Section 3.5.4).

Sludge age can be calculated using Formula 4. Control is achieved by adjusting the ratio of return activated sludge (RAS) and surplus activated sludge (SAS) from the secondary clarifier (see Section 3.5.4).

Formula 4

$$\text{Sludge age (days)} = \frac{\text{Mass of sludge in aeration tank}}{\text{Mass of sludge lost}}$$

$$= \frac{\text{MLSS x Volume of aeration tank}}{\text{Mass of sludge lost (SAS and final effluent)}}$$

Sludge age in nitrifying plants

Ammonia is toxic to fish, especially when oxygen levels are low. Sludge age is a particularly important parameter when nitrification is required, although paper mill effluent generally contains only low levels of ammoniacal nitrogen.

Nitrogen is usually added to the effluent as a nutrient (see Section 3.5.5) to ensure good growth of carbon-oxidising bacteria, ie those bacteria removing carbonaceous BOD. Most paper mills add nutrient at a constant rate. More advanced metering equipment is becoming available that allows nutrient to be added on the basis of monitored total organic carbon (TOC) and flow rate.

Effective monitoring and control

Shotton Paper (see Industry Example 3 in Section 6) is undertaking trials of a TOC meter linked to effluent BOD. The mill is particularly concerned to avoid overdosing with nitrogen during nutrient addition, as its consent conditions include a limit on ammoniacal nitrogen.

Allowing the activated sludge plant to operate under conditions at which slower growing nitrifying bacteria will develop provides protection against the presence of excess nitrogen should the BOD load fall suddenly. This increase in concentration of ammoniacal nitrogen serves as a food source for any nitrifiers present and an illegal discharge is avoided. This strategy can be particularly useful for discharges to inland waters under a stringent consent condition for ammoniacal nitrogen. Under such circumstances, the growth of nitrifying bacteria can be encouraged by maintaining the nutrient dose rate for NH_4-N a few ppm higher than normal. The development of nitrifying bacteria usually requires a minimum sludge age of 10 - 12 days.

Non-nitrifying plants, ie those removing organic carbon only, may only require a sludge age of 2 - 7 days, although a higher figure would also be acceptable.

Nitrifying plants, ie those also requiring ammoniacal nitrogen removal, should have a sludge age of typically 10 - 15 days.

3.5.3 The relationship between F:M ratio and sludge age

Since the sludge age is related to the MLSS, it is proportional to the F:M ratio. It is therefore possible to obtain an approximate value for sludge age using Formula 5. This equation uses the yield coefficient (Y), which can also be expressed as kg of sludge produced (as dry solids) per kg BOD removed. The sludge age value obtained from Formula 5 is approximate because the yield coefficient varies with the amount of inert material entering the effluent plant. However, experience has shown that, for the paper industry, a coefficient value of 0.6 - 0.7 provides a fairly accurate value for sludge age. While this calculation is only an approximation, it is nevertheless a useful rule of thumb and an easier alternative to Formula 4.

Formula 5

$$\text{Sludge age (days)} = \frac{1}{\text{(F:M) x Yield coefficient (Y)}}$$

The Paper Company Limited calculates the sludge age of its activated sludge plant

The example calculation in Section 3.5.1 showed that The Paper Company Limited was operating its activated sludge plant at an F:M ratio of 0.2.

Using the rule of thumb above, taking a median value for Y:

$$\text{Sludge age (days)} = \frac{1}{\text{(F:M) x Yield coefficient (Y)}}$$

$$= \frac{1}{0.2 \times 0.65} = \frac{1}{0.13} = \textbf{7.7 days}$$

Interpreting the results of F:M ratio and sludge age calculations

In general terms, a fall in the F:M ratio produces:

- a subsequent reduction in the rate of growth of the biomass, ie the system moves towards being limited by the amount of food available;
- an increase in the sludge age;
- an improvement in the quality of the treated effluent.

In practice, the F:M ratio is a function of the type of activated sludge process. Table 3 shows the F:M ratios and sludge ages that should be maintained for commonly used secondary treatment processes.

Process	F:M ratio	Sludge age (days)
Conventional activated sludge:		
nitrifying	0.1 - 0.2	10 - 15
non-nitrifying	0.1 - 0.6	2 - 15
Pure oxygen process	0.04 - 0.1	15 - 40
Extended aeration	0.05 - 0.15	10 - 30
Aeration ditch	0.05 - 0.3	5 - 30

Table 3 Recommended F:M ratios and sludge ages for different processes

3.5.4 The importance of sludge age

Sludge age provides an indication of how much biomass is retained in the aeration tank. It is related to:

- the amount of biodegradation that may occur;
- the level of intensification of the treatment process;
- the type of micro-organisms present.

Sludge age is therefore a useful control parameter. The relationship between sludge age and BOD removal efficiency is shown in Fig 5.

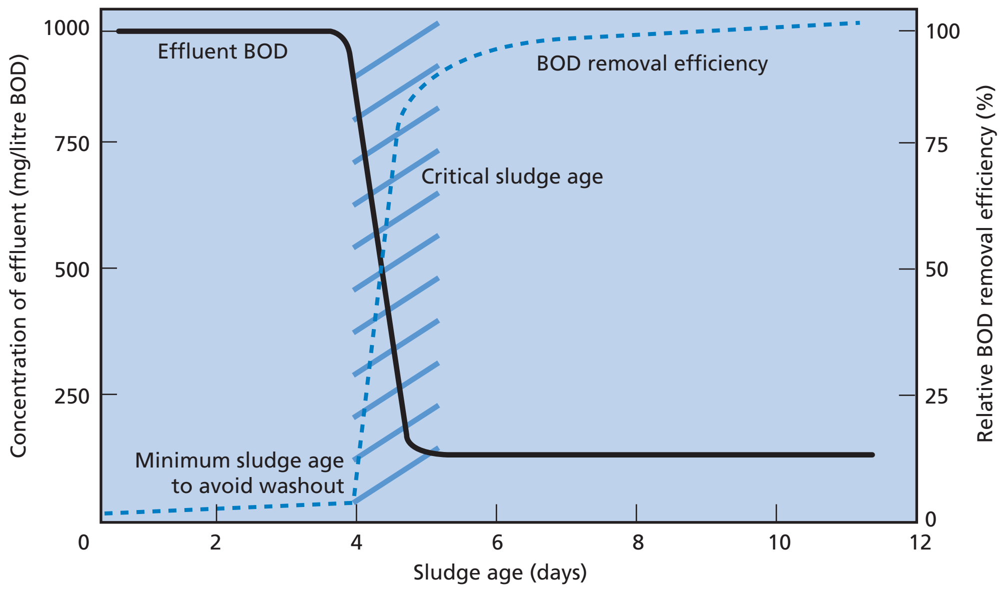


Fig 5 The relationship between sludge age and BOD removal efficiency

Fig 5 highlights a number of important points.

- Below a minimum sludge age, biomass is removed from the aeration tank faster than it is being replaced by new cell growth. This process is referred to as washout.
- There is also a maximum or critical sludge age. Above this age, any increase in performance is negligible.
- There is a period between washout and the critical sludge age where biomass activity may increase or decrease rapidly.

The plant should therefore be operated so that the sludge age falls within the shaded area of the graph in Fig 5. The exact position of this shaded area will depend on the treatment process, but typical target values for sludge age are given in Table 3.

In the case illustrated, the critical sludge age is well within the accepted limits for a non-nitrifying conventional activated sludge plant.

Sludge age is controlled by varying the amount of sludge lost from the system. This is achieved by the following steps:

1 Adjusting - by whatever means is available - the relative flows of return activated sludge (RAS) and surplus activated sludge (SAS) from the secondary clarifier.

2 Re-calculating the sludge age.

3 Repeating this procedure until an acceptable sludge age is obtained.

When calculating sludge age, it is important to include the mass of solids lost in the final effluent in the amount of sludge wasted from the system.

Effluent plant optimisation

Bridgewater Paper (see Industry Example 1 in Section 6) maintains steady state conditions within its activated sludge plant by operating within carefully controlled parameters. Optimisation of plant performance is based on preventing problems rather than treating the symptoms. Variations in the amount and strength of the influent to the plant are smoothed out in a balancing tank to provide a reasonably constant BOD load. The health of the biomass is examined under the microscope as part of a programme of regular monitoring. The required F:M ratio and sludge age are achieved by careful control of the MLSS and the rate of loss of surplus activated sludge (SAS).

3.5.5 Nutrient addition

Like other living organisms, the biomass associated with the activated sludge process requires a 'balanced diet' to ensure full and healthy growth. Two of the most important macro-nutrients - nitrogen (N) and phosphorus (P) - are often lacking in paper mill effluent. Minimum nitrogen and phosphorus levels must be maintained to ensure the healthy growth of floc-forming bacteria.

To correct this nutrient imbalance, it is common practice to add supplementary nitrogen and phosphorus. This is done either by using a common source of nitrogen and phosphorus such as ammonium phosphate or by adding a tailor-made 'cocktail' of chemicals as supplied by a number of specialist nutrient suppliers. New dosing systems are now coming onto the market that control nutrient addition on the basis of flow rate and a load parameter such as total organic carbon (TOC).

An external supplier will also be able to advise on levels of micro-nutrients, eg iron and other trace elements. Lack of micro-nutrients is often overlooked as a cause of poor biomass performance.

Although suppliers may include regular testing of the influent to check the BOD:N:P ratio during their service, the cost of it is incorporated into the price of the chemicals. Depending on the mill's expertise in analysis and control, it may be more cost-effective to add nitrogen and phosphorus using a standard source available from most commodity chemical suppliers.

To ensure that biomass growth is not limited by lack of nutrients, the following minimum ratio should be maintained in the influent to the plant.

BOD:N:P = 100:5:1

3.5.6 Optimising secondary clarifier performance

The effectiveness of an activated sludge process relies on the removal of biomass from the secondary clarifier or settlement tank (see Fig 4, Section 3.5). Ineffective operation of the clarifier - for a number of reasons - is a common cause of poor overall plant performance.

The loss of biomass from the secondary clarifier depends on the sludge's settling characteristics. Good settling characteristics are associated with a fast settling rate and dense flocs. Various factors affect the settling characteristics of the biomass, thus making optimisation of the performance of the secondary clarifier more difficult. These factors include:

- **Upward flow rate (UFR).** Like primary settlement tanks (see Section 2.4.3), secondary clarifiers are sensitive to wide variations in hydraulic flow. Conditions should be controlled to ensure an upward flow rate of 1.6 m/hour ± 20% (ie ± 0.32). UFR is calculated as in Formula 1.

section 3

Formula 1

$$\text{UFR (m/hour)} = \frac{\text{Effluent flow (m}^3\text{/hour)}}{\text{Tank surface area (m}^2\text{)}}$$

- **Retention time (RT).** This is also important within the clarifier, with 4 - 5 hours being a typical value for a secondary clarifier. This allows enough time for settlement to occur but with little or no consolidation, thus avoiding potential problems with denitrification (see below).
- **Extent of formation of a sludge blanket.** As the cross-sectional area of the clarifier increases near the surface, a point is reached where the effective UFR is equivalent to the rate of gravitational fall of the floc particles.[7] Under such conditions, the particles are essentially motionless and a 'blanket' or layer of sludge accumulates. This blanket is important as it acts as a filter, thus reducing the fines, ie the suspended solids, in the final effluent.
- **Physical nature of the flocs.** This is critical to their settling characteristics. The open structure associated with filamentous bacteria is particularly detrimental to good settling characteristics and measures should be taken to discourage the growth of these bacteria (see Section 3.6.2).
- **Mixed liquor suspended solids (MLSS).** The actual MLSS associated with the return activated sludge (RAS) also has an effect on the settling characteristics. In general, the higher the MLSS, the lower the settling velocity and hence a slower settlement rate.
- **Denitrification.** The conversion of nitrate to nitrogen may cause the sludge to rise owing to bubbles of gas attaching themselves to the floc particles. This problem is not particularly prevalent in the paper industry as the low levels of ammoniacal nitrogen in the mill effluent mean that nitrification is not required and nitrogen is not produced. However, operators should be aware of the possibility of denitrification. Methods of discouraging denitrification are listed in Section 3.7.1.

3.5.7 Measurement of settling characteristics

In addition to maintaining an optimum upward flow rate (UFR) and confirming that denitrification is not occurring in the sludge, the physical nature of the flocs and the MLSS of the return activated sludge (RAS) should be monitored. Early identification of changes in the

[7] Other factors - as dictated by Stokes' law - are at play here, but these are outside the scope of this Guide.

settling characteristics due to altered physical structure allows the operator to anticipate bulking. This in turn may allow bulking to be controlled without the need to add chemicals (see Section 3.6.3).

In its simplest form, the measurement of settling characteristics consists of placing a sample of the activated sludge in a measuring cylinder and timing how quickly it settles. There are two standard test methods based on this principle. The two tests are often confused and it is important to be clear which test is being carried out.

Sludge volume index (SVI)

This test, which is the simplest test of settling characteristics, is less likely to be used in mills than the second test, $SSVI_{3.5}$ (stirred specific volume index).

The SVI is defined as the volume occupied by 1 g of activated sludge after 30 minutes settlement in a one-litre measuring cylinder. The test involves:

- determining the MLSS of the activated sludge (see Section 3.5.1);
- pouring 1 litre of stirred activated sludge into a one-litre measuring cylinder (the sludge must not have been allowed to settle);
- reading off the volume occupied by the settled sludge after 30 minutes;
- calculating the SVI using Formula 6.

Formula 6

$$\text{SVI (ml/g)} = \frac{\text{Volume of settled activated sludge (ml)}}{\text{MLSS (g)}}$$

SVI decreases for a sludge of improved settling characteristics. A value of over 200 ml/g indicates poor settlement and is indicative of filamentous bacteria or 'bulking' activated sludge.

An SVI value of 40 - 60 ml/g indicates good settlement, although 80 - 120 ml/g is more normal. An effluent treatment plant with an SVI value of 140 ml/g or higher has poor settlement.

However, the basic SVI test has two main problems, ie:

- The test conditions do not represent those in the clarifier. The relatively narrow bore of a standard one-litre measuring cylinder means that 'drag' from the walls may make the sludge settle more slowly than in the clarifier.
- The settling speed depends on the MLSS value, with higher values giving lower settling speeds.

Stirred specific volume index ($SSVI_{3.5}$)

The $SSVI_{3.5}$ test, a development of the SVI test, overcomes the first of these problems by stirring the cylinder at 1 rpm using a proprietary stirrer kit designed for this purpose. This represents the dynamics of the conditions within the clarifier much better than the basic SVI test.

To allow for the effect of the MLSS on the settlement characteristics of the sludge, the $SSVI_{3.5}$ is expressed as for a sample with an MLSS of 3.5 g/litre (ie 3 500 mg/litre). This is a 'typical' MLSS value for a conventional activated sludge plant. SSVI values obtained for sludges that do not have an MLSS of 3 500 mg/litre are converted to $SSVI_{3.5}$. This is achieved by applying a correction factor derived from a series of SSVI tests carried out by the mill's laboratory staff at different values of MLSS, both above and below 3 500 mg/litre.

The $SSVI_{3.5}$ test is generally more reliable and reproducible than the SVI test and should be included in the plant's regular testing regime.

Typical $SSVI_{3.5}$ values for a conventional activated sludge process are 80 - 120 ml/g. Lower values are common for pure oxygen processes.

An $SSVI_{3.5}$ of greater than 150 - 160 ml/g indicates a potential problem, which should be investigated.

3.5.8 Dissolved oxygen

In addition to 'food' availability and MLSS levels (expressed as the F:M ratio), another important operating parameter is the level of dissolved oxygen (DO). This indicates the availability of oxygen to the biomass and is fundamental to both the performance and efficiency of the activated sludge process.

As most paper mills do not require nitrification, this Guide is concerned mainly with the oxygen requirement for non-nitrifying systems. However, as nitrification has benefits in some situations, eg denitrification in an anoxic zone, some comparative data are quoted for nitrifying systems. Nitrification affects the overall oxygen requirement. Calculation of the requirement for a non-nitrifying system is merely simpler.

In general, the dissolved oxygen content of an activated sludge plant should not be allowed to fall below 0.5 mg/litre. A normal value is 1 - 2 mg/litre. Unnecessary aeration wastes energy.

Dissolved oxygen control

One of the highest operating costs associated with the activated sludge process is the energy used to operate the air blowers/diffusers. Cost savings can therefore be achieved by operating at the lowest practicable dissolved oxygen value for the plant. This value is specific to each plant.

Control of dissolved oxygen allows the mill to optimise its oxygen and energy consumption. The rate of oxygen addition should be altered so it remains proportional to the BOD load in the influent. Oxygen addition should be controlled on the basis of the total organic carbon (TOC) content of the influent, as this is much easier to monitor on-line than BOD.

The dissolved oxygen probe and its associated control circuitry is a critical item of equipment. A good probe costs £1 000 - £2 000. However, a good probe is much less likely to break down under industrial/field use and give erroneous readings. Over-aeration wastes energy, while under-aeration kills a large proportion of the microbial population, which can lead to a failure to comply with the mill's discharge consent and potential pollution of the receiving water. Over-aeration typically wastes an estimated 20% of the blower energy consumption. Over-oxygenation in a plant using pure oxygen also leads to significant extra oxygen costs, eg up to £2 000/year on a typical oxygen bill of £10 000/year.

Monitoring the dissolved oxygen at different points throughout the aeration tank is also worthwhile. Oxygen demand is highest at the inlet to the aeration tank but even in well-mixed tanks there may be areas with low oxygen values. To remedy this the aeration rates of the blowers/aerators should be altered to ensure that oxygen is available where it is actually needed.

Buying the most reliable and robust dissolved oxygen probe that the mill can afford will prove a good investment. An accurate and reliable probe will soon pay for itself by reducing energy consumption and removing the risk of consent failure due to under-aeration.

Optimising the depth of immersion of the aerator blades in the aeration tank also produces significant cost savings.

3.5.9 Optimising aeration systems

Monitoring the dissolved oxygen content allows the mill to control the aeration process and reduce waste - particularly unnecessary energy consumption. However, this requires flexibility within the aeration system. If this is not the case, mills should consider installing a more suitable system. This will depend on the aeration method involved.

Diffused air

Installing variable speed motors on the blowers/aerators provides a greater degree of control and potential energy savings compared with running a bank of blowers controlled by switching one or more of them on or off.

Surface aerators

Linking the dissolved oxygen probe to a variable speed motor or to a gearbox allows the aeration rate to be slowed down or speeded up as demanded by the dissolved oxygen level.

For a fixed speed motor, the probe can be linked to an adjustable outlet weir or bellmouth controlling the level of liquid in the aeration tank. This link allows aeration to be controlled by adjusting the level of liquid in the aeration tank relative to the aerator. This arrangement works well with brush aerators used with an aeration ditch (a fairly common arrangement in the paper industry). It is less satisfactory for conventional aerators because the unit remains operating at the same speed.

Mechanical and/or electrical alterations to aeration equipment have a short payback due to the significant energy savings. When the aeration capacity is reduced, it is important to ensure that adequate mixing is maintained.

Pure oxygen systems

Pure oxygen or oxygen-enriched activated sludge systems are becoming increasingly common for industrial effluent treatment, particularly in the paper industry. As well as new units, a number of mills have retrofitted a pure oxygen system to an existing conventional aeration plant. This has allowed the aeration plant to cope with an increase or major change in mill production.

Upgrading to a pure oxygen activated sludge system

Retrofitting a pure oxygen system at Inveresk Graphic Paper Sector's Kilbagie Mill has reduced operating costs and improved the quality of the final effluent (see Industry Example 2 in Section 6). Despite the increase in effluent flow and strength, the cost of supplying oxygen is less than the energy costs associated with the previous conventional aeration system.

Retrofitting a pure oxygen system to an existing activated sludge process enables the control system to be adjusted so that pure oxygen is introduced only during periods of high demand (high BOD load), ie to provide supplementary capacity. When 'normal' conditions return, the pure oxygen system can be switched off, thus optimising the use of more expensive pure oxygen.

As with diffused air and surface aerators, significant efficiency savings can be achieved through using dissolved oxygen probes and feedback control of oxygen input. For pure oxygen systems, this control works directly from the oxygen supply rather than by turning recirculation/mixing pumps on and off. New plants with pure oxygen systems are invariably designed with feedback control from dissolved oxygen probes as an integral part of the operating system. Very accurate dissolved oxygen levels can therefore be maintained - usually between an upper and a lower set point - thus avoiding unnecessary oxygen use.

Pure oxygen systems have a number of operational advantages over conventional aeration systems, including:

- smaller footprint owing to their ability to intensify the process by operating at higher MLSS levels;
- significantly reduced sludge disposal costs due to operation at extremely long sludge ages and encouragement of endogenous respiration (ie the bacteria start to feed on themselves);
- lower energy consumption due to elimination of the need to blow the nitrogen content of the air (70% by volume) into the tank and then blow it out again;
- reduced potential for odour due to the surface of the aeration tank remaining essentially intact.

Before installing or retrofitting a pure oxygen system, each mill should assess its technical requirements and decide whether the use of more expensive oxygen will prove cost-effective in the long-term.

3.5.10 Aerator efficiency

Knowledge of the theoretical oxygen requirement for a specific plant, ie the rate of use of oxygen by that plant, is also important when optimising plant performance.

The energy used to operate the aerators is generally the highest cost associated with running an effluent treatment plant.

For standard carbonaceous treatment processes, the oxygen requirement should typically be 1.0 - 1.2 kg oxygen per kg BOD removed. This figure increases to over 1.5 kg oxygen per kg BOD removed for plants that are expected to nitrify.

To ensure the efficiency of the aerators, it is necessary to monitor electricity consumption compared to the quantity of oxygen dissolved. This varies for different aeration methods, but as a general rule, an aerator should be capable of dissolving 2 kg oxygen/kWh. Typical performance in the paper industry is nearer 1.5 kg oxygen/kWh. If the actual figure is much lower, the aeration system should be reviewed because inefficient systems waste money. As shown in the example, even small efficiency improvements can have a significant impact on operating costs.

Example cost savings from optimising aerator efficiency

At The Paper Company Limited, the plant parameters are:

Influent flow rate	250 m^3/hour, ie 6 000 m^3/day or 6 000 000 litres/day
Influent BOD	300 mg/litre, ie 0.3 g/litre
MLSS	3 000 mg/litre, ie 3.0 g/litre
Volume of aeration tank	3 000 m^3

The maximum requirement for BOD removal is therefore:

6 000 m^3/day @ 0.3 g/litre BOD = 6 000 x 1 000 x 0.3 g BOD/day

= 6 000 x 0.3 kg BOD/day

= 1 800 kg BOD/day

At an oxygen requirement of 1.2 kg oxygen/kg BOD removed, this amount of BOD requires 2 160 kg oxygen/day.

At an aeration efficiency of 1.5 kg oxygen/kWh (typical of the industry), this would use 1 440 kWh/day. At a typical cost of 5 pence/kWh, the power cost for oxygenation is £72/day or £26 280/year.

But, at an aeration efficiency of 2 kg oxygen/kWh, only 1 080 kWh/day would be required. This would give a power cost for oxygenation of £54/day - a saving of £18/day or **£6 570/year**.

Increasing aeration efficiency

Ways in which aeration efficiency can be improved include:

- servicing the air compressors regularly;
- inspecting the diffusers for physical damage/blockages;
- avoiding excessive inert solids in the aeration tank;
- avoiding overdosing anti-foaming agents (see Section 3.7.2) into the aeration tank.

Significant cost savings can be obtained by:

- controlling the dissolved oxygen content and thus reducing energy consumption by the blowers - and controlling oxygen use in pure oxygen systems;
- optimising immersion depths to provide oxygen where it is needed;
- reducing energy consumption by optimising aeration efficiency to as near 2 kg oxygen/kWh as possible.

3.6 TACKLING THE PROBLEM OF BULKING ACTIVATED SLUDGE

Bulking activated sludge is a term used to describe sludges with poor settling characteristics. The phenomenon generally results from either:

- filamentous bacteria; or
- excessive bound water within the sludge floc.

Fig 6 shows the 'bridges' between flocs caused by filamentous bacteria and Fig 7 excessive filaments leading to bulking. It may be helpful to compare Figs 6 and 7 with Fig 3 (see Section 3.4), which shows healthy, rounded sludge flocs.

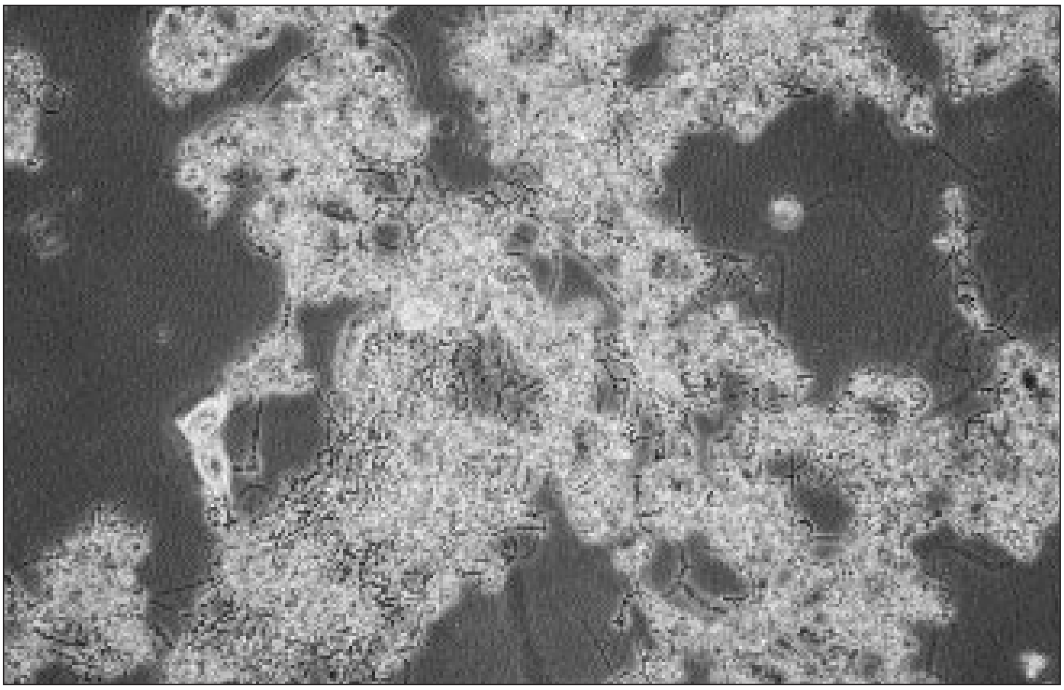


Fig 6 Filamentous bacteria causing 'bridging' between flocs (x100)

In the UK paper industry a frequent problem is bulking activated sludge, which is most often due to the presence of filamentous bacteria. This Guide describes techniques that various UK mills have found to be effective in combating bulking activated sludge.

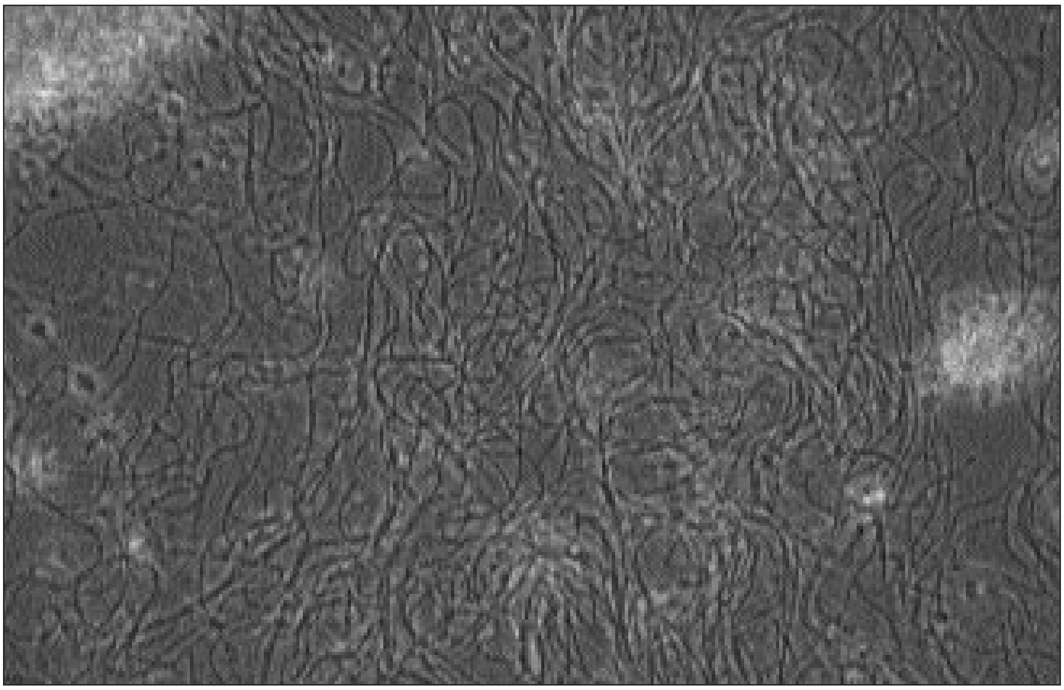


Fig 7 Excessive filaments leading to bulking (x400)

Prevention is better than cure. Taking time to understand and solve the basic problem will cost less in the long-term than applying a 'quick fix'.

3.6.1 Common causes of bulking activated sludge

The main causes of bulking activated sludge are associated with:

- the nature of the effluent from the mill;
- the operation of the plant;
- the design of the plant.

Effluent treatment plant operators have no influence on the plant design, but a major influence on its performance. They have much less control of the nature of the effluent leaving the mill, but this can be overcome by effective balancing (see Section 2) and dialogue between the mill and the effluent treatment plant.

The nature of the influent to the activated sludge plant is a critical factor in the plant's performance. Regular communications and discussions between mill staff and effluent plant staff about the effects of variations in mill output on the operation of the effluent treatment plant are essential.

Factors affecting the operational performance of the activated sludge plant include:

- Variations in the pH, flow, load and nutrient content of the influent to the aeration tank.
- Maintenance of correct dissolved oxygen levels, F:M ratios and recycle rates for return activated sludge (RAS).
- The retention time in the aeration tank and the clarifier.
- The presence or lack of a selector zone. A selector zone, where the influent and RAS are mixed, helps to prevent bulking activated sludge.

It is important to decide whether the problem is a 'one-off' or short-term, or whether there is a fundamental and deep-rooted problem which produces conditions that favour the growth of filamentous bacteria.

The prevention and control techniques described in Sections 3.6.2 and 3.6.3 respectively are applicable to occasional occurrences of bulking activated sludge and should not be used as a long-term solution to the problem of persistent outbreaks. If the problem is persistent, changes to the design of the plant to favour the growth of floc-forming bacteria rather than filamentous bacteria should be considered. Advice on plant design is beyond the scope of this Guide and should be obtained from a specialist consultant or plant manufacturer. The Environment and Energy Helpline on 0800 585794 can provide names of possible consultants.

3.6.2 Preventing bulking activated sludge

It is important to examine the activated sludge under the microscope.

- Confirm that the problem is due to filamentous bacteria (see Figs 6 and 7).
- Identify the species present. This will tell the mill employees whether the problem is the same as before and can be dealt with accordingly or whether it is something different requiring the specialist advice of an external consultant.

Oxygen limitation is the single most common cause of bulking in UK paper mills. The F:M ratio and sludge age are also important. Too low an F:M ratio can cause the growth of certain strains of filamentous bacteria, whereas too high an F:M ratio can encourage the presence of small dispersed floc that also lead to poor sludge settling characteristics. A long sludge age can be identified by the type of micro-organism present (see Section 3.3).

Other common causes of bulking include wide variations in BOD and pH. Such variations can be controlled by ensuring adequate upstream balancing (see Section 2) of the influent to the activated sludge plant. Talking to mill staff about the need for a balanced flow and the consequences of poor control will also help. A nutrient balance that favours the growth of floc-forming bacteria should also be maintained (see Section 3.5.5).

Checklist 2 provides a list of measures that operators can take to prevent bulking due to the presence of filamentous bacteria.

3.6.3 Controlling bulking activated sludge

Although prevention is better than cure, this is not always practicable. A number of techniques have been developed for short-term control of filamentous bacteria.

Use of oxidising agents

If the measures described in Checklist 2 have proved unsuccessful or are not practicable, adding a strong oxidising agent to the return activated sludge (RAS) stream can be effective.

When using strong oxidising agents, care should be taken to avoid the formation of chlorinated organics such as pentachlorophenol (PCP). Discharge of these toxic substances to the environment is controlled under Integrated Pollution Control (see Section 1.4). Phenol is present naturally in the raw materials of the papermaking process and may therefore be present in the effluent. The potential for the formation of PCP and other chlorinated organics means that chlorine and its compounds should be used with care.

Checklist 2 For preventing bulking activated sludge

- ☐ Maintain a good, positive dissolved oxygen level within the aeration tank. To prevent bulking, increase the dissolved oxygen level slightly to above 2 mg/litre. Do not waste energy by operating at an unnecessarily high dissolved oxygen level.
- ☐ Ensure that the F:M ratio is maintained according to the plant's original design parameters. Table 3 (see Section 3.5.3) gives recommended F:M ratios for common activated sludge processes.
- ☐ If the optimum sludge age (see Table 3) is not being achieved, it should be controlled by adjusting the amount of sludge lost from the system (see Section 3.5.4).
- ☐ Ensure adequate and effective upstream balancing of the influent to remove wide variations in pH and BOD load. Ideally, balancing capacity should be 12 - 24 hours of flow. A simple acid/alkali dosing system for pH correction can also be effective.
- ☐ Maintain sufficient nutrients within the system to encourage the growth of floc-forming bacteria. Aim for a BOD:N:P ratio of 100:5:1.

Table 4 gives the dose rates for three common oxidising agents.

Oxidising agent	Dose rate	Comments
Chlorine (as gas or hypochlorite)	5 - 10 g chlorine/kg MLSS/day	Use of chlorine gas is problematical owing to handling and associated health and safety precautions.
Hydrogen peroxide (H_2O_2)	0.2 - 0.4 kg H_2O_2/kg MLSS/day	A 50% solution has proved effective for the short-term treatment of filamentous bacteria. Minimises the formation of chlorinated organics.
Ozone	0.5 - 0.7 g ozone/kg MLSS/day	Minimises the formation of chlorinated organics.

Table 4 Use of oxidising agents to control bulking activated sludge

Use of biocides

A number of companies supplying chemicals to the paper industry have developed non-oxidising biocide formulations. These biocides, which are often based on formaldehyde or glutaraldehyde, have proved effective for the control of filamentous growth. There is no evidence of problematic side effects.

Flocculant addition

Adding high molecular weight polymers can also be effective in achieving short-term improvements in $SSVI_{3.5}$ levels (ie lowering the value), counteracting the raised levels caused by a predominance of filamentous bacteria. The polymers increase the bulk density of the flocs and thus increase settlement rates.

The high cost of these synthetic flocculants, even at a typical dose rate of 2 mg/litre, makes this a short-term option only.

3.7 OTHER OPERATIONAL PROBLEMS ASSOCIATED WITH THE ACTIVATED SLUDGE PROCESS

3.7.1 Rising sludge not associated with 'bulking'

When rising sludge is observed in the secondary clarifier, care must be taken to identify the cause of the problem. Rising sludge is not always due to the presence of excessive amounts of filamentous bacteria. Examination of the biomass under the microscope is the best diagnostic technique.

Denitrification occurring in the secondary clarifier is another common cause of rising sludge; the nitrogen gas produced by denitrification attaches to the flocs and causes them to float. The problem can usually be identified by bubbles of gas breaking through the surface of the clarifier.

Denitrification is usually prevented by providing an anoxic zone - or oxygen-limited environment - prior to the bioreactor. In this zone, nitrate and nitrite are utilised as a preferential source of oxygen and are therefore minimised in the effluent within the clarifier.

In the absence of an anoxic zone, denitrification in the secondary clarifier can be discouraged by:

- Increasing the return activated sludge (RAS) recycle rate.
- Reducing the flow rate into the clarifier.
- Reducing the sludge age by increasing sludge loss.
- Maintaining an excessive dissolved oxygen level in the aeration tank. However, this should be below 4 mg/litre.

3.7.2 Foaming

Foaming is the presence of a stable 'mousse-like' foam on the surface of the aeration tank and is usually caused by the presence of *Nocardia*, a type of filamentous bacteria. A hydrophobic material secreted by the bacteria is also thought to help to maintain the foam layer. This foam can also appear on the surface of the clarifier. Foaming causes significant nuisance problems, eg odour and foam dispersed around the plant by the wind.

The *Nocardia* foam is often associated with a plant that is running at a higher MLSS value than its design specification and hence a greater than normal sludge age. Increasing the aeration to maintain the dissolved oxygen (DO) level needed for this high MLSS exacerbates the problem by entrapping more air within the flocs.

Increasing sludge loss to lower the MLSS and sludge age is the most effective way to bring the problem under control. Reducing aeration (assuming that sufficient DO can be maintained) can also be effective.

As with other filamentous organisms, chlorination of the RAS or spraying hypochlorite directly onto the foam can be effective. Care should be taken when using anti-foaming agents as they generally act by altering the surface tension. This can have an adverse effect on DO, which may drop to unacceptable levels. Increasing aeration in an attempt to maintain DO levels will then just exacerbate the problem.

3.8 MONITORING AND CONTROL OF THE ACTIVATED SLUDGE PROCESS

A number of variable parameters affect the quality of the final treated effluent and/or the operating costs of the effluent treatment plant.

An essential aspect of the management of an activated sludge process is the setting up of a full and comprehensive data collection system. This monitoring regime should provide the operator with all the information needed to optimise the process.

It is equally important to use these collected data to maintain optimum conditions throughout the process.

section 3

Fig 8 shows a typical daily log sheet for the monitoring and control of an activated sludge process completed by an operator at The Paper Company Limited. The data include those used in earlier examples from this fictitious company.

Appendix 4 contains a blank form which may be photocopied as required for use at individual mills. This form is intended for guidance only because exact requirements will vary from plant to plant.

Checklist 3 For activated sludge

- ☐ Treat the bacteria and other micro-organisms present as a sensitive colony of living biomass.
- ☐ Monitor the effluent plant on a daily basis. Photocopy the blank example operator's log sheet (see Appendix 4) and use this to record data. Take remedial action in response to unexpected events or trends away from best practice.
- ☐ Examine sludge samples under the microscope routinely, checking particularly for evidence of excessive filamentous bacteria or *Nocardia* (these cause bulking activated sludge and foaming respectively).
- ☐ Set up an on-site analytical testing regime or contract it out to a local specialist laboratory.
- ☐ Calculate the food:mass (F:M) ratio. Is it within the limits given in Table 3 (see Section 3.5.3)?
- ☐ Is nitrification required, ie is NH_4-N present in the effluent consent?
- ☐ Calculate the sludge age. Is it within the limits given in Table 3 (see Section 3.5.3)?
- ☐ Adjust the BOD:N:P ratio in the influent to 100:5:1 by adding controlled amounts of supplementary nitrogen and phosphorus.
- ☐ Maintain the UFR to the secondary clarifier at 1.6 m/hour ± 20% (ie ± 0.32) and check the retention time within the clarifier is 4 - 5 hours.
- ☐ Check for evidence of denitrification. If occurring, take action to prevent nitrate conversion to nitrogen gas.
- ☐ Measure the settling characteristics of the sludge in the secondary clarifier (the faster the settling rate and denser the flocs the better).
- ☐ Use a reliable and accurate DO probe. If necessary, buy one.
- ☐ Operate at as low a DO value as practicable without limiting oxygen availability, ie >0.5 mg/litre and between 0.5 - 2 mg/litre.
- ☐ Link the DO probe to provide feedback control of oxygen input.
- ☐ Measure the DO distribution in the aeration tank and optimise aeration to provide oxygen where most needed.
- ☐ Control the rate of oxygen addition according to variations in the influent's total organic carbon.
- ☐ Calculate the plant's theoretical oxygen requirement.
- ☐ Monitor the amount of energy used by the aerator and calculate the aeration efficiency. Optimise aeration efficiency to achieve a dissolution rate of 1.5 - 2 kg oxygen/kWh.

3.9 ATTACHED GROWTH SYSTEMS

Attached growth or fixed film systems are becoming more common for the biological treatment of paper mill effluent. Aerobic filters - also known as trickling or percolating filters - are the most widely encountered, but other systems, eg the rotating biological contactor, are also found in the industry.

All attached growth systems rely on an artificial support medium upon which a microbiological slime is encouraged to grow. Like activated sludge systems, it is imperative that the slime receives a constant supply of food (BOD) and oxygen. An efficient route for transporting dead cells and other inert material away from the active site is also essential. The removal of this waste material is known as 'sloughing'. Effective sloughing requires the correct permeability and flow conditions within the support media. The solids produced by sloughing are removed from the system as humus in a downstream secondary clarifier.

The operational problems associated with suspended growth systems are usually due to the failure to provide:

- a constant supply of food and oxygen;
- effective sloughing of the support media.

Ways of avoiding operational problems associated with these parameters are described below.

3.9.1 Aerobic biofilters

One of the main points to note about all biological filters is that they have, unfortunately, been named incorrectly. BOD removal and degradation rely on a complex series of biological processes rather than physical filtration. In fact, upstream removal of solids from the effluent is essential to prevent fouling and subsequent blockage of the filter media. Fig 9 shows the layout of a typical percolating filter.

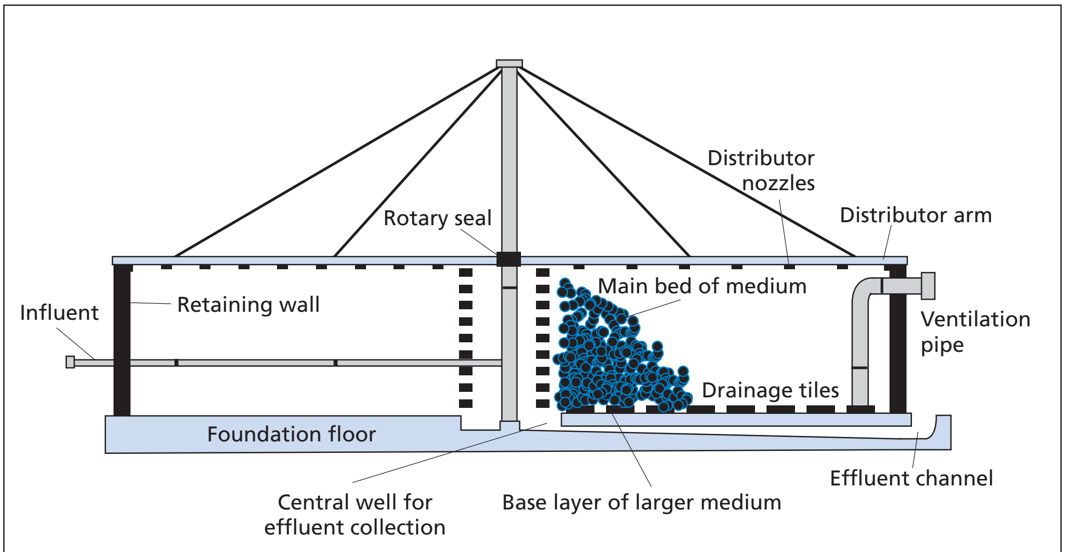


Fig 9 Design of a percolating filter

Basic microbiology

When considering how to deal with common operating problems, it is important to understand some of the basic microbiology of aerobic biofilters.

As with the activated sludge process, large and complex colonies of bacteria and protozoa help to make up the biological slime. However, biofilters also contain a significant number of macro-invertebrates - particularly worms and flies such as *Anisopus* and *Psychoda.* These macro-invertebrates have an important part to play in the breakdown and biodegradation of the bacterial slime as it grows on the surface of the support media.

Owing to the role played by macro-invertebrates, temperature is more critical than with the activated sludge process. During colder winter conditions, the activity of the macro-invertebrates falls more than that of the bacteria and protozoa within the slime. This comparative decline can lead to a substantial increase in slime thickness, which in turn has serious consequences in terms of physical blocking of the filter. It can be overcome by using warm effluent.

Support media

Historically, media materials have included various types of stone - with blast furnace slag being fairly common. Many of the older filters in use in the paper industry still achieve an effective performance with this type of medium.

The new generation of plastic media offers a number of advanced features, including:

- They are chemically inert.
- They offer high voidage, ie 'space' within the body of the filter.
- They offer high surface area per unit volume.
- They are lightweight (thus allowing higher structures than with stone filters).

High-rate filtration

This technique makes use of the open structure and low weight associated with plastic media. High-rate filtration is generally used for partial or 'roughing' treatment of paper mill effluent. It is particularly useful when only a relatively low percentage of BOD removal is required, eg 40 - 70%. High-rate filtration is more common in the paper industry when discharge is to an estuary or as a pre-treatment prior to trade effluent discharge.

Conventional or low-rate filtration is generally thought to have become high-rate filtration when the hydraulic loading rate exceeds 3.0 m^3/m^2 of surface area/day. Maximum values can be as high as 20 - 30 m^3/m^2/day.

The technique also has the advantage of a small plant footprint.

3.9.2 Avoiding operating problems with biofilters

Most of the problems associated with the operation of biofilters are due to some kind of physical blockage - often the result of operation outside the filter's design specification.

For all types of filter it is vital that the hydraulic loading rate and organic loading rate are kept within the limits necessary to ensure:

- the growth of the bacterial slime is not too excessive;
- slime growth is regularly and efficiently removed from the surface of the media and hence from the body of the filter.

As a general guide, the hydraulic loading rate and organic loading rate should be within the limits given in Table 5 for low-rate and high-rate filtration.

Type of filtration	Hydraulic loading rate*	Organic loading rate
Conventional or 'low-rate'	Generally 1 - 3 $m^3/m^2/day$	0.08 - 0.25 kg $BOD/m^3/day$
'High-rate'	3 - 30 $m^3/m^2/day$	0.3 - 2.0 kg $BOD/m^3/day$

* Also referred to as the wetting rate or irrigation rate.

Table 5 Operating limits for biofilter operation

Nitrifying plants

Hydraulic and organic loading rates are even more important if nitrification is required. This is not generally necessary in the UK paper industry as mill effluents tend to have a low ammoniacal nitrogen content. However, should nitrification be required, the upper limits to achieve 90% nitrification are a hydraulic loading rate of 0.6 $m^3/m^2/day$ and an organic loading rate of 0.1 kg $BOD/m^3/day$.

Common operational problems

Table 6 summarises the main operational problems associated with aerobic biofilters and some solutions (see also Checklist 4).

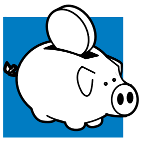
Problem	Solution/prevention
Excessive slime growth or ineffective sloughing causing blockages and subsequent ponding.	Avoid operating outside the maximum and minimum operating parameters specified in Table 5.
Solids in the influent blocking the support media, rotor arms and/or nozzles of the distribution pipework.	Ensure effective removal of coarse solids - especially fibres - during primary treatment.
Physical damage to the underdrain system.	Ensure the underdrains are capable of supporting the combined weight of the support and biomass. Effective operation unachievable until the underdrain system has been inspected and, if necessary, replaced.
Spray drift and associated odour problems.	Ensure there is sufficient freeboard at the top of the bed.

Table 6 Problems associated with biofilter operation and their solutions

3.10 ANAEROBIC EFFLUENT TREATMENT

The UK paper industry is beginning to accept anaerobic biological treatment of effluent, ie treatment in the absence of oxygen, as an appropriate technique. In this respect, the paper industry has tended to lag behind other industries where anaerobic treatment has been used for a number of years. However, some paper mill effluents are not suitable for anaerobic treatment due to their relatively low BOD, compared to some industries.

As with the aerobic activated sludge process, anaerobic treatment is essentially an intensification of a naturally occurring phenomenon. When decaying leaves and other organic matter are allowed to decompose at the bottom of stagnant ponds, methane (CH_4) - often referred to as marsh gas - is produced as a consequence of the action of anaerobic bacteria.



Unlike aerobic treatment, anaerobic treatment converts most of the organic carbon associated with the influent BOD to methane rather than to biomass. Anaerobic treatment processes therefore have significantly lower sludge disposal costs than aerobic processes.

3.10.1 The use of anaerobic treatment in the paper industry

Anaerobic treatment systems require a higher BOD loading - in terms of kg of BOD/m^3 of reactor volume - than aerobic systems. For paper mills with an effluent containing typically 100 - 300 mg/litre, eg white mills such as tissue and newsprint, the size of reactor required would be too large to be justified on economic grounds. However, for brown mills, eg cardboard/packaging, where the effluent BOD concentration may be 1 000 mg/litre or more, the cost savings associated with anaerobic treatment produce an acceptable payback.

Anaerobic secondary treatment

Some mills, eg Smurfit Townsend Hook's mill at Snodland in Kent, use anaerobic processes as a pre-treatment prior to an aerobic process. As described in Industry Example 4 in Section 6, anaerobic pre-treatment has allowed the mill to reduce overall running costs by reducing the load of the aeration lagoons and reducing sludge disposal costs.

3.10.2 Advantages and disadvantages of anaerobic treatment

For the paper industry, the main advantage of anaerobic treatment is that most of the organic carbon in the effluent is converted to methane rather than being used as a food source for new cell growth. The amount of waste sludge produced is therefore approximately 20 - 33% of the amount produced if the same load had been treated by an aerobic process (see Section 5.1).

A significant disadvantage for the paper industry is that anaerobic treatment alone is unlikely to produce an effluent suitable for discharge to a river or an estuary. In such cases, the main BOD load is removed in an anaerobic plant with an aerobic plant used to polish the effluent prior to final discharge. However, a much smaller aerobic polishing plant is needed than for aerobic treatment alone. In cases where the effluent is discharged to sewer as trade effluent (when the sewage works provides further treatment), anaerobic treatment is commonly the only on-site secondary treatment technique used.

The main advantages and disadvantages of anaerobic treatment are summarised in Table 7.

Advantages	Disadvantages
Lower operating costs due to: ■ less sludge production; ■ lower mixing costs.	Higher capital costs.
	Commissioning and initial acclimatisation phases can be long.
Useful by-product, ie methane gas.	Some constituents of treated effluent can be toxic/corrosive, eg hydrogen sulphide.
Fewer odour problems (provided appropriate abatement techniques are employed).	Can generally only be utilised as a pre-treatment stage prior to effluent polishing.
Lower macro-nutrient and micro-nutrient requirements due to slower microbiological growth.	Bacteria may require external source of heat.
Can remain in a dormant state for extended periods while decommissioned.	Require more steady state conditions.
	Less tolerant to toxic shock.

Table 7 Advantages and disadvantages of anaerobic treatment of paper mill effluents

3.10.3 Common operational problems

Table 8 summarises the main causes of a decline in the performance or efficiency of an anaerobic treatment plant and suggests measures to avoid these problems (see also Checklist 3).

Problem	Solution
Lack of macro-nutrients	Maintain BOD:N:P ratios at 500:5:1.
pH change	Maintain the reactor pH 6.8 - 7.5.
Temperature change	The optimum reactor temperature for the anaerobic bacteria is 35 - 37°C.
Lack of micro-nutrients	Maintain the minimum quantities of micro-nutrients required by the process - especially iron, calcium, magnesium and zinc.
Significant quantities of fats, oils (especially mineral oils) and greases	Remove these contaminants in an efficient dissolved air flotation (DAF) unit upstream of the reactor. All these contaminants may inhibit bacterial growth and mineral oils may poison the bacteria.
Physical blockage of the reactor inlet pipework	Effective screening and primary treatment is essential.
Overloading	Care should be taken to ensure that the hydraulic and organic loading rates do not exceed the values recommended by the plant supplier.

Table 8 Anaerobic effluent treatment: common operating problems and their solutions

Checklist 4 For other biological processes

Aerobic biofiltration

- ☐ Check that large solids have been removed in the primary treatment plant.
- ☐ Maintain the hydraulic loading rate and organic loading rate within the operating limits specified in Table 5 (see Section 3.9.2).
- ☐ Ensure that slime removal occurs regularly and efficiently.
- ☐ Carry out routine microscopic examinations of the biological slime.
- ☐ In cold climatic conditions, take action to avoid excessive slime thickness due to reduced macro-invertebrate activity.
- ☐ Do not overload the underdrains with support media and biomass.
- ☐ Ensure that there are no restrictions on air flow through the support media.

Anaerobic effluent treatment

- ☐ Assess the economics of using anaerobic treatment for effluents with a BOD of ≥ 1 000 mg/litre.
- ☐ Maintain the reactor under the following conditions:
  - pH 6.8 - 7.5;
  - 35 - 37°C;
  - BOD:N:P = 500:5:1;
  - minimum amounts of micro-nutrients (especially Fe, Ca, Mg and Zn).
- ☐ Remove suspended solids by upstream processes.
- ☐ Remove fats, oils and greases in an upstream DAF unit.
- ☐ Keep the hydraulic loading rate and organic loading rate within the reactor specifications.

4 TERTIARY TREATMENT

Tertiary treatment is the term used to describe the polishing of the effluent following primary and secondary biological treatment. The decision to subject an effluent to tertiary treatment depends on a number of factors, but mainly:

- the quality required to render the treated effluent suitable for recycling, ie return to the papermaking process or low quality duties within the mill;
- the quality required for the final effluent to comply with the consent conditions imposed by the regulatory authorities (direct discharge to controlled waters) or the water companies (discharge as trade effluent to sewer).

4.1 WATER RECYCLING

There are two options for recycling water in a paper mill, ie before and after effluent treatment (see Fig 10).

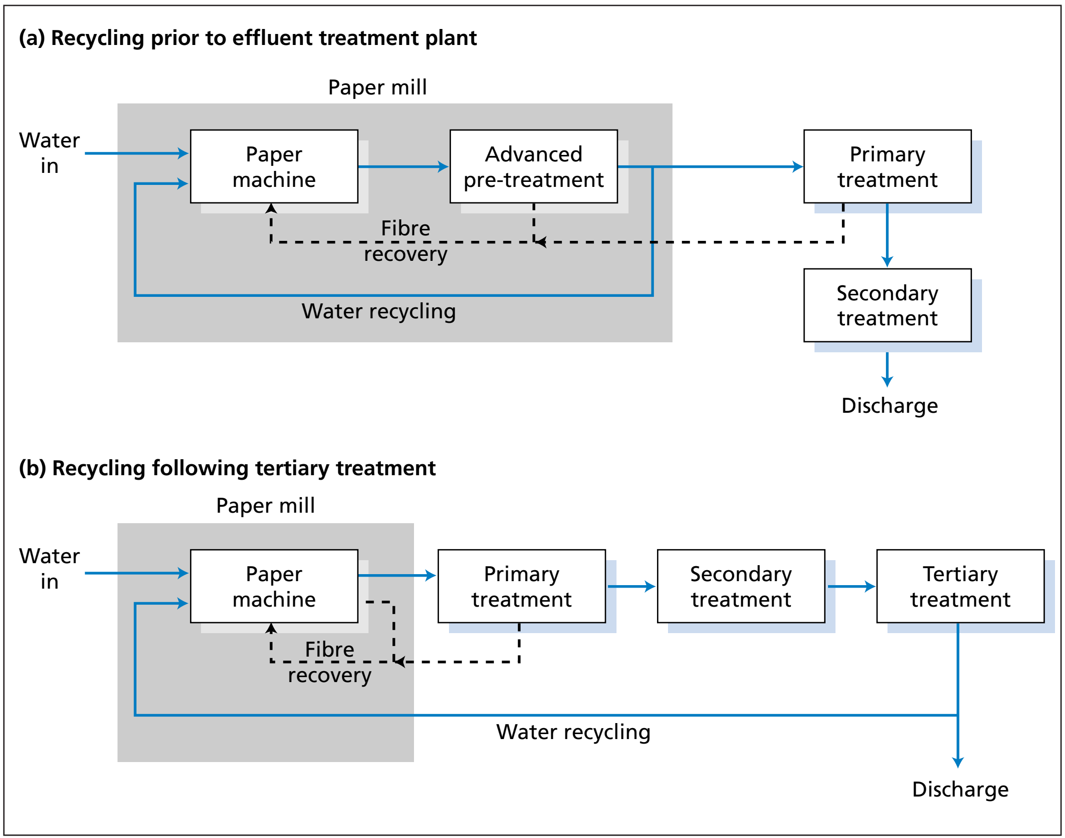


Fig 10 Recycling options

Minimising water use by reducing consumption and recycling water within the papermaking process has a number of advantages, including:

- reducing the amount of fresh water required by the mill;
- reducing the flow and load to the effluent treatment plant, thus reducing plant operating costs (energy, chemicals, maintenance, etc) and possibly size;
- reducing the amount of sludge requiring final disposal;

- reducing the flow of effluent discharged to controlled waters;
- reducing trade effluent charges for those mills discharging to sewer.

Ways of minimising water use in paper mills are described in more detail in Good Practice Guide (GG111) *Practical Water Management in Paper and Board Mills*. This Guide is available free of charge through the Environment and Energy Helpline on 0800 585794.

While water recycling prior to effluent treatment is the preferred option, some mills may find that water recycling after tertiary treatment proves more practical as there is no need to make fundamental changes to the papermaking process.

The decision whether to recycle water within the mill or after tertiary effluent treatment depends on the particular requirements of individual mills. For example, tertiary treatment may be necessary to meet tighter consent conditions. If so, the mill may be able to achieve cost savings by returning some of the higher quality effluent to the papermaking process. The destination of the recycled effluent may also influence the decision. Stock preparation, boiler feed water, floor cleaning, etc all require water of a different quality.

4.2 EFFLUENT POLISHING

Some effluents require tertiary treatment to enable the mill to meet stringent discharge consents. In addition to the standard consented parameters (flow rate, pH, temperature, COD/BOD and turbidity), the mill's consent may specify limits on a number of other parameters/substances. Specialised treatment prior to discharge is therefore required to meet these additional consent conditions. This treatment will depend on the nature of the mill's processes and the nature of the receiving waters.

4.2.1 Ammonia

Ammonia is usually removed from paper mill effluent by allowing the activated sludge plant to operate under nitrifying conditions, ie with a sludge age greater than 10 days (see Section 3.5.2).

Separate nitrifying filters can also be installed and these are fairly common in the paper industry. Such filters are normally variations on the standard percolating or high-rate aerobic filters described in Section 3.9.1. They may be installed after activated sludge or attached growth systems.

4.2.2 Colour

Colour can be a problem with effluents from de-inking plants owing to the pigments associated with inks and dyes. These complex organic molecules tend not be degraded by biological processes and are often referred to as residual or 'hard' COD.

Colour is usually removed or reduced by adding a strong oxidising agent, eg chlorine, hypochlorite, hydrogen peroxide or even ozone. Following such treatment, the resulting lower molecular weight organics may actually cause a slight increase in BOD. In such circumstances, part of the treated effluent is generally recirculated back through the secondary biological treatment plant.

4.2.3 Turbidity

A tertiary solids removal filter is often needed to remove residual suspended solids. Excessive suspended solids in a final effluent usually indicate a process failure upstream - particularly for activated sludge plants.

A standard sand or dual-media filter, eg sand/anthracite, may be satisfactory depending on the severity of the problem and the nature of the solids. A number of constantly self-cleaning sand filters are now available which are extremely effective in removing suspended solids from the final effluent.

4.2.4 Schedule 5 materials

As explained in Section 1.4, these are the prescribed substances for release into water listed in Schedule 5 of the Environmental Protection (Prescribed Processes and Substances) Regulations 1991 and subsequent amendments. Schedule 5 materials, eg mercury, cadmium and pentachlorophenol (PCP), are known to exhibit high levels of toxicity to aquatic organisms. Chief Inspector's Guidance Note IPR6/9 *Paper Making and Related Processes, Including Mechanical Pulping, Re-cycled Fibres and De-inking*[8] gives the limits for the releases of prescribed substances from paper mills to water and advises on quantifiable levels above the ultimate limit of detection.

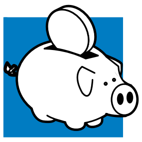
Although biological treatment is effective (anaerobic processes more so than aerobic ones) in degrading most organic compounds, there is a limit to the extent of removal of Schedule 5 substances. Many Schedule 5 substances - particularly those heavy metals arising from de-inking processes, eg mercury and cadmium - end up in waste sludges and thus become a solid waste rather than an aqueous waste problem. For advice on the disposal of waste sludges containing Schedule 5 substances, contact the local office of the Environment Agency, the Scottish Environment Protection Agency (SEPA) or the Environment and Heritage Service (in Northern Ireland).

Chlorinated organics in the effluent from the secondary biological treatment plant can be removed using membrane technologies such as reverse osmosis (RO) and ultrafiltration (UF). Membrane technology may also be effective in removing inorganic salts, bacteria and viruses from the effluent. It has also been used by some mills to achieve zero liquid effluent (ZLE). Further details on membrane treatment techniques are given in Good Practice Guide (GG54) *Cost-effective Membrane Technologies for Minimising Wastes and Effluents*. This Guide is available free of charge through the Environment and Energy Helpline on 0800 585794. The materials removed from the effluent form a concentrated aqueous stream (the retentate or reject stream), which requires disposal by a reputable waste disposal contractor. Options for disposing of this waste stream should be discussed with the Environment Agency, SEPA or the Environment and Heritage Service.

[8] Available from The Stationery Office (PO Box 276, London SW8 5DT. Tel: 0171 873 9090. Fax: 0171 873 8200), Stationery Office bookshops, accredited agents and some larger booksellers.

5 SLUDGE TREATMENT AND DISPOSAL

Solid waste management is a major issue for effluent treatment plants, with sludge disposal options limited by environmental legislation and ever increasing waste disposal costs.



The cost of sludge disposal is the largest component of the cost of operating a biological treatment plant. Sludge treatment to reduce the volume of sludge requiring disposal will produce savings through reduced transport and other costs, eg landfill charges. **However, mills that take action to reduce the amount of sludge produced in the first place will save considerably more money.**

Reducing disposal costs is an important objective for effluent plant mangers, generally through reducing the sludge volume. This Section outlines:

- ways of reducing the amount of sludge produced;
- techniques for reducing sludge volumes prior to disposal by landfilling, landspreading or incineration.

A detailed discussion of advanced and innovative sludge treatment and disposal techniques is beyond the scope of this Guide. The Environment and Energy Helpline on 0800 585794 holds a selection of directories of equipment suppliers and consultants. Helpline staff can also suggest other sources of information. Section 5.4 contains a sludge treatment checklist for mills to photocopy and use as required.

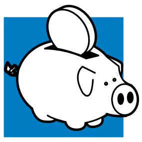
5.1 SLUDGE PRODUCTION IN EFFLUENT TREATMENT PLANTS

When seeking to minimise the amount of sludge produced by the effluent treatment plant, a mill should:

- take action to reduce the amount and strength of the effluent requiring treatment;[9]
- optimise fibre recovery in the mill and from primary treatment;
- optimise the primary treatment process (see Section 2) to reduce the load on the secondary biological treatment process;
- optimise the performance of the secondary biological treatment plant (see Section 3).

Any fibres and other solid waste, eg inorganic chalk fillers, that cannot be recovered must be disposed of in an environmentally acceptable way. In addition, aerobic treatment processes convert a high proportion of the organic load to new bacteria cells. The wasting of this biomass - as surplus activated sludge (SAS) - further contributes to the solid material requiring disposal. These disposal costs are just one component of the overall running costs of the effluent treatment plant.

[9] Contact the Environment and Energy Helpline on 0800 585794 for advice and details of relevant Environmental Technology Best Practice Programme publications.



Anaerobic processes (see Section 3.10) convert most of the organic load to methane gas as opposed to biomass cells. Sludge disposal costs from anaerobic processes are therefore significantly lower than with aerobic processes.

Table 9 shows the approximate amounts of sludge produced from different secondary biological treatment processes.

Biological process	Approximate sludge arisings (kg sludge*/kg BOD removed)
Conventional activated sludge	0.6 - 1.0
Extended aeration/oxidation ditch	1.0
Anaerobic systems	0.2

* As 100% dry solids.

Table 9 Approximate amounts of sludge generated by various biological processes

5.2 THE BENEFITS OF REDUCING SLUDGE VOLUMES

Many of the larger UK paper mills produce significant volumes of sludge. Sludge treatment, if practised, is generally undertaken off-site with only a small number of mills currently undertaking on-site treatment, eg incineration, composting and anaerobic digestion.

Reducing the volume of sludge requiring treatment or disposal produces significant cost savings, mainly by reducing tankering charges. For landfill disposal, it also reduces landfill reception charges. The relative reduction in volume associated with an increase in dry solids content of the sludge is shown in Fig 11.

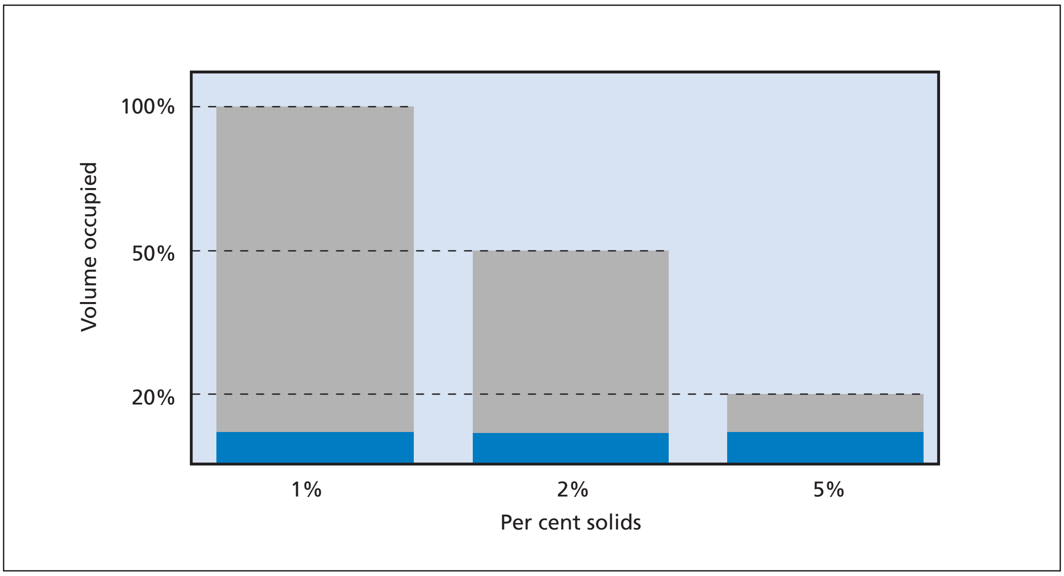


Fig 11 Relationship between sludge dry solids and volume

5.3 SLUDGE THICKENING

Most paper mills focus on reducing their sludge disposal costs by thickening the sludge. Thickening - one of the simplest dewatering techniques - consists of allowing the sludge solids to settle within suitably designed thickening tanks.

With regards to thickening, there is a fundamental and important difference between the sludges produced by primary and secondary effluent treatment plants in paper mills. Primary sludges, which consist mainly of inorganic material and/or waste fibres, are generally able to settle and compact without the need for chemical additions, eg coagulant/flocculant. The associated water is not trapped within the sludge. The opposite applies to secondary biological sludges, where the water is bound within the flocs and is generally more difficult to remove. Some form of chemical addition is always necessary to optimise the dewatering of biological sludges.

Where possible, optimise the thickening process by mixing any primary sludges with secondary biological sludges. The exact ratio will depend on individual mills and the relative volumes of sludges requiring disposal.

5.3.1 Optimising sludge thickening

The sludges removed from the bottom of primary and secondary settlement tanks generally contain 0.5 - 1.0% dry solids. Sludges from dissolved air flotation (DAF) units have slightly higher values - possibly up to 4% dry solids. Further simple consolidation of the sludge in settlement tanks is relatively straightforward, but the process can be optimised by:

- Using a tall and narrow settlement tank rather than a low one with a large surface area. The efficiency of the dewatering process depends on the height of the sludge layer and not on the volume of liquid above it.
- Considering the use of two tanks. This allows for quiescent settling of one tank while the other is filling up, but its cost-effectiveness depends on the actual pattern of primary solids/surplus activated sludge (SAS) removal. If a two-tank arrangement is not possible, the sludge inlet should be near the top of the tank - possibly flowing onto a baffle plate - to minimise hydraulic disturbance.
- Providing gentle agitation within the tank to help reduce 'banding' of the sludge and to promote the release of any entrained gases. The most common method is a picket fence within the tank.
- Selecting the optimum time for sludge to remain in the thickening tank. Residence time depends the nature of the sludges, but 24 hours is typical within the paper industry. Excessive retention must be avoided to minimise the possibility of anaerobic conditions occurring, with associated odour and corrosion problems.
- Adding sludge to the thickener at the rate of 20 - 30 m^3 of feed/m^2 of surface area/day.

A standard gravity/picket fence thickener should be able to produce a sludge with up to 4 - 8% dry solids. The extent of the increase in dry solids content depends on the nature of the raw sludge and particularly the relative content of fibrous sludge from the primary treatment stage.

Effective sludge management

The dry solids content of sludge from picket fence thickeners at UK Paper's Kemsley site in Kent is doubled by mixing primary treatment plant sludge with surplus activated sludge (SAS). For details of sludge management at the Kemsley site, see Industry Example 5 in Section 6.

5.4 SLUDGE DEWATERING

For many mills, sludge thickening is sufficient to reduce the volume of sludge to a more manageable level for off-site disposal. For larger mills, the thickening process is a first stage prior to further dewatering to produce a material - often referred to as sludge cake - which may contain 20 - 50% dry solids. This is treated as a solid waste. The point at which the sludge ceases to be a liquid and becomes a solid is a grey area, but a sludge containing more than 10% dry solids is difficult and expensive to pump. Sludge cake has the advantage of lower disposal costs; alternatively, it is suitable for further treatment, eg digestion, composting, drying or incineration.

For most sludges, some form of chemical conditioning is required to help separate the bound and entrained water from the flocs. A wide range of high molecular weight polymeric flocculants are available. The cost of these chemicals should be more than offset by the improved performance of the dewatering process. A regular testing regime should be carried out to optimise dosage.

Table 10 gives details of dewatering techniques used in the paper industry, together with typical performance levels.

Technique	Process type	Comments	Dry solids content of cake
Filter or plate press	Batch	Can be manually intensive.	Up to 40%
Belt press	Continuous	Requires regular and specialised maintenance for optimum performance. Chemical costs generally quite high.	Up to 35%
Screw press	Continuous	Particularly suited to mill waste with a high proportion of primary sludge.	25 - 30%
Centrifuge	Continuous	Minimal odour problems due to closed nature of the centrifuge.	40% (for fibrous sludges)

Table 10 Common dewatering techniques used in the UK paper industry

Checklist 5 For sludge treatment

Waste minimisation

- ☐ Minimise the amount of sludge produced by reducing effluent generation and optimising the performance of the primary and secondary biological treatment stages.
- ☐ Reduce the volume of sludge by reducing its water content.

Thickening

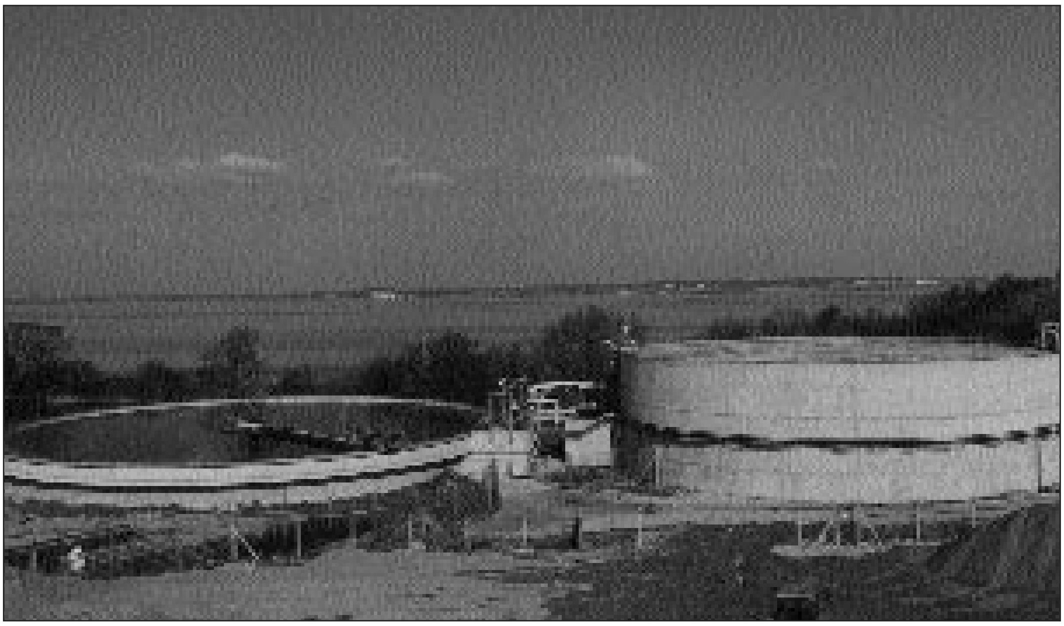
- ☐ Mix sludges from the primary and secondary biological treatment stages, according to their availability and composition.
- ☐ Use a tall and narrow settlement tank, with gentle agitation.
- ☐ Minimise hydraulic disturbance during sludge addition, preferably by using two tanks in a fill/settle cycle.
- ☐ Optimise the residence time in the tank.
- ☐ Add sludge at a rate of 20 - 30 m^3/m^2/day.

Dewatering

- ☐ Optimise dosage rates for chemical conditioners and monitor performance against chemical use.

Effluent plant optimisation at Bridgewater Paper

Bridgewater Paper manufactures approximately 240 000 tonnes/year of high quality newsprint on three machines at its site in Ellesmere Port, Cheshire. Recycled fibre from the on-site de-inking plants makes up 99% of the mill's feedstock.



The effluent treatment plant at Bridgewater Paper discharges into the River Mersey. The consent conditions are:

- suspended solids 45 mg/litre (90th percentile);
- BOD 25 mg/litre (100th percentile);
- pH 5 - 9.

Fig 12 shows the current arrangement of the effluent treatment plant.

Bridgewater Paper has found that rapid changes in influent volume or quality upset the biomass more than the actual load. To maintain steady state conditions, the plant is operated within tightly defined parameters. Monitoring is regular and frequent. Problems with bulking activated sludge are also combated by controlling the source of the problem as opposed to treating the symptoms.

Variations in the quality of the mill effluent, eg suspended solids, BOD, pH and flow rate, are smoothed out in a balancing tank located before primary treatment in a dissolved air flotation (DAF) unit.

Regular microscopic examination of the biomass in the activated sludge plant and identification of the species and number of organisms present provides operators with

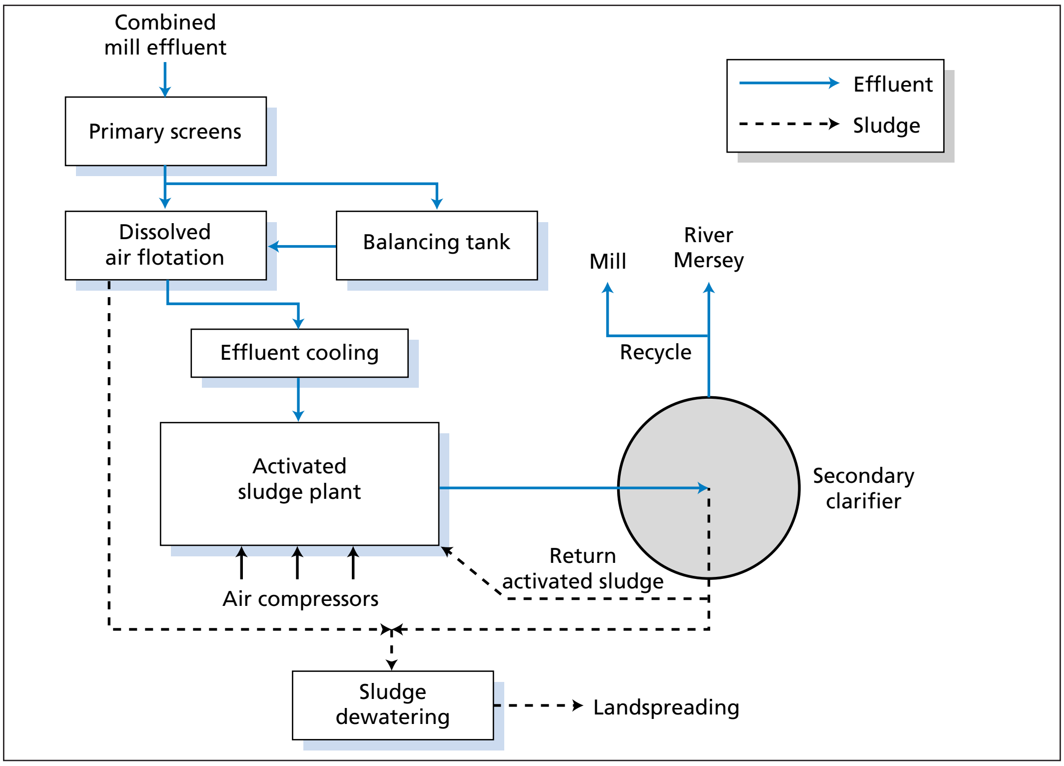


Fig 12 Layout of effluent treatment plant at Bridgewater Paper, Ellesmere Port

valuable process information. For example, *Arcella* are often observed after an upset to the activated sludge plant and also contribute to turbidity in the final effluent. During normal operation, operators expect to identify free swimming ciliates, rotifers, vorticella and other stalked ciliates - all species indicative of a healthy biomass.

The plant is controlled to an F:M ratio of approximately 0.12, with a sludge age of approximately eight days. The 'food' available to the biomass is measured in terms of BOD. Control is achieved by carefully monitoring the MLSS and the rate of loss of surplus activated sludge (SAS). This control technique is helped by having a fairly constant BOD load of approximately 3.5 - 4.5 tonnes/day and proves the value of efficient upstream balancing.

Bridgewater Paper also exerts tight control over the aeration plant compressors (two duty and one stand-by units) to maintain a residual dissolved oxygen (DO) level of 2 - 5 mg/litre at the outlet of the aeration tank.

Biological foaming incidents are controlled using a proprietary anti-foaming agent that does not affect surface tension and oxygen uptake rates within the aeration tank. When high levels of filamentous bacteria are observed in the biomass and sludge settlement is hindered, the problem is controlled by adding an oxidising agent - sodium hypochlorite - to the return activated sludge at a dose rate of 15 - 20 g/kg MLSS/day.

Bridgewater Paper adopted the practice of re-using treated effluent in the mid-1980s. The mill currently recycles approximately 25 - 30% of the treated effluent from the secondary biological treatment plant. The 200 m^3/hour flow is sterilised before being used in a number of papermaking processes.

The waste sludges from the de-inking plant, primary treatment plant and secondary biological treatment plant are combined and dewatered using a mixture of belt and screw presses. Part of the filtrate from the sludge presses is recovered and re-used in the de-inking process, while the rest is sent back to the effluent treatment plant. Sludge cake is used for off-site land reclamation, disposed of by landspreading or used to condition agricultural soils.

Upgrading to pure oxygen activated sludge at Inveresk Graphic Paper Sector

Inveresk Graphic Paper Sector's Kilbagie Mill near Edinburgh manufactures high quality office and business stationery papers using a feedstock with a recycled fibre content that ranges from 0 - 100%. The recycled fibre is recovered at the mill's on-site de-inking plant.

The effluent treatment plant at Kilbagie Mill discharges into the Forth Estuary. The consent conditions are:

- suspended solids 0.4 tonnes/day (95th percentile);
- BOD 1.2 tonnes/day (95th percentile);
- pH 6 - 9.

The load on the effluent treatment plant varies from 0.5 - 9.0 tonnes/day, depending on whether the de-inking plant is operational.

The current arrangement of the effluent treatment plant is shown in Fig 13.

In 1994, the effluent treatment plant at Kilbagie Mill was extended to coincide with the commissioning of the recycled pulp plant. The new system, which incorporated submerged aerators to oxygenate the biomass, was designed to treat an increased load of 5 tonnes/day of BOD. However, the submerged aerators struggled to cope with the peaks and troughs - typical of the paper industry - and energy costs increased significantly. Another problem was

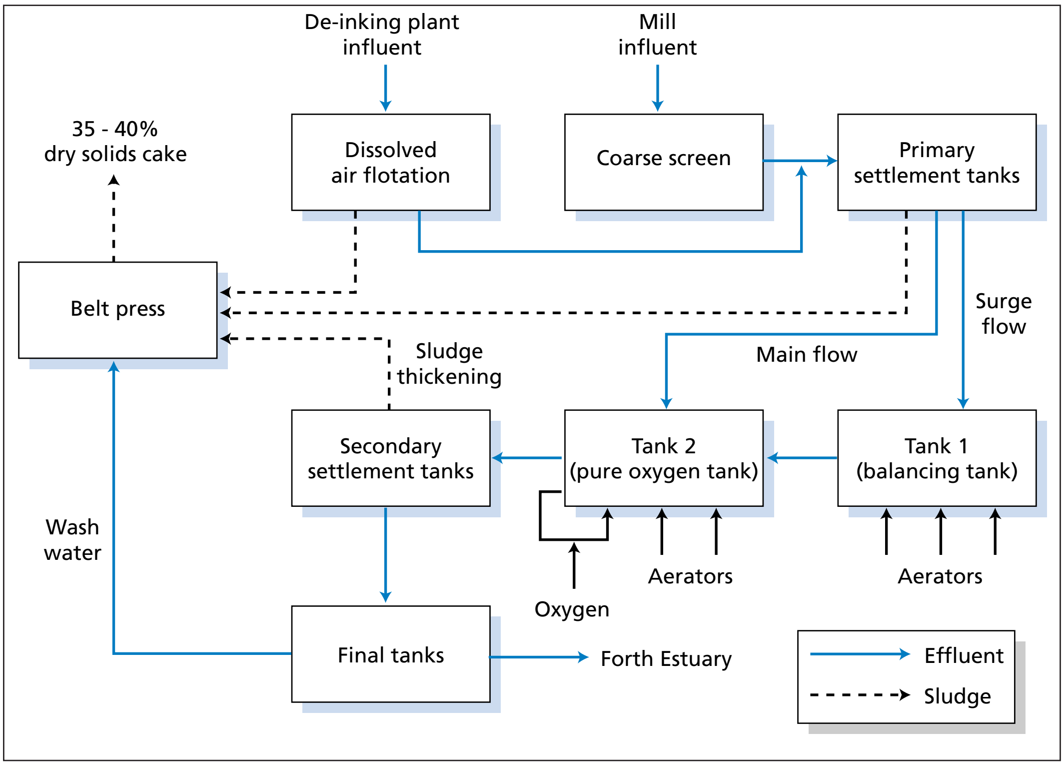


Fig 13 Layout of effluent treatment plant at Inveresk Graphic Paper Sector's Kilbagie Mill

that the system could not handle extra effluent flow generated by activities such as machine boil-outs, start-ups or storms. New environmental legislation also meant that Inveresk Graphic Paper Sector faced stricter discharge consents.

To solve these problems, retrofitting a pure oxygen system was proposed. This had the advantage of being more efficient than conventional aeration, thus allowing effluent to be treated at twice the rate in a smaller reactor volume. The oxygen dissolution equipment is capable of operating efficiently in the existing 6 m-deep tank, something that the original air-based system could never achieve. This also meant that an existing treatment tank could be converted into a balancing tank to accommodate surge flows, thus avoiding the need for capital expenditure.

Since the pure oxygen system was installed, operating costs have fallen by 40% despite the fact that the plant is treating more effluent with a higher BOD than before. The costs associated with oxygen supply are less than the cost of the electricity to power the submerged aerators. In addition, the effluent treatment plant, which is at the edge of the site, now needs much less monitoring by mill staff.

A further development has been the installation of a selector zone within the main body of the pure oxygen activated sludge tank. This has helped to minimise bulking activated sludge problems. Influent, return activated sludge (RAS) and nutrients are all added at this point, under conditions of high floc loading. This encourages the growth of floc-forming bacteria and discourages the growth of filamentous bacteria.

Retrofitting a pure oxygen system to the existing treatment plant not only cut costs, but has also led to an improvement in the quality of the final effluent. The oxygen activated sludge plant now operates at an F:M ratio of 0.15 and an MLSS of 4 000 - 4 500 mg/litre. The final effluent is regularly well within the mill's consent conditions.

Effective monitoring and control at Shotton Paper

Shotton Paper in Deeside, North Wales, manufactures approximately 1 500 tonnes/day of high quality newsprint from two machines. The feedstock consists of 35:65 virgin: recycled, with the recycled fibre being produced at the on-site de-inking plant.

Sampling from the aeration lagoon

The effluent treatment plant discharges into the Dee Estuary. The consent conditions are:

- suspended solids 60 mg/litre;
- BOD 50 mg/litre;
- pH 6 - 9;
- ammoniacal nitrogen 4 mg/litre.

Fig 14 shows the current arrangement of the effluent treatment plant at Shotton Paper.

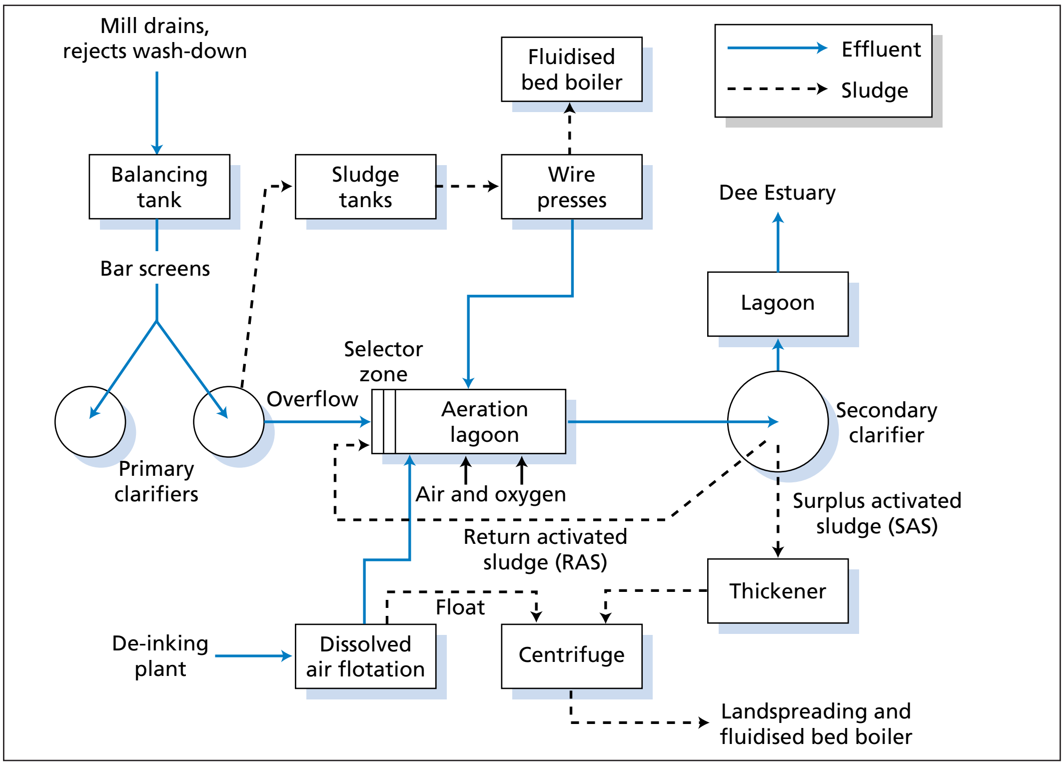


Fig 14 Layout of effluent treatment plant at Shotton Paper, Deeside

Shotton Paper has achieved process optimisation through careful monitoring and control. Microscopic examination of the microbiology of the activated sludge plant is considered fundamental to process control. With experience, operators are able to assess the health of the biomass by identifying the protozoa and other microbiological species present.

The aeration lagoon has both a pure oxygen injection system and mechanical aerators to maintain a healthy, positive dissolved oxygen level and to minimise foaming and bulking problems. The aeration lagoon, which has a 16 - 20 hours retention time, is sampled regularly. Selector zones ensure optimum conditions to encourage the growth of healthy floc-forming bacteria at the expense of filamentous bacteria.

Supplementary nitrogen and phosphorus are added to maintain the BOD:N:P ratio at 100:5:1. A total organic carbon (TOC) meter is currently under trial to ensure the nitrogen dose is always proportional to the BOD in the effluent. This avoids overdosing of nitrogen and potential problems in complying with the ammoniacal nitrogen limit in the mill's discharge consent.

Approximately 20% of the treated effluent is currently recycled for use in the recycled fibre plant and effluent plant.

Surplus activated sludge (SAS) is mixed with primary/fibrous sludges in the sludge dewatering facility to optimise dewaterability, leading to a drier sludge for further use.

Anaerobic secondary treatment at Smurfit Townsend Hook

Smurfit Townsend Hook manufactures two paper grades, on three paper machines at its site in Snodland, Kent, where paper was first made in 1814. The paper grades are blade-coated paper manufactured from 100% bleached chemical wood pulp and corrugated paper produced from recycled corrugated boxes. As part of the papermaking process, all three machines use starch as a strengthening agent. This gives rise to high BOD concentrations in the feed to the effluent treatment plant.

The effluent treatment plant discharges into the River Medway, which is tidal at Snodland. The consent conditions are:

- suspended solids 60 mg/litre;
- BOD 40 mg/litre;
- pH 6 - 9;
- temperature 30°C.

The current arrangement of the effluent treatment plant at Snodland is shown in Fig 15.

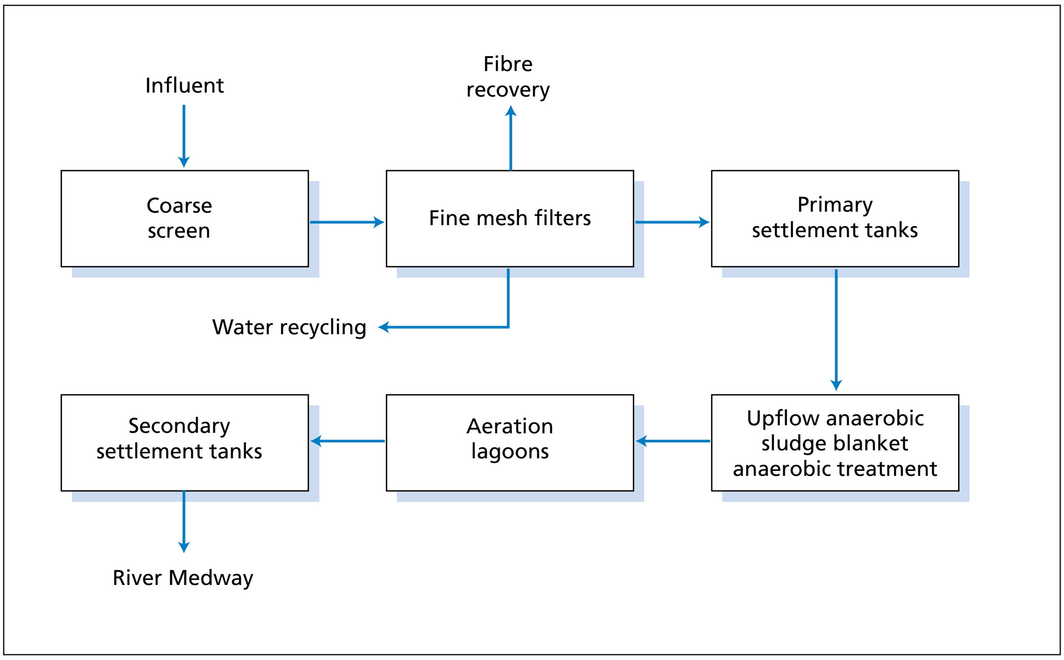


Fig 15 Layout of effluent treatment plant at Smurfit Townsend Hook

Smurfit Townsend Hook had successfully operated an aerobic biological treatment plant for a number of years. However, the Company began to evaluate possible pre-treatment options with the aim of reducing the high biological load on the aerobic process. This, in turn, would minimise the risk of exceeding the mill's consent conditions.

It was decided to install an anaerobic pre-treatment stage. This offers the following advantages to the overall operation of the effluent treatment plant:

- significantly reduced load - and hence associated running costs - on the aeration lagoons;
- improved quality of the final effluent;
- reduced site sludge disposal costs;
- potential for use of methane gas as an energy source within the mill;
- reduced occurrence of bulking activated sludge in the aeration lagoons.

An upflow anaerobic sludge blanket (UASB) reactor was commissioned in 1994. The plant has performed consistently well and helped reduce overall running costs as well as optimising the effluent treatment process.

Effective sludge management at UK Paper, Kemsley

The effluent treatment plant at UK Paper's Kemsley site is one of the most advanced plants in the UK in terms of management and control (pictured below, photo courtesy of Dames & Moore). The effluent treatment plant actually receives effluent from both UK Paper's and St Regis's mills in Kemsley and primary effluent from the nearby UK Paper mill at Sittingbourne. The plant is managed by Grovehurst Energy Ltd.

Fig 16 shows the arrangement of the effluent treatment plant at Kemsley. The effluent from the Sittingbourne mill is pumped approximately 2.5 miles to the Kemsley site.

Many of the control and optimisation features described in this Guide are demonstrated at the Kemsley site. This Industry Example concentrates on sludge disposal and management aspects of the operation.

The overall size of the operation (38 000 m^3/day with a BOD load equivalent to sewage from a town with a population of 450 000) means that efficient sludge management is necessary to minimise disposal costs. Central to this optimisation is the mixing of primary sludge with surplus activated sludge (SAS) from the aeration lagoons to maximise dewaterability. The combined sludge is co-settled in picket fence thickeners to, on average, approximately 4% dry solids. On its own, the SAS would only dewater to approximately 2% dry solids.

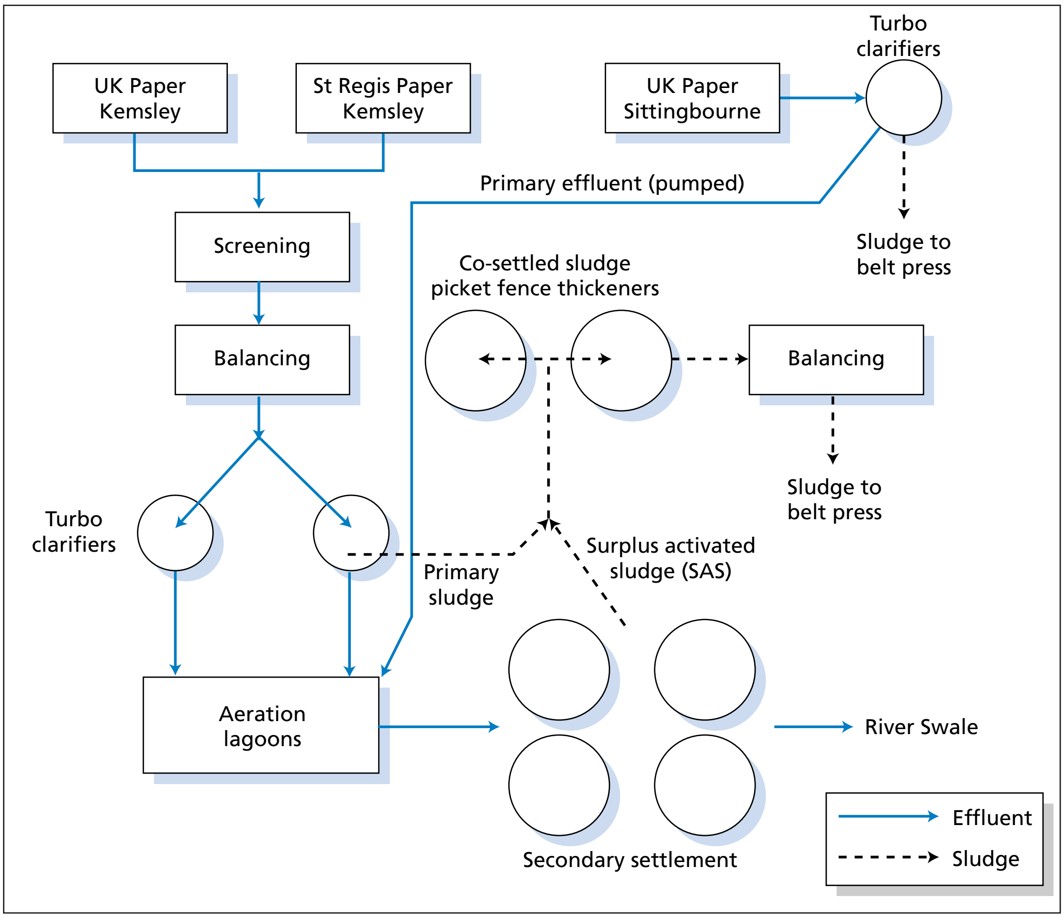


Fig 16 Layout of effluent treatment plant at UK Paper, Kemsley

The co-settled sludge is discharged from the picket fence thickeners via variable speed transfer pumps controlled by internal blanket level detectors. It is then balanced to ensure steady state conditions for input to the belt press, where the resulting sludge cake has a dry solids content of 23%. The cake is disposed of to land, as are the primary sludges from the Sittingbourne belt presses.

As well as the higher dry solids content, processing co-settled sludges has significantly reduced the risk of the odour problems typical of dewatering biological sludges. When the amount of primary sludge available is insufficient, this problem is overcome by dosing with ferric salts.

If necessary, obtain help.

The Environment and Energy Helpline (0800 585794) can:

- Send you copies of relevant Environmental Technology Best Practice Programme publications.
- Suggest other sources of information.
- Provide free, up-to-date information on a wide range of environmental issues, legislation, technology and equipment suppliers.
- Arrange for a specialist to visit your company if you employ fewer than 250 people, at the discretion of the Helpline Manager.

7.1 USEFUL PROGRAMME PUBLICATIONS

All Environmental Technology Best Practice Programme publications are available free of charge to UK businesses through the Environment and Energy Helpline on 0800 585794.

- Good Practice Guide (GG26) — *Saving Money Through Waste Minimisation: Reducing Water Use*
- Good Practice Guide (GG37) — *Cost-effective Separation Technologies for Minimising Wastes and Effluents*
- Good Practice Guide (GG54) — *Cost-effective Membrane Technologies for Minimising Wastes and Effluents*
- Good Practice Guide (GG67) — *Cost-effective Water Saving Devices and Practices*
- Good Practice Guide (GG82) — *Investing to Increase Profits and Reduce Wastes*
- Good Practice Guide (GG109) — *Choosing Cost-effective Pollution Control*
- Good Practice Guide (GG111) — *Practical Water Management in Paper and Board Mills*
- Environmental Performance Guide (EG69) — *Water Use in UK Paper and Board Manufacture*
- New Practice Case Study (NC47) — *Simple Separation Technology Recovers Raw Material Costs*

Appendix 1

GLOSSARY

Adsorbable organic halogens (AOX)	Generic group of halogenated organic materials, some of which are prescribed substances.
Anoxic zone	An area - usually prior to the biological reactor - where oxygen is limited and where certain micro-organisms obtain oxygen from nitrate or nitrite ions for respiration instead of using dissolved oxygen.
Biochemical oxygen demand (BOD)	The amount of oxygen consumed during the biological oxidation - by micro-organisms - of biodegradable organic material in the effluent. The standard test takes five days and is referred to as the BOD_5 test. Generally measured in mg/litre.
Bulking activated sludge	Term used to describe sludge in the secondary clarifier with poor settling characteristics. Often due to the presence of a high proportion of filamentous bacteria and a lack of healthy floc-forming bacteria.
Chemical oxygen demand (COD)	The amount of oxygen consumed during the chemical oxidation of organic and inorganic material in the effluent, eg using potassium permanganate or chromic acid. Generally measured in mg/litre.
Denitrification	The biological reduction of nitrate to nitrogen gas. This process is often 'forced' in an anoxic zone.
Direct toxicity assessment (DTA)	A monitoring tool used to establish the effect of an effluent on various life forms in the receiving water.
Dissolved oxygen (DO)	A measure of the amount of oxygen available to the biomass within the bioreactor. Generally measured in mg/litre or ppm. Varies between 0.5 - 3.0, depending on the process.
Food to mass ratio (F:M ratio)	The ratio of the bacterial food, ie BOD load, and the mass of bacteria available to treat the BOD. An important control parameter for the activated sludge process. Also referred to as the sludge loading rate (SLR).
Integrated pollution control (IPC)	A regime for the control of discharges of prescribed substances to land, water and air introduced by Part I of the Environmental Protection Act 1990.

Integrated pollution prevention control (IPPC)
Pollution control regime introduced by the Integrated Pollution Prevention and Control Directive (96/91/EC). The IPPC regime is largely based on IPC, but is more comprehensive. IPPC applies to paper and board plants with a production capacity exceeding 20 tonnes/day.

Mixed liquor suspended solids (MLSS)
A measure of the solids content of an activated sludge reactor. Generally measured in mg/litre or g/litre.

Mixed liquor volatile suspended solids (MLVSS)
A measure of the organic fraction, ie active biomass, within an activated sludge reactor. More meaningful than the MLSS. Generally measured in mg/litre or g/litre.

Nitrification
The biological oxidation of ammoniacal nitrogen to nitrate. A two-stage process requiring two distinct bacteria genera: *Nitrosomonas* sp. convert ammoniacal nitrogen to nitrite (NO_2^-) and then *Nitrobacter* sp. convert nitrite to nitrate (NO_3^-).

Pentachlorophenol (PCP)
A toxic and persistent halogenated organic compound. Frequently present in pulps or formed in processes where chlorine is present. PCP is used as a fungicide to preserve starches and paper.

Retention time (RT)
The time spent by the effluent in the bioreactor, ie the volume of the reactor divided by the average flow rate. Also referred to as hydraulic retention time (HRT). Generally measured in hours.

Return activated sludge (RAS)
Biomass separated from the treated effluent in the secondary clarifier and subsequently returned to the aeration tank of the activated sludge plant.

Selector zone
An area where return activated sludge (RAS) and influent are mixed to provide a high F:M ratio. This encourages selective growth of healthy floc-forming bacteria and helps to avoid the growth of filamentous bacteria.

Sludge age
Often referred to as the mean cell residence time. A measure of the time the biomass is retained within the system. Closely related to the F:M ratio and an important plant control parameter.

Sludge volume index (SVI)
An indicator of the settling characteristics of secondary biological sludges. Measured by monitoring the volume (in ml) occupied by 1 g of activated sludge after a 1 litre sample has been allowed to settle for 30 minutes. The resulting calculation requires a knowledge of the MLSS of the activated sludge. Generally measured in ml/g.

Stirred specific volume index ($SSVI_{3.5}$)

Similar to SVI except that the sample is stirred slowly during the 30 minute settlement period. More reproducible than SVI figure. Normally determined at an MLSS of 3.5 g/litre. Generally measured in ml/g.

Surplus activated sludge (SAS)

Biomass wasted from the system, ie not returned to the aeration tank, in order to control the MLSS level within the bioreactor.

Total organic carbon (TOC)

A measure of the organic carbon content of an effluent. A useful indication of the organic strength, particularly suited to on-line monitoring. Generally measured in mg/litre.

Upward flow rate (UFR)

A measure of the load entering a tank from its base. Effluent flow in m^3/hour per m^2 of tank surface area. Units are therefore m^3/m^2/hour or m/hour.

Appendix 2

USEFUL FORMULAE

Formula 1

$$\text{UFR (m/hour)} = \frac{\text{Effluent flow (m}^3\text{/hour)}}{\text{Tank surface area (m}^2\text{)}}$$

Formula 2

$$\text{RT (hours)} = \frac{\text{Tank volume (m}^3\text{)}}{\text{Average effluent flow rate (m}^3\text{/hour)}}$$

Formula 3

$$\text{F:M} = \frac{[\text{Influent flow rate (m}^3\text{/day) x Influent BOD (g/litre)}]}{[\text{MLSS (g/litre) x Volume of aeration tank (m}^3\text{)}]}$$

Formula 4

$$\text{Sludge age (days)} = \frac{\text{Mass of sludge in aeration tank}}{\text{Mass of sludge lost}}$$

$$= \frac{\text{MLSS x Volume of aeration tank}}{\text{Mass of sludge lost (SAS and final effluent)}}$$

Formula 5

$$\text{Sludge age (days)} = \frac{1}{\text{(F:M) x Yield coefficient (Y)}}$$

Formula 6

$$\text{SVI (ml/g)} = \frac{\text{Volume of settled activated sludge (ml)}}{\text{MLSS (g)}}$$

Appendix 3
HOW TO PERFORM A JAR TEST

The 'jar test' simulates what happens in the effluent treatment plant when coagulants/flocculants are added.

The basic apparatus for the jar test consists of six standard 600 ml beakers standing side-by-side on a frosted glass stand lit from below. To obtain the same stirring conditions in all six beakers, each beaker contains an identical, flat stainless steel stirrer paddle connected to a common drive powered by a variable speed motor. These paddles are started as soon as a 500 ml sample of effluent and the chemical dose have been placed in the six beakers.

Some proprietary kits for carrying out jar tests eliminate the delay in dosing each beaker in turn by having a set of stainless scoops mounted above the beakers on a common shaft. Some units have more than one set of scoops, thus providing a set for each chemical. The correct amount of chemical is measured into each scoop and added to the beakers simultaneously by turning the common shaft.

Once the chemicals have been added, the samples are subjected to a 'fast' stir, eg 60 - 80 rpm for 1 - 4 minutes, followed by a 'slow' stir, eg 5 - 20 rpm for 15 - 20 minutes. The stirrers are then stopped and the flocs allowed to settle out. Each set of tests generally takes about 30 minutes. The effects of changing one common variable, eg the amount of coagulant, are studied by keeping the other variables and conditions constant.

At the end of the settling period, the floc and supernatant water are observed with the help of the illumination provided through the frosted glass stand.

The following observations should be recorded for each beaker:

- size of floc (see Table A1 for standard descriptions);
- settling rate;
- the appearance of the supernatant liquid (including the amount and appearance of residual flocs).

The ideal result is a large, dense floc with a clear, colourless supernatant. The worst case is that the effluent is more turbid than at the beginning of the test and there are only a few pieces of debris on the bottom of the beaker.

Table A1 gives the standard descriptions used when recording floc size. Large flocs tend to settle fastest. In general, performance will be satisfactory if a floc settles within 4 minutes of standing.

Description	Floc dimension
Pin-point	Extremely fine, but visible
Fine	0.5 mm average
Medium	1.0 mm average
Large	2.0 mm average

Table A1 Standard description for flocs formed in the jar test

The appearance of the supernatant liquid tells the operator whether the use of coagulants/flocculants has been effective in removing colour and/or turbidity from the effluent. The operator can also gain an impression of how easy it will be to separate the treated effluent and the settled flocs.

The success of the jar test, which can be a lengthy procedure if several variables are being investigated, depends on the operator making consistent observations and recording them methodically.

Appendix 4

BLANK DAILY LOG SHEET

This example daily log sheet for use in the secondary biological stage of the effluent treatment plant is intended to be photocopied and used as required. It can be either used as it stands or adapted to suit a mill's particular needs. For some mills, data entry on a computer may facilitate calculation and data analysis.

These daily log sheets should be retained and the reason(s) for abnormal readings investigated. Trends away from best practice should also be analysed and, if necessary, remedial action taken.

Effluent Treatment Plant: Daily Log Sheet

Date:

Operator:

1. Influent

Sample	Temp	pH	Concentration (mg/litre) SS	COD	BOD*	N	P	Filter	Fibre	Flow rate
Grab sample										m^3/hour
24 hour composite										m^3 in 24 hr

†Calculate

Load (kg/day) SS	COD	BOD*	N	P	Filter	Fibre

Volume of aeration tank = m^3

Calculate using Formula 1

2. Bioreactor

Sample	Temp	pH	DO	$SDVI_{3.5}$ (ml/g)	MLSS 24 hr average (mg/litre)	Mixed liquor solids (kg)	F:M ratio (day^{-1})	Flow/RAS ratio	SAS wasted (kg dry solids day^{-1})	Aerators run time (hours/day)	Power consumed (or O_2 used) (kWh or kg/day)
Time (early am)											
Time (midday)											kWh
Time (late pm)											

Microscopic examination
Comments:

† Multiply concentration (mg/litre) of 24 hour composite sample by flow rate (m^3/day), to give load in g/day. Divide by 1 000 to give load in kg/day.

* On a daily basis, calculate BOD from COD:BOD ratio of the effluent. Check this ratio weekly by measuring the BOD of a representative effluent sample.

NB.
Keep units consistent.
1 m^3 = 1 000 litres

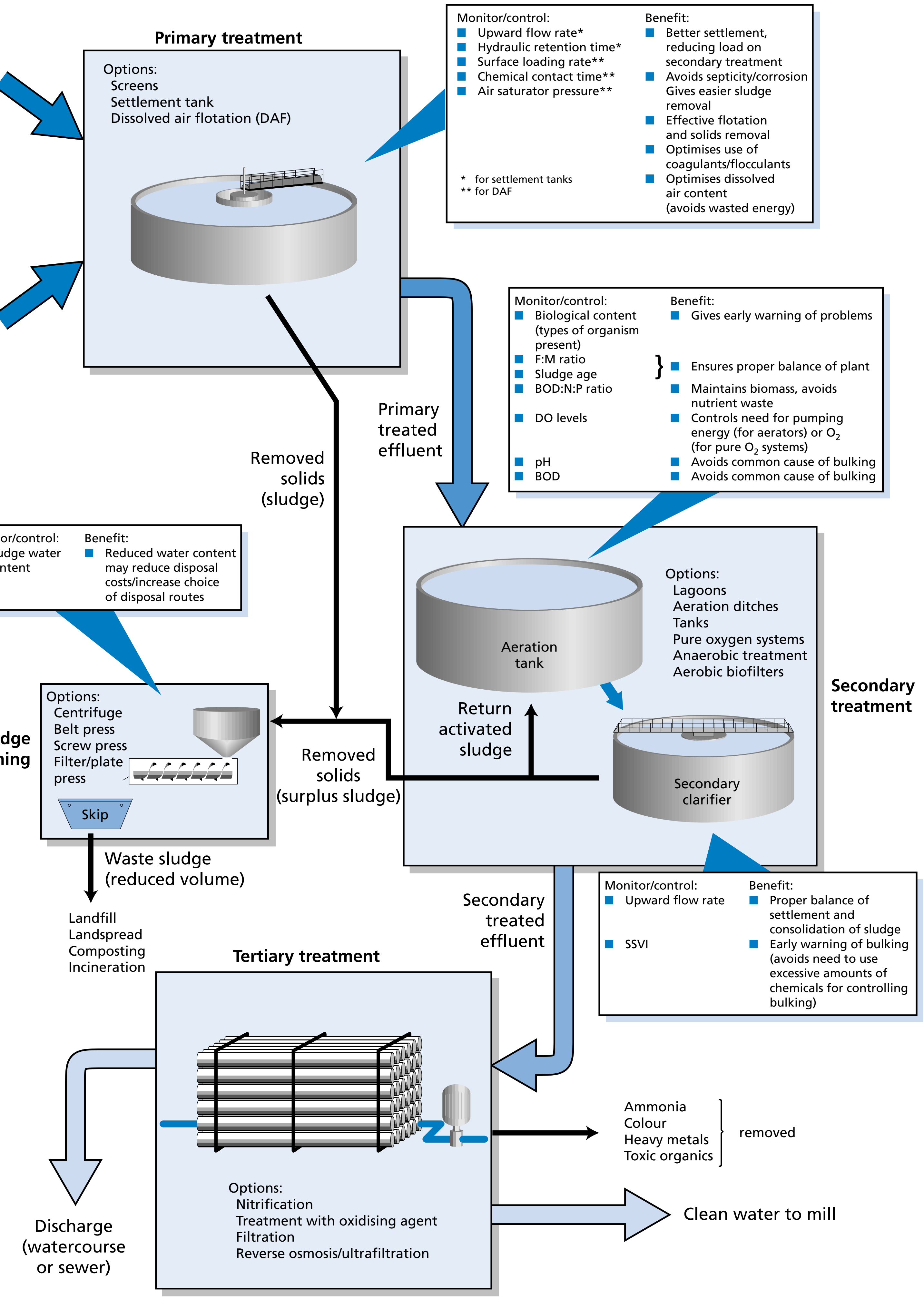
3. Final effluent

Sample	Temp	pH	Concentration (mg/litre) SS	COD	BOD*	Filter	Fibre	Flow rate
Grab sample								
24 hour composite								m^3 in 24 hr
Consent								

†Calculate

	Load (kg/day) SS	COD	BOD*	Filter	Fibre
Consent					


De-inking
plant
effluent
Mill
effluent
Monit
Slu
co
Slu
thicken


Primary treatment
Options:
Screens
Settlement tank
Dissolved air flotation (DAF)
Monitor/control:
Upward flow rate*
Hydraulic retention time*
Surface loading rate**
Chemical contact time**
Air saturator pressure**
* for settlement tanks
** for DAF
Benefit:
Better settlement, reducing load on secondary treatment
Avoids septicity/corrosion
Gives easier sludge removal
Effective flotation and solids removal
Optimises use of coagulants/flocculants
Optimises dissolved air content (avoids wasted energy)
Primary treated effluent
Removed solids (sludge)
Monitor/control:
Biological content (types of organism present)
F:M ratio
Sludge age
BOD:N:P ratio
DO levels
pH
BOD
Benefit:
Gives early warning of problems
Ensures proper balance of plant
Maintains biomass, avoids nutrient waste
Controls need for pumping energy (for aerators) or O_2 (for pure O_2 systems)
Avoids common cause of bulking
Avoids common cause of bulking
or/control:
udge water
ntent
Benefit:
Reduced water content may reduce disposal costs/increase choice of disposal routes
Aeration tank
Options:
Lagoons
Aeration ditches
Tanks
Pure oxygen systems
Anaerobic treatment
Aerobic biofilters
Secondary treatment
Return activated sludge
Secondary clarifier
Options:
Centrifuge
Belt press
Screw press
Filter/plate press
Skip
dge
ning
Removed solids (surplus sludge)
Waste sludge (reduced volume)
Landfill
Landspread
Composting
Incineration
Secondary treated effluent
Monitor/control:
Upward flow rate
SSVI
Benefit:
Proper balance of settlement and consolidation of sludge
Early warning of bulking (avoids need to use excessive amounts of chemicals for controlling bulking)
Tertiary treatment
Ammonia
Colour
Heavy metals
Toxic organics
removed
Clean water to mill
Options:
Nitrification
Treatment with oxidising agent
Filtration
Reverse osmosis/ultrafiltration
Discharge (watercourse or sewer)

The Environmental Technology Best Practice Programme is a joint Department of Trade and Industry and Department of the Environment, Transport and the Regions programme. It is managed by AEA Technology plc through ETSU and the National Environmental Technology Centre.

The Programme offers free advice and information for UK businesses and promotes environmental practices that:

- **increase profits for UK industry and commerce;**
- **reduce waste and pollution at source.**

To find out more about the Programme please call the Environment and Energy Helpline on freephone 0800 585794. As well as giving information about the Programme, the Helpline has access to a wide range of environmental information. It offers free advice to UK businesses on technical matters, environmental legislation, conferences and promotional seminars. For smaller companies, a free counselling service may be offered at the discretion of the Helpline Manager.

FOR FURTHER INFORMATION, PLEASE CONTACT THE ENVIRONMENT AND ENERGY HELPLINE

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