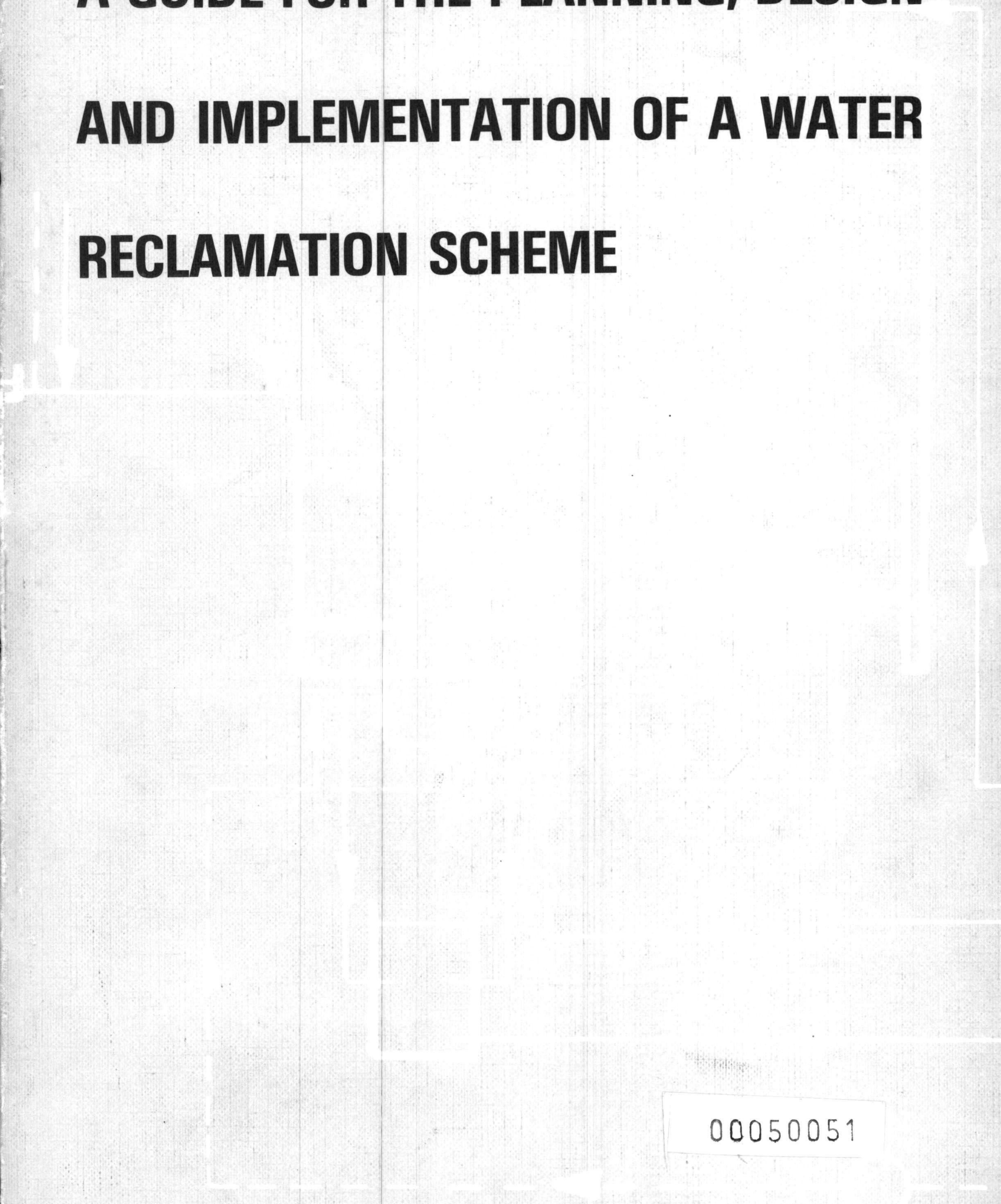
A GUIDE FOR THE PLANNING, DESIGN AND IMPLEMENTATION OF A WATER RECLAMATION SCHEME



A GUIDE FOR THE PLANNING, DESIGN AND IMPLEMENTATION OF A WATER RECLAMATION SCHEME

Prepared for the

WATER RESEARCH COMMISSION

by

PGJ MEIRING & PARTNERS, PRETORIA

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FOREWORD

Traditionally, water demand in South Africa has been met by conventional surface and groundwater supplies located within a reasonable distance from the consumer areas. From a cost-benefit point of view, there has been no justification for the large-scale development of unconventional sources of supply such as the desalination of sea water or the direct reclamation of purified effluents.

In certain areas of the country, however, we are rapidly approaching situations where projected water demands cannot for much longer be met by conventional sources and this will force the development of unconventional sources of supply. Water reclamation is one of the unconventional sources which may — in one form or another — become the preferred, or even the only economically feasible, option for supplementing existing water supplies in selected areas. It is, therefore, timeous that a guide for the planning, design and operation of water reclamation schemes, which consolidates existing knowledge, should now be published.

Research into water reclamation in this country has a history of twenty years. It commenced in 1962 with research by the National Institute for Water Research (NIWR) which led to the commissioning of the 4,5 Mℓ/d reclamation plant in Windhoek, South West Africa/Namibia in 1968. This pioneer plant was planned, designed and operated without the benefit of consolidated guidelines, but it did have the benefit of direct involvement of the research team concerned. Since then intensive and wide-ranging research on all aspects of water reclamation has been proceeding in this country and overseas, and a large reserve of knowledge has been accumulated. This Guide draws on the accumulated knowledge and tribute is due to all the dedicated researchers who made this guide possible.

I trust that the Guide will serve its intended purpose of providing decision makers, planners and designers with the basic information — as available at this time — which can assist them in coming to rational decisions when considering and implementing water reclamation schemes.

M R HENZEN
CHAIRMAN : WATER RESEARCH COMMISSION

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INTRODUCTION

The amount of fresh water available for exploitation by man is limited to that present in the natural water cycle and in countries not blessed with a high rainfall, the ever increasing demands for fresh water have placed a severe strain on this available quantity.

In certain areas the supply of water from natural resources such as lakes and rivers are being tapped to the full, and man has shown great ingenuity in extending his fresh water supplies through dam construction, supplementing underground aquifers and through pumping from one catchment to another, even at great cost.

The time, however, will inevitably arrive — and indeed in certain areas it already has — that the cost of providing further fresh water supplies will create a financial imbalance.

Present day man's technological efforts are spectacularly directed towards interplanetary expeditions, nuclear power generation and the design of the most destructive weaponry, but one of the most critical challenges that he will face in the not too distant future is how to maintain, at a reasonable price, the water in the tap in his house.

It is ironical that with an increase in living standards, suggesting an increase in understanding of his environment, man tends to show a pronounced increase in water consumption. It should therefore be our first and logical endeavour to use water sparingly, i.e. to *improve the water utilization efficiency* of the society we live in, and to reduce the throughput of water per unit of productivity.

Water reclamation on the other hand aims at ensuring that water in the natural water cycle is used more than once before it leaves that cycle; it therefore endeavours to *improve the efficacy of water as a resource.*

There has been a rapid technological development in the field of water reclamation in recent years, encouraged mainly by expected shortfalls in the fresh water supplies of many countries. In this regard South Africa, being a relatively industrialized country enjoying only scanty precipitation over very large areas, is no exception and the expected shortfalls have led her to pioneer certain concepts in this field.

This guide supplements the earlier 'Manual for Water Renovation and Reclamation', also sponsored by the Water Research Commission, but compiled by the National Institute for Water Research of the South African Council for Scientific and Industrial Research. The present guide, prepared by a firm of Consulting Engineers, relates the South African experience to that of overseas institutions, and it is intended to provide guidelines and procedures for the planning, design and implementation of water reclamation schemes. It is directed towards three groups of professional people who will all play key roles in any reclamation project:

- The planner and decision maker, with whom lies the responsibility to determine the goals of reclamation and to co-ordinate and supervise the entire project.
- The process engineer, with whom lies the responsibility to select the appropriate process sequence to ensure that the predetermined quality goals are met.
- The designer, with whom lies the responsibility to design the plant.

As with the aforementioned 'Manual for Water Renovation and Reclamation', this Guide does not profess to be the last word on water reclamation but rather it attempts to highlight the recent advances made in the field of water reclamation. By its very nature research is an ongoing subject and it is imperative that all interested parties keep abreast of the latest developments.

The Guide comprises six parts, the first five considering different aspects of water reclamation and the sixth detailing research and full scale applications in Southern Africa:

Part I:	"Planning for Water Reclamation" is of a conceptual nature and is directed towards the planner whose responsibility it will be to decide upon the need for water reclamation.
Part II:	"Processes and Operations in Water Reclamation", covers the process aspects of water reclamation on a technical level and is directed towards the process engineer.
Part III:	"Plant Design Guidelines" provides design criteria and procedures and is directed towards the designer.
Part IV:	"Operation and Maintenance" covers the operational and maintenance aspects of water reclamation.
Part V:	"Cost Estimation in Water Reclamation" covers the methods that are available for producing a cost estimate.
Part VI:	"Water Reclamation in Southern Africa" details research and full-scale water reclamation installations in Southern Africa.

It is hoped that the various sections of the Guide are sufficiently interrelated and presented in such a way as to satisfy the needs of both planners and engineers.

BASIC TERMINOLOGY

The following definitions have been adopted for the purposes of this guide:

WASTEWATER — Any untreated liquid discharge resulting from use of water for domestic, industrial or agricultural purposes.

PRIMARY TREATMENT — The application of screening, degritting and sedimentation to a wastewater.

SECONDARY TREATMENT — The application of biological purification processes to a primary treated wastewater, followed by clarification.

TERTIARY TREATMENT — The application of treatment processes such as sand filtration, micro screening, chlorination, maturation ponds and grass plots to a secondary effluent.

ADVANCED WASTEWATER TREATMENT — Treatment systems that remove more contaminants from wastewater than conventional primary, secondary or tertiary treatment.

DIRECT REUSE — The use of treated wastewater without an intervening discharge to a water course, an impoundment, or an aquifer.

INDIRECT REUSE — The use of water withdrawn from a water course, impoundment or aquifer to which treated wastewater is discharged.

WATER RECYCLING — The direct reuse of treated wastewater at an earlier stage in a sequence of use.

WATER RECLAMATION — The production of water from a wastewater for a particular reuse application.

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PLANNING FOR WATER RECLAMATION

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CHAPTER 1

GENERAL CONSIDERATIONS IN WATER RECLAMATION

Fresh water supplies in many countries are rapidly being exhausted due to population growth, industrial and agricultural development and improved living standards. Furthermore, effective use of this water is being impaired through quality deterioration brought about by the discharge of increasing volumes of partially treated wastewaters and pollution from non-point sources.

This problem is further aggravated by the tremendous growth in the number of synthetic chemicals produced, many of which reach the water environment and are suspected to possess toxic or carcinogenic properties. Many of these substances are resistant to degradation by the self-purification processes of the water environment and by conventional biological treatment systems and can pass through conventional water treatment plants to reach consumers.

The deterioration in fresh water quality due to wastewater discharges should no longer be permitted in water stress areas and every endeavour should be made to maintain the quality of 'clean' water supplies. Water reclamation not only reduces the demand on fresh water supplies but also protects the quality of supplies. water supplies but also protects the quality of existing supplies.

The rate of quality deterioration of fresh water supplies in South Africa has to a large extent been retarded through the imposition of strict discharge regulations in terms of the Water Act (Act 54, 1956). These regulations have resulted in the construction of relatively sophisticated wastewater treatment plants, discharging highly treated effluents.

Such effluents are already suitable for certain categories of reuse, but in general require further treatment if they were to be considered for more extensive reuse, and obviously so in the case of direct augmentation of supply systems.

So as to achieve this 'further treatment' , these effluents are frequently discharged to watercourses on the assumption that the self-purifying and dilution capacity of such watercourses will satisfy this need, and that purification will result in water of acceptable quality at the potable water treatment plant. This constitutes the so-called 'indirect' reuse system.

However, intensive research in connection with the cumulative adverse effects of pollutants in the water environment, particularly in respect of public health requirements, has exposed notable limitations in the ability of self-purification to cope with ever-increasing waste loads.

In South Africa, and particularly in the Pretoria/Witwatersrand/Vereeniging area, substantial flows of treated sewage effluent find their way to natural water courses and thus into the domestic water supplies. The increasing deterioration in water quality in these catchments is a matter of grave concern and, in some instances, the conventional water purification plants have reached the stage where advanced treatment techniques have become a necessity. The major problems encountered are the proliferation of algae and aquatic plants due to nutrients such as nitrogen and phosphorus and the presence of dissolved inorganic and organic compounds.

It appears therefore that there remains but two alternatives: either treating the waste waters to such standards that the reclaimed water may be reused directly for specific applications, or employing 'planned indirect reuse' whereby the return flows receive a measure of advanced treatment to meet the requirement of a clean water environment.

1.1 CATEGORIES OF REUSE OF RECLAIMED WATER

Water can be reclaimed for four categories of use:

- Irrigation
- Cooling systems
- Industrial use
- Potable supply systems.

The different levels of reuse all indicate that the reclaimed water should be considered as a supplementary source of water. As the reuse of reclaimed water releases equal volumes of fresh water for domestic consumption, the level of reuse should be carefully evaluated on a quantity/quality basis in order to ascertain the level most beneficial to the community.

In order to be viable, reclamation systems should at all times produce water of the required quality, be available on demand and be an economical substitute for fresh water supplies.

1.2 THE PARTIES INVOLVED

Many authorities or parties are involved in a reclamation scheme, namely:

- *The local authority* who in most areas would be responsible for the wastewater collection system, the treatment plants (including operating personnel) and the distribution network.

- *The consumer* who will use the reclaimed water and whose primary concern will be quality and availability. In most cases the consumers also discharge wastes into the sewers.

- *The provincial authority* who has to approve of the expenditure of public monies for reclamation schemes required by local authorities.

- *The health authority.* Any reclamation system in South Africa, be it for industrial or potable reuse, has to be approved of by the Department of Health. (Refer to section 1.3 for further discussion.)

- *The water authority.* The use of water and discharge of treated effluents in South Africa is controlled under the Water Act, which is administered by the Department of Environment Affairs in consultation with the South African Bureau of Standards and the Department of Health. (Refer to section 1.3 for further discussion.)

The course of action to be taken in planning, gaining approval for and finally implementing a water reclamation scheme is discussed in section 1.4.

1.3 LEGISLATION AFFECTING THE REUSE OF RECLAIMED WATER IN SOUTH AFRICA

Water Act No. 54 of 1956

In terms of the South African Water Act, intake quantities of public water for municipal, urban and industrial purposes, and the siting of industries using water, are strictly controlled. Water abstracted for industrial (including municipal) use must be returned as far as it is practically feasible, undiminished in quantity, to the stream of its origin after it has been purified to very stringent standards.

Main Objectives

Embodied in the Water Act is the philosophy that (i) purification of effluent is considered to be part of the industrial process and (ii) the industrial activities of the upstream user should not be to the detriment of the downstream user. In this way it is endeavoured to obtain maximum use from the country's limited water resources.

It is recognised that the siting of an industry could have an important impact on the water supply environment. For instance the erection of an industry producing a mineralized effluent could be limited under the Act to industrial sites near to the coast, where its effluent could be discharged to sea with no adverse effects.

Consideration is also given to the control of incidental pollution, i.e. pollution not arising from industrial use of water.

Relevant Sections

Some of the more salient points arising from pertinent Sections of the Act are summarized below:

Section 12:

An industrialist wishing to start a new industry must apply for a permit from the Minister of Environment Affairs if he intends using more than an average of 250 m^3 per day (or a maximum quantity of more than 300 m^3 on any one day) of public water for industrial purposes. All industrialists, wishing to start a new industry must advise the Department of Environment Affairs as to how they propose to purify the resulting effluents.

Section 21:

The purification of wastewater resulting from the use of water, including sea water, for industrial purposes forms part of the industrial process.

The standards which must be achieved through such purification are prescribed by the Department of Environment Affairs after consultation with the South African Bureau of Standards, and comprise (i) those applied generally (the General Standard) and (ii) those applied for specified streams, specified areas and for specified industrial purposes (the Special Standard) Appendix 1 to this part of the Guide lists the two sets of standards.

It should be mentioned that the Minister of Environment Affairs may after careful consideration and in consultation with the Bureau and the Department of Health grant permits of exemption from the standards and from the stipulation that water abstracted be returned to the stream of origin. Anyone may appeal to the Water Court against the conditions of a permit.

Discharge of industrial wastes to a sewer owned by a local authority does not require a permit, since the authority takes responsibility for effluent purification and disposal. Water used for industrial purpose may be diminished in quantity before return by essential consumptive use. It should be noted that the use of water by a local authority is considered an 'industrial' use.

Section 22:

Local Authorities may use purified sewage effluent for any approved purpose (or discharge it to a public stream).

Financial Backing

Sections 56 and 57:

The Minister of Environment Affairs may, out of moneys provided by Parliament for the purpose, construct a Government water works which he may deem necessary or desirable for the purpose of conserving or utilizing any water. He may also do so on behalf of any person and may enter into agreements with such person in any matter incidental thereto.

Section 162:

The Minister may on the other hand only grant a subsidy towards the cost of constructing a water works, the cost of which exceeds a certain maximum amount, if the amount of the subsidy and of any loan to be granted in respect thereof, have been specifically approved by Parliament.

Health Act No. 63 of 1977

The Minister of Health is empowered according to the Health Act to promulgate regulations, after consultation with the Ministers of Environment Affairs and Finance, which provide for:

- The supply of water for human use and the establishment of sewage and water purification works.
- The management and control of such works.
- The number of personnel to be employed at such works, prescribing their qualifications, health requirements and compulsory medical examinations.
- The quality of water intended for human consumption, the volume of water to be available for human consumption, and the system of distribution of such water.
- Water sampling and analysis, the addition of agents to water intended for human use.
- Subsidies on running costs.

Salient Points

It appears from this summary of the relevant sections that:

- The South African Water Act favours the concept of water reclamation.
- The necessary legal machinery exists to enforce a rationale when it comes to the siting of industry to facilitate water reclamation.
- Regionalization of sewage purification works so as to facilitate the erection of economically viable water reclamation plants can be enforced by the Department of Environment Affairs.
- The necessary controls exist to ensure that an effluent is of such quality that reclamation thereof is not impaired.
- The necessary powers are vested in the Department of Environment Affairs to ensure, in consultation with the Minister of Health, that the quality of the reclaimed water is compatible with the intended form of reuse.
- Reclaimed water is also public water and the reuse of such water is subject to a permit from the Department of Environment Affairs.
- Local authorities can be made to supply effluent for reuse, rather than fresh water, by applying some pressure in the form of restrictions in their water permits. Similarly, by limiting the water supply to a factory, reuse of water is encouraged.
- Powers are vested in the Department of Environment Affairs to subsidise waterworks and even to construct waterworks themselves. A water reclamation plant is considered a waterworks.
- Powers are vested in the Department of Health to ensure that a community receives a wholesome water.
- The Department of Health is to ensure that personnel responsible for the operation and management of both a sewage purification works and a waterworks are suitably qualified and trained.
- All sewage treatment and water reclamation schemes have to be approved of by the Department of Health.

1.4 COURSE OF ACTION TO BE FOLLOWED IN THE PLANNING AND IMPLEMENTATION OF A WATER RECLAMATION SCHEME

Liaison Committee

The activities or interests of the various authorities or parties involved (refer to section 1.2) should be co-ordinated by the establishment of a liaison committee at the outset of the planning stage. In cases where water reclamation schemes are orientated towards specific consumers, these should also be represented.

This committee would consider the need for water reclamation and aspects such as the assessment of required quality criteria and, in the case of reclamation for potable reuse, the implementation of a public acceptance programme. The public acceptance programme, iniated at this early stage of the project, should be continued for some time after the actual scheme becomes operational.

Although the planner and his advisers will provide most of the input to the committee, it is essential that the representatives of the authorities become totally familiar with, and indeed give their approval to, the overall aims of the project.

Technical Planning

On completion of this initial stage, the committee should become more technically orientated through the co-option of technical experts. Once again the planner and his advisers will provide most of the input and the committee would now oversee items such as pilot plant studies, (when required), economic analyses of various process configurations and finally the selection of the optimum configuration.

Detailed Design

Detailed design of the scheme should then commence and, once completed, details thereof should be forwarded to the Departments of Environment Affairs and of Health for their formal approval. Any departures from the original concepts agreed upon by the liaison committees, should be discussed with the authorities concerned. Should the departures be of major significance, however, the planner should re-convene the liaison committee and gain its approval.

Once the reclamation scheme becomes operational, it is important to ensure that a framework for cooperation between the operating bodies, the consumer and the system designer be established. This framework should be less formal than that for the design stage and should have the following aims:

- The consumer should be able to report directly to a member of the controlling authority whenever water of substandard quality is received.
- The operating body, in consultation with the designer, should monitor the performance of the scheme, particularly that of the reclamation plant. Such a 'follow-up' should compare the actual plant performance with that predicted and with the design criteria employed. This is important, as experience gained from one scheme could be used not only for possible improvement of that scheme but also for the design of future reclamation schemes.

CHAPTER 2

SPECIFIC FACTORS TO BE CONSIDERED IN WATER RECLAMATION

2.1 QUALITY CRITERIA FOR RECLAIMED WATER

It is technically possible to produce reclaimed water of any desired quality, but it will be appreciated that the quality requirements have a direct bearing on the technical complexity, and hence the economic viability, of a water reclamation system. It therefore becomes important that the quality criteria for reclaimed water be realistic and can be achieved within imposed economic restrictions.

The quality criteria should be considered at two levels, namely that required for the specific application and that required to protect the health of the user at the point of reuse. Quality criteria based on health considerations are generally more stringent than those based on the technical requirements only.

As sewage and fresh water qualities differ from area to area, quality criteria established elsewhere should not be applied without careful assessment of the local conditions. However, such criteria and the reasons for adopting them, do form the essential basic guidelines for the decisions that will have to be made in the local context.

In assessing quality criteria in terms of local conditions, cognisance should be taken of the fact that most criteria are in terms of 'concentration' whereas the 'contaminant load' (i.e. product of quantity and concentration) could be more indicative of possible deleterious effects that the reclaimed water would have. This view could well result in the criteria for a specific application differing from area to area.

The reliability of the reclamation process should be emphasized in all discussions on end water quality. This aspect is particularly important in reclamation for potable supply systems and is discussed in detail in Part II, section 1.2.

Survey of Potential Users

In deciding upon the final destination of the reclaimed water (and hence its quality) a survey of industries and agricultural concerns should be undertaken in the area falling under the jurisdiction of the planner. The survey should include (but not necessarily be limited to) factors such as:

- Fresh water usage, both present and future.
- Water economy measures that could be undertaken.
- Potential for the use of reclaimed water.
- If there is a potential, what quality would be required?
- Projected cost implications of using reclaimed water.
- Projected benefit to the fresh water supply of local community.
- Possibility of guaranteeing reclaimed water quality.

In parallel to the survey, detailed population and fresh water usage projections should be established.

Once the projections and the survey have been completed and analysed, the planner will be able to establish the qualities of reclaimed water that would offer the most benefit to the fresh water supply and hence to the community as a whole.

Catchment quality control

Once the required quality of reclaimed water has been ascertained, attention should be paid to the nature and characteristics of the wastewater from which the reclaimed water will be produced. It may be found that the wastewater contains industrial discharges of organic substances intractible to biological degradation and/or physical chemical treatment. In such cases, the polluter must be pinpointed and the discharge diverted from the sewerage system to an alternative disposal site. Where such discharges cannot be diverted, strict in-house control and treatment must be exercised before the effluent is released. Industrial pollution management and the co-ordination between townplanning and the water reclamation system, with particular regard to siting of industry, are discussed in sections 2.3 and 2.4 respectively, while the implementation of a catchment quality control programme is discussed in Part II, section 1.2.

2.2 CHARACTERISTICS OF THE WASTEWATER

A knowledge of the characteristics of the wastewater from which the reclaimed water is to be produced, will assist in identifying the treatment sequence necessary to produce the required final water quality.

The pollutants in a wastewater may be characterized by two groups of parameters, namely the 'physico-chemical' parameters and the 'health affecting' parameters.

2.2.1 Physico-chemical parameters

The parameters by which the overall inorganic component of a wastewater may be gauged include the pH, conductivity, alkalinity, hardness and total dissolved inorganic solids.

In addition, the nitrogen, phosphorus and heavy metal contents are frequently measured, with the latter generally being required when industrial wastes are present in the wastewater.

The overall organic component of a wastewater may be gauged by the following parameters:

- 'Chemical Oxygen Demand' (COD), which is a measure of the oxygen required to chemically oxidize the organic matter present.

- 'Total Organic Carbon' (TOC), which measures the organic carbon by means of controlled combustion.

The 'Biochemical Oxygen Demand' (BOD) is frequently used to report the strength of a wastewater, but this parameter only indicates the *portion* of the organic matter present in a wastewater that can be oxidized biochemically within a period of time (usually 5 days). In this regard it should not be used to indicate the magnitude of the organic component of a wastewater but should rather be used in conjunction with the COD or TOC to indicate the biodegradability thereof.

Organic nitrogen and phosphorus contents are often analysed and reported either separately or together with their inorganic counterpart. For example Total Kjeldahl Nitrogen (TKN), a regularly reported parameter, is a measure of the organic and free and saline ammonia nitrogen present in wastewater.

Suspended matter, be it inorganic, organic or microbiological in nature, is measured by the parameter 'suspended solids'.

TABLE 1.1 EFFECTS AND SPECIFIC TYPES OF POLLUTION IN INDUSTRIAL WASTE DISCHARGES[2]

Water pollutants	Industries and industrial activities responsible	Adverse effects
Colour	Pulp and paper, textiles, abattoirs, steel, dairy	Visually objectionable
Solids	Pulp and paper mills, textile factories, tanning, canning, breweries, steel mills, boiler-house operations, mining (drainage from mine dumps), abattoirs	Blockage of sewer lines and equipment, damage to rivers by deposit of solids and depletion of oxygen
Oil and grease	Abattoirs, wool-washeries, tanneries, metal finishing, dairy plants, steel mills, oil refineries, railway workshops, locomotive, truck and aircraft washing, engineering works	Blockage of sewer lines and equipment, floating scum on water which prevents transfer of oxygen, anaerobic conditions, unpleasant smell and attraction of flies
Organic wastes	Pulp and paper, textiles, abattoirs, tanneries, canning, brewery, starch and yeast factories	Overloading of conventional sewage treatment plants, depletion of oxygen in rivers
Insecticides, pesticides	Chemical, food and textile factories	Toxic to bacterial and aquatic life, puts sewage treatment works out of action
Heavy metals	Pickling, plating	
Cyanide	Metal finishing, plating, cooking, refineries	
Chemical wastes	Coking, synthetic dyes, chemicals, plastics, solvents, textile finishing, Kraft and sulphite pulp	Unpleasant taste and odour, toxic to aquatic life
Acids (mineral and organic)	Steel pickling, chemicals, food processing, acid mine drainage	Corrosion of concrete structures
Alkalis, sodium	Metal finishing, plating, textile and pulp mills, tanneries, water softening, ion-exchange installations	Toxic to fish, rendering water unsuitable for irrigation by causing brack conditions due to imbalance of ions
Nitrogen, phosphorus	Fertilizer plants, synthetic detergents	Rapid growth of aquatic organisms, algae, *Sphaerotilus natans*
Carbohydrates	Fruit and vegetable canning, sugar milling	
Heat	Cooling, all processes	Stimulates organic growth and reduces oxygen in water
Detergents	Textiles, metal finishing	Foaming
Pathogens, viruses, worm eggs	Hospitals, abattoirs	Spreading of disease

2.2.2 Health affecting parameters

Health affecting parameters may be divided into two groups: one concerned with the short term effects and the other with long term effects.

The first group is concerned with the microbiological component of the wastewater and comprises parameters such as the total plate, virus and parasitic ova counts as well as tests for the presence of faecal coliforms, *Pseudomonas aeruginosa, Clostridium perfringens, Staphylococcus aureus* to name but a few.

The second group is concerned with the organic micro-pollutant and heavy metal components and comprises those compounds that are suspected of possessing carcinogenic, mutagenic, teratogenic or long term toxic properties.

The increasing number of chemical products available on the market, together with the advent of sophisticated analytical tools, has resulted in some 350 organic compounds being detected in drinking water, albeit at micro and sometimes at nanogram per litre levels.[1]

For quality parameter and research purposes, these organic micro-pollutants have been divided into three main groups: Organohalogen compounds, organophosphorus compounds and polynuclear aromatic hydrocarbons (PAH) with the respective concentrations being established by 'extraction' and gas chromatography.

2.3 INDUSTRIAL POLLUTION MANAGEMENT

In many instances the wastes that industry discharges to the sewers are detrimental to the production of a high quality reclaimed water. Control of the industrial discharges therefore becomes of great importance to the overall reclamation scheme.

The pollutants in industrial wastewaters are generally present in much higher concentrations than in domestic wastes. The type, number and concentration of undesirable components depends upon the industrial process. Table 1.1[2] illustrates the range of wastewater contaminants produced from industry.

Effect of pollutants

Many of these pollutants, particularly those from the synthetic chemical industry (insecticides etc.) are reported to possess carcinogenic, mutagenic and teratogenic properties.[1] Many resist degradation by the self-purification processes of the water environment as well as the controlled environment of the conventional biological treatment systems and as they are little affected by conventional potable water treatment systems they eventually find their way into potable water supplies.[1]

Discharge standards

An industry that discharges to a public watercourse in South Africa must comply with the discharge standards promulgated under the Water Act No. 54 of 1956 and referred to as the 'General Standard'. More stringent standards, known as the 'Special Standard', are enforced for discharge to certain rivers. The South African Water Act is further discussed in section 1.3.

The municipal use of water is, under the terms of the Water Act, classed as an industrial use and as such all municipal discharges must comply with the relevant standard.

The municipalities may accept industrial wastes into their sewers and hence their sewage treatment works but the responsibility for ensuring that the municipal discharge complies with the standard rests solely with the municipality. The municipalities are therefore allowed to promulgate their own drainage regulations with which industry must comply should discharge to the sewerage network be contemplated. These regulations endeavour to ensure that the municipal sewage works would not be overtaxed or put out of order. They are indicative of the amount of pretreatment required of industry. Table 1.2 compares the regulations of four South African cities with the 'General Standards'.

It will be appreciated that industry, apart from being a polluter, is of importance to the local community and the country as a whole. The discharge regulations should, therefore, be carefully drawn up and be based on local conditions and not on extreme requirements which apply elsewhere.

The regulations should relate to quantitative rather than qualitative considerations, which implies that large cities can generally be more lenient than small ones.

In the case of a water reclamation system — in existence or envisaged — the regulations should also take special cognisance of the type of industry and its location with respect to the water reclamation plant. This aspect of location of industry is discussed in greater detail in section 2.4, "Co-ordination between town planning and the water reclamation plant".

Pollution control

In general, the following guidelines to industrial pollution control are suggested:

- Industries which may give rise to toxic and intractable wastes, should be prevented from discharging to the public sewers and their wastes should be treated and disposed of by other means.

  This could include regional detoxication and disposal plants, as practiced in West Germany,[3] or cartage to municipal toxic waste disposal sites as practised in certain areas of South Africa.[4] The disposal of toxic wastes should be carefully controlled and a 'Code of Practice' has recently been drawn up by a firm of cartage contractors in South Africa.[5]

- Industries which produce biologically degradable wastewater should be allowed to discharge to the public sewers and regulations similar to those shown in Table 1.2 should be initially adopted, subject to review after an extended period of operation of the reclamation plant.

The operating costs (including capital redemption) associated with the combined treatment works should

TABLE 1.2 COMPARISON OF MUNICIPAL DRAINAGE REGULATIONS WITH WATER ACT 'GENERAL STANDARD'

	Water Act No. 54, 1956	**City drainage by-laws**			
	General Standards	**Johannesburg**	**Pretoria**	**Durban**	**Cape Town**
pH	5,5 – 9,5	> 6,0	6 – 10	> 6,0	5,5 – 12,0
Faecal coli	Nil	N.S.	N.S.	N.S.	N.S.
Dissolved O_2	> 75%	N.S.	N.S.	N.S.	N.S.
Temperature	<35 °C	N.S.	N.S.	75°C	43 °C
Chemical oxygen demand (COD)	75	N.S.	5 000	N.S.	N.S.
4 h OA	10	1 400	200	N.S.	N.S.
TDS	] Not increasing to] more than 500] above intake	N.S.	2 000	N.S.	1 000 – 2 000
Electrical conductivity (mS/m)	N.S.	500	N.S.	N.S.	300 – 500
Suspendid solids	max. 25	N.S.	600	2 000	1 000
Sodium (as Na)	] Not more than] 90 above intake	N.S.	N.S.	N.S.	N.S.
Soap, oil and grease	max. 2,5	N.S.	400	50	400
Substances not in solution (incl. fat, oil, grease, waxes, etc.)	N.S.	2 000	N.S.	N.S.	N.S.
Substances soluble in petroleum ether	N.S.	500	N.S.	N.S.	N.S.
Chlorides	N.S.	N.S.	N.S.	1 000	N.S.
Free Cl	max. 0,1	100	N.S.	N.S.	N.S.
Free and saline NH_3	10	N.S.	N.S.	N.S.	N.S.
Silver (as Ag)	N.S.	N.S.	Nil	N.S.	N.S.
Iron (as Fe)	N.S.	]	N.S.	N.S.	N.S.
Chromium (as Cr)	0,5	] total concen-	20	50]	
Copper (as Cu)	1,0	] tration of all	20	50]	
Nickel (as Ni)	N.S.	] metals 50;	20	50]	
Zinc (as Zu)	5,0	] individual	20	50]	total not
Cadmium (as Cd)	N.S.	]metal 20	20	50]	to exceed
Arsenic (as As)	0,5	]	N.S.	N.S.]	50
Boron (as B)	1,0	] total of all	N.S.	N.S.]	
Lead (as Pb)	1,0	] metals 20;	N.S.	N.S.]	
Selenium (as Se)	N.S.	] individual	N.S.	N.S.]	
Mercury (as Hg)	N.S.	] metal 5	N.S.	N.S.]	
Sulphides (as S)	1,0	50	25	50	50
Fluorides (as F)	1,0	5	N.S.	N.S.	N.S.
Phenols	0,1	N.S.	N.S.	N.S.	N.S.
Formaldehyde	N.S.	50	N.S.	N.S.	N.S.
Cyanides (as CN)	0,5	20	10	20	20
Total sugars and starch	N.S.	1 500	N.S.	1 500	1 500
Tar and tar oils not soluble in water	N.S.	N.S.	60	60	60
Calcium carbide	N.S.	Nil	Nil	Nil	Nil
Total sulphates	N.S.	1 800	300	200*	500

N.S. = Not specified

*Sulphate in solution

be allocated to industry and municipality on an equitable basis. It is usual to charge industry a monthly or annual tariff to cover the portion of the operating costs attributable to the industry and the tariffs should not only be based on volume, organic strength and suspended solids content but should also include a parameter that takes into account other characteristics of the waste; e.g. conductivity, heavy metal concentrations, etc.

2.4 CO-ORDINATION BETWEEN TOWN PLANNING AND WATER SUPPLY SYSTEMS

The ever increasing demands for fresh water and the advent of water reclamation has highlighted the fact that in the past little consideration was given to the integration of future water supplies within the overall town planning context.

Many cities throughout the world are founded in locations where they either pollute their own water supplies or those of others. It has, therefore, become essential that the future planning of new cities or industrial townships take into account factors such as:

- Source of fresh water supply.
- Point of discharge of sewage effluents.
- Required quality of such discharges.
- Possibility of water reuse.
- Irrigation and/or land treatment in order to protect downstream users.
- Land disposal of such wastes that may so contaminate the area's effluents that reclamation would be uneconomical.

In addition, the co-ordination between town planning and water supplies should be organized not only on a local authority level but also on a regional and national level.

Regional and national level

The co-ordination on a regional and national level would have the overall aim of planning the location of new cities, new industrial areas, power generation centres, and mining and agricultural concerns for a considerable time into the future so that optimum use can be made of existing fresh water sources and of possible reclamation.

Water schemes should no longer be looked at in isolation and water reclamation is now as much a part of the water supply system as any other source of surface or groundwater.

Industries using large quantities of water while simultaneously increasing the mineral salt content of the water should where possible be sited near the coast or, in the case of landlocked countries, in an area divorced from any water reclamation scheme.

Those industries requiring large quantities of cooling water should be situated in areas where abundant supplies of water are to be found.

The provision of dams or lakes for recreational purposes should be carefully considered as there are many instances where such lakes have become polluted by the city's wastewaters or where it has been necessary to pump all such effluents away from the lake's catchment.

Local Authority level

Co-ordination between town planning and the water supply systems on a regional and national level would be ineffective if co-ordination on the local authority level was inadequate.

The co-ordination on a local authority level should consider the following guidelines:

- Industrial and domestic areas should where possible be segregated in such a way that separate sewers could be used to convey the respective wastes to the sewage treatment plant. This is of particular relevance in instances where reclamation for potable purposes is to be practised, as arrangement could then easily be made to exclude industrial wastes from the reclamation plant.
- In instances where separate sewers are not feasible, those industries which give rise to toxic and intractible wastes should be located at suitable sites in order to avoid discharge to the sewers and to facilitate treatment and disposal by alternative means (refer to section 2.3).
- Industries which produce biologically degradable wastewater should be sited to benefit from purification facilities provided for domestic wastewaters but should, where possible, discharge into the sewer at a point downstream of domestic discharges. By so doing it is possible to erect a reclamation plant at a point where it receives only domestic wastes (refer to section 6.2).
- Dual supply systems for industrial areas should be considered at the planning stage (refer to section 6.3).
- Those industries that are liable to contaminate water supplies through atmospheric discharges should be carefully sited.
- Those industries that produce saline wastewaters should also be carefully sited.
- It would be advantageous to site wastewater treatment facilities within convenient reach of water-intensive industries which could utilize treated effluents as intake water.
- Municipal solid waste disposal sites should be so sited, constructed and protected that no pollution of streams or groundwater occurs.
- The location of underground aquifers should be considered, both from the point of pollution protection and from the point of integrating them in future water reclamation schemes.
- The implementation of a strict trade waste policy should be considered at the early planning stages (refer to section 2.3).

2.5 MANPOWER QUALIFICATION REQUIREMENTS

A water reclamation plant should not be looked upon as an upgraded sewage treatment facility but rather as an industry that has to comply with the stringent regulations pertaining to the production of a commodity intended for human consumption.

In South Africa the Minister of Health may, after consultation with the Minister of Water Affairs, promulgate regulations relating to the number, duties and educational qualifications of persons employed at works producing water intended for human consumption or food processing. (Act No. 63, 1977 C. 37 (d)).

No regulations or guidelines relating to educational qualifications required of persons in charge of conventional water treatment plants have as yet been issued and, *ipso facto,* the same apply for water reclamation plants producing water for potable use. However, it is common knowledge that the person in charge of a conventional water treatment plant of any consequence is usually a qualified chemist or professional engineer and a close parallel is to be found in the pharmaceutical industry where it is a statutory requirement that any factory manufacturing medicines should be under control of a registered pharmacist (Hazardous Substances Act, Act 15, 1973). The factory and its products are under regular surveillance by an inspectorate also consisting of qualified pharmacists.

In general, it should be stated that the manager and senior personnel of a water reclamation plant carry grave responsibilities, and the remuneration associated with these posts should be sufficient to ensure that the incumbants of such posts are both adequately qualified and of responsible and reliable character.

It has been proved over many years of research and development that a plant where operator control is emphasized, can supply a fail-safe product on a continuous basis.[6] Automatic and sophisticated equipment, however useful, cannot compensate for inadequacy of personnel who must of necessity control and care for such equipment. Water reclamation plants, incorporating advanced treatment, should therefore not be operated by personnel trained to operate conventional water or wastewater treatment plants only. A higher level of education and training is required since these plants are more complex.

Performance objectives established beforehand for each unit process have to be maintained. The control analyses and readings required to ensure compliance with such objectives, together with the monitoring of parameters required to serve as a record of process and plant performance, must be recorded as part of an overall control strategy. It is therefore considered advisable that operators of water reclamation plants which produce water for potable use, should be certificated Water Quality Technicians (certificated in terms of the Health Act No. 63 of 1977).

Qualifications and training *per se* will not ensure the conscientious performance of the managerial and operational staff of a water reclamation plant. To generate their enthusiasm and provide them with job satisfaction the staff will have to be properly motivated and made to realize that their work is of great importance to, and is being recognized and appreciated as such by, the community they serve.

2.6 REGIONAL RECLAMATION STRATEGY

Water reclamation on a regional basis can be considered in the case of urban complexes where many authorities would otherwise have to implement water reclamation on an individual basis.

Regional water authorities have been created in many developed countries and the reader is referred to the literature for further discussion on this subject.[7,8]

It must be noted however that regionalization does not necessarily require that all sewage flows be directed to a centralized facility from which the reclaimed water would be distributed. It may well be prudent for the planners to site small plants adjacent to users of large quantities of reclaimed water, with all sludge generated by such plants being discharged to plants far removed from the urban areas (refer to section 6.1).

CHAPTER 3

INDUSTRIAL USE OF RECLAIMED WATER

3.1 INDUSTRY AS A POTENTIAL USER OF RECLAIMED WATER

Typical water intake figures for various industries are shown in Table 1.3.[9] Lower water usage is an indication of efficient management and is usually accompanied by lower product wastage.

Industry requires water for:

Cooling systems
Steam generation
Process water
Product washing
Plant and equipment washing
Air conditioning
Transport of materials
Classification of ores
Personnel consumption and sanitation

Steam generation, air conditioning, human consumption and certain stages in the production of textiles, rayon viscose pulp and plastics require a water of potable or higher quality, while a water of lower, non-potable quality could be employed for the other uses.

Implementation of water reuse by industry is dependent upon factors such as:

- Guarantee of quality.
- Reliability of supply
- Proximity of reclamation plant (which influences overall cost of reclaimed water at factory).
- Economic incentives (such as reduced effluent discharge tariffs, reduced rates etc.)

3.2 USE OF RECLAIMED WATER FOR POWER STATION COOLING SYSTEMS

Tertiary effluent is used for cooling purposes at a number of municipal power generating stations in South Africa and Table 1.4 indicates the volumes used.[9]

The recycling of cooling water is limited by progressive concentration of dissolved mineral salts. The maximum concentration of dissolved solids which can normally be tolerated in cooling water is about 1 200 to 1 500 mg/ℓ. With proper water conditioning, however, a total dissolved solids concentration of 4 000 mg/ℓ can be tolerated without undue scale formation or corrosion hazard.[10]

Reclaimed water that is to be used in once-through heat exchangers or as the make-up in open recirculation cooling circuits should comply at least with the General Standard for discharge (S.A. Water Act No. 1956), with the following additions and/or alterations:

- The water should be stable according to the Langelier and Ryznar Indecies.[10]
- The phosphorus content should be limited to a value that is dependent upon the physico-chemical characteristics of both reclaimed and circulating water.[11]
- The suspended solid content should be low so as to reduce the likelihood of solid deposition and build up occurring.

TABLE 1.3 INTAKE WATER USE PER UNIT PRODUCED[9]

Process		Water intake per unit
Kraft pulp, unbleached grade		12 to 15 m³/t
NSSC pulp, unbleached grade		10 to 12 m³/t
Linearboard, fluting paper	on paper machine	13 to 17 m³/t
Newsprint, fine paper	on paper machine	17 to 30 m³/t
Cardboard	on paper machine	1,5 to 22 m³/t
Steel		4 to 200 m³/t
Breweries		8 to 13 ℓ/ℓ of product
Milk powder		Nil to 18 m³/t
Cotton, wet processing		80 to 600 m³/t
Wool washing		7 to 40 m³/t
Wool, dyeing and finishing		100 to 600 m³/t
Abattoirs		0,2 to 9 m³/cattle unit
Abattoirs with meat canneries		0,8 to 20 m³/cattle unit
Thermal power stations		2,5 to 8,7 ℓ/kWh

TABLE 1.4 VOLUMES OF TERTIARY EFFLUENT USED FOR COOLING PURPOSES[9]

	Capacity MW	Tertiary effluent m^3/d
Cape Town (Athlone)	180	10 000
Bloemfontein	102,5	7 500
Johannesburg (Orlando)	300	58 000
Johannesburg (Kelvin)	600	
Pretoria West	180	27 300 (including ash handling)
Pretoria (Rooiwal)	300	18 200

- A total chlorine residual of at least 1 mg/ℓ should be maintained at the point of reuse.

3.3 USE OF RECLAIMED WATER FOR GENERAL INDUSTRIAL PURPOSES

The requirements for water quality, published in the literature for various industries, are seldom based on a critical examination of the needs of each step in the manufacturing process. An investigation into the actual water quality requirements will usually enable the standards of water quality to be lowered, at least for the bulk of the water used. Consequently the use of reclaimed water on a much greater scale will be possible — usually with an economic return.

Reclaimed water that is to be used for general industrial purposes, such as the manufacture or processing of metals, unbleached pulp, newsprint, paperboard and leather, should comply at least with the General Standard, with the following additions and/or alterations:

- The ammonia-nitrogen, suspended solid and turbidity values should be as low as possible to ensure effective disinfection.
- The colour of the water should be aesthetically acceptable but requirements at the actual point of reuse should be considered.
- The phosphorus content should be limited to the value required at the actual point of reuse.
- A total chlorine residual of at least 1 mg/ℓ should be maintained at the point of reuse.
- The heavy metals content should comply with the requirements at the actual point of reuse, but should nevertheless not exceed the limits of the General Standard.
- The water should be stable according to the Langelier and Ryznar Indices.

There are certain industries, as mentioned in section 3.1, that require a water of higher quality than that proposed above. Such industries include those that manufacture high quality paper, textiles and uncoloured plastics and in these instances the water should be low in colour, iron and manganese contents as well as being soft.

Water quality standards recommended for these industries by the State Water Quality Control Board of California, USA and other authorities are presented in Table 1.5.[2]

Experience gained in South Africa indicates that, particularly in the case of fine paper production, the water should have low dissolved organic matter and phosphorus contents.[2] It is considered that a COD level of less than 50 mg/ℓ and total phosphorus level of less than 0,5 mg/ℓ, should cover this requirement.

Data abstracted from the literature (together with that presented in Table 1.5) indicate that in the case of fine paper production, heavy metals — notably iron, manganese and copper — should be absent from the water as these elements reportedly impair the brightness of the end product.

TABLE 1.5 MAXIMUM PERMISSIBLE CONCENTRATIONS IN HIGH-QUALITY WATER FOR SPECIFIC INDUSTRIAL USES[2]

(All values in mg/ℓ except colour)

	Textiles	Viscose pulp	Fine paper pulp	Plastics uncoloured
Colour (platinum)	0 — 20	5	5	2
Hardness as $CaCO_3$	0 — 20	8	100	N.S.
Alkalinity	N.S.	50	75	N.S.
Total solids	N.S.	100	250	200
Turbidity (SiO_2)	3 — 27	5	10	2
Fe	0,1 — 1,0	0,0005 — 0,05	0,01	0,02
Mn	0,05 — 1,0	nil — 0,03	0,05	0,02
Fe + Mn	0,05 — 1,0	—	0,05	0,02

N.S. = Not Specified

TABLE 1.6 TYPICAL QUALITIES OF RECLAIMED WATER USED BY TWO SOUTH AFRICAN FINE PAPER PRODUCERS[9]

(All units in mg/ℓ except where otherwise indicated)

Quality parameter	SAPPI	Mondi
pH	6,7	7,0
Conductivity (mS/m) 20 °C	120	—
Colour (Hazen units)	10	7
Suspended solids	nil — 1	nil
COD	40	43
Total hardness (as $CaCO_3$)	240	104
Total alkalinity (as $CaCO_3$)	150	74
Bicarbonate alkalinity (as $CaCO_3$)	150	—
Total phosphate (as P)	0,6 — 1,2	0,6
Detergents	0,7 — 0,9	0,1
Sulphates (as SO_4)	185 — 235	152
Fe	0,06	0,08
Mn	0,50	nil
Co	0,34	—
Ni	0,26	—
Cu	0,025	—
Cr	nil	—
Brightness* (average) of test sheets % Elrepho	84,2 — 84,5	—

*Brightness of test sheets for comparison:
82,4 with Rand Water Board water
85,6 with distilled water

Experience in South Africa, however, has shown that the iron and manganese contents of reclaimed water are generally insignificant in comparison with the amount of the same constituents derived from other sources, such as the manganese contributed by the lime used for re-causticizing after the soda-recovery process and the iron contributed by the pipework.[9] It can thus be concluded that water quality requirements should be based on practical local experience and not on general literature reports.

The use of reclaimed water in the pulp and paper industry in South Africa has been practised over a number of years and Table 1.6 shows the qualities of reclaimed effluent used in two such instances.[9] Further details of the use of reclaimed water at these two mills are discussed in Part VI.

CHAPTER 4
AGRICULTURAL USE OF RECLAIMED WATER

The policy in South Africa relating to the reuse of effluents for agricultural irrigation differs in many respects from the policies adopted in other countries. The South African approach is that in general irrigation with effluents is to be discouraged, with the following two exceptions:[12]

- The irrigation of public parks and sports fields which would otherwise require fresh water.
- In areas on the coast where the wastewater would otherwise be discharged to sea and where a better use of the effluent cannot be found.

The fact that large quantities of secondary effluent are still being used for irrigation (26,8% of all effluents in the Pretoria-Witwatersrand-Vereeniging complex[13]), is due mainly to circumstances which prevailed before the promulgation of the Water Act in 1956, when local authorities had no other option but to resort to this means of disposal. Since the introduction of the Water Act, the percentages of effluent used for irrigation have steadily dropped through the diversion of purified effluents to the streams of origin or for other uses.

Apart from the two instances mentioned above, the reuse of effluents for irrigation is as far as possible limited to cases where the producers of effluent find it difficult to meet the effluent standards for river discharge. In such cases, irrigation is primarily regarded as a means of disposal rather than reuse, and permits are issued only for a limited period of time to give the user an opportunity to comply with the standards.

Before granting such a permit, the Directorate of Water Affairs consults the Soil and Irrigation Research Institute of the Department of Agriculture and Fisheries, as well as the Department of Health on the feasibility of the project.

Some 85% of the irrigated effluents emanate from Municipalities and are used to irrigate pastures, plantations, golf courses, sportsfields and parks. Irrigation with sewage effluents is controlled through standards that have been formulated by the South African Department of Health and which are summarized in Table 1.7.[14,15]

In evaluating the quality of water or effluent required for agricultural reuse, factors such as health aspects, the soil/reclaimed water interaction and the plant/reclaimed water interaction should be assessed. Appendix II to this first part of the Guide presents a brief discussion of these factors.

TABLE 1.7 STANDARDS FOR IRRIGATION WITH RECLAIMED WASTEWATERS IN SOUTH AFRICA[14]

	PS	PST	STD	SP-STD	OD
IRRIGATION					
Crops eaten raw]	*	*	*	ϕ	*
Lawns (children associated)]					
Cut flowers]	*	+	ϕ	ϕ	+
Crops not eaten raw]					
Fruit trees and vines	*	+	ϕ	ϕ	+
Pasturage (not for cows)	*	+	ϕ	ϕ	+
Pasturage (milk cows)	*	*	ϕ	ϕ	*
Dry fodder crops]	+	ϕ	ϕ	ϕ	+
Seed production]					
Timber plantations]					
Nurseries]					
Sports fields:					
Developmental stage	+	ϕ	ϕ	ϕ	+
Non-contact	+	+	+	ϕ	+
Contact	*	+	+	ϕ	+
Schools	*	+	+	ϕ	+
Parks:					
Develpmental stage	+	ϕ	ϕ	ϕ	+
Non-recreational	+	+	+	ϕ	+
Public	*	+	+	ϕ	+

CODE OF ABBREVIATIONS

ϕ — Use permitted without restriction
\+ — Use permitted with restriction
* — Use not permitted

CLASSIFICATION OF TREATED EFFLUENTS

PS — Primary and Secondary Treatment. Humus tank effluent.
PST — Primary, secondary and tertiary treatment.
STD — Effluent measures up to General Standard (i.e. Nil E. coli/100 mℓ.)
SP-STD — Advanced treatment measures up to the Special Standard and the quality measures with general drinking water standards.
OD — Oxidation dams with effluent with less than 1 000 E.coli/ 100 mℓ

CHAPTER 5

WATER RECLAMATION FOR POTABLE SUPPLY SYSTEMS

5.1 GUIDELINES FOR ESTABLISHING QUALITY CRITERIA FOR REUSE IN PUBLIC SUPPLY SYSTEMS

The quality criteria for reuse in potable supply systems should be based on the following considerations:

- The criteria should be based on the best knowledge available, local experimental work, and the qualities of both wastewater and available fresh supplies

- The criteria should take cognisance of experience gained in similar instances locally and elsewhere in the world.

- The criteria should be such that they can be technically achieved. Criteria should not be set at levels that cannot be detected, or technically achieved or are such that reclamation becomes economically unfeasible.

- The criteria should take cognisance of toxicity experiments with fish, rats etc. reported both locally and worldwide.

- The criteria should take into account all reported experience with potable reuse.

- Realistic and scientifically justifiable criteria, even if they should bring about a sharp short term rise in the cost of potable water, need not be a long term deterrent. If more water is a prerequisite for the future development of a viable community the demand and supply situation will soon establish a new price structure.

5.2 HEALTH ASPECTS OF WATER RECLAMATION FOR POTABLE SUPPLY SYSTEMS

The most important aspect to take into account when considering and planning for water reclamation for potable purposes is that of safeguarding public health. Reassurances in this regard will be the first requirement from the health authorities and will also play an important role in determining the attitude of the public towards a reclamation project.

It must be realized that reclaimed water originates from a polluted source and therefore the conventional approach of establishing a list of standards and monitoring water quality to ensure compliance with these standards is not sufficient. Additional precautions must therefore be taken and safeguards applied — indeed a reclamation strategy must be adopted for the protection of public health. Such a strategy will have to include at least the following lines of defence:

- Sewage catchment quality control (refer Part II, section 1.2).

- Application of well proven reclamation technology incorporating multiple safety barriers. The various processes are described in Part II.

- Vigilant surveillance and monitoring (refer sections 5.3 and 5.5 and in Part IV, section 1.3).

The following two groups of contaminants are of concern to public health: pathogenic micro-organisms including viruses; toxic substances such as heavy metals and organic chemicals which are suspected to have mutagenic or similar effects when consumed at very low concentrations over long periods of time.

5.2.1 Pathogens

It is well known that a number of diseases such as cholera, dysentery, typhoid and paratyphoid fevers, gastroenteritis and hepatitis can be transmitted by water. However, it is also well known that a properly treated and disinfected water is completely free from pathogens.

Comparative analyses over a period of more than seven years' research at the experimental 4,5 Mℓ/d Stander Water Reclamation Plant in Pretoria have shown that the microbiological quality of reclaimed water was equivalent to or better than that of the best conventional supplies and that the following standard proved sufficient for routine monitoring of the reclamation plant.[16]

Total bacterial plate count:	not greater than 100/mℓ
Total coliforms:	0/100 mℓ
Total enteric viruses:	0/10 ℓ
Total coliphages:	0/10 ℓ

Investigations at the Stander Water Reclamation Plant indicated that *E. Coli* B bacteriophages could be used as a viral indicator in water and reclaimed water, since they are present in greater numbers than enteric viruses in wastewater and appear to be more resistant than enteric viruses to disinfectants. The coliphage test is a rapid, economical and simple method for screening the removal of viruses while the 'total plate count' is a highly sensitive indicator of the bacteriological quality of water.

These conclusions would appear to have been confirmed by an earlier report[17] that coliphages could well be used as viral indicators in water and wastewater.

In the case of water reclamation for potable supply systems, the coliphage test could well be utilized for routine microbiological monitoring of the reclamation plant with other prescribed monitoring such as 'total plate count' and 'total coliforms', while the more time consuming and complex 'viruses count' be used for regular checks at predetermined intervals within an overall control and monitoring programme.

Influence of suspended matter and turbidity

Investigations into the effect of suspended matter and turbidity on virus and bacteria removal has indicated that incomplete particulate matter removal can result in viruses and bacteria being 'shielded' in the disinfection stage.[18] A water with a very low turbidity value can therefore be expected to have a low bacteria and virus count. As the turbidity content of a water has a direct influence on the efficacy of the disinfection step, the standards for reclaimed water for public supply systems must include a turbidity value.

5.2.2 Toxic Substances

Standards have been promulgated for heavy metal contents of potable water (Table 1.8 summarizes). Research into the nature of organic micropollutants, their likely effect on public health and their removal in a water reclamation plant is however, incomplete.

TABLE 1.8 STANDARDS FOR HEAVY METAL CONTENTS OF POTABLE WATER (mg/ℓ)

Metal	E.E.C.[19]	W.H.O.[20]	E.P.A.[21]	S.A.B.S[22]
Iron	3,30	—	—	—
Copper	0,05	0,05	—	1,00
Zinc	3,00	5,00	—	5,00
Arsenic	0,05	0,05	0,05	0,05
Cadmium	0,005	0,01	0,01	0,05
Chromium (total)	0,05	—	0,05	0,05
Lead	0,05	0,10	0,05	0,05
Selenium	0,01	0,01	0,01	—
Mercury	0,001	0,001	0,002	—
Barium	0,10	—	1,00	—

TABLE 1.9 ORGANIC MICROPOLLUTANT QUALITY STANDARDS (μg/ℓ)

Micropollutant	E.E.C.[19]	E.P.A.[21]
Pesticides		
Lindane	—	4
Endrin	—	0,2
Toxaphene	—	5
Methoxychlor	—	100
*2,4-D	—	100
*2,4,5-TP	—	10
Total pesticides	10	—
PAH		
Total PAH	0,2	0,2

*2,4-D and 2,4,5-TP are chlorophenoxy herbicides.

Organic micropollutants fall into two main categories: those that were originally present in the wastewater and those that are formed during the treatment process.

Micropollutants originally present

Of the organic micropollutants which can be present in the wastewater three separate groups are of public health concern: organo-chlorine pesticides and other related compounds, organo-phosphorus pesticides and polynuclear aromatic hydrocarbons (PAH).[23] Table 1.9 lists the limits recommended for a limited number of the above compounds in a potable water.[19,21]

The table indicates that the EEC standard for pesticide content is much more stringent than that of the EPA, while the total PAH standards are identical. This discrepancy with regard to pesticide content may possibly be attributed to the fact that the research to date has not been conclusive in the establishment of the actual 'health' limits.

Research has however, indicated that the Stander Plant reduces the organic micropollutants to very low levels, with the activated carbon stage being responsible for the major portion of the overall removal.[23] The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 14,[24] to a publication by Stander[1] and to section 6.1 of Part II of this guide for further details of the removals of organic micropollutants at the Stander Plant.

Suspended matter and PAH removal

A recent report states that PAH compounds are adsorbed onto suspended matter present in a wastewater and that the suspended matter removal operation, usually included in a reclamation plant, can reduce the PAH content of a typical sewage effluent to below 0,020 μg/ℓ.[25]

Micropollutants formed during treatment

The disinfection of water at a reclamation plant has generally been accomplished through breakpoint chlorination, although ozone, chlorine dioxide and chloramines are now being increasingly used.

Chlorination of a water containing organic matter has been shown to produce chloroform and other volatile halogenated hydrocarbons (VHH) which at certain concentrations are reported to be a public health concern.[1,24,26] Table 1.10 shows the increase in VHH content of the reclaimed water after passage through the Stander plant.[24]

The presence of VHH compounds in potable water supplies in areas of the USA prompted the recent EPA regulation which limits the trihalomethane (THM — similar to VHH) content of a drinking water to 100 μg/ℓ and requires cities of 75 000 or more people to install granular activated carbon columns at their potable water treatment plants.[27]

Tap water in Pretoria is derived from impoundments which receive some, even if a relatively small

TABLE 1.10 AVERAGE CONCENTRATION OF THE VOLATILE HALOGENATED HYDROCARBONS IN THE INFLUENT TO AND THE FINAL WATER FROM THE STANDER PLANT (μg/ℓ)[24]

Water	CCl_4	$CHCl_3$	C_2Cl_4	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$
Influent	0,02	0,68	1,39	0,13	0,09	0,17
Final	0,66	17,66	0,07	11,92	10,55	4,38

percentage of, purified sewage. This is a fairly common situation in South Africa but nowhere does the potable supply exceed the 100 μg/ℓ VHH limit.[28] However, the use of reclaimed water for public supplies requires that quality standards should include a VHH limitation.

Importance of activated carbon

Activated carbon adsorption is thus an important process in the overall reclamation system as it reduces the VHH compounds — albeit not particularly effectively (refer to Part II, section 6.1) — as well as those organic micropollutants originally present in the intake to the reclamation plant.

Further discussion

More detailed discussion on the removal of organic matter through activated carbon adsorption and the merit of preceeding the activated carbon columns by ozone are presented in Part II, sections 6.1 and 6.2 respectively.

5.3 PROPOSED STANDARDS FOR RECLAIMED WATER FOR POTABLE USE

The standards proposed in Table 1.11 for the potable use of reclaimed water take into cognisance the results obtained from Windhoek[29] and the Stander plant,[24] as well as the requirements of the WHO[20] and recent USA regulations.[27]

Overall reclamation plant process configurations required to comply with the above quality standards are presented in Part II, section 13.

TABLE 1.11 PROPOSED STANDARDS FOR POTABLE RECLAIMED WATER

Parameter	Objective
pH	Final effluent pH to obtain stability with respect to colour, carbonate and corrosion
Chemical Oxygen Demand	< 15 mg/ℓ
Ammonia (NH_3-N) and chloramines	< 0,5 mg/ℓ
Nitrate Nitrogen (NO_3-N)	< 10 mg/ℓ*
Total phosphorus (PO_4-P)	< 0,5 mg/ℓ
Heavy metals and trace elements	To comply with local drinking water standards or with WHO standards
Total Organic Carbon	< 3,0 mg/ℓ
Volatile halogenated hydrocarbons (VHH)	< 0,1 mg/ℓ
Turbidity	< 0,4 JTU
Total Dissolved Solids	< 500 mg/ℓ above that of the potable water supply from which the reclaimed water initially originated
Stability	Water must be stable according to the Langelier, Ryznar and corrosivity indices
Microbiological quality	Free chlorine residual of 0,5 mg/ℓ (0,3 to 0,7) at point of discharge into potable water supply plus compliance with the following: total plate count: not greater than 100/mℓ total coliforms: 0/100 mℓ total enteric viruses: 0/10 ℓ total coliphages: 0/10 ℓ

*If the reclaimed water is to be blended with potable supplies the NO_3-N can be higher than 10 mg/ℓ provided that the net value is less than 10 mg/ℓ

5.4 COMPARISON OF CONVENTIONAL WATER TREATMENT WITH RECLAMATION FOR POTABLE USE

The most important contaminants to be removed by reclamation for potable use are heavy metals, pathogenic microorganisms and potentially hazardous organic chemicals.

Extensive studies on the removal of these classes of compounds at Water Factory 21 in California, and the Stander (Pretoria) and Windhoek Water Reclamation Plants proved the consistency with which these compounds are being removed to concentrations within the limits specified for drinking water and if the process safeguards discussed in Part II, section 1.2 are implemented, a high order of reliability can be expected from any reclamation plant.

The same can unfortunately not always be said for conventional water purification plants normally designed to remove gross particulate contaminants and to provide disinfection. There is a major difference between a water treatment plant and a potable water reclamation plant in that the process units in the latter system are selected and eventually operated to remove specific contaminants in accordance with proper and sophisticated chemical engineering practices.

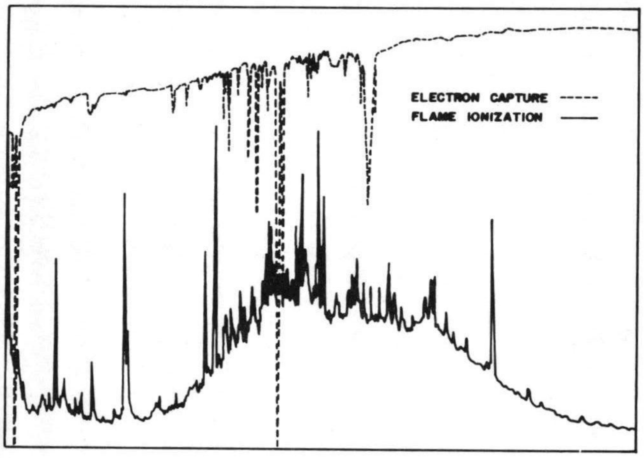

FIGURE 1.1(a): **G.C. Profile — secondary sewage effluent**[30]

Trace organics

It is recognised that there are numerous organic compounds present in drinking waters today. If it can be proved that the number and concentration range of organics can, through proper water reclamation technology, be reduced to levels which are lower — and often much lower — than those found in present-day drinking water, a substantial burden would be taken off the minds of those people concerned with public health.

Figure 1.1 compares two gaschromatograph (GC) profiles:[30] Figure 1.1(a) shows an electron capture (dotted line) and flame ionization (solid line) chromatograph of the organic matter present in a secondary sewage effluent, while Figure 1.1(b) represents the same type of analysis performed on the reclaimed water produced at the Stander Water Reclamation Plant from the same secondary sewage effluent as for Figure 1.1(a).

Note the difference in baseline shift, the reduction in the numbers of organic compounds, as well as a substantial reduction in the concentration of the remaining organics.

Figures 1.2, 1.3 and 1.4 show GC Profiles of Rand Water Board water, Rietvlei Dam water and Hartbeespoort Dam water respectively, the former two being potable supplies for Pretoria while the latter is a potable supply for Brits.[30]

The GC Profiles clearly show the difference in baseline shift between reclaimed water (Figure 1.1(b)) and three potable water supplies as derived from a river and two dams that receive wastewaters from nearby cities (Figures 1.2, 1.3 and 1.4).

It is evident from these profiles that reclaimed water contains less organic substances and at lower concentrations than the water from polluted sources that is purified by conventional means.

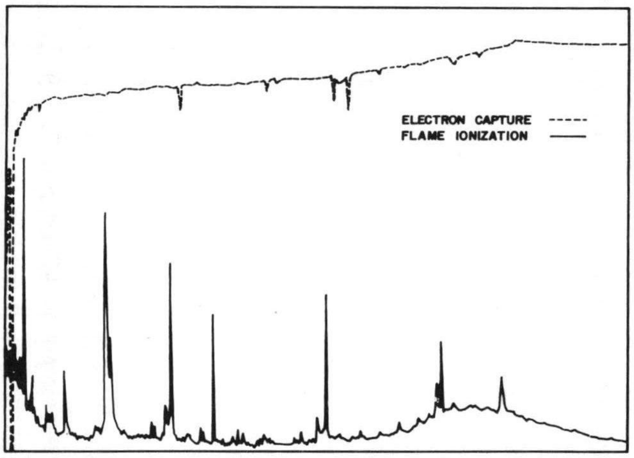

FIGURE 1.1(b): **G.C. Profile — Stander Reclamation plant effluent**[30]

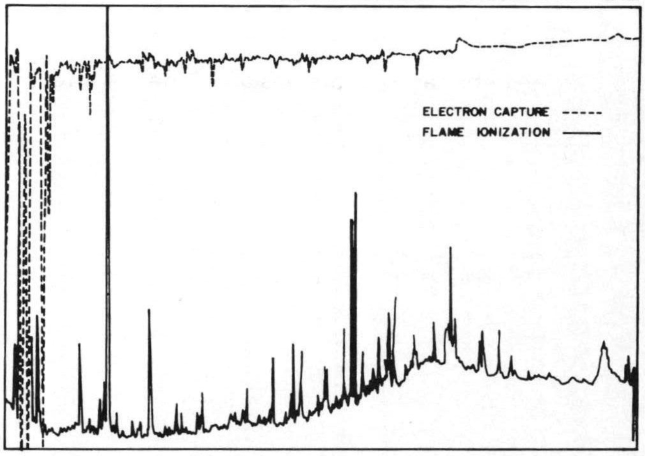

FIGURE 1.2: **G.C. Profile — Rand Water Board drinking water supply (Klapperkop, Pretoria)**[30]

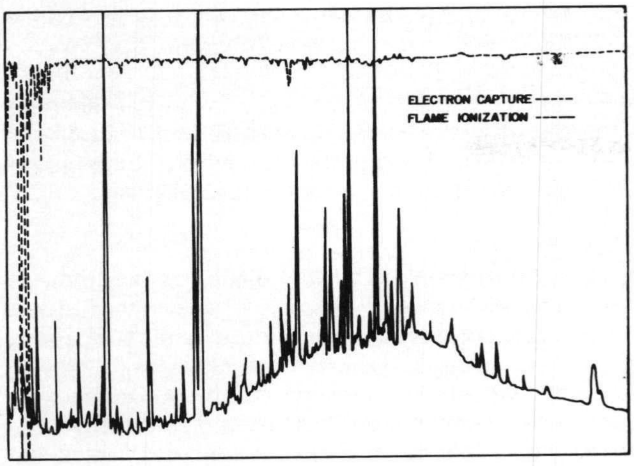

FIGURE 1.3 G.C. Profile — Rietvlei Dam drinking water supply (Pretoria)[30]

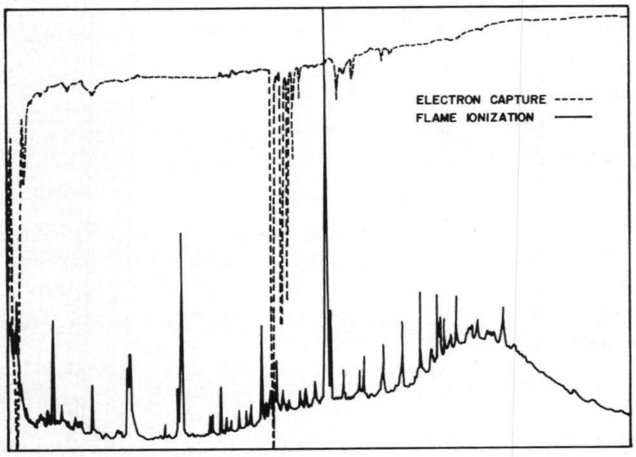

FIGURE 1.4 G.C. Profile — Hartebeespoort Dam drinking water supply (Brits)[30]

5.5 THE SIGNIFICANCE OF QUALITY CONTROL

Steps should be taken in the design of the plant to ensure that the quality will at all times fall within an agreed-upon statistical quality variation.

This aspect applies to all forms of reuse but is of the utmost importance in the case of reclamation for potable water supplies.

The quality of water to be supplied is generally discussed in depth during the initial planning stages and is in some instances guaranteed by the controlling body. Failure to comply with the quality requirements could jeopardize the entire reclamation scheme and not only involve substantial capital outlays to rectify the situation but it could also adversely influence attitudes towards future reclamation schemes.

Methods of safeguarding quality should therefore be carefully evaluated and then incorporated in the overall design of the water reclamation plant (refer to Part II, chapter 1). The instrumentation that forms part of the safeguards should be carefully selected and its installation supervised by specialist instrument engineers — particularly in the case of reclamation for potable supplies. All operators and maintenance personnel should be versed in the function and/or peculiarities of the equipment prior to 'take over' of the plant.

It will be appreciated that consistent compliance with quality requirements, together with relevant records are excellent 'sales aids' for public persuasion.

5.6 PUBLIC ATTITUDES TOWARDS WATER RECLAMATION

Various surveys to determine public attitudes towards water reclamation have been carried out in the USA. Surveys in areas of California yielded the following conclusions:[31,32]

- The public was not well informed on reclamation practices in their community and there was a definite need for better and perhaps more direct methods of information dissemination on these projects.
- The two main reasons cited for rejection of direct personal contact with reclaimed water were psychological repugnance and health considerations, indicating a need to familiarize the public with the water reclamation projects in such a manner that will assure them of no detrimental effects.
- A highly educated public would necessitate less intense and specialized educational efforts to alter attitudes toward reclaimed water than would be required for less educated communities.
- The three variables which correlated with rejection of reclaimed water were aversion to uncleanliness, aversion to human waste and overconcern with health, indicating the need for intense public education on reclaimed wastewater concerning its purity in relation to drinking water and its health effects.

It is natural for man to find the idea of water reclamation for potable reuse repugnant.

The issue is therefore emotionally charged and under such circumstances the general public tends to believe the worst and therefore would accept any argument which will justify its instinctive aversion and give it scientific credence.

The emotional interest and debate which usually centres around the concept of reclaiming wastewater for potable reuse make it an ideal subject for television and human interest features. The wise planner should therefore make use of this selfsame interest to educate the public.

Informing the public

It is important that the public should be well informed and the day on which reclaimed water is recycled for the first time should be well publicized in advance. However, even long before that time a well directed publicity campaign should be mounted to pass on to the public the necessary scientific knowledge to leave them assured of the superior quality of the water they will in future receive, and of the measures taken to ensure that this high quality will be maintained at all times.

A public information programme conducted over a considerable period will be necessary and should give attention to aspects such as the following:

- The public should be fully informed on matters concerning their conventional water supply and the planned reclamation system as an integral part of the water economy of their community.

- Water officials should emphasise that there is a need for reclamation to ensure future socio-economic progress of the community, and that the costs are more favourable than any other alternative.

- The purity and safety of reclaimed water should be stressed as opposed to the many problems, inconveniences and health implications that would be associated with severe water restrictions.

- The public should be familiarized with the technical details of the reclamation process and the multiple safety barriers incorporated e.g. by providing opportunities to visit a demonstration facility, and to ask questions.

- Every effort should be made to inform the community in clear and concise terms of the extent of the past, present and expected future water shortages.

- Great care should be taken with the public media in order to ensure that this delicate and potentially emotional matter is not misconstrued thereby awakening public resistance.

Virtually no public resistance was experienced in Windhoek in 1969 after the above steps had been implemented over a number of years prior to the discharge of reclaimed water into the potable supply network.

CHAPTER 6

INTEGRATION OF RECLAIMED WATER WITH THE WATER SUPPLY SYSTEM

6.1 GENERAL QUALITY AND QUANTITY CONSIDERATIONS IN INTEGRATED SYSTEMS

In contemplating the integration of reclaimed water into a water supply system, careful consideration should be given to the quality and quantity aspects involved as these two factors will generally indicate the viability of such a scheme.

In inland areas where treated municipal and industrial wastes are discharged into the fresh water supplies, these aspects can best be considered through the development of a mathematical model that covers the entire area and takes into account the effect that varying quality and quantity of such wastes will have on the fresh water quality.

The Pretoria-Witwatersrand-Vereeniging complex (PWV complex) draws the bulk of its fresh water supplies from the Vaal Barrage on the Vaal River. It has been estimated that some 35% of the water abstracted from the Barrage consists of purified sewage effluent and industrial wastes.[33] Preliminary investigations indicated that the potential for reuse in this area will not be governed by the organic and microorganic contents of the sewage and industrial wastes, but rather by the mineral salt loads discharged to the tributaries of the Vaal River by the mining industry, industrial wastes and surface runoff.[33] Control of these highly saline discharges would therefore appear to be a prerequisite for water reuse.

A mathematical model has been developed for the area in order that the feasibility of the various options that are available for reducing and/or safeguarding the mineral salt quality of the water supplied to the PWV complex may be investigated.[34]

A domestic sewage generally contains a contaminant fraction of some 0,1% by mass, indicating that an untreated domestic sewage is less contaminated (or polluted) than most brackish waters. In addition, relatively inexpensive biological treatment can reduce this contaminant fraction by some 95% and thereby render the sewage effluent a valuable source of water, particularly in arid and semi-arid areas where the alternative water sources are brackish water or sea water.

6.2 INTEGRATION OF RECLAIMED WATER WITH POTABLE SUPPLY SYSTEMS

There are two opposing schools of thought as to the safest way of integrating reclaimed water with the potable water supply system.

The first school reasons that the direct integration of reclaimed water with the water supply system for potable use is preferable. Due to the higher standard of treatment and control that would be exercised at the reclamation plant a safer water will be produced than by the present situation of massive indirect reuse whereby effluent of cities are being discharged into river systems after secondary treatment and disinfection to be withdrawn from the river and used for a downstream potable water supply. A large number of people throughout the world drink water derived from such rivers without due regard to the wastewater content.

The second school of thought maintains that the health risks of direct integration of the reclaimed water for potable supplies are still too high. Wastewaters being discharged to rivers and lakes that form potable water supplies should be treated to standards higher than that of the receiving waters and the treatment facilities for the water supply downstream should be upgraded to give double protection. At the same time the dilution, self purification and natural die-off of organisms will ensure lower risks. The upgrading of the water treatment plants should include all unit processes and fail-safe procedures as would normally be associated with the reclamation plant.

Each reclamation project will be sufficiently different to require a detailed study to determine whether direct or indirect reuse is the best solution in terms of cost and health protection.

The incidence of micro-organics in potable water supplies is due not only to an over-assessment of the self-purification capability of the water environment but also to the inability of conventional water treatment plant process units to remove compounds present at micro-concentration levels.

It has been argued that the implementation of advanced treatment systems as essentially end-of-the-line quality control tools, i.e. as curative technologies built into public water supply facilities, would be a retrogressive step as it would leave the backdoor open to increased pollution with consequent progressive escalation of unit production costs and complexity of purification facilities.[1]

It is submitted that a sewage treatment and advanced treatment plant designed for direct reclamation and integration with a potable water supply system has definite advantages over the indirect reuse alternative in that it not only comprises controlled biological and advanced physical/chemical treatment stages, but the quality of plant influent can be controlled so as to reduce the intractible, toxic material content of the reclaimed water.

The following additional points should also be considered when reclamation for potable water supplies is contemplated:

- Discharges from industries that manufacture pesticides and other synthetic organic compounds that are reported to possess health-affecting properties should be diverted from the plant influent. This aspect is further discussed in sections 2.3 (Industrial pollution management) and 2.4 (Town planning).

- Water of potable quality should only be distributed to those users requiring such a quality. For example, water should not be reclaimed for potable purposes while water from conventional supplies is used by industry or agriculture.

- Reclamation plants should if possible only be operated in times of water shortage as they are operating cost intensive.

- The reclaimed water should, if possible, be distributed over the entire community so as to ensure overall quality equalization.

- In a community in which only a portion of the total sewage flow is to be reclaimed, the advanced treatment and associated biological treatment plant need not be situated at the same site as the main sewage treatment plant. Figure 1.5 indicates a typical scheme whereby a constant flow of domestic sewage is reclaimed while the sludges generated, excess domestic flows and all industrial wastes pass to the main sewage treatment plant.

  This system has particular merit in cases where the main sewage treatment plant is far from the city as it will reduce not only the pipeline costs for routing the reclaimed water back to the city, but also the hydraulic load on the sewer.

  As in this system sludge treatment and disposal is not practised at the biological and advanced treatment plants, it should be possible to site the plants in close proximity to the residential areas of the city thus also reducing pipeline costs.

- Proper monitoring programmes of both plant influent and product water should be instituted so as to ensure effective control of reclaimed water quality.

6.3 INTEGRATION OF RECLAIMED WATER WITH NON-POTABLE SUPPLY SYSTEMS

The most important aspect of the reuse of non-potable quality effluent is that the supply must be bacteriologically safe. This is of particular importance in the case of industrial and unrestricted agricultural reuse where physical contact between humans and water may occur.

Careful attention should also be paid to the prevention of cross-connections between non-potable and potable supplies. In cases where non-potable water is stored at an industrial site with provision for potable make-up during emergency or peak demands, the potable water inlet pipe should be positioned well above the highest expected level in the storage tank. The use of valves or blanked off flanges to separate the two waters should not be tolerated.

Where non-potable water is supplied not only for industrial use but also for irrigation and toilet flushing within a community, the supply of water should not be guaranteed by the provision of cross-connections between the potable and non-potable supplies, but rather by steps such as storage at the reclamation plant.

Steps should be taken to differentiate between the pipes carrying the two classes of water — particularly within industrial concerns. Such differentiation can be achieved by simple (but durable) colour coding. In addition the pipes conveying the non-potable water should be positioned in ducts so that they are readily accessible for inspection and, if necessary, maintenance.

In the case of the non-potable water being used for machinery and floor washing or for garden irrigation, hose connection points should be clearly marked with signs indicating that the water is not fit for human consumption.

In addition to the above health considerations, the following considerations should receive attention:

- Dual systems should be used wherever possible so that the highest quality water may be preserved for potable purposes. Generally, however, dual systems

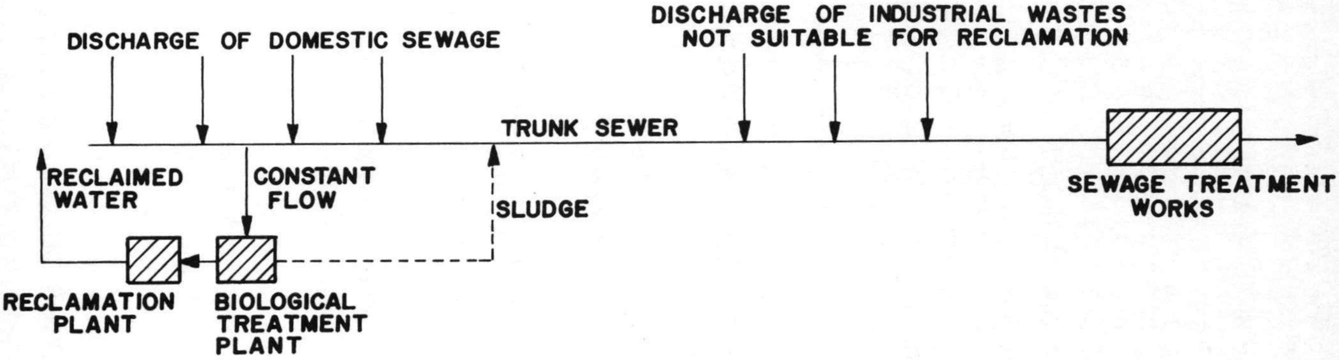

FIGURE 1.5: Reclamation plant sited away from main treatment plant

APPENDIX I

TABLE 1.12 GENERAL AND SPECIAL STANDARDS FOR DISCHARGE, IN TERMS OF THE SOUTH AFRICAN WATER ACT, ACT NO. 54 OF 1956

Parameter	General Standard	Special Standard
Colour, odour, taste	nil	nil
pH	5,5 — 9,5	5,5 — 7,5
Dissolved Oxygen (%)	≮ 75	≮ 75
Temperature (°C)	≯ 35	≯ 25
Typical Faecal Coliforms (per 100 mℓ)	nil	nil
Chemical Oxygen Demand (mg/ℓ)	≯ 75	≯ 30
Oxygen Absorbed (mg/ℓ)	≯ 10	≯ 5
Total Dissolved Solids	≯ 500 mg/ℓ above intake	≯ 15% above intake
Suspended Solids (mg/ℓ)	≯ 25	≯ 10
Sodium (mg/ℓ)	≯ 90 above intake	≯ 50 above intake
Soap, oil, grease (mg/ℓ)	≯ 2,5	nil
Residual Chlorine — as Cl (mg/ℓ)	≯ 0,1	nil
Free and Saline ammonia — as N (mg/ℓ)	≯ 10	≯ 1
Nitrate — as N (mg/ℓ)	not specified	≯ 1,5
Arsenic (mg/ℓ)	≯ 0,5	≯ 0,1
Boron (mg/ℓ)	≯ 1,0	≯ 0,5
Chromium — total (mg/ℓ)	≯ 0,5	≯ 0,05
Copper (mg/ℓ)	≯ 1,0	≯ 0,02
Phenol (mg/ℓ)	≯ 0,1	≯ 0,01
Lead (mg/ℓ)	≯ 1,0	≯ 0,1
Copper (mg/ℓ)	≯ 0,5	≯ 0,02
Sulphides — as S (mg/ℓ)	≯ 1,0	≯ 0,05
Fluorine (mg/ℓ)	≯ 1,0	≯ 1,0
Zinc (mg/ℓ)	≯ 5,0	≯ 0,3
Phosphate — total as P (mg/ℓ)	not specified*	≯ 2,0**
Iron (mg/ℓ)	not specified	≯ 0,3
Manganese (mg/ℓ)	not specified	≯ 0,1
Cyanide — as CN (mg/ℓ)	not specified	≯ 0,5

* In terms of Government Notice No. 7159 of 1 August 1980, effluents draining to certain sensitive areas must have soluble orthophosphate (as P) concentrations of less than 1,0 mg/ℓ

**In terms of Government Notice No. 7159 of 1 August 1980 this figure has been amended to not greater than 1 mg/ℓ of soluble orthophosphate (as P).

APPENDIX II

FACTORS TO BE CONSIDERED IN THE AGRICULTURAL REUSE OF RECLAIMED WATER

The use of treated sewage effluents for irrigation has been practised in South Africa for many years without any apparent deleterious effect on crops and soil. Table 1.13 shows the volumes irrigated as a percentage of the total sewage flows discharged by a number of South African cities.[10]

When evaluating the quality of water for agricultural reuse, the following four factors should be considered:

- health aspect
- soil/reclaimed water interaction
- plant/reclaimed water interaction
- technical aspects, which do not fall within the scope of this guide.

1. HEALTH ASPECT

The health aspects of using reclaimed water for agricultural purposes covers two considerations; (i) direct contact of humans or animals with the reclaimed water, and (ii) the subsequent consumption of fruit and vegetables irrigated with the reclaimed water.

Pathogens, whether viruses or bacteria, are able to survive for several days in the leafy areas of most fruit and vegetables and hence present serious health risks.[35]

Health authorities therefore restrict the type of crops that can be irrigated with an effluent which has not undergone a high degree of disinfection. Irrigation with non-disinfected effluent is allowed for industrial crops, seed crops, tree nurseries and other crops not destined for direct human consumption.

The use of reclaimed water for unrestricted irrigation of fruits and vegetables necessitates a high degree

TABLE 1.13 DAILY VOLUMES OF SEWAGE EFFLUENTS REUSED FOR IRRIGATION IN SOUTH AFRICA[10]

Locality	**Total vol. available (m^3/d)**	**Vol. reused (m^3/d)**	**% of total reused**	**Pasture**		**Crops (m^3/d)**	**Parks (m^3/d)**	**Trees (m^3/d)**	**Sports fields (m^3/d)**	**Disposal rate (m^3/d/ha)**
				Vol. (m^3/d)	**Area (ha)**					
Johannesburg	317 800	113 500	35,7	113 500	1 820					62
Cape Town	143 000	500	0,3						500	
Pretoria	86 000	16 500	19,2				200	16 300		
Port Elizabeth	88 000	6 800	7,7						6 800	
Germiston	52 600	8 000	15,2			8 000				
Bloemfontein	25 000	300	1,2			200			100	
Benoni	20 400	2 000	1,0			400	1 000		600	
Pietermaritzburg	27 300	6 800	24,9					6 800		
Kimberley	8 000	1 600	20,0						1 600	
Carletonville	4 500	4 500	100,0					4 500		
Krugersdorp	17 000	13 600	80,0	13 600	100					
Klerksdorp	5 800	5 800	100,0			5 600			200	
Randfontein	4 500	1 400	31,1			1 400				
Grahamstown	2 300	2 300	100,0			2 300				
Worcester	5 900	5 900	100,0	5 900	150					39
Westonaria	6 800	6 800	100,0			6 800				
King William's Town	2 300	2 300	100,0	1 400	77				900	18
Total	817 200	198 600	24,3	134 400		24 700	1 200	27 600	10 700	
Percentage				67,7		12,4	0,6	13,9	5,4	
Industries										
Ngodwana Pulp and Paper		1 300		1 300	54					24
AE & CI Modderfontein		1 100			1 028					1

of both treatment and disinfection. There are, therefore, two sets of criteria for irrigation, one for 'restricted' use and the other for 'unrestricted' use, with the main difference being that of degree of treatment and disinfection.

Nutrients such as nitrogen and phosphorus need not be removed from the reclaimed water when then aim is 'restricted' agricultural reuse. However, the health aspect of 'unrestricted' irrigation necessitates a high degree of disinfection in order to produce a pathogen-free water. Such a water must therefore contain a free chlorine residual and in order to achieve this residual as economically as possible the effluent to be disinfected should have a low ammonia and organic matter content.

Effluents from conventional sewage treatment plants are suitable for 'restricted' irrigation while the free chlorine residual requirement for 'unrestricted' irrigation would indicate a higher degree of treatment.

A number of countries have standards or recommendations referring to the agricultural use of reclaimed water and these standards generally have clauses which refer to the levels of treatment and disinfection that must be imparted to a sewage effluent prior to its use as an irrigant. Table 1.7 in Chapter 4 summarizes the standards in South Africa.[14]

2. SOIL/RECLAIMED WATER INTERACTION

The following aspects should be taken into consideration:

Suspended matter in the reclaimed water

Continuous irrigation of heavy clayey soils with an effluent containing suspended matter has been shown to result in the soil-pores becoming clogged while irrigation of light sandy loam soils with a similar water will improve the organic content of the soil with little soil-pore clogging being noticed.[36] Criteria for the suspended matter content of a reclaimed water to be used for irrigation should be based on the soil conditions in the area concerned.

The effect of sodium

Irrigation with a water having a high sodium content can destroy the clay particle aggregation of soils, whereby the permeability of both air and water is drastically reduced. The effect of sodium is less pronounced in light soils containing little clay.

The sodium hazard can be evaluated by two parameters, namely the 'exchangeable sodium percentage' (ESP) and the 'sodium adsorbtion ratio' (SAR). Critical values for the ESP and SAR are 15 and 13 respectively, while the desirable values are less than 10 and 9 respectively.[36]

The salinity of the reclaimed water

Irrigation with highly mineralized waters necessitates the use of additional of water to leach out the accumulated salts in the soil in order to maintain a threshhold total dissolved solids concentration in the root-zone of the plants. Figure 1.8 shows the additional volumes of water of varying salinity required for leaching to maintain soil TDS values at 5 000 mg/ℓ (curve a) and at 10 000 mg/ℓ (curve b).[10]

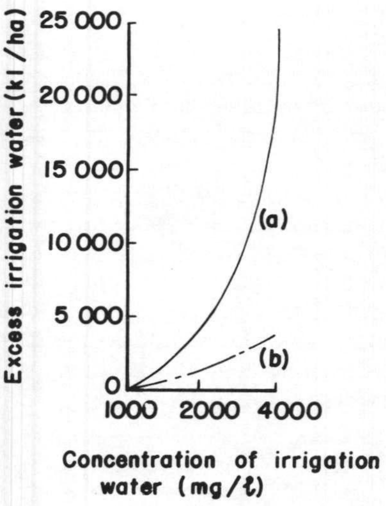

FIGURE 1.8: Additional water requirements to maintain soil solution TDS values[10]

The type of soil

Soil conditions should be carefully evaluated, as good drainage properties can be of greater importance for crop growth than the TDS of the irrigation water. Saline waters may often be used on open, well-drained soils but care should be taken to protect underground aquifers.

The presence of underground potable water aquifers

The reclaimed water application rates should be carefully evaluated in the laboratory using soil samples from the area to be irrigated in order to ensure that no 'breakthrough' of inferior quality water into the potable water aquifer occurs.

Irrigation in dolomitic areas should be restricted, particularly if public supplies are extracted downstream of the irrigation site.

3. PLANT/RECLAIMED WATER INTERACTION

The following aspects should be taken into consideration:

Nutrient content of the reclaimed water

Nutrients present in the reclaimed water, such as nitrogen, phosphorus, potassium etc., can enhance the crop growth and thus save on artificial fertilizers. However, crops respond differently to different nutrient loadings and cases have been reported where continued application of nitrogen, for example, has delayed the maturing and harvesting of cotton and sugar cane, has decreased the sugar content of sugar beets and the starch content of potatoes and has adversely affected the quality and quantity of some fruit and vegetable crops.[37]

In addition, a build up of phosphorus in a soil has been shown to reduce the uptake of zinc and magnesium by fruit trees and thereby stunt their growth.[38]

It may be concluded that nutrients in the reclaimed water are valuable but that the economic value of such nutrients should be related to the crop response under the local conditions rather than to the nominal nutrient contents in the water.

Trace element content of the water

Boron, although an element essential for plant growth, becomes toxic at application concentrations of greater than 0,5 mg/ℓ.[39] The sensitivity of plants to boron varies: avocado, citrus and deciduous fruit crops are the most sensitive, whereas beet, alfalfa, gladiola, onions and potatoes are among the most tolerant crops.[36]

Heavy metals at certain concentrations can become toxic to a wide range of crops. Table 1.14 lists heavy metal concentration limits for continuous irrigation, based on standards in Germany[40] and standards published by the U.S. Water Pollution Control Authority[36] and the E.P.A. (U.S.A.)[39]

The limits shown in Table 1.14 are for continuous irrigation and could well be higher for intermittent irrigation. The limiting concentrations should thus be evaluated under local conditions.

The salinity of the reclaimed water

The mineral salt content of irrigation water can restrict crop growth. The actual salt concentrations detrimental to crop growth depend upon a number of parameters such as soil permeability, water application rate, method of irrigation and crop tolerance.

Table 1.15 shows the proposed critical limits for the use of domestic effluents for irrigation in Israel.[36]

TABLE 1.14 HEAVY METAL LIMITATIONS FOR CONTINUOUS IRRIGATION (mg/ℓ)

Metal	Germany	USWPCA (1968)	EPA (1972)
Iron (Fe)	-	-	5,0
Lead (Pb)	—	5,0	5,0
Zinc (Zn)	2,0	5,0	2,0
Nickel (Ni)	0,5 — 1,0	0,5	0,2
Copper (Cu)	5,0	0,2	0,2
Manganese (Mn)	—	2,0	0,2
Chrome (Cr)	—	5,0	0,1
Cadmium (Cd)	—	0,005	0,01
Lithium (Li)	—	5,0	2,0
Aluminium (Al)	—	1,0	5,0
Arsenic (As)	0,3	1,0	0,1
Cobalt (Co)	0,5 — 1,0	0,2	0,05
Boron (B)	0,3	—	0,7
Fluorine	—	—	1,0
Selenium	—	—	0,02

TABLE 1.15 SUGGESTED CRITICAL LIMITS FOR DOMESTIC EFFLUENTS USED FOR IRRIGATION IN ISRAEL[36]

Composition	Sensitive crops	Tolerant crops
Electrical conductivity (micromhos/cm)	2 000	3 000
Chloride (mg/liter)	200	450
Sulfate (mg/liter)	300	500
Boron (mg/liter)	0,7	2,5
SAR value	8	15

Table 1.16 presents a classification of mineral water quality requirements for agricultural use based on South African conditions[10] while Table 1.17 lists some crops that are sensitive, moderately tolerant and tolerant to saline effluents.[41]

TABLE I.16 MINERAL QUALITY REQUIREMENTS FOR AGRICULTURAL USE[10]

Agricultural use	Total dissolved solids (mg/ℓ)	Remarks
Crops	< 500	Satisfactory for all crops
	500 — 1 000	Water that can have detrimental effects on sensitive crops; additional water may be required for leaching
	1 000 — 2 000	Water that may have adverse effects on many crops and thus requires careful application practice
	2 000 — 5 000	Water that can be used for tolerant plants on permeable soils with careful management practice
Livestock	2 500* — 5 000^{+}	*Threshold value at which poultry or sensitive animals might show slight effects from prolonged use $^{+}$Animals in lactation or production might show definite adverse reaction

TABLE 1.17 CROP SENSITIVITY

Sensitive
citrus, pears, almonds, peaches, apricots, apples, beans, cabbage, potatoes, sweet potatoes, egg plant, celery

Moderately tolerant
grapes, figs, olives, pomegranate, lucerne, tomatoes, sorghum, winter cereals, rice, sunflowers, lettuce, carrots, parsnips, squash, onions

Tolerant
beet, rape, kale, cotton

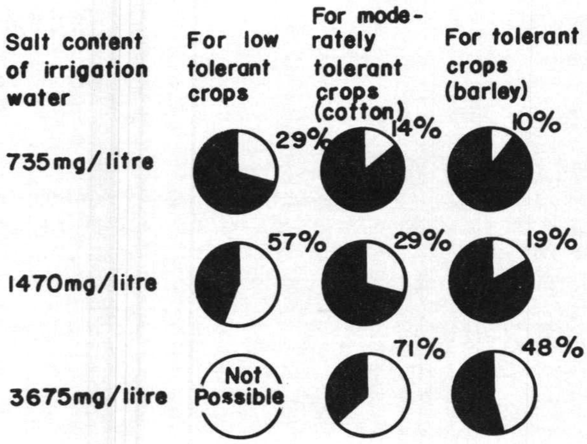

FIGURE 1.9: Percentage leaching necessary for different water salinities[10]

As was mentioned in Section 2 of this appendix, the higher the salinity of water, the greater the water requirements for preventing salt accumulation in the soil at the root zone. Figure 1.9 indicates the percentage of leaching required for different crops as a function of the effluent salinity. It shows that an increase in salinity from 735 to 1 470 mg/ℓ will result in an extra 28% of irrigation water being required for sensitive crops to effect the necessary degree of leaching.[10]

REFERENCES

1. Stander G.J. Micro-organic Compounds in the Water Environment and their Impact on the Quality of Potable Water Supplies. *Water SA* **6**(1) 1. (1980)
2. Funke J.W. A Guide to Water Conservation and Reclamation in Industry. CSIR Guide K9, Pretoria, (1969).
3. Knutze E. Location, Control and Disposal of Liquid Wastes from Trade and Industry in the Federal Republic of Germany. *Prog. Wat. Tech.,* **10**(1/2) 399 (1978).
4. V.d. Merwe P.H. and Van Biljon S.N. Industrial Sludge Handling and Disposal. *Wat. Polln. Cont.* **72**, 199, (1973).
5. Scott P. The Treatment and Disposal of Toxic and Hazardous Waste. Paper presented at Biennial Conference of IWPC (SA Branch), Pretoria, June 1980.
6. Hart O.O. Operational Guidelines. Chapter 13 of the 'Manual for Water Renovation and Reclamation". CSIR Technical Guide K42, Pretoria, (1978).
7. Okun D.A. Regionalization of Water Management: A Revolution in England and Wales.
8. Jacobs R.L. and Hoge C.H. Developing a Regional Wastewater System J. WPCF **42**, 1951 (1970).
9. Funke J.W. and Van Vuuren L.R.J. Water Conservation, Reuse of Effluent and Prevention of Pollution in the South African Industry. Group discussion on Water Reuse organized by the Iranian Ministry of Power and Energy, Tehran, 1—2 November, (1977).
10. Hart O.O. and Van Vuuren L.R.J. Water Reuse in South Africa. Chapter 13 of 'Water Renovation and Reuse', edited by Shuval H. and published by Academic Press Inc., London (1977).
11. Osborn D.W. Factors Affecting the Use of Purified Sewage Effluents for Cooling Purposes. *Wat. Polln. Cont.* **69**, 456, (1970).
12. Rudd R.T. Water Pollution Control and Industrial Use of Water in South Africa, including Reuse of Effluent. Group Discussion on Water Reuse, organized by Iranian Ministry of Power and Energy, Tehran, November (1977).
13. Odendaal P.E. and Van Vuuren L.R.J. Reuse of Wastewater in South Africa — Research and Application. Paper presented at Water Reuse Symposium, Washington, March, (1979).
14. Smith L.S. Health Considerations in Prescribing Microbiological Quality of Effluents. Paper presented at Biennial Conference of Inst. Wat. Polln. Cont. (S.A. Branch), Port Elizabeth, March (1978).
15. Department of Health. Guide: 'Permissible Utilization and Disposal of Treated Sludge Effluent'. Reference 11/2/5/3 Pretoria, (1978).
16. Grabow W.O.K. Bateman B.W. and Burger J.S. Microbiological Indicators for Routine Monitoring of Wastewater Reclamation Systems. *Prog. Wat. Tech.* **10**(5/6) 317, (1978).
17. Kott Y., Ben-Ari H. and Vinokur L. Coliphages Survival as Viral Indicator in Various Wastewater Quality Effluents. *Prog. Wat. Tech,* **10**(1/2), 337 (1978).
18. Van Duuren F.A. The Significance of Microparticles in Water Purification. Paper presented at Biennial Conference of Inst. Wat. Polln. Cont. (SA Branch), Port Elizabeth, March (1978).
19. European Economic Community (EEC). Limits for Surface Water Intended for the Abstraction of Drinking Water. *World Water,* June (1978).
20. World Health Organization (WHO). *International Standards for Drinking Water.* 3rd Edn, Geneva, (1971).
21. United States E.P.A. *National Interim Drinking Water Regulations Federal Register,* **40**, 248, December (1975).
22. South African Bureau of Standards. Specification for Water for Domestic Supplies (metric units). SABS Spec. No 241-1971 Pretoria (1971).
23. Van Rensburg J.F.J., Van Rossum P.G. and Hatting W.H.J. The Occurrence and Fate of Micropollutants in a Water Reclaimed for Potable Reuse. *Prog. Wat. Tech.* **10**(1/2) 41 (1978).
24. Hattingh W.H.J. Health Aspects. Chapter 14 of the 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42, Pretoria, (1978).
25. Packham R.F. The Chemical Composition of Drinking Water in Relation to Public Health. Paper presented at Biennial Conference of the Inst. Wat. Polln. Cont. (SA Branch), Port Elizabeth, March, (1978).
26. Hart O.O. The Placing of the Disinfection Stage in a Reclamation Plant to Reduce Haloform Formation. *Water SA* **5**(4) 178.
27. United States E.P.A. *Federal Register, Feb. 9th,* (1978).
28. Van Rensburg J.F.J. and Van Rossum P.G. Organic Chemical Pollution of the Fresh Water Supplies of the P.W.V. Area. Paper presented at Biennial Conference of Inst. Wat. Polln. Cont., Port Elizabeth, March (1978) (in Afrikaans).
29. Van Vuuren L.R.J., Clayton A.J. and Van der Post D.C. Current Status of Water Reclamation at Windhoek. WPCF 51st Annual Conference. Anaheim 1—6 Oct. 1978.
30. Hart O.O. Contribution to a Debate at the 50th Annual Conference of the California Water Pollution Control Association, April (1978).
31. Olson B.H. and Pratte J. Public Acceptance of Expanded Uses of Renovated Wastewater. *Prog. Wat. Tech.* **10**(1/2) 319 (1978).
32. Ongerth H.J. and Van Jopling W.F. Water Reuse in California. Chapter 8 of 'Water Renovation and Reuse', edited by Shuval H.I. and published by Academic Press Inc., London (1977).
33. Henzen M.R., Van Vuuren L.R.J. and Stander G.J. Implications of the Mineral Load in the Vaal Barrage Water System on Wastewater Reclamation Symposium on the Dissolved Solids Load in the Vaal Barrage Water System. Inst. Wat. Polln. Cont., Johannesburg, Nov. (1969).
34. Stewart, Sviridov and Oliver (Project Managers), Water Pollution and Effluent Reclamation in the Pretoria-Witwatersrand-Vereeniging-Sasolburg Complex, Volume 1, April (1979).
35. Shuval H.I. Health Considerations in Water Reuse. Chapter 2 of 'Water Renovation and Reuse', edited by Shuval H.I. and Published by Academic Press Inc., London (1977).
36. Feinmesser A. and Noy J. The Use of Wastewater for Agricultural Irrigation. Chapter 3 of 'Water Renovation and Reuse', edited by Shuval H.I. and published by Academic Press Inc., London, (1977).
37. Bouwer H., Bauer W.J. and Dryden F.D. Land Treatment of Wastewater in Today's Society. *Civil Engineering — ASCE, January, 78,* (1978).
38. CH_2M Hill, Inc. and Strong, Lamb and Nelson Ltd. Technical Memorandum V-3 concerning criteria for the land application of treated sewage effluent on orchards in the Kelowna, B.C. vicinity, submitted to the Kelowna Study Team, 4 June (1976).
39. Advanced Treatment and Reuse of Municipal Wastewater. Report prepared by Tahal for Mekorot Water Company, Israel, April (1976).
40. Müller W.J. Water Reuse in the Federal Republic of Germany. Chapter 9 of 'Water Renovation and Reuse', edited by Shuval H.I. and published by Academic Press Inc., London (1977).
41. Abbott A.L. Private Communication (1976).

PART II
PROCESSES AND OPERATIONS IN WATER RECLAMATION

CONTENTS

INTRODUCTION

This section of the guide is directed towards the process engineer whose responsibility it will be to select the sequence of treatment units to produce a water of predetermined quality. Factors such as the unit processes available, their efficacies with respect to contaminant removal, catchment quality control, overall process reliability and methods of incorporating existing treatment facilities within an overall reclamation scheme are discussed.

The approach in this guide is that the biological treatment step is an integral part of the reclamation scheme and must be considered as such, both at the design stage and in terms of operation and control such that the treatment afforded to a wastewater can be optimized. The diagrams therefore that are presented in the text will depict the biological treatment plant as one of a series of unit processes required for the reclamation of a wastewater.

However, it is proposed that where possible, there be a physical separation between the biological treatment plant and the subsequent advanced treatment plant. This will preclude any health risks that could be associated with aerosols and with physical contact of the biological plant operators with the reclaimed water. This separation will also enhance the public's acceptance of the scheme, as the influent to the advanced treatment plant will be seen to be a relatively high quality water and not a raw sewage.

It must therefore again be emphasized that while discussions and diagrams presented in this section of the guide may refer to the integration of the biological and advanced treatment unit processes, physical separation of the two stages is recommended.

CHAPTER 1

PRINCIPLES OF PROCESS DESIGN

1.1 THE PROCESS APPROACH IN WATER RECLAMATION

A reclaimed water of virtually any quality may be produced from a wastewater by the judicious selection of the unit processes which constitute the biological treatment and advanced treatment plants.

The process approach to the design should be such that the overall configuration is the simplest technically, is reliable and is the most cost effective for the final water quality required.

In deciding upon the treatment plant configuration, cognisance should be taken of the following points:

- The biological purification step which generally precedes the advanced treatment plant, should be capable of producing a high quality secondary effluent (refer to section 2.1).
- In some instances it may be prudent to provide for hydraulic and quality equalization of the secondary effluent before intake into the reclamation plant.
- The unit processes and their combinations should be capable of producing water of the desired quality at all times and multiple safety barriers should be provided for the removal of each pollutant. This is of particular importance in the case of reclamation for potable supplies.
- Provision should be made for automation of the unit process operations and for operational flexibility to compensate for fluctuations in water quality and for changes in the performance of process units.
- Stand-by units should be available to ensure continuity and stability of plant performance.

1.2 PROCESS RELIABILITY WITH PARTICULAR REFERENCE TO RECLAMATION FOR POTABLE SUPPLIES

Process reliability may be defined as 'the ability of the treatment units to remove contaminants continuously to meet the quality standards set for the product water at all times'. The units must also be able to meet these standards in cases of fluctuating intake water quality.

The reliability of the various unit processes should be individually evaluated, either through pilot scale tests (refer to Part III, chapter 1) or through performances at similarly configurated reclamation plants in other locations, prior to the final design stage.

The State of California, U.S.A., has promulgated criteria concerning 'General requirements of design'[1] and 'Alternative reliability requirements for uses requiring oxidized, disinfected wastewater or oxidized, coagulated, clarified, filtered, disinfected wastewater'[2] with the sole purpose of ensuring reliability of end product quality. Table 2.1 summarizes the 'General Requirements of Design'.

Experience in South Africa, particularly with the operation of the Windhoek and Stander plants, has indicated that a high degree of treatment reliability will be assured if the following guidelines are followed:[3,4]

- Establishment of a minimum of two contaminant barriers for each of the hazardous substances or microorganisms.
- Establishment of a monitoring system whereby the necessary parameters are monitored with a frequency that is truly representative of product quality.
- Establishment of a final safety barrier in the form of automatic control instrumentation that would divert subquality effluent away from the potable supply to an alternative disposal site, preferably to the municipal sewage treatment plant.
- The plants should be designed for a constant flow, necessitating the inclusion of flow balancing facilities.
- The plants should have a 24 h attendance.
- Provision should be made for the automation of essential unit operations, but in general the plants should be operator-orientated to ensure maximum control through continuous observation and analysis.
- All operating instructions should be clear and the operating staff should be adequately trained. Enthusiasm amongst the operating staff should be fostered.
- A realistic preventative maintenance programme should be drawn up and strictly adhered to.
- Operating and maintenance records should be carefully compiled and regularly evaluated so as to be able to guage plant and equipment reliability as well as product quality.
- Spare parts that are essential to the 'smooth' running of the plants should be stored on site.

TABLE 2.1 GENERAL REQUIREMENTS OF DESIGN – STATE OF CALIFORNIA, USA[1]

60333. *Flexibility of Design.* The design of process piping, equipment arrangement, and unit structures in the reclamation plant must allow for efficiency and convenience in operation to permit the highest possible degree of treatment to be obtained under varying circumstances.

60335. *Alarms.*

(a) Alarm devices required for various unit processes as specified in other sections of these regulations shall be installed to provide warning of:

  (1) Loss of power from the normal power supply.

  (2) Failure of a biological treatment process.

  (3) Failure of a disinfection unit process.

  (4) Failure of a coagulation unit process.

  (5) Failure of a filtration process.

  (6) Any other specific process failure for which warning is required by the regulatory agency.

(b) All required alarm devices shall be independent of the normal power supply of the reclamation plant.

(c) The person to be warned shall be the plant operator, superintendent, or any other responsible person designated by the management of the reclamation plant and capable of taking prompt corrective action.

(d) Individual alarm devices may be connected to a master alarm to sound at a location where it can be conveniently observed by the attendant. In case the reclamation plant is not attended full time, the alarm(s) shall be connected to sound at a police station, fire station or other full-time service unit with which arrangements have been made to alert the person in charge at times that the reclamation plant is unattended.

60337. *Power supply.* The power supply shall be provided with one of the following reliability features:

(a) Alarm and standby power source.

(b) Alarm and automatically actuated short-term retention or disposal provisions as specified in Section 60341.

(c) Automatically actuated long-term storage or disposal provisions as specified in Section 60341.

- Alarms should be located at strategic points in the overall process train.

In addition, it is essential that all waste discharges to the sewer system feeding the biological treatment and advanced treatment plants be carefully monitored and controlled.

Control of wastewater discharges into sewers has been exercised for many years by local authorities in South Africa in order to protect the operation of sewage treatment works against discharges of toxic material and also to ensure that the quality of purified effluent conforms to the requirements of the General Standard imposed in terms of the Water Act (refer to Part I, section 2.3).

However, where reclamation for potable use is envisaged, the domestic and industrial wastes should either be segregated (refer to Part I, section 2.4) or a catchment quality control programme implemented whereby the discharges of persistent chemicals that reportedly possess long term health effects are controlled.

Catchment Quality Control

The catchment quality control (CQC) programme should be similar to that implemented by the Thames Water Authority in England[5] and should consist of several definite stages or phases by which a thorough study of all potentially dangerous wastewaters is carried out. The study should be conducted under direct control of responsible health authorities and the legislative means necessary to obtain the information is provided for in the South African Health Act of 1977.

The programme should be co-ordinated by a CQC group, headed by a scientist with a wide knowledge of both industrial processes and industrial effluent treatment and control, and should comprise the following stages:

Stage 1

A list of all industrial concerns that discharge into the sewerage system should be compiled. Those concerns that do not use significant quantities of suspect chemicals, such as food industries, should be eliminated from further consideration. A list of concerns requiring further investigation should then be compiled.

Stage 2

The industries on the short list should then be visited to establish details of all water-using processes, the chemicals used and the approximate quantities of the chemicals discharged each year.

The visits should be preceded by letters to the industries concerned, explaining the purpose of the visit and undertaking to observe strict confidentiality on the details of information given.

Stage 3

An expert panel consisting of (but not necessarily limited to) the CQC scientist, local water supply control chemists and representatives of the Department of Health, including a toxicologist, should then consider the list of chemicals discharged (compiled under stage 2). Chemicals that are biodegradable, harmless or insoluble in water, should be eliminated from further consideration.

Discharge quantities should be calculated for the remaining chemicals and concentrations established, based on the lowest expected sewage flow that would arrive at the future treatment works' site. A short list of those chemicals whose annual concentrations exceed a predetermined level should then be compiled. A level of 0,1 $\mu g/\ell$ was adopted in the Thames Water Authority's programme.[5]

Stage 4

Those industries that discharge chemicals on the stage 3 short list should then be revisited and topics such as improved housekeeping, chemical substitution, on-site pretreatment and transport to alternative disposal sites should be discussed and the feasibility thereof investigated. The controlling authority should participate, and indeed provide expert input, in order to ensure that the eventual solution is to the satisfaction of both the industry and the authority.

Transport to and the supervision of alternative disposal sites should be a service provided by the authority, and will require the co-operation of various government departments, such as Health and Water Affairs.

Catchment quality control should be a continuous process. Once the reclamation plant is operational, all hazardous discharges should be reviewed annually so as to permit proper account to be taken of changes in process and the use of new chemicals. In addition, a monitoring programme on the quality of incoming effluent should be maintained.

1.3 THE PRODUCTION AND TREATMENT OF BY-PRODUCTS

The most significant by-product of wastewater treatment and water reclamation is sludge. The sludges must be disposed of in a manner which does not create nuisance or health hazards. Chemicals can often be recovered from the chemical sludges, particularly those that derive from lime treatment of wastewaters.

The decision on the treatment and final disposal of sludges should be included in the initial planning stage of the reclamation scheme, as experience has shown that sludge handling and disposal costs could well be half the total cost of treatment.

Figure 2.1 illustrates the variety of treatment processes and transportation stages which may be adopted between separation of the solids portion (the sludge) from the liquid and its final disposal.

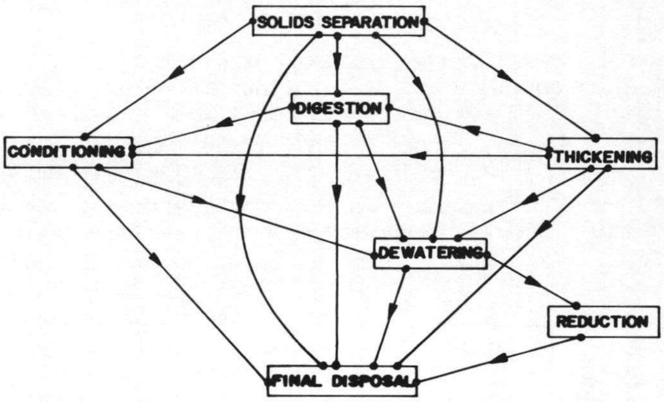

FIGURE 2.1: **Variety of treatment processes between solids separation and final disposal**

The treatment and disposal of the sludges should take into account factors such as: land requirements, land availability, proximity of residential dwellings, toxicity of the sludge and fuel costs.

The quantities of sludges generated together with possible forms of treatment and disposal are discussed in greater detail in chapter 12.

1.4 THE ROLE OF EXISTING WASTEWATER TREATMENT PLANTS IN WATER RECLAMATION SCHEMES

The general expectation in South Africa that reclamation of wastewater will in the future become more prevalent has resulted in many wastewater treatment plants being designed with the ultimate aim of reclamation in mind. Many South African cities use tertiary treated effluents for power station cooling water and low level industrial uses while paper mills in Durban and Springs further upgrade the quality of such effluents for reuse within their processes. Expectations are that the lower quality secondary effluents will in the future continue to be reclaimed for sub-potable quality uses while the higher quality effluents discharged from present day sophisticated treatment processes will be used for reclamation for potable supplies.

In most instances, due to growth in the demand for water, there is a corresponding growth in the demand for treatment of wastewater. When existing sewage works become inadequate they must either

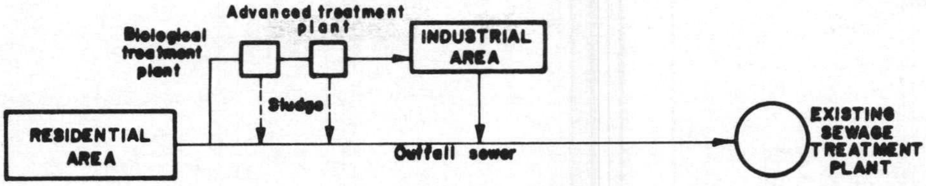

FIGURE 2.2: Possible method of relieving an overloaded sewage treatment plant

be extended or the pollution load discharged to them reduced through the construction of a new sewage works at a different site. No matter which alternative is adopted, consideration should be given in many areas of the country to ensuring that the new treatment units could form part of a future reclamation scheme.

The construction of a new biological treatment plant at a site other than that of the existing sewage treatment plant, and as a part of a future reclamation scheme, has the advantage that it can be sited close to the area of future reclaimed water consumption and close to the main outfall sewer that discharges to the existing plant. The advantage stems from reduced reclaimed water conveyance costs, reducing the load on the main outfall sewer, the ability to exclude industrial effluents from the plant influent and the fact that all sludges generated may be returned to the sewer for treatment and disposal at the existing plant, which is invariably far removed from residential areas.

The exclusion of sludge treatment will enable the new biological treatment plant to be sited in close proximity to residential areas.

Figure 2.2 shows an example of the above principle, indicating that by constructing the reclamation plant near the junction of the outfall sewers from the residential and industrial areas, one could reclaim mainly domestic sewage for industrial use, pump the reclaimed effluent the relatively short distance to the industrial site, 'relieve' the main outfall sewer, reduce the load on the existing treatment plant, treat the excess sludge at the existing treatment plant or, as may be the case, on land nearby.

Separate biological treatment plant

Even when situated on the same site as the existing sewage treatment plant, the construction of a new biological treatment plant upstream of the advanced treatment plant has the advantage of individual control of that portion of the sewage flow destined for reclamation.

Figure 2.3 illustrates the modified Windhoek reclamation scheme where the flow destined for the reclamation plant is tapped off the main sewage flow after primary sedimentation and treated in a biological nitrogen and phosphorus removal plant prior to being conveyed to the advanced treatment plant. The balance of the settled sewage is treated by an existing biological filtration plant and maturation ponds prior to discharge to the dry river bed as before.

Although the cost of electricity in the area is high, the choice of the relatively energy intensive activated sludge process, in preference to a conventional biological filtration plant, is more than justified when the chemical costs for the removal of both nitrogen and phosphorus from biological filter effluents are con-

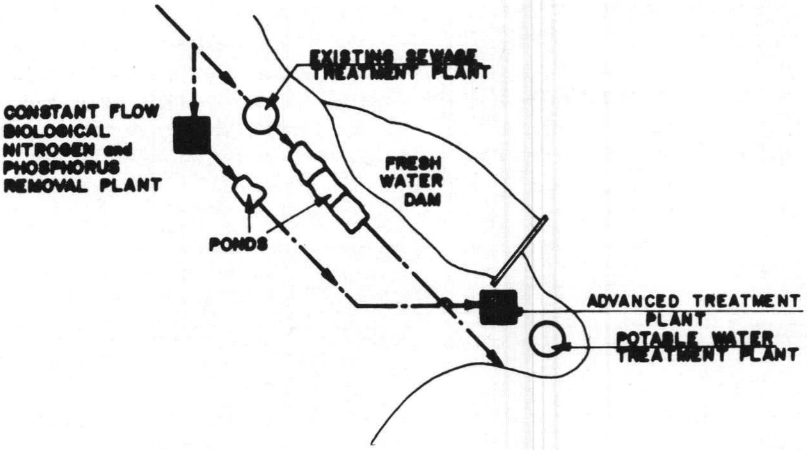

FIGURE 2.3: Windhoek reclamation scheme

sidered. However, as there is no need for nutrient removal from that portion of the flow that is discharged to the river bed, the use of the activated sludge process in this instance cannot be justified.

Apart from an economically optimized plant, the inclusion of a new biological unit in the reclamation scheme has the advantage that more effective control can be exercised over the quality of secondary effluent produced for reclamation. Wastewater containing matter detrimental to the production of the reclaimed water can be by-passed to, and treated in, the existing sewage treatment plant to the normal discharge standards.

Reclamation of existing secondary effluents

There are at present a number of sewage works in South Africa that incorporate the biological removal of both nitrogen and phosphorus, and in these instances there should be little difficulty in advanced treatment for potable purposes. It may however be necessary to install a form of hydraulic and quality equalization prior to the advanced treatment plant.

The characteristics of the secondary effluents discharged from biological filtration plants, high rate activated sludge plants and oxidation pond schemes may, however, pose problems when reclamation for potable purposes is considered.

Biological filtration plants generally produce effluents with significant quantities of both ammonia and nitrate nitrogen. The ammonia nitrogen content may be reduced through either biological nitrifiction or the use of chlorine; the former method has an overall economic advantage. The nitrate nitrogen (NO_3-N) content need only be reduced if after subsequent dilution with fresh water the resulting NO_3-N content would still exceed the 10 mg/ℓ standard (refer to Part 1, section 5.3). In the event of NO_3-N removal being required, consideration should be given to installing a biological nitrification/denitrification step after the biological filters.

The carbon source necessary for denitrification (refer to section 10.1) could be either methanol or molasses or it could be a portion of the settled sewage. While the latter carbon source is obviously cheaper, its use depends upon the total load received at the plant and the ability to maintain the optimum C:N ratio in the influent to the denitrification stage.

High rate activated sludge plants will, by virtue of their short SRT, not nitrify unless the mixed liquor temperature is high. The nitrogen content of such effluents will be predominantly in the ammonia form and can be removed through either lime addition followed by ammonia stripping or through biological nitrification/denitrification. The former system has many disadvantages and is rapidly disappearing from water reclamation practice (refer to section 10.1) while the latter system requires a carbon source for the denitrification step.

Effluents from *existing oxidation pond systems* generally contain significant ammonia concentrations and have a low C:N ratio. Figure 2.4 shows the layout of the Que Que works in Zimbabwe, where a portion of the raw sewage is diverted away from old oxidation ponds to a recently commissioned biological nitrification/denitrification plant. The oxidation pond effluent discharges into the nitrification zone of the new plant and by regulating the split of the raw sewage flow, optimum nitrogen removal is obtained.

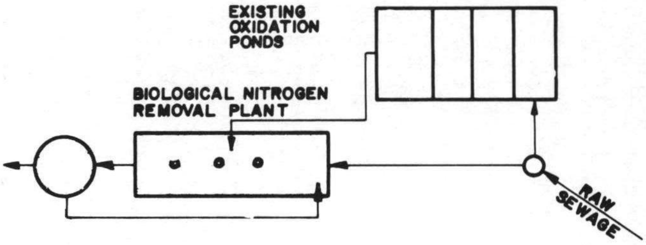

FIGURE 2.4: The Que Que plant, Zimbabwe

This plant represents an excellent example of the incorporation of existing oxidation ponds into an overall nitrogen removal scheme.

The effluents discharged from *extended aeration activated sludge plants* generally contain very little ammonia nitrogen but significant quantities of nitrate-nitrogen. Manipulation of the oxygen input, particularly in the case of surface aeration plants, will enable a significant degree of denitrification to be achieved.[6] Further nitrate reductions from these secondary effluents can be achieved through the addition of methanol (or other external carbon source) just upstream of a sand or preferably a dual-media filter.

Summary

The high quality water required for potable purposes should preferably be produced through the construction of a separate, constant feed biological treatment stage with the existing sewage works being retained to treat peak flows and those wastewaters considered detrimental to the production of the high quality reclaimed water.

CHAPTER 2

POSSIBLE OVERALL PROCESS CONFIGURATIONS

The production of a reclaimed water from a raw sewage is generally achieved through a combination of biological and physico-chemical treatment stages. The physico-chemical treatment stage, referred to as the advanced treatment plant, generally succeeds the biological treatment plant although in certain instances it may be necessary to precede as well as succeed with chemical treatment — the so-called integrated system.

2.1 THE ROLE OF THE BIOLOGICAL TREATMENT PROCESS IN WATER RECLAMATION

A biological treatment unit makes use of living organisms to purify the wastewater and as such it should be protected against shock loads of toxic material and operational inadequacies. Protection of the biological system entails the surveillance of industrial discharges (refer to Part I, section 2.3), exclusion of storm flows and pH equalization where necessary.

The removal of organic matter in biological treatment units is discussed in general terms in section 5.2 and Table 2.2 lists typical qualities of effluents produced by the various forms of biological treatment together with advantages and disadvantages when considered in the water reclamation context.

Long SRT activated sludge systems have the advantage of being stable, reliable, very efficient in the removal of organic carbon compounds, efficient in the removal of ammonia compounds, suspended solids and turbidity, and can be designed to remove both nitrogen and phosphorus with little or no addition of chemicals. These characteristics have rendered this type of process very cost effective as a unit process for water reclamation.

In addition the reduced low molecular mass content of effluents from long SRT activated sludge plants greatly enhances the performance of a subsequent activated carbon adsorption stage.[7] Further discussion on the removal of organic matter by activated carbon and the merit of preceding the activated carbon stage by a biological treatment unit is presented in section 6.1.

High rate (short SRT) activated sludge systems are generally more prone to instability in the presence of toxic elements than the low rate (long SRT) and from experience gained at Pretoria the low rate activated sludge system is more stable than conventionally loaded biological filters.[8]

In areas having a low per capita water usage (i.e. high sewage strength) and yet still requiring a water reclamation scheme, there could be merit in preceeding the biological nitrogen (and phosphorus) removal plant by an anaerobic pond, which would not only equalize the flow to the N and P removal plant but would also reduce the organic load thereto through anaerobic digestion.

2.2 THE BIOLOGICAL AND PHYSICO-CHEMICAL CONFIGURATIONS

Water reclamation is generally achieved through a biological treatment plant preceding a series of physico-chemical unit processes as detailed in chapter 13.

Primary chemical treatment

There have been instances, however, where the raw sewage has undergone chemical coagulation and precipitation prior to the biological treatment stage, with chemicals such as polymers, mineral salts and lime being applied.

Polymers are generally only used in upgrading the performance of existing clarifiers; they do not themselves remove phosphorus or heavy metals. Mineral salts and lime are effective coagulants, removing substantial amounts of the suspended solids, organic matter, phosphorus and heavy metals present in the wastewater.

Primary lime treatment (PLT)

The cost effectiveness of the biological treatment unit justifies the implementation of a catchment quality control programme to protect the biological system, as discussed in section 1.2. Primary lime treatment (PLT) can form a part of this ‘protection’ as it is effective in precipitating most heavy metals that could otherwise disrupt the biological process (refer to chapter 8).

Figure 2.5 illustrates a flowsheet of a PLT process installed at Contra Costa in California, USA and at Canberra, Australia.[9]

The advantages of this process are claimed to be the following:

- The enhanced removal of suspended and colloidal organic material results in a much shorter hydraulic retention time as well as a lower power consumption.
- The recarbonation of the lime-treated liquid is effected by CO_2 developed in the biological system. The addition of CO_2 is a costly process in the independent physico-chemical process, but it can be obtained as a by-product in the biological process. The effluent from the biological system will then have good stability.

TABLE 2.2 TYPICAL CHARACTERISTICS OF VARIOUS BIOLOGICAL TREATMENT PROCESSES

Biological Process	Advantages	Disadvantages	Typical effluent qualities (mg/ℓ)				
			COD	NH_3-N	NO_3-N	PO_4-P	S.S.
Trickling filters							
High Rate	Efficient in removing high loads Can serve as shock load barrier Energy efficient	Effluent requires further treatment Variable effluent quality	100–200	30–35	nil	7–9	25–75
Low Rate	Low energy cost Better treatment than High rate	High construction cost Variable ammonia conversion thus high chlorine cost	50–100	5–15	20–25	7–9	20–30
Activated sludge							
High Rate (Low SRT)	Effective COD removal No nitrification, therefore suitable for physical-chemical ammonia removal Lower energy cost than low rate (high SRT) system Lower capital cost than low rate (high SRT) system	Less resistant to shock loads More difficult to operate than low rate system Ammonia in effluent adversely effects chlorination costs Additional units required for nitrification/denitrification Require chemicals for N and P removal	50–100	30–35	nil	5–7	20–30
Low Rate (High SRT)	More effective COD re- Complete nitrification, therefore low chlorination costs Reduced operating costs of subsequent activated carbon adsorption Greater stability and ease of operation Produces a stable sludge requiring no further digestion Superior sludge settling properties therefore possible to operate at higher MLSS concentrations Can be manipulated to achieve partial N and P removal	Higher capital cost than high rate system Higher energy cost than high rate system Alkalinity correction may be required	40–80	0,5–1,0	25–30	6–8	15–25
Low Rate (High SRT) designed for biological N and P removal	No chemicals required for N removal Reduced chemicals required for optimum P removal No alkalinity correction required Lower energy cost than for conventional low rate system	Reliable dissolved oxygen control required Influent organic load variation must be balanced Chemicals may be required for consistently low P removal	40–80	0,1–1,0	3–5	0,5–1,5	10–20
Pond systems	Low energy cost Ease of operation	High land requirements Increase in salinity due to evaporation Variable ammonia removal, thereby effecting chlorination costs Chemicals required for both N and P removal Chemicals required for suspended matter removal	75–150	10–30	5–20	6–8	40–120
Rotating Disc units	Low energy require- Can be low or high rate, depending on nitrification requirements	High capital cost Inflexible Chemicals required for both N and P removal	40–100	0,5–30	0–30	5–8	5–25

Note: The effluent qualities listed are those emanating from the various biological systems *without* any chemical addition and for wastewaters of predominantly domestic origin.

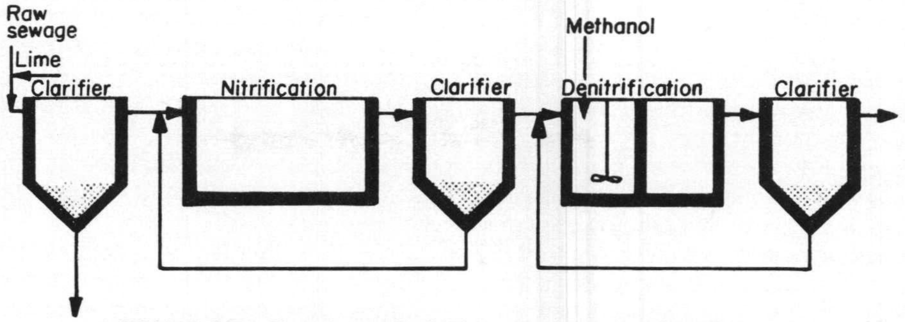

FIGURE 2.5: Flowsheet of a PLT process incorporating nitrogen removal[9]

- The clarity of the effluent is very good and a high quality effluent is produced, suitable for most industrial applications.

- Lime sludge from the primary lime clarifier can be segregated in centrifuges, the lime re-calcined and re-used after further classification.

- The biological system is protected from toxic heavy metal concentrations.

- A substantial portion of the influent phosphorus is removed.

As lime precipitation removes more carbonaceous than nitrogenous material it is likely, particularly in areas with a high per capita water usage, that there would be insufficient organic carbon in the lime clarifier effluent to ensure optimum nitrogen removal through the conventional biological nitrification/denitrification system (refer to chapter 10). In such instances, a non-nitrogenous carbon source such as methanol would be added to a separate denitrification zone subsequent to the nitrification stage — refer to Figure 2.5.

In addition to the above, the primary lime sludge produced from the PLT clarifier in the flowsheet depicted in Figure 2.5 will contain a substantial organic fraction which is usually separated (centrifugal classification — refer to Part III, section 2.11.1) prior to the lime recalcining furnace, albeit at variable efficiency and at considerable operating cost. A recent study on the application of PLT at a large scale plant indicated that the savings that could be realised by removing much of the organic load in the primary lime clarifier is offset by the cost of classifying the resulting sludge.[10]

These two disadvantages of the PLT process can be overcome by adoption of the flowsheet depicted in Figure 2.6. This will not only ensure sufficient carbon (in the form of volatile acids) for the conventional nitrification/denitrification process, but the primary lime sludge would contain much less organic matter, thereby enabling dry classification, a less costly operation, to be practised after the recalcination step.[11]

In addition to the advantages claimed for the PLT process as installed at Contra Costa and Canberra (Figure 2.5), the 'modified' PLT process (Figure 2.6) has the following further advantages:

- The use of methanol for denitrification will be eliminated or reduced to a minimum.

- The lime sludge will contain less organic material, resulting in a higher quality recalcined lime.

Extensive studies with primary lime treatment followed by dissolved air flotation and biological treatment (the LFB process) have been conducted in South Africa.[12]

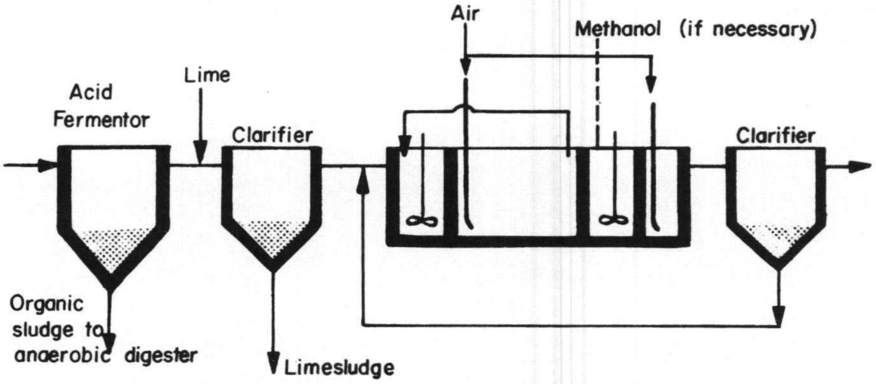

FIGURE 2.6: Modified PLT process followed by conventional biological nitrogen removal process[11]

Primary mineral salt treatment

More recent studies have included the use of ferric chloride as the primary coagulant with a view of reducing the chemical and maintenance costs.[13]

The modified LFB process which incorporates ferric chloride primary coagulation and a partial denitrification stage has been successfully operated at pilot plant level. This process represents a truly integrated chemical-biological-chemical plant and the reader is referred to Part VI for further discussion thereon.

Tertiary chemical treatment

Tertiary chemical treatment facilities using lime and/or mineral salts have been successfully used at the Stander, Windhoek, Cape Flats and Athlone reclamation plants (refer to Part VI for details of these plants).

A tertiary chemical treatment system is ideal for those cases where the demand for reclaimed water is intermittent as it would only be operated when the high quality water is required and for the rest of the time the overall plant would function as a normal sewage treatment plant discharging a high quality secondary effluent.

A further factor to be considered when comparing primary and tertiary treatment systems is that if a breakdown were to occur in the former, the biological unit would not be able to handle the extra organic load and a poor quality effluent would be discharged, most likely to a river. In contrast, a breakdown in a tertiary treatment system would not have such dire consequences as a well treated secondary effluent would then be discharged.

CHAPTER 3
THE USE OF CHEMICALS IN WATER RECLAMATION

3.1 LIME

Lime treatment has until fairly recently been considered an essential component of a water reclamation plant producing water for reuse applications with high quality requirements. The resulting high pH not only enables ammonia to be stripped in a subsequent stage but it also causes the coagulation of organic matter, the precipitation of phosphorus and heavy metals and the inactivation of most micro-organisms.

A concerted research effort was therefore conducted, both in South Africa and overseas, into this unit process and a store of knowledge has now been compiled.

However, the inconsistent performance of the ammonia stripping stage has resulted in nitrogen removal now being achieved through the more reliable biological nitrification/denitrification system. This latter system consistently produces low effluent ammonia concentations and thereby enables the breakpoint chlorination step to be more economically and effectively achieved. This replacement has removed one of the main advantages of the lime treatment process and its inclusion, in preference to the other chemical coagulants, should be economically justifiable.

The alkalinity of a wastewater in the pH range 6,5 to 7,5 is predominantly in the bicarbonate (HCO_3^-) form, although a small amount of dissolved carbon dioxide (H_2CO_3) is also present. The addition of lime results in a change in the carbonic species distribution with the H_2CO_3 and HCO_3^- being converted to $CO_3^=$ and OH^- ions, thereby forming insoluble $CaCO_3$ and (ultimately) $Mg(OH)_{22}$ (at pH values $> 10,5$) which precipitate out of the wastewater.

The insoluble $CaCO_3$ acts as a coagulant because the dissolved lime/insoluble $CaCO_3$ suspension acts as a positively charged $Ca(OH)_2$ sol, encouraging flocculation by adsorbing and enmeshing the coagulated colloids.

The addition of lime to a wastewater will have the following effects:

- Significant removals of suspended and colloidal matter. Removals of 60—80% have been reported.[14,15,16]

- Significant removals of organic matter, with greater removals being achieved with raw sewages (60—70%)[14] than with secondary effluents from biological treatment schemes (30—35%).[17]

- Precipitation of phosphorus as hydroxyapatite (refer to section 10.2 for further discussion).

- Precipitation of heavy metals, predominantly in the hydroxide form[17] (refer to section 8.3 for further discussion).

- Molecular mass distribution of the organic compounds present in the effluent can be affected[18] (refer to section 4.3 for further discussion).

- Varying degrees of removal of long chain and polynuclear aromatic hydrocarbons.[18]

- Inactivation and removal of most micro-organisms.[18]

The pH to which lime is added is dependent upon the required clarity of the lime treated effluent which in turn is dependent upon the position of the lime treatment stage in the overall wastewater treatment scheme. For example, the clarity of an effluent resulting from the treatment of a raw sewage prior to biological treatment need not be as high as that of an effluent resulting from the treatment of a biologically treated (i.e. secondary) effluent.

Effect of wastewater characteristics

The effectiveness of lime coagulation is dependent upon the alkalinity, calcium and magnesium hardness and orthophosphate content of the sewage. Figure 2.7 shows the relationship between pH and relative effluent suspended solids concentrations for different conditions of alkalinity, hardness and orthophosphate levels.[14]

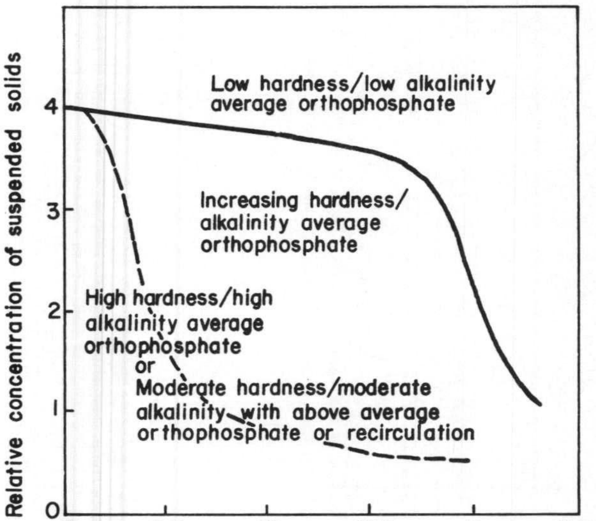

FIGURE 2.7: Relationship between pH and suspended solids[14]

Magnesium

The presence of magnesium ions in a wastewater plays an important role in the achievement of optimum clarification during high lime treatment. This is due to the formation of the gelatinous magnesium hydroxide precipitate, at pH values of over 10,5, which acts as a nucleus for enhanced flocculation.

The particular magnesium ion concentration required for optimum clarification varies from effluent to effluent[17] but it has been reported as being between 45 and 50 mg/ℓ (at pH levels of 11,3 — 11,4) for oxidation pond effluents.[19]

A magnesium ion concentration that is too high, however, results in the formation of fine, light flocs which tend to be retained in the clarifier effluent, creating process control and operational difficulties. Polyelectrolytes would be used as floc-aids in such cases as they would also be when magnesium ions are present in low concentrations.

The bulky magnesium hydroxide precipitate tends to increase the overall volume of sludge discharged from the lime clarifier, which in certain instances is a disadvantage of the high lime process.

Lime dosage

The buffering capacity of a wastewater is largely dependent upon its alkalinity and the higher the bicarbonate alkalinity, the greater will be the lime dose required to attain a desired pH level. Figure 2.8 shows the effect of alkalinity on lime dosage.[14]

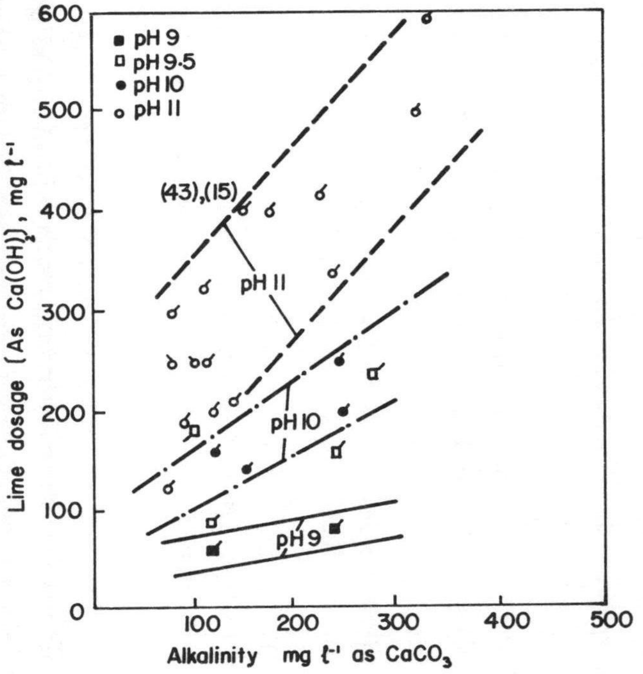

FIGURE 2.8: **Relationship between alkalinity and lime dosage required for a given pH[14]**

Sludge

The quantity of sludge produced through lime treatment of an effluent, be it a raw sewage or a secondary effluent, is affected by the following parameters:

- Alkalinity: wastewaters of high alkalinity (e.g. 350 mg/ℓ as $CaCO_3$) can produce significantly more sludge than low alkalinity waters.
- Initial Ca^{++} and Mg^{++} concentrations.
- Initial suspended solids concentration.
- pH of coagulation which controls the lime dose to which the quantity of sludge produced is related.
- The form and degree of bound water associated with the sludge particles.

Typical characteristics, quantities and methods of treatment and disposal of lime sludges are discussed in chapter 12.

Water stabilization

Lime also finds application in water stabilization (refer Chapter 9).

Lime feeding

Systems for handling and dosing lime to an effluent are discussed in Part III, section 3.1.

3.2 MINERAL SALTS

The mineral salts are playing an increasingly important role in water reclamation as, as has been discussed in section 3.1, the necessity for lime treatment no longer exists in many instances.

Aluminium sulphate (alum), sodium aluminate and the chlorides and sulphates of iron (both ferrous and ferric) find application in water reclamation.

Alum and iron salts, together with anionic polyelectrolytes, serve as coagulants for raw wastewaters and for phosphorus removal, whereas sodium aluminate is only used for phosphorus removal, albeit with not very impressive results.[20] Ferric chloride occasionally finds application as a floc-aid in the lime treatment stage of a reclamation plant (typical dosage being 5 to 15 mg/ℓ Fe^{3+}).

Raw sewage coagulation

Mineral salt addition to raw sewages reportedly results in COD and suspended solids removals of 60% and 80% respectively.[21,22]

Phosphorus removal

Soluble phosphorus residuals of 0,1 — 0,5 mg/ℓ can generally be attained at mass ratios, i.e. mass of cation

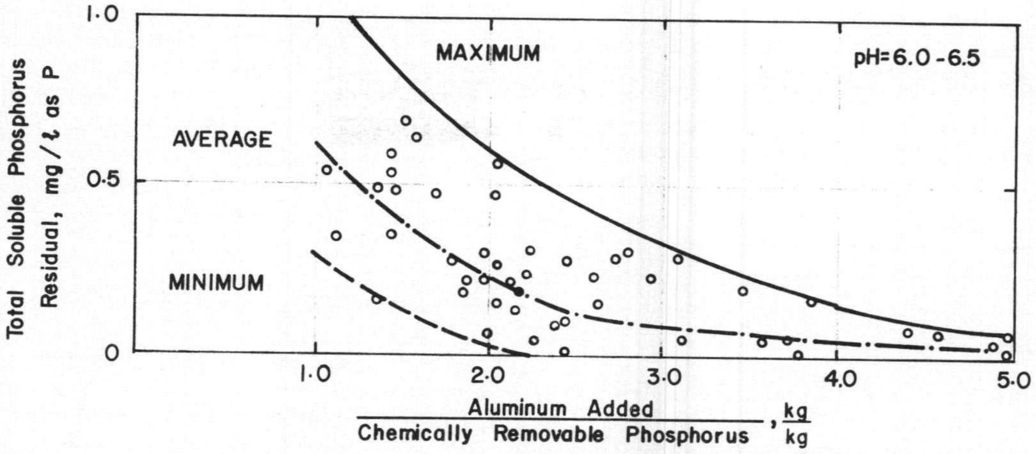

FIGURE 2.9: Effect of aluminium addition on total soluble phosphorus residual[23]

(Al^{3+}, Fe^{3+}, Fe^{2+}) to mass of phosphorus (P), of 1,5 to 3,0:1.

Figure 2.9 shows the results of aluminium sulphate addition to a particular secondary effluent in the U.S.A.[23]

Alkalinity reduction

As alum and the iron salts are salts of strong acids, their addition to a water is similar to an acidimetric titration and as such the alkalinity of the water is decreased. Alkalinity reductions of 4,2; 2 and 1,3 mg (as $CaCO_3$) per mg Al^{3+}, Fe^{3+} and Fe^{2+} added respectively have been reported.[20] Sodium aluminate, on the other hand, tends to increase the alkalinity.

TDS increase

A further disadvantage of mineral salt addition is that of dissolved solids increase, as the anionic portion of the salts (e.g. SO_4^{2-}, Cl^- etc.) remains in solution.

Sludge

The sludge volumes and masses resulting from the addition of iron and aluminium salts to a raw wastewater varies greatly and should be estimated from laboratory tests. In the case of iron salts, the sludge volume could well be 1,5 times that resulting from conventional settling, while for aluminium salts the volume may be similar to that from conventional settling.[16]

The addition of mineral salts, either to or before the secondary clarifier at an activated sludge plant, for phosphorus removal can be expected to increase the sludge mass by 20 — 50% while the sludge volume increases by zero — 35%, depending upon whether iron or aluminium salts are added.

The sludges resulting from mineral salts addition to a raw wastewater are less easily dewatered than conventionally settled sludges although their dewatering properties are readily improved by chemical conditioning.[16] 'Biological plus chemical sludges generally exhibit similar dewatering properties to the 'biological' sludges from high rate activated systems, whereas their dewatering properties are significantly inferior to those of 'biological' sludges resulting from low rate activated sludge systems.

Typical quantities and methods of treatment and disposal of the 'chemical' sludges are discussed in Chapter 12.

Chemical feeding

Systems for handling and dosing the mineral salt solutions are discussed in Part III, sections 3.3 and 3.4.

3.3 POLYELECTROLYTES

Most polyelectrolytes used are synthetic polymeric materials often based on polyacrylamide and are termed anionic, cationic, or non-ionic depending on the charge of the ionized groups present in the polymer chain.

Polyelectrolytes can act in two ways: firstly by reducing the zeta potential of colloids and sludge particles (cationic polyelectrolytes), and secondly by adsorption bridging between positively charged coagulated particles (anionic polyelectrolytes). They therefore find application as coagulants or secondary flocculants (also known as 'floc-aids').

Coagulants

Polyelectrolytes are used as coagulants in the field of sludge conditioning prior to mechanical dewatering (centrifuge, vacuum filter, belt press etc.) where typical dosages are 2 to 4 kg cationic polyelectrolyte/ton dry solids in the sludge.

The use of polyelectrolytes as coagulants has only recently been extended to coagulation of raw wastewaters where dosages of 1 to 10 mg/ℓ are reported to result in significant suspended solids and COD removals,[16] but costs are prohibitive.

Flocculation aids

Their use as flocculation aids is generally in applications in which lime and/or the mineral salts serve as the primary coagulant. Dosages of 0,25 to 1,0 mg/ℓ of both the anionic and non-ionic polyelectrolytes are common, irrespective of the primary coagulant.

Polyelectrolyte feeding

Polyelectrolytes are available in liquid or powder form with the latter usually being the most economical.

When planning polyelectrolyte make-up and dosing facilities cognisance must be taken of the storage life of the particular form of polyelectrolyte envisaged — generally one year for powders and six months for liquids.

Systems for handling and dosing polyelectrolyte solutions are discussed in Part III, section 3.2.

3.4 CAUSTIC SODA (SODIUM HYDROXIDE)

Caustic soda finds wide application in water reclamation plants as a means of pH control.

The most common point of pH control is at the breakpoint chlorination stage where the pH should be maintained in the 7,0 — 7,5 range. The addition of chlorine to a water destroys alkalinity but this alkalinity decrease can be offset by the addition of 1,12 mg NaOH for each mg chlorine added.

Caustic soda is also used to offset the alkalinity decrease caused by the mineral salts, through the addition of 1,7; 0,8 and 0,5 mg NaOH for each mg Al^{3+}; Fe^{3+} and Fe^{2+} added.

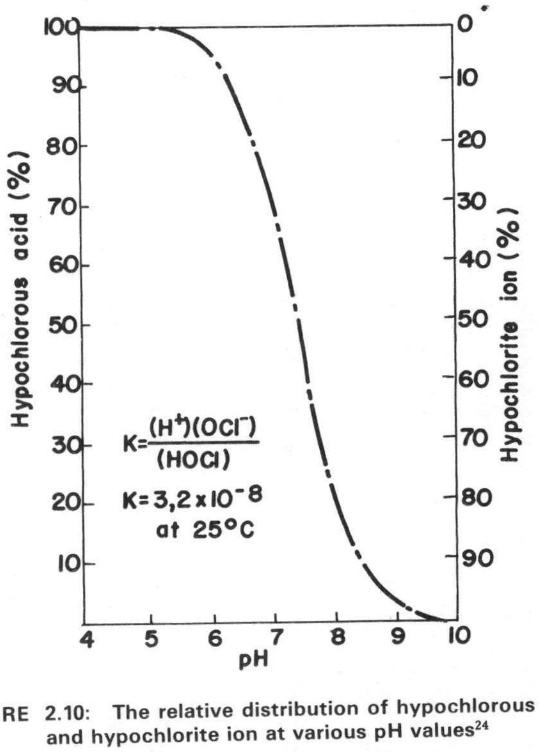

FIGURE 2.10: The relative distribution of hypochlorous acid and hypochlorite ion at various pH values[24]

The use of caustic soda in large quantities has the disadvantage that the sodium content of the reclaimed water will be increased.

A system for handling and dosing caustic soda is discussed in Part III, section 3.5.

3.5 CHLORINE

Chlorine is used for a variety of purposes, depending upon particular situations and/or stages of treatment. The principle purposes of chlorination are:

- Disinfection of secondary and higher quality effluents.
- Oxidation of ammonia and or organic matter.
- Destruction and control of iron-fixing and slime-forming bacteria.
- Destruction and control of psychoda (filter flies) and slime growth on trickling filters.
- Control of septic conditions and resulting odours (e.g. H_2S).
- Control of algae and related organisms.

Chlorine reactions

The interactions of chlorine with water may be represented by the following equilibria:

$$Cl_2 + H^2O \rightleftharpoons HOCl + H^+ Cl^-$$

$$HOCl \rightleftharpoons H^+ + OCl^-$$

The relative proportion of the equilibrium species, HOCl and OCl^-, depends upon the pH of the water, as illustrated in Figure 2.10.[24]

Form of chlorine

Chlorine may be applied in one of many forms:

- Liquified chlorine gas
- Sodium hypochlorite
- Calcium hypochlorite
- Chlorinated lime

The hypochlorites are salts of hypochlorous acid, HOCl, and yield HOCl and OCl^- in aqueous solution with the relative proportion of $HOCl^-$ being dependent upon the pH — Figure 2.10 refers.

Sodium hypochlorite may either be bought in bulk and transported to the treatment works or it can be generated *in situ* from a brine solution by electrolytic means.

Chlorinated lime is similar to sodium hypochlorite with respect to its properties and applications.

The choice between different commercial products is usually made largely on the basis of cost per unit of available chlorine, handling properties, stability, and considerations regarding the solubility of reaction products. For example, the calcium salts of hypochlorous acid may produce substantial amounts of $CaCO_3$ sludge, a problem not encountered with sodium hypochlorite. It is generally found that for large applications the use of gaseous chlorine offers the most economical overall solution.

Important applications

The most important applications of chlorination in water reclamation are those of (i) disinfection and (ii) ammonia removal to render the water hygienically safe for the intended form of reuse.

Ammonia is removed through oxidation to nitrogen gas. Intermediate nitrogen compounds — the chloramines — are initially formed before further oxidation to nitrogen gas. The point at which nitrogen gas is formed and free chlorine residuals are observed, is termed the 'breakpoint' for the particular wastewater.

Effective disinfection can only be achieved with a free chlorine residual. Attaining 'breakpoint' is therefore a prerequisite for both complete ammonia removal and disinfection.

The aspect of disinfection is further discussed in section 7.2 and the reader is also referred to the 'Manual for Water Renovation and Reclamation', Chapter 7.

Disadvantages of chlorination

There are disadvantages in the addition of large quantities of chlorine gas to a wastewater:

- An increase in acidity and a corresponding reduction in alkalinity, leading to instability which has to be rectified by the addition of stabilizing chemicals (refer to Chapter 9).
- The addition of both chlorine and stabilizing chemicals leads to an increase in the total dissolved solids (TDS) content of the water.
- Surface oxides may be formed in subsequent activated carbon treatment units, which adversely affect the adsorptive capacity of the carbon.
- Chlorinated organic compounds which are reportedly toxic or carcinogenic may be formed (refer to section 6.3).

Chlorinators

The equipment required for handling and dosing gaseous chlorine are discussed in Part III, section 2.6.

3.6 CHLORINE DIOXIDE

Chlorine dioxide (ClO_2) is an unstable gas and is therefore generated on site by reaction of chlorine and sodium chlorite. Chlorine dioxide is a stronger oxidant than chlorine, and thus, unlike chlorine it does not combine with ammonia before oxidizing it, which is a definite advantage in nitrogen control. Chlorine dioxide is also used for oxidation of sulphides, iron, and manganese. It is reportedly a good bactericide but presently suffers from a cost disadvantage.

3.7 OZONE

Ozoine is a highly reactive gas, being a more powerful oxidizing agent than chlorine. As a result of its reactivity, ozone cannot be stored or transported over long distances but is generated at the application site.

The strong oxidizing properties have resulted in ozone being used for colour removal, iron and manganese removal, algae removal, odour and taste removal, suspended solids flocculation, disinfection and oxidation of dissolved organics.

Advantages over chlorination

The advantages that ozonation has over chlorination may be summarized as follows:

- The total dissolved solids content does not increase.
- There is no alkalinity decrease and associated stability problems.
- Ozone can, at pH values below 8,5, disinfect without having to first oxidize residual ammonia in the water.
- Ozone, being a powerful oxidizing agent, can oxidize a wider variety of organic compounds than almost any other oxidizing agent. Ozone can cleave high molecular mass organic compounds to lower mass organic materials, and can decolourize many highly coloured organic compounds.
- Ozonation of a water prior to activated carbon can result not only in improved organic matter removal but also longer periods between carbon regenerations.

Point of application

Ozone is applied at different stages in an overall treatment sequence, depending upon the purpose for which it is applied. For example, for iron and manganese removal from a surface water, it is applied in the early stages of treatment. For organic removal it is usually applied at a stage after the easily degradable and perhaps coaguable material has been removed and for disinfection it is applied at, or near, the end of the treatment sequence.

The effect that ozone has on organic matter is discussed in sections 6.1 and 6.2 while the efficacy of ozone as a disinfectant is discussed in section 7.2.

Ozone generation and contact systems

The various types of ozonators and contact systems that could be used at a reclamation plant are discussed in Part III, section 2.7 and the 'Manual for Water Renovation and Reclamation', Chapter 8.

3.8 CARBON DIOXIDE

Lime addition to pH values greater than 10 can form a part of a water reclamation plant, with application either upstream or downstream of a biological treatment stage. Effluents with these high pH values can adversely affect subsequent biological treatment systems as well as causing carbonate scale formation in pipelines, in tanks and on mixers.

The high pH values are usually reduced in a separate 'recarbonation' stage, in which carbon dioxide (CO_2) is added to the effluent in order to achieve the required pH level.

CO_2 production

Gaseous carbon dioxide can be produced *in situ* by scrubbing and compressing the combustion products of lime recalcining furnaces and sludge incinerators or by generators designed specifically for the combustion of hydrocarbons. Of these three sources, the latter finds the most application.

The gases generated usually have a CO_2 content of between 6 and 18%, depending upon the fuel source and combustion efficiency.

These low concentrations, together with the fact that the solubility of CO_2 is limited, indicate that the rate of mass transfer (hence the mass transfer coefficient) can drastically affect the overall performance of the system. The mass transfer coefficients are dependent upon temperature and pH and as the transfer rates are generally low, packed columns or vigorously stirred reactors are required for efficient contacting. These limitations, together with the fact that the required CO_2 dosage may vary throughout the day, have resulted in the use of pressurized liquid CO_2, with a CO_2 content of 99,5%, finding increased application.

The use of CO_2 produced from the burning of fuels should not be considered in the case of potable water reclamation due to the introduction of hydrocarbons into the water that could react with the chlorine to form toxic compounds.

CO_2 requirements

The method of ascertaining the CO_2 requirements for a particular duty are adequately covered in the literature[25] and the 'Manual for Water Renovation and Reclamation', Chapter 5.

Adsorption

Typical systems for contacting the CO_2 with the effluent are discussed in Part III, section 2.4.

3.9 ACTIVATED CARBON

The activated carbon stage is an essential unit operation of a water reclamation plant designed for potable reuse as it removes a large percentage of the intractible, and sometimes toxic, material present in the wastewater flow.

Removal is due primarily to adsorption on to the carbon although biological removal of residual biodegradable organics can also occur as a result of growths on the carbon granules. Adsorption is facilitated by the large surface area of the activated carbon which results from its high porosity.

Manufacture

Activated carbons may be manufactured from a variety of carbonaceous material, such as wood, coal, peat, sawdust and lignite.

The quality of activated carbon can vary considerably, being dependent upon the nature of its base material, and it is therefore essential that the correct carbon be selected for the intended duty.

Characterization

Activated carbons are usually characterized by a number of parameters the most common being: the iodine number; apparent density; particle size distribution; abrasion resistance; adsorption capacity for methylene blue, molasses, tannin and phenol; ash content; moisture content; surface area and pore size distribution.

The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 9 and to the U.S. Environmental Protection Agency publication 'Process Design Manual for Activated Carbon Adsorption' for description of the above parameters.

Table 2.3 summarizes the minimum requirements for a granular activated carbon that is to be used in a water reclamation plant.[26,27]

Table 2.4 illustrates typical profiles of a range of water treatment carbons; Type A carbon is used in the carbon columns at the Stander plant.[26]

TABLE 2.3 MINIMUM REQUIREMENTS FOR CARBON[26,27]

Paramter	Specification
Recommended iodine number, mg iodine per g carbon	> 900
Apparent density, kg/m^3	> 360
Particle size distribution:	
● uniformity coefficient	< 2,1
● percentage oversized particles (relative to manufacturer's specifications)	< 15
● percentage undersized particles	< 5
● effective size range, mm	0,6 to 1,0
Abrasion resistance, %	> 70
Ash content, %	< 8

TABLE 2.4 CHARACTERISTICS OF TYPICAL WATER TREATMENT CARBONS[26]

Parameter	Carbon Types A (coal based)	 B (coal based)	 C (peat based)	 D (hardwood based)
Iodine number, mg iodine adsorbed per g carbon	970	1 200	980	1 350
Apparent density, kg/m³ (as received)	484	450	364	370
Particle uniformity coefficient	1,97	1,85	NA*	NA
Effective particle size, mm	0,70	0,88	NA	NA
Average particle size, mm	1,5	1,5	NA	NA
Abrasion resistance, %	82	72	NA	NA
Ash content, %	5,3	6,8	5,6	4,9
BET** surface area, m²/g	950	960	950	1 570

* NA not applicable (extruded carbons).
**BET Brunauer, Emmett and Teller
Types A and B from different manufacturers.

Carbon regeneration

Thermal regeneration of 'spent' (or 'exhausted') carbon is essential for all water reclamation plants. However, regeneration reduces the adsorptive capacity of a carbon, particularly for the low molecular weight organic compounds.

The removal of organic matter by activated carbon is discussed in section 6.1 while typical details of carbon adsorption columns and regeneration furnaces are discussed in Part III sections 2.5 and 2.8 respectively.

CHAPTER 4

THE REMOVAL OF SUSPENDED MATTER AND TURBIDITY

4.1 THE NATURE OF SUSPENDED MATTER IN WASTEWATER

A domestic wastewater is of complex composition, containing polluting matter in many forms. It contains, in addition to dissolved matter, material in suspension, of both inorganic and organic nature. Table 2.5 shows a suspended particle size distribution together with the relevant inorganic and organic components for a typical sewage.[16]

TABLE 2.5 PARTICLE SIZE DISTRIBUTION OF A TYPICAL SEWAGE[16]

Solid type	Size Range µm	Organic mg/ℓ	Organic %	Inorganic mg/ℓ	Inorganic %
Settleable	> 100	90	30	30	10
Supra colloidal	1 — 100	55	18	25	8
Colloidal	0,001 — 1	30	10	10	4
Soluble	< 0,001	125	42	235	78

Coarse solid material and most of the insoluble inorganic matter are removed by the preliminary process of screening and grit removal. Primary sedimentation will then remove most of the settleable solids and a proportion of the supra colloidal particles. The purpose of primary sedimentation is to remove the maximum amount of polluting matter in the form of readily settleable solids from the sewage as quickly and as economically as possible.

The efficacy of primary settlement with regard to suspended matter removal is dependent upon the size and density of the sewage particles which in turn are dependent upon the age of the sewage and the degree of fragmentation of the individual particles (through pumping, for example).

Colloids are particles kept in suspension by virtue of the fact that they have a surface charge, which is measured as zeta potential. There is a mutual repulsion of the colloidal particles of like charge, but the repulsion can be reduced either by reducing the zeta potential of the colloidal particles or by supplying sufficient kinetic energy to the system to overcome the potential energy barrier, i.e. the rate of particle collision is increased.

The zeta potential of the colloid may be reduced by addition of ions of opposite charge. Sewage normally contains negatively charged colloids and to achieve chemical coagulation, cations are required. Multivalent cations are most effective and therefore salts of aluminium, iron and calcium are most commonly employed. The insoluble hydroxides formed from the ions may then act as flocculation agents by adsorbing and entraining the coagulated colloid.

However, some sewage colloids are of a nature which precludes the coagulating agents also acting efficiently as flocculating agents, and addition of secondary cations is required, e.g. lime and ferric chloride. Polyelectrolytes may be used to achieve secondary flocculation (after primary coagulation).

Addition of chemicals to the primary settlement stage will therefore result in a substantial removal of the supra-colloidal and colloidal particles.

The biological treatment stage which usually follows primary sedimentation removes the supra-colloidal fraction together with a significant portion of the colloidal fraction.

The suspended matter in secondary effluent usually comprises colloidal and settleable fractions, with the latter predominating. The settleable solids concentration is usually 10 to 30 mg/ℓ, with the solids being of microbiological and inorganic nature.

The settleable solid content of a secondary effluent is dependent to a large degree upon the form of biological treatment employed. This aspect is further discussed in section 4.2.

4.2 THE PERFORMANCE OF CLARIFIERS FOLLOWING BIOLOGICAL TREATMENT UNITS

The clarifier following a biological treatment unit has the function of separating the solids that have been formed through biological metabolism of the nutrients present in the sewage.

Secondary effluents demonstrate a different settling pattern to that of granular material (e.g. sand), as the settleable solids present are usually in a flocculated form. Generally this very light floc settles at a slower rate than the floc of raw sewage but, being already in a flocculated condition, it does not require a long time to develop. Secondary clarifiers consequently require lower overflow rates but shorter detention periods than primary clarifiers.

Clarifiers following biological filtration

The sludge originating in a *biological filter* is termed humus. It consists of the colloidal organic solids in the sewage which have been rendered settleable by biological flocculation and of a certain amount of detached or decomposed slime growth or film which is carried into the effluent by the passage of the sewage through the filter. The rate of growth of the film on the filter media varies with the seasons. This film, which contains bacteria, fungi and adsorbed sewage solids, "unloads" or "sloughs" periodically from the filter causing the concentration of the solids in the effluent to vary seasonally over a wide range.

The rate of discharge of solids is highest during

Spring, mainly due to the increased activity of Psychoda fly larvae which act as scourers.

The quantity and settling rate of suspended matter is dependent upon the degree of organic loading applied to the filter. A lightly loaded filter generally produces a smaller quantity of humus than its highly loaded counterpart, and the resulting floc is also more compact and settles more readily.

The concentration of solids in a humus tank influent is generally in the 50 to 150 mg/ℓ range with the higher values being obtained in early Spring. These concentrations are too low for either zone or hindered settling to occur and as such the overflow rate (in $m^3m^{-2}h^{-1}$) and hydraulic retention time are the usual design parameters for humus tanks.

Typical values for overflow rate and retention time adopted in South Africa to ensure an effluent suspended solid concentration of less than 25 mg/ℓ are 1 $m^3m^{-2}h^{-1}$ at average flow (2 $m^3m^{-2}h^{-1}$ at peak dry weather flow) and 1,5 h at peak dry weather flow respectively.

Research has been conducted in the U.K. into the upgrading of the performance of humus tanks following conventionally loaded biofilters by means of banks of inclined tubes or plates.[28] The findings were generally that the hydraulic capacity of humus tanks can be uprated by a factor of about three — although at these higher capacities there will be brief periods during the Spring 'flush' when the suspended solids in the humus tank effluent will exceed the 25 to 30 mg/ℓ limit.

Clarifiers following activated sludge treatment

The clarifier following an *activated sludge* system receives influent liquor with a suspended solids content of usually between 3 000 and 6 000 mg/ℓ. The clarifier must be so designed that efficient solids separation occurs and an effluent low in suspended solids is discharged. The solids in the effluent from an activated sludge clarifier are mostly of microbiological origin and as such they contribute to the COD of the effluent. Figure 2.11 indicates the effect that the suspended solids content has on the COD of an effluent discharged from an activated sludge plant.

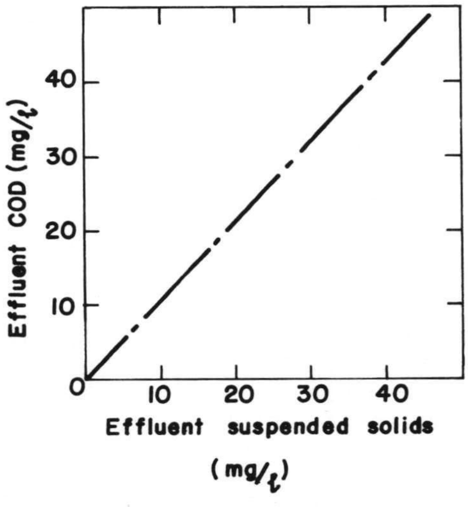

FIGURE 2.11: Effect of suspended solids on effluent COD

The relatively high concentration of influent suspended solids results in the phenomena of zone and hindered settling occurring, whereby there is a definite interface between the sludge and supernatant liquor as the sludge layer descends to the bottom of the tank.

Solids loading

It is common practice to design the activated sludge clarifiers on the basis of overflow rate ($m^3mf^{-2}h^{-1}$) and solids loading (kg $m^{-2}h^{-1}$). However, it has been observed in practice that where the performance of activated sludge clarifiers has been unsatisfactory the reason has usually been a solids overload.[29] More attention should therefore be paid to the expected clarifier solids loading at the design stage.

The solids loading on a clarifier is the rate of mass flow per unit area or 'mass flux', and is made up of two components: that due to the settling of the floc under gravity and that due to the withdrawal of sludge from the bottom of the tank. Figure 2.12 indicates a typical plot of solids loading versus solids concentration, showing that the total flux curve asymptotes to a line which represents the mass flux due to sludge withdrawal alone and it will be observed that there is a minimum in this curve.

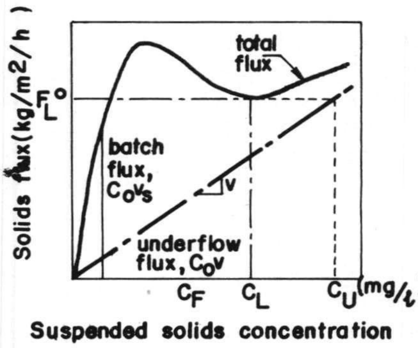

FIGURE 2.12: Typical Solids Flux Curve

This minimum represents the maximum value of the solids loading which may be applied to a tank before solids rise and eventually flow into the effluent.

Under normal operating conditions, the maximum solids loading is dependent upon the settleability of the sludge and the rate of sludge return. However, as the rate of sludge withdrawal is increased, a situation can be reached in which the solids loading is dependent only upon the settling velocity of sludge.[29] The upflow velocity in the clarifier must therefore be less than the settling velocity of the sludge in order to prevent solids carry-over, should the latter situation arise.

The viscosity of the sludge reportedly affects the settleability of activated sludges, with poorer settling being obtained at low temperatures.[30]

Laboratory scale investigations into the effect of solids retention time (SRT) on settleability and dewaterability of activated sludge produced in the Johannesburg area, showed that in general both the settleability and dewaterability improved with increasing SRT, although at SRT values of between 6 and 9 days both characteristics deteriorated. Figures 2.13 and 2.14 show the variations of dewaterability (in terms of capilliary suction time, CST) and settleability (in terms of clarifier effluent suspended solids) respectively with SRT.[31]

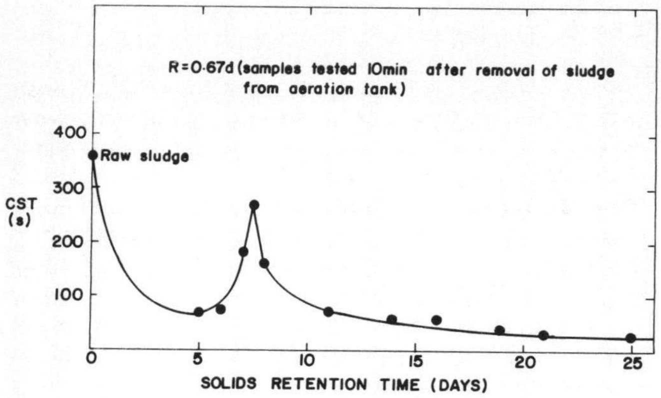

FIGURE 2.13: Variation in dewatering characteristics of a 3 per cent activated sludge with change in solids retention time (SRT)[31]

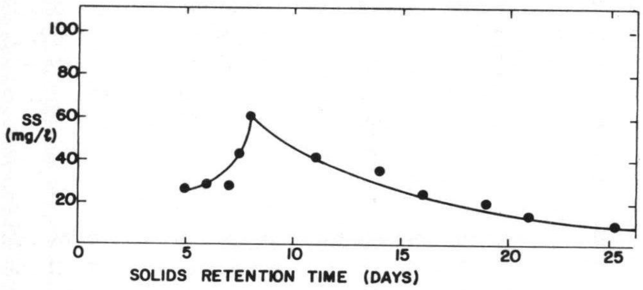

FIGURE 2.14: Variation in SS concentration with solids retention time (SRT)[31]

These results have subsequently been verified at full scale plant level. Further experimental work carried out at the Johannesburg plants into the biological removal of both N and P has indicated that the sludges resulting from these plants, which all have SRT values in excess of 15 days, exhibit excellent settling properties.[32]

It was also shown that these settling properties result in clarifier effluent suspended solid contents of 15 to 20 mg/ℓ and underflow concentrations of up to 1,6% solids at *peak* upflow rates of 1,5 to 2,0 m/h. Average values of effluent suspended solids vary from 10 to 15 mg/ℓ.[32,33]

Settling characteristics

The sludge settling characteristics in an activated sludge system may occasionally deteriorate through the formation of a family of organisms that inhibit the overall sludge mass settlement. These organisms are usually of a filamentous nature and their presence can be caused by a number of factors, such as: low reactor dissolved oxygen; low reactor MLSS; low reactor pH; excessively long reactor SRT; wastes that are high in carbohydrates and sulphides and low in nutrients; and shock or toxic loads on the sludge system.

The long SRT system is much less prone to sludge settleability upsets, and as filamentous organisms are obligate aerobes, the creation of anaerobic and anoxic zones for the removal of phosphorus and nitrogen (refer to chapter 10) adds increased stability to the overall system.

Clarifier details

Design details of secondary clarifiers are discussed in Part III, section 2.2.

4.3 THE PERFORMANCE OF CLARIFIERS IN THE CHEMICAL COAGULATION AND CLARIFICATION PROCESS

Chemical coagulation of wastewater plays an important role in a water reclamation plant, being applied to either raw or settled sewages prior to biological treatment or to biologically treated secondary effluents.

The performance of the clarifiers in these applications, with respect to suspended matter and turbidity removal, are discussed under two headings: (i) clarifiers in raw sewage coagulation and (ii) clarifiers in secondary effluent coagulation.

Raw sewage coagulation

Chemical addition to raw sewage is practised at a number of water reclamation plants, with lime, alum and the ferric salts being the usual additives.

Lime addition is frequently accompanied by the addition of small amounts (5 to 15 mg/ℓ) of ferric salt as Fe^{3+} (usually ferric chloride) or an anionic polyelectrolyte (0,25 to 1,0 mg/ℓ). The actual quantity of lime added depends on the alkalinity of the sewage, as discussed in section 3.1 and the pH required.

Clarifier hydraulic loadings of 1 to 4 $m^3m^{-2}h^{-1}$ have been reported to result in 80 to 90% removal of suspended matter and turbidity.[34,35,36]

Typical mineral salt dosages for raw sewages vary from 50 to 500 mg/ℓ for aluminium sulphate and 30 to 250 mg/ℓ for ferric chloride, with the higher values being required for strong sewages.[22,37,38] Suspended matter and turbidity removals as high as 70 to 90% can be expected.

Investigations carried out in South Africa into the addition of ferric chloride to a raw sewage have shown that by continually recycling a portion of the chemical-raw primary sludge back to the chemical reactor lower chemical dosages can be employed.[13]

Hydraulic loadings on the clarifiers reportedly range from 0,8 to 2,0 $m^3m^{-2}h^{-1}$.[13.39]

Pilot plant scale studies in France have indicated that 'high rate' clarifiers, equipped with inclined plate modules, can be successfully applied for the clarification of weak raw sewages.[40] Hydraulic loading rates of 10 to 15 $m^3m^{-2}h^{-1}$ together with a chemical combination of aluminium sulphate, lime and anionic polyelectrolyte, resulted in 70 to 90% suspended matter removals.

Secondary effluent coagulation

The suspended matter concentration in the effluent from a correctly functioning, long SRT activated sludge system, will be in the 10 to 25 mg/ℓ range while the turbidity will be greater than 10 JTU (possibly near 50 JTU).

Although the turbidity of lime treated effluents is generally between 1 and 6 JTU, experience at the Stander Plant has shown that these turbidities are usually related to fine suspended total hardness.[17]

Performance of secondary lime clarifiers should therefore be gauged by the turbidity and not by suspended matter. The performance objective of the lime clarifier at the Stander Plant is an effluent turbidity of less than 4 JTU which is achieved with hydraulic loadings of 1,5 to 2,0 $m^3m^{-2}h^{-1}$ and small doses of flocculant aids.[17]

Inclined plate/tube modules

The efficacy of inclined plate and tube modules in a tertiary lime clarifier has also been evaluated at the Stander Plant,[41] with the following results:

- The hydraulic load on the clarifier may be increased.
- A reduction in the chemical dosage required to achieve a certain level of clarification.
- Improvement of performance *per se*.

Oxidation pond effluent

Lime treatment has also been applied to oxidation pond effluent in Israel where the experiments indicated that optimum clarification occurred when at least 50 mg/ℓ Mg^{2+} was present in the clarifier influent. Alternatively, similar results could be obtained at a 35 mg/ℓ Mg^{2+} level if 0,5 mg/ℓ of a suitable anionic polyelectrolyte were added.[42]

Mineral salt addition

Chemical clarification of secondary effluents through the addition of mineral salts (usually with polyelectrolytes as floc-aids) normally gives rise to sludges that do not settle as readily as the lime clarified secondary sludges and, as such, lower upflow rates are employed, 0,8 to 1,4 $m^3m^{-2}h^{-1}$ being a typical range.[39]

Clarifier details

Design details of chemical clarifiers are discussed in Part III, section 2.2.

4.4 THE FILTRATION OF EFFLUENT

The main reasons for the inclusion of a filtration step in a water reclamation plant are:

- Removal of residual biological floc.
- Removal of residual turbidity.
- Removal of residual precipitates from the chemical clarification or phosphorus removal step.

Slow sand filters

The sand filter is by far the oldest and most widely used type of filter in water and wastewater treatment. Slow sand filters generally do not find application in a water reclamation plant on account of the large areas of land required and the high labour costs for cleaning. Apart from removing substantial portions of the suspended matter i.e. 60 — 80%, slow sand filters are also effective in the removal of bacteria.

Rapid gravity sand filters

Rapid gravity sand filters operate at rates some 30 times as high as those pertaining to slow sand filters, and as a result the 'filter cycles' are much shorter. An inherent disadvantage of the rapid gravity filters is that during 'backwashing' the grading of the media is disturbed.

Suspended solid removals are similar to those obtained from the slow sand filters but little or no bacterial reduction is achieved.

Rapid gravity sand filters have found use as 'denitrification' reactors in that the addition of a carbon source (usually methanol) to the filter influent enables low residual nitrate contents to be discharged from the plant. This phenomenon is due to the presence of a micro-biological growth on the sand particles.

Upflow sand filters

Upflow sand filters generally achieve longer filter cycles than their rapid gravity counterparts on account of the media being graded from coarse at the bottom to fine at the top, i.e. in the direction of the flow. Hydraulic loading rates and suspended solid removals are similar to those for rapid gravity filters.

Pressure filters

Pressure filters are similar to rapid gravity sand filters in that the operating principles and backwashing methods are identical for both and the only real difference lies in the method whereby the head is produced. Pressure filters can operate at higher head losses than gravity filters and thus obtain slightly longer filter runs. The disadvantage of pressure filters is that the backwashing process cannot be observed to establish whether the sand is in a satisfactorily condition. Filter runs of 48 to 72 hours are achieved at the Stander Plant and a head loss of up to 5,0 m is allowed before backwashing. The performance of pressure filters is generally the same as that for gravity sand filters.

Dual and multi-media filters

Recent reports emphasize the increasing interest in the development of dual and multi-media filtration techniques for rapid gravity sand filters. The most commonly used combination in dual media filters is anthracite on top of quartz sand with the main improvement being a reduction in the rate of head loss. The lengths of filter runs with a dual media bed may be 1,5 to 3,0 times that of a conventional sand bed and backwashing is generally achieved by air scour followed by water scour.

Microstrainers

Microstrainers, while being completely different to sand or dual medial filters, are often employed to reduce the suspended matter content of a secondary effluent albeit with varying degrees of success. This alternative form of 'filter' consists of a rotating drum to which a stainless steel cloth of pre-selected mesh size is fitted. Suspended solid removals of up to 80% may be achieved.

Further details

Further details of the abovementioned filters together with relevant design data are presented in Part III, section 2.3 and the 'Manual for Water Renovation and Reclamation', Chapter 6.

CHAPTER 5

THE REMOVAL AND FATE OF ORGANIC MATTER THROUGH BIOLOGICAL AND LIME TREATMENT

5.1 THE NATURE OF ORGANIC MATTER IN WASTEWATER

While the organic content of a wastewater is generally measured by a 'blanket' parameter such as the COD or TOC (refer to Part I, section 2.2), it is sometimes useful to know the nature of the individual organic constituents, particularly in cases where industrial discharges are accepted into a municipal sewerage system.

Domestic sewage

The main source of organic matter in a domestic sewage is human excreta, with minor sources being the other human activities of working, washing and cooking. Table 2.6 summarizes organic groups identified as being present in solution and suspension in domestic wastewaters.[38.42]

The table shows that carbohydrates, fats, proteins and amino acids form the main portion of the groups so far identified. In general however, the nature of the organic matter present in a purely domestic wastewater is such that a high quality secondary effluent can be produced by relatively simple and inexpensive biological treatment systems.

Industrial wastewaters

The discharge of an industrial waste into a municipal sewerage system is one aspect that should be carefully considered as industrial wastes can introduce a myriad of organic compounds into the sewage flow; Table 2.7 shows the expected organic constituents of various industrial wastewaters.[43]

The presence of industrial wastes in a municipal sewage flow can impair the treatment efficiency of biological treatment systems — either through organic or inorganic constituents.

Should there be the slightest doubt in the process engineer's or designer's mind as to the likely effect of a

TABLE 2.7 ORGANIC CONSTITUENTS OF INDUSTRIAL WASTEWATERS[43]

Type of wastewater	Organic constituent
Cotton	Starch, gum, wax, dextrin, glucose, pectin, detergents, alcohols, acetic acid, methylcellulose
Wool	Grease, soap, detergents
Flax	Volatile fatty acids
Laundry	Soap, detergent, grease, carboxymethylcellulose, optical brighteners
Brewery	Carbohydrate, lipids, B-group vitamins
Distillery	Sugar, alcohol
Dairy	Lactose, lactic acid, casein, fats
Cannery	Sugar, acids
Sugar beet	Sucrose, raffinose, batanin
Sugar refinery	Sucrose, amino acids, amines, fatty acids
Grass silos	Glucose, galactose, fructose, xylose, arabinose, acetic and lactic acids
Wood	Carbohydrates, lignin, vanillin, furfural, acetic, butyric and oxalic acids, alcohols, terpenes
Coke ovens	Phenols, 'tar' acids, pyridine, quinoline
Oil refinery	Phenols, hydrocarbons, alcohols, ethers, ketones, acrylonitrile

TABLE 2.6 MAIN ORGANIC CONSTITUENTS OF DOMESTIC SEWAGE[38.43]

	Concentration (mg/ℓ)					
Constituent	Solution			Suspension		
	UK	USA	Israel	UK	USA	Israel
Carbohydrates	70	10	68	34	34	0
Fats	0	0	—	140	26	365
Proteins and amino acids	18	9	124	42	27,5	152
Volatile acids	25	0,3	190	—	—	0
Non-volatile acids	34	28,5	—	12,5	—	—
Others (as C or vol. solids)	4,5	1	—	2,5	11	—
Organic carbon	90	—	—	211	—	—
Volatile solids	—	80	—	—	16	—

particular industrial waste, laboratory scale (or preferably pilot plant scale) experiments should be initiated.

5.2 REMOVAL OF ORGANIC MATTER IN BIOLOGICAL TREATMENT UNITS

Most organic chemicals tend to be 'biodegradable' but for many reasons are not 'biodegraded' in a biological treatment plant. The most important reasons are the following:[44]

- The necessary organisms may not have been present in sufficient numbers because of too high a rate of treatment.
- The biological population may not have been acclimatised in the case of organic compounds that are only occasionally present in the wastewater.
- There is a threshold concentration for most compounds, related to maintenance energy, below which the organisms will not grow and thus will not degrade the organic compound.

Investigations into the effect of molecular structure upon the biodegradability of organics resulted in the conclusions that molecular size, insolubility, the nature, position and number of substituents in the molecule, the presence of heterocyclic molecules and a high degree of branching increase the resistance to biodegradation.[45]

As a general rule alcohols, aldehydes, acids, esters, amides and amino acids tend to be more readily degraded than the corresponding alkanes, olefines, ketones, decarboxylic acids, nitriles, amines and chloroalkanes.

Biological treatment reduces the strength of the waste (in terms of COD, BOD, TOC etc.), with the easily biodegradable material being readily removed while the slowly and unbiodegradable material remains in the treated effluent. The greater proportion of slowly and non-biodegradable matter in the effluent affects the ratios of the strength parameters, as is indicated in Table 2.8.

TABLE 2.8 RATIOS BETWEEN ORGANIC POLLUTION PARAMETERS

Sample	$\frac{COD}{BOD}$	$\frac{COD}{TOC}$
Settled domestic sewage (SDS)	1,85–2,04	3,19–3,28
Settled effluent from 'high rate' biological filters treating SDS	2,24	3,32
Settled effluent from conventional filters treating SDS	4,74–5,19	2,89–3,14

Note: Figures abstracted from data presented in 'Notes on Water Research', published by the Water Research Centre, U.K.[46]

Organic nitrogen and phosphorus compounds are hydrolyzed to their inorganic counterparts of ammonia and orthophosphates respectively, which in certain instances may be removed from the wastewater flow.

The removal of soluble biodegradable material in an activated sludge system increases with solids retention time (SRT) up to approximately 12 days, whereafter the removal remains practically constant. Figure 2.15 illustrates the soluble biodegradable COD removal as a function of the system's SRT.[47]

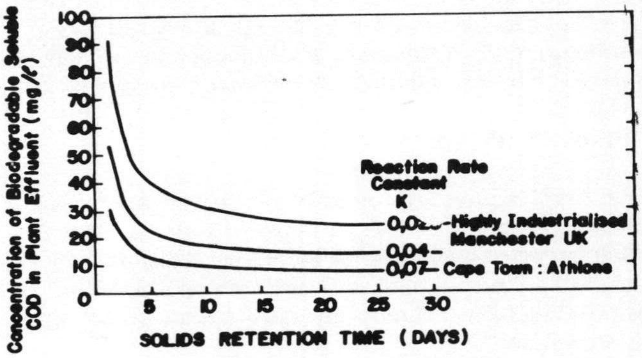

FIGURE 2.15 Soluble biodegradable COD removal as a function of system SRT[47]

Use will invariably be made of activated carbon adsorption as a final polishing step in the production of potable or other high quality water. The molecular mass distribution of the organics present in the carbon column influent influences the degree of adsorption attained as organic compounds of low molecular mass and of a hydrophilic nature are poorly adsorbed.[48] Investigations into the effect that an activated sludge plant's SRT has on the quality of effluent subsequently discharged from activated carbon columns, indicated that as the SRT was increased from 5 to 20 days, so the fraction of low molecular mass, soluble organic material in the carbon column influent decreased, resulting in an improvement in the product quality.[7] Figure 2.16 in-

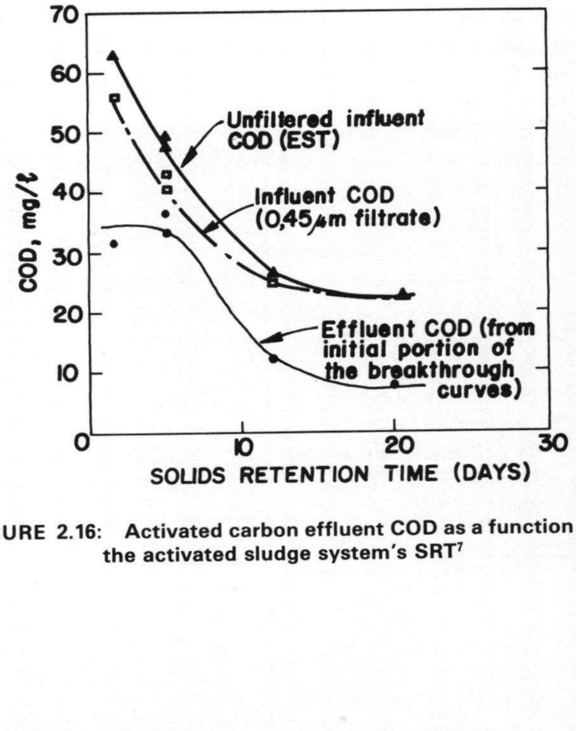

FIGURE 2.16: Activated carbon effluent COD as a function of the activated sludge system's SRT[7]

dicates the relationship obtained between the adsorption column effluent COD and the activated sludge SRT.[7]

It may therefore be concluded that in instances where activated sludge plants are to precede carbon adsorption columns, there is definite merit in employing SRT values of greater than 15 days.

5.3 REMOVAL OF ORGANIC MATTER BY LIME

The addition of lime to a raw sewage or a secondary effluent will result in the removal of most of the suspended and colloidal fractions of the organic matter present.

Treatment of raw sewage

Lime treatment of a strong raw sewage (i.e. COD approx. 1 000 mg/ℓ) has been shown to produce an effluent with the following soluble organic fractions:[38]

- *Low molecular mass organic acids and carbohydrates*

  These compounds are highly soluble and represent the largest fraction of organics remaining. As a result of their hydrophilicity and solubility they are not readily carbon adsorbable (refer to 6.1) but they are readily biodegradable (refer to 5.2).

- *Low molecular mass, relatively hydrophobic compounds*

  This group comprises MBAS,* phenols, most organic toxicants and odorants, such compounds being readily adsorbable but not so readily biodegradable.

- *Medium and low molecular mass compounds*

  This group is both biodegradable and adsorbable but not as readily as the former and latter fractions respectively.

Table 2.9 indicates the removal and relative distribution of the various organics after lime treatment of a wastewater in Israel.[38]

The table shows that the effluent contained essentially soluble organic compounds of which the low molecular mass, soluble organic acids constituted the largest fraction.

The above findings would indicate that if a carbon adsorption stage is to follow lime treatment of a strong raw sewage, a biological treatment stage should be interposed between the two unit operations. This biological treatment will remove the poorly adsorbed low molecular mass organics and by so doing will extend the activated carbon cycle time.

This consideration does not necessarily apply in areas where high per capita water consumptions lead to weak sewages — for example in the USA where raw sewage COD values are generally in the 200—300 mg/ℓ range.

TABLE 2.9 CONCENTRATION OF ORGANIC GROUPS IN RAW AND CHEMICALLY TREATED MUNICIPAL WASTEWATER IN TERMS OF COD (mg/ℓ)

Component	Raw		After lime treatment
	Total	Soluble	
Proteins	276	124	87
Carbohydrates	68	68	54
Oils, grease (fats)	365	—	24
Soluble acids	190	190	180
Detergents	62	62	22
Total classified	961	444	367
Unidentified	324	158	43
TOTAL COD	1 285	602	410
BOD_5	449	245	205

A further point to be considered is that of the 'age' of the sewage at the point of treatment. The 'older' the sewage, the more likely it is that acid fermentation would have occurred in the sewers, leading to breakdown of organic matter to volatile low molecular mass organic acids (e.g. acetic, propionic etc).

Laboratory scale studies into the activated sludge treatment of the effluent from a lime clarified strong raw sewage indicated that the lime treatment effluents are substantially more biodegradable than conventionally settled sewages, on account of the abundance of soluble low organic acids.[49] These studies also indicated that the kinetic constants pertaining to the activated sludge treatment of the lime clarifier effluent could be substantially different to those pertaining to the treatment of conventional settled wastewaters.

Treatment of secondary effluent

Experience in South African has shown that high lime treatment of secondary effluent is practically ineffective in removing chlorinated pesticides and phenol, and that it presents a varied 'track record' when other selected organic compounds are considered. Table 2.10 shows the removal of selected organic compounds achieved in the pilot reclamation plant at Daspoort, Pretoria.[50]

High lime treatment of activated sludge effluent at the Stander Plant in Pretoria showed an average reduction in soluble TOC of 31%.[51] The higher molecular mass ranges (from a relative molecular mass of 780 upwards) showed an average decrease in TOC of 57% while the average decrease for the lower ranges was only 22%. Therefore, a larger proportion of the soluble high molecular mass organics are removed by high lime treatment than the lower molecular mass organics. The conclusion from the study was that hydrolysis of the higher molecular mass compounds into lower order compounds did not occur.

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*'Methylene Blue Active Substances', a test for the presence of surface active detergent compounds.

TABLE 2.10 REMOVAL OF ORGANIC COMPOUNDS IN THE HIGH LIME TREATMENT PROCESS[50]

Compound	Feed concentration (mg/ℓ)	Removal (%)	Compound	Feed concentration (mg/ℓ)	Removal (%)
Lindane	20	0	Trichlorophenol	450	27,8
Dieldrin	40	12,5	Hexachlorobenzene	80	93,8
Chlordane-1	300	39,3	Acenaphthene	600	27,0
Chlordane-2	300	18,0	Fluoranthene	500	78,8
Demeton-S-methyl	3 100	66,8	Pyrene	500	85,4
Parathion	4 300	19,1	Dibutylphthalate	400	87,0
Fenitrothion	4 300	21,6	O-nitrotoluene	400	23,5
Fenthion	4 300	22,1	Tetradecane	200	95,5
Phenol	600	4,7			
Hexachlorobutadiene	110	71,8			

CHAPTER 6

THE EFFECT OF ACTIVATED CARBON, OZONE AND CHLORINE ON ORGANIC MATTER

6.1 REMOVAL OF ORGANIC MATTER BY ACTIVATED CARBON ADSORPTION

A changing world

Until recently the use of activated carbon as part of a process train for the production of a potable water was limited to the removal of tastes and odours from surface waters.

Traditional water quality parameters gave little warning of what was to happen when during five years of drought (1952—1957) the City of Chanute, USA ran short of its normal supply of river water and by force of circumstances resorted to recycling of secondary sewage effluent from a 17 days retention pond.[52] This direct recycling which had a duration of several months resulted in a sharp increase of certain dissolved organic material not removed by either the sewage purification process or by the subsequent water treatment plant and resulted in the tap water foaming and being of a pale yellow colour.

As would be expected, the Chanute experience caused a public outcry and resulted in a very serious setback to the concept of water reclamation. This might not have happened if Chanute had employed activated carbon adsorption as part of the process train. Today it is generally agreed that economic beneficiation of a raw water of dubious origin, if the product is to be of a potable quality, is entirely dependent on the remarkable performance capability of activated carbon.

Taste and odour removal

The use of activated carbon for taste and odour removal has been standard practice for many years in Europe.

The use of granular activated carbon in the United States was at one time abandoned in favour of powdered activated carbon as the latter has the advantage that dosages can be adapted to the influent organic load and because it can easily be applied intermittently. However, in recent years granular carbon has regained favour, particularly in those applications where continuous carbon contacting is required.

The main use of activated carbon filters in Great Britain has been for dechlorination, but its use for taste removal is not unknown. The carbon used most frequently is in the powdered form, with dosages varying from 5 to 50 mg/ℓ.

In Southern Africa activated carbon columns were used for the first time in the production of a domestic water supply when they were introduced as an essential step in the water reclamation plant at Windhoek in 1969. Carbon columns have been used since 1978 at the Brits Municipal waterworks for taste and odour removal, producing a water of acceptable aesthetic quality.

In the latter instance, the intake to the waterworks is from the Crocodile River, the flow of which is derived from the heavily eutrophied Hartbeespoort Dam situated some 15 km upstream from the water intake.

Progress

The production of activated carbons, and the research that goes with producing the different forms are today actively pursued in many of the industrialized countries of the world.

It is an expression of faith in the ability of granular activated carbon that the new EPA regulations may make granular activated carbon filters a regulatory requirement, primarily aimed at the removal of residues of complex organic compounds present in certain raw water supplies.[53]

Factors influencing adsorption

Today activated carbon is being increasingly used to remove trace organics from potable water supplies, but it is important, nevertheless, to realise that granular activated carbon adsorption is not a panacea and that its performance can be influenced by a number of factors, such as the molecular structure, molecular mass, solubility and degree of ionization of the adsorbate as well as the temperature of the effluent or water.

These factors are briefly discussed below and the reader is referred to the literature for further discussion on this topic.[48,54]

- *Molecular structure:* branched chain organic compounds are more readily adsorbed than straight chain compounds, with the type and location of the functional group affecting the degree of adsorption.

- *Molecular mass:* low molecular mass organic compounds, particularly those that are oxygenated, are poorly adsorbed. In general adsorption from an aqueous solution increases as an homologous series is ascended — Traube's Rule.[48]

- *Solubility:* adsorption increases as the solubility decreases and in general the solubility of an organic compound in water decreases with increasing chain length (i.e. increase in molecular mass).

- *Ionization:* adsorption of structurally simple organic compounds is at a minimum for ionized (or charged) species and at a maximum for neutral species. As compounds become more complex so the effect of ionization becomes of decreasing importance.

A change in ionization of the simple compounds can drastically affect adsorption. In general, adsorption of the typical organic pollutants from water is increased with decreasing solution pH.

- *Temperature:* adsorption reactions are normally exothermic; thus the extent of adsorption generally increases with decreasing temperature.

Low molecular mass organics

The poor adsorption of the low molecular mass organics is perhaps the single most important factor affecting the overall performance of an activated carbon contactor.

These low molecular mass organics are generally biodegradable so there therefore appears to be merit in installing a biological treatment stage prior to the activated carbon columns.

Experience gained in the USA has indicated that the mode of operation of an activated sludge plant has a marked effect on the organic content of the effluent discharged from the carbon columns.[7]

Effect of activated sludge SRT

Figure 2.16 shows that as the activated sludge plant SRT was increased from 5 to 20 days, so the COD of the carbon column effluent decreased by some 75%, as a result of the reduced low molecular mass organic content of the effluent discharged from the long SRT activated sludge system.[7]

Findings similar to those discussed above have been obtained by others who report that the activated carbon removal of TOC from filtered mixed liquor samples increased for the succeeding compartments of a plugflow activated sludge unit.[55]

The above discussion with regard to the removal of low molecular mass organics highlights the importance of either preceding the carbon stage by a long SRT activated sludge system or of encouraging biological growths on the carbon itself.

Removal of toxic organic compounds

Activated carbon has a limited adsorptive capacity for the volatile halogenated hydrocarbons (VHH), some of which might possess toxic properties (refer to Part I, section 5.2), and as a result their breakthrough occurs after a short period of time.[56]

The VHH compounds are formed through breakpoint chlorination of inadequately treated effluents which contain significant quantities of organic compounds (some of which act as precursors to VHH formation).

The VHH content of the influent to the activated carbon stage may be reduced by one or various combinations of the following methods:

- By the installation of a long SRT activated sludge system in order to produce a high quality secondary effluent (refer to section 5.2).
- By positioning the breakpoint chlorination stage between the primary and secondary activated carbon stages.
- By replacing breakpoint chlorination upstream of the activated carbon stage by an alternative form of disinfection, such as ozone or chlorine dioxide.

Pesticides and polynuclear aromatic hydrocarbons (PAH)

The low solubilities of chlorinated pesticides and polynuclear aromatic hydrocarbons render them readily adsorbable. Table 2.11 summarizes the results obtained at the Daspoort pilot plant, where the influent to the plant was spiked with relatively high concentrations of chlorinated hydrocarbons, pesticides and polynuclear aromatic hydrocarbons.[50]

The table shows that activated carbon was particularly effective in the removal of the bulk of the compounds added. However it should be noted that identification of the peaks appearing in the chromatograms was not done and that the disappearance of one peak, interpreted as the disappearance of the compound tested, could be misleading as a new compound may well have been formed.

Biologically activated carbon filters

Biological growths in activated carbon columns have been observed at a number of installations throughout the world and when controlled effectively these biologically activated carbon (BAC) filters have the following properties:[57,58,59]

- Adsorptive removal of biologically resistant compounds which may possess toxic and/or carcinogenic properties.
- Biological removal of low-molecular mass oxygenated compounds for which activated carbon has only a limited capacity.
- Reduced carbon exhaustion rates, hence extended regeneration cycles leading to reduced regeneration costs.

A further feature of the BAC filters is that of 'order of breakthrough'. Under *non*-bioactive conditions high molecular mass organics (pesticides etc.) will generally break through after the biodegradable organics, due to the lower adsorptivities of the latter. However, under conditions of bioactivity, the high molecular mass organics will break through *before* the biodegradable organics, and the removal of the latter can continue for extended periods (months to years) and indeed even after the carbon has become 'saturated'.

The lower molecular mass, non-biodegradable organics will, however, break through the moment the carbon becomes saturated with respect to these substances.

Both anaerobic and aerobic conditions within the columns will promote biological growths, but aerobic conditions are generally preferred as they prevent the formation of hydrogen sulphide gas.

TABLE 2.11 EFFICACY OF THE PILOT RECLAMATION PLANT IN THE REMOVAL OF TOXIC ORGANIC COMPOUNDS[50]

Unit process	Removal	Compounds Lindane	Dieldrin	Chlordane-1	Chlordane-2	Demeton-S-Methyl	Parathion	Fenitrothion	Penthion	Phenol	Hexachloro-butadiene	Trichlorophenol	Hexachloro-benzene	Acenaphthane	Fluoranthene	Pyrene	Dibutylphthalate	O-nitrotoluene	Tetradecane
High lime treatment (B1)	Feed concentration $\mu g\ \ell^{-1}$	20	40	300	300	3 100	4 300	4 300	4 300	600	110	450	80	600	500	500	400	400	200
	Removal (%)	0	12,5	39,3	18,0	66,8	19,1	21,6	22,1	4,7	71,8	27,8	93,8	27,0	78,8	85,4	87,0	23,5	95,5
	Overall removal (%)	0	12,5	39,3	18,0	6,8	19,1	21,6	22,1	4,7	71,8	27,8	93,8	27,0	78,8	85,4	87,0	23,5	95,5
Stabilization (B2)	Feed concentration $\mu g\ \ell^{-1}$	22	35	182	246	1 030	3 480	3 370	3 350	572	31	325	5	438	106	73	52	306	9
	Removal (%)	0	0	0	2,0	0	0	0	0	29,7	96,8	0	—	94,8	80,2	86,3	0	73,2	>88,9
	Overall removal (%)	0	10,0	36,7	19,7	29,4	19,1	12,1	14,2	33,0	>99,1	24,0	>99,9	96,2	95,8	98,0	52,5	79,5	>99,5
Sandfiltration (SF)	Feed concentration $\mu g\ \ell^{-1}$	25	36	190	241	2 190	3 480	3 780	3 690	402	<1	342	—	23	21	10	190	82	<1
	Removal (%)	0	22,2	41,6	13,3	21,0	17,8	20,6	18,7	0	—	6,4	—	13,0	33,3	20,0	0	9,8	—
	Overall removal (%)	0	30,0	63,0	30,3	44,2	35,5	30,2	30,2	31,0	>99,1	28,9	>99,9	96,7	97,2	98,4	34,5	81,5	>99,5
Chlorination (Cl)	Feed concentration $\mu g\ \ell^{-1}$	30	28	111	209	1 730	2 860	3 000	3 000	414	—	320	—	20	14	8	262	74	—
	Removal (%)	80,0	3,6	32,4	31,6	99,6	99,9	>99,9	58,3	82,1	—	25,0	—	75,0	21,4	50,0	27,9	17,6	—
	Overall removal (%)	70,0	32,5	75,0	52,3	99,7	>99,9	>99,9	70,9	87,7	>99,1	46,7	>99,9	99,2	97,8	99,2	52,8	84,8	>99,5
Active carbon filtration (C1)	Feed concentration $\mu g\ \ell^{-1}$	6	27	75	143	7	<4	<4	1 250	74	—	240	—	5	11	4	189	61	—
	Removal (%)	>98,3	98,9	92,0	98,9	98,6	—	—	>99,9	97,6	—	97,4	—	78,0	—	—	99,0	93,4	—
	Overall removal (%)	>99,5	>99,3	98,0	>99,5	>99,9	>99,9	>99,9	>99,9	99,7	>99,1	98,6	>99,9	99,8	97,8	>99,2	>99,9	>99,0	>99,5
Active carbon filtration (C2)	Feed concentration $\mu g\ \ell^{-1}$	<0,1	<0,3	6,0	<1,5	<0,1	<4,0	<4,0	<0,1	1,8	—	6,2	—	1,1	—	—	1,9	<4,0	—
	Overall removal (%)	>99,5	>99,3	98,0	>99,5	>99,9	>99,9	>99,9	>99,9	99,7	>99,1	98,6	>99,9	99,8	>97,8	>99,2	>99,9	99,0	99,5

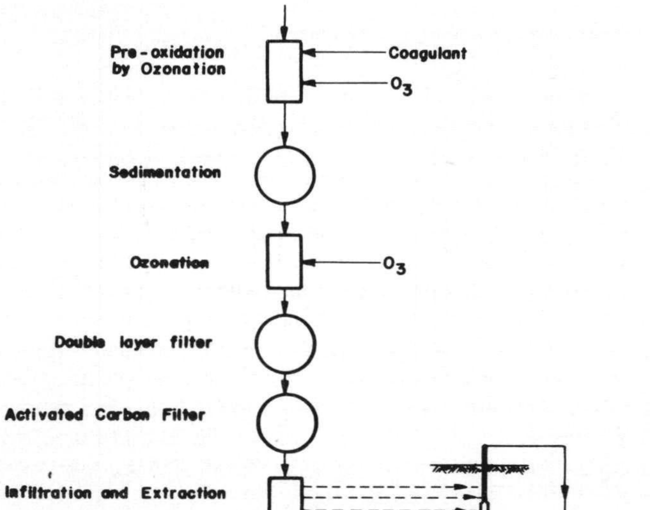


FIGURE 2.17: Flowsheet of the Mülheim potable water treatment plant

The reader is referred to the paper by Weber and Ying[57] for further discussion on the improved organic matter removal through the BAC filters.

The effect that upsteam unit operations have on the biological growths and the effect that the biological growths have on the final effluent quality are highlighted by the experience at the Rheinisch-Westfälische-Wasserwerke in Mülheim/Ruhr.[58]

The Mülheim plant, W. Germany, some years ago introduced breakpoint chlorination to oxidize ammonia, which in the River Ruhr water can reach maximum values as high as 4 — 6 mg/ℓ. As would be expected this gave rise to high concentrations of organo-chloro compounds which the activated carbon filters, originally introduced to remove the remaining chlorine, could only partly remove. Also, the traditional practice to infiltrate this water into the underground could not be abolished because, without the biological treatment associated therewith, taste and odour formation occurred within the distribution system.

When subsequently the management at Mülheim changed their treatment process by replacing chlorination with ozonation (see Figure 2.17) the performance improved dramatically — see Table 2.12.[58] Instead of breakpoint chlorination, pre-oxidation is effected by

TABLE 2.12 MÜLHEIM PLANT. PARALLEL PROCESS DATA USING CHLORINATION (1975) AND OZONATION (1977)[58]

Stage — Treatment	1975	1977	1975			1977		
			DOC mg/ℓ	** UV (254 nm) m^{-1}	UV/ DOC	DOC mg/ℓ	UV (254 nm) m^{-1}	UV/ DOC
Raw Water from River Rühr			3,9	6,8	1,7	3,6	6,1	1,7
Pre-oxidation	10—50 mg/ℓ Cl_2	1 mg/ℓ O_3						
Dosing	4—6 mg Al^{3+}	4—6 mg/ℓ Al^{3+}						
Mixer power input	0,1 kW/m^3	2,5 kW/m^3						
Retention time	0,5 min	0,5 min						
Flocculation	5—15 mg/ℓ $Ca(OH)_2$	5—15 mg/ℓ $Ca(OH)_2$						
Sedimentation	1,5 h	1,5 h						
After Flocculation and Sedimentation			3,2	4,5	1,4	4,0	3,2	1,1
Ozonation	—	2 mg/ℓ O_3 5 min						
Pre-flocculation		0,2 Al^{3+} 0,1 Polyel						
Filtration	10,7 m/h	9 m/h						
After Filtration			3,2	4,4	1,4	2,6	1,8	0,7
Activated Carbon Filter	22 m/h 2 m deep	18 m/h 2m*						
After Activated Carbon Filter			3,0	4,0	1,3	2,3	1,6	0,7
Ground passage	12—50 h	12—50 h						
After Ground passage			1,8	3,1	1,7	0,9	1,4	1,6
Safety chlorination	0,4 — 0,8 mg/ℓ	0,2 — 0,3 mg/ℓ						

* Depth of carbon filters to be doubled to allow more complete biological activity (See text)
**UV extinction at 254 mm
DOC = dissolved organic carbon

means of ozonation at a dosage of 1 mg/ℓ with the subsequent and main ozonation dosage being approximately 2 mg/ℓ.

Breakpoint chlorination in the original scheme inhibited biological growths in the upper portions of the carbon columns and the resulting depletion of adsorption and biological growth sites resulted in early breakthrough of low molecular mass, biodegradable organics. Ozonation however not only oxidized the higher molecular mass organics into readily biodegradable compounds but it also allowed the entire carbon columns to act as biological growth sites, thereby actually improving the overall organic matter removal. Carbon dioxide production nearly equalled the reduction in organic carbon and nitrification was complete — all signs of an active biological growth.

Table 2.12 indicates that the retention in the carbon filter was not long enough to ensure complete biological degradation, as a further considerable reduction was observed after the ground passage although this reduction may be attributed to groundwater dilution. Steps are however being taken to increase the carbon retention period to 30 minutes (on an empty column basis) whereafter residual organic carbon contents of less than 1 mg/ℓ are expected.

Seeding of carbon columns

To establish steady state activity in a fresh filter may take two to three weeks particularly if ammonia removal is required. It is therefore not surprising that plant operators have found it beneficial to remove only some 80 per cent of the carbon charge when a column is to be charged with freshly regenerated carbon.

Prevention is better than cure

The ability of a water reclamation plant to produce water of potable quality depends entirely on its ability to prevent substances of toxicological importance leaving the plant. The capacity of activated carbon to adsorb complex organohalogens should not be overtaxed and for that reason activated carbon should be regenerated whenever the adsorption sites for low molecular mass organics are saturated as indicated by increasing effluent concentrations. Everything possible should therefore be done to limit the concentration of the compounds which must be removed from the water to acceptable levels.

Breakpoint chlorination of a raw water which contains large numbers of organic precursors should be avoided if at all possible, since VHH compounds will be formed and these compounds will put an unnecessary load on the carbon columns. Attention is therefore again drawn to the methods that are available to ensure that the carbon column influent has a low VHH content.

6.2 THE EFFECT OF OZONE ON ORGANIC MATTER

Ozone has found extensive use in the disinfection of potable waters, particularly in Europe where it was first introduced in 1886. Recent advances in ozone technology have indicated that not only does ozone act as an effective disinfectant but it also has the ability to 'react' with complex, high molecular mass organic molecules to form their more simple, biodegradable derivatives.

Action

The action of ozone on dissolved or suspended matter present in an effluent is based on direct oxidation, ozonolysis and catalytic oxidation.[60,61]

- *Direct oxidation* is characterized by the loss of one atom of oxygen. Ozone acts in this way upon hydroxy-organics (especially phenolics) and upon amines, although not ammonia.
- *Ozonolysis* is characterized by the ozone breaking up the $-C=C-$ double bond of unsaturated organic compounds, resulting in the formation of simple organic molecules having different characteristics and properties. Ozone is purported to act in this way on aromatic compounds (the organo-phosphorated ones in particular), detergents and certain cellular elements such as viruses.
- *Catalytic oxidation* is characterized by the oxidation process taking place at higher rates and also with lower temperatures when ozone is present — as opposed to the situation when only air or oxygen is present.

Disinfection and sterilization

The efficacy of ozone as a disinfectant is discussed in section 7.2.

Effect on pesticides

Ozone has a destructive effect only on certain organo-chlorinated compounds, such as Lindane, Dieldrin, DDT and HCH, but is quite effective in destroying the organo-phosphorus compounds, such as Parathion, Malathion, Fernitrathion and Ronnel.[60,62]

Effect on phenols and phenolic compounds

Ozone is effective in destroying phenol and the phenolic compounds — chlorophenols in particular. The ozone dose varies not only with the pH but also with the nature of the phenol to be removed, i.e. pure phenol, diphenols, triphenols, cresol or napthol.[60]

In contrast to the effect of conventional oxidants such as chlorine dioxide or hydrogen peroxide on phenols, which produce quinones, the use of ozone produces aldehydes, carbonic acid, formic acid, glyoxalic acid and oxalic acid, most of which are biodegradable[61] (refer to section 5.1).

Effect on detergents

In general, positive results can be expected in the removal of detergents by ozone, with the ozone requirement being in the region of 3 mg ozone per mg of detergent.[61]

Effect on taste and colour

Ozone is more effective in taste elimination than chlorine dioxide and the most effective taste elimination is achieved through the use of ozone followed by activated carbon.[60]

Ozone gives treated water a blue colour if the preceding treatment has been carried out correctly, otherwise recolouration might occur through the micro-flocculation of dissolved matter after the ozonation step. Ozonation is thus placed towards the end of the overall treatment sequence.

As with taste removal, the most effective colour removal is achieved through the use of ozone followed by activated carbon.[60]

Formation of a settleable precipitate

The organic matter that is responsible for the presence of taste and/or colour in an effluent is either in dissolved or stable suspension (colloidal) form. The products of the oxidation by ozone will either remain dissolved or they will precipitate out.

Ozone also has a micellizing effect on colloidal suspension leading to enhanced flocculation/coagulation of those effluents with substantial turbidities.

Ozonation of an effluent that contains significant quantities of taste (or colour) forming compounds and/or turbidity can therefore be expected to give rise to the formation of a precipitate which must be removed, either by sand or activated carbon filtration, prior to discharge to the carbon adsorption or post disinfection stage.

Experience at the Stander plant has indicated that with an effluent turbidity of less than 1 JTU, no precipitates were formed.[63]

However, as sand filtration commonly precedes the ozonation step, there is definite merit in making use of the micellizing property of ozone by routing the ozone contactor off-gases to a point just upstream of the sand filters. This form of off-gas use has been implemented at the Mülheim plant in West Germany (refer to Figure 2.17 in section 6.1), although in this instance a sludge blanket clarifier is used in lieu of sand filters.

Sand filtration between ozonation and carbon adsorption

Pilot scale research conducted in the USA has shown that there may also be merit in positioning sand filters between the ozonation and carbon adsorption stages.[64] The filters in this instance receive a highly oxygenated wastewater flow and significant organic matter removal through biological action is reported to occur.

Effect on activated carbon adsorption

Ozonation prior to an activated carbon adsorption stage has the effect of enhancing biological growths on the carbon, due to the breakdown of high molecular mass organics to simpler, biodegradable compounds by the ozone. The net result is that the overall organic matter removal by the carbon adsorption stage is significantly enhanced. This phenomenon has been observed at plants in the USA,[56] Germany (refer to 6.1) and South Africa.[63]

The BAC filter has in some instances resulted in pronounced extensions in the regeneration cycle. The capacity of the carbon at Mülheim to remove organics from water derived from the river Ruhr increased by a factor of 10,[59] whereas that at Düsseldorf where water from the Rhine is treated, increased by only 40%.[65]

This marked 'difference in the increase' is believed to be due to the presence in the Rhine of high concentrations of complex halogenated organics which are much more resistant to oxidation by ozone than are non-halogenated organics and thus are less easily converted into readily biodegradable compounds.

The conditions prevailing in a BAC filter are synergistic in that although (aerobic) bacteria are necessary to obtain the benefits from BAC, so also is the adsorptive capacity of the granular activated carbon (GAC). The conclusions formed from the results obtained with potable waters in Germany with respect to the combination of ozone and activated carbon are:[59]

- more effective removal of dissolved organics from solution by the BAC system, (up to 200%);
- increased capacity of the carbon to remove organics by biological activity (by a factor up to 10);
- increased operating life of the carbon columns especially if the GAC can be kept free of halogens, (up to 3 years);
- biological conversion of ammonia to nitrate in the GAC columns;
- use of less ozone for removing a given amount of organics than using ozonation alone;
- filtrates from BAC systems in potable water plants can be treated with small quantities of chlorine to produce a water of acceptable bacteriological quality.

Effect of ozone on chlorine demand

Cognisance should be taken of the fact that a water possessing no chlorine demand prior to ozonation may well posses one after: this is due to the fact that ozonation breaks down certain chlorinated compounds into substances that may well have a demand.[60]

6.3 THE EFFECT OF CHLORINE ON ORGANIC MATTER

Analytical tools

The quality and safety of a potable water supply, and specifically the degree of organic contamination, have until fairly recently been judged on simple yardsticks such as the presence of colour, taste and odour. No accurate or practical tool was available to identify natural and man-made micro-pollutants. In the past decade, however, highly sensitive analytical techniques, capable of identifying and even quantifying specific organic compounds at very low concentrations have been developed and an astonishing picture emerged of the extent to which micro concentrations of rather unwanted compounds are present in the water environment.

Table 2.13 highlights the increase in VHH in the Vaal River between the pump station at Suikerbosch and the intake at Vereeniging, with the increase being attributed to a tributary which drains extensive urban and industrial areas and which receives substantial volumes of secondary sewage effluents.[66]

Organo-chlorines

Chlorine has been considered an effective disinfecting agent for more than a century. It was known that micropollutants present in water supplies derived from organic compounds introduced by municipal or industrial effluent discharges, by runoff water from residential and agricultural areas or produced by aquatic organisms and decaying vegetation, could cause taste and odour in water, especially when chlorinated. However, these were problems of aesthetics which were controlled by the introduction of activated carbon.

TABLE 2.13 INCREASE IN VHH IN VAAL RIVER WATER ($\mu g/\ell$)[66]

Sampling Point	CCl_4	$CHCl_3$	C_2Cl_4	$CHBr\ Cl_2$	$CHBr_2Cl$	$CHBr_3$	Total VHH
Zuikerbosch	0,01	0,11	0,15	0,03	0,00	0,00	0,30
Vereeniging	0,01	0,24	0,47	0,04	0,02	0,00	0,78

It therefore came as a shock when it was disclosed that chlorine reacted with certain organic compounds or "precursors" to form halogenated compounds, some of which purportedly possess carginogenic properties.

Of these compounds the organochlorines are the most numerous and no less than 231 such compounds had been identified in the water environment by 1978.[67] They are not removed in conventional water treatment processes and must have been present in man's drinking water supplies ever since chlorination was introduced.

Chlorine disinfection and breakpoint chlorination

Conspicuous amongst these halogenated compounds are the VHH of which chloroform ($CHCl_3$) is the most common and usually occurs in the highest concentrations. Chlorine disinfection produces substantially lower levels of VHH than does breakpoint chlorination, as is shown in Table 2.14.[68]

TABLE 2.14 EFFECT OF CHLORINATION ON THE OCCURRENCE OF SOME HALOGENATED COMPOUNDS IN TAP WATER (μg/ℓ)[68]

Parameters	Type of treatment with chlorine		
	None	Disinfection	Breakpoint chlorination
Number of supplies	13	4	3
Chloroform	<0,01—2,0	<0,1—10	25—60
Bromodichloromethane	<0,01—0,9	<0,01—10	15—55
Dibromochloromethane	<0,01—0,1	0,01—5	3—10
Dichloroiodomethane	<0,01	<0,01—0,3	0,01—10
Bromochloroiodomethane	<0,01	<0,01—0,03	<0,01—0,3
Bromoform	<0,01	<0,01—1,0	3,0—10
1,1-Dichloroacetone	<0,005	<0,005	0,1—0,1
Trichloronitromethane	<0,01	<0,01—3,0	<0,01—3,0

Treatment technique

Laying down comprehensive maximum concentration levels for individual compounds suspected of carcinogenic, mutagenic and teratogenic properties is proving to be a difficult, if not impossible, task. One means of evading this problem might be to prescribe a reliable treatment technique, if indeed such a technique exists.

The recent EPA (United States) regulations which stipulate the inclusion of activated carbon adsorption to reduce the VHH content of a potable water to less than 100 μg/ℓ reflects this thinking. There is much debate about these regulations, however, as activated carbon has a limited capacity for the VHH compounds — as is discussed in section 6.1.

Occurrence of VHH in South African waters

Table 2.15[69] indicates the increase in VHH concentrations in the fresh water supplies of the PWV complex in South Africa, with the increases shown being attributable to the chlorination stage at the conventional water treatment plants. The VHH content of both intake and reclaimed water at the Stander Plant are also shown for comparison.[69] It can be seen that apart from the Brits water, the total VHH contents are significantly lower than the EPA 100 μg/ℓ standard.

TABLE 2.15 THE OCCURRENCE OF VHH IN THE WATER OF THE PWV COMPLEX[69]
(AVERAGE CONCENTRATIONS, μg/ℓ)

Sampling point	Total VHH	Tetrachlorine methane CCl_4	Chloroform $CHCl_3$	Tetrachloro-ethylene C_2Cl_4	Bromodichloromethane $CHBrCl_2$	Dibromochloromethane $CHBr_2Cl$	Bromoform $CHBr_3$
Rietvlei Dam							
— Raw	1,0	0,1	0,5	0,1	0,01	<0,01	<0,01
— Treated	10,1	0,2	3,4	0,1	3,9	1,3	0,2
Hartbeespoort Dam							
— Raw	8,0	0,4	5,2	0,4	0,8	0,4	0,1
— Treated	34,1	0,8	12,3	0,3	13,5	6,0	0,4
Rand Water Board Brits							
— Raw	0,79	0,04	0,38	0,03	N.D.	N.D.	N.D.
— Treated	81,0	1,1	31,5	0,25	17,9	9,6	N.D.
Rand Water Board Brits							
— Raw	2,7	0,02	1,9	0,05	0,29	0,08	N.D.*
— Treated	16,4	0,3	5,6	0,3	5,5	3,1	0,4
Stander Plant							
— intake	2,1	0,03	0,8	0,5	0,1	0,04	N.D.
— Reclaimed water	6,9	0,3	4,1	0,5	0,8	0,6	0,4

*N.D. — Not Detected

Planning and process implications

The above discussions indicate that although the levels of VHH in fresh water supplies are below a proposed blanket standard, it is important that consideration be given to methods of reducing the formation of these compounds at both water purification and water reclamation plants. Methods to be considered in a potable water reclamation scheme are summarized below, and in certain instances are further discussed in other sections of the guide:

- Ensure that water is reclaimed from predominantly domestic sewage — refer to Part I, section 2.4.
- Ensure that the water to be chlorinated has a low VHH precursor content — refer section 6.1.
- Ensure that the unit processes upstream of the activated carbon stage are such that the formation of VHH is minimized — refer to section 6.1.
- Employ a disinfectant other than chlorine in the final disinfection stage prior to discharge to the supply system. The alternative should not only reduce VHH formation but it should also form a residual to prevent reinfection in the distribution network; chloramines[153] and chlorine dioxide[70] can be considered in this regard — refer section 7.2.

CHAPTER 7

THE FATE OF MICRO-ORGANISMS IN RECLAMATION PROCESSES

7.1 THE ROLE OF CHEMICAL TREATMENT IN THE REMOVAL OF MICRO-ORGANISMS

Turbidity

The removal of suspended matter from water intended for either industrial or domestic use is not only of aesthetic importance but also has an important functional significance. It has been shown that there is a correlation between removal of suspended matter, whether organic or inorganic, and other microparticles such as bacteria and viruses from water.[71] It is also relevant that suspended organic matter or flocculant inorganic particles can 'shield' micro-organisms from disinfectants. A significant degree of shielding is also achieved when the bacteria and viruses themselves are subjected to coagulation and flocculation.

Reliable instrumentation is available for the measurement of turbidity and as a result the turbidity parameter has found wide application as a quality parameter at a number of water reclamation plants. However, a low turbidity value does not mean that the effluent is devoid of suspended particles. As such the turbidity test can in no way be accepted as a bacterial and viral quality indicator but rather as a quality criterium to be achieved prior to the disinfection stage (refer to Part I, section 5.2).

Physical removal

Removal of microparticles which would include colloids, bacteria and viruses, signifies a physical phase separation whereas control of viability by disinfection does not entail removal. Effective and completely satisfactory physical removal of pathogens cannot be achieved by current processes of water purification.

Coagulation, flocculation and eventually phase separation are affected by the superficial physical-chemical characteristics of microparticles and not for instance by their internal structure. In the case of disinfection the opposite is true.

Coagulation is achieved by effective destabilization of a suspension whereby the zeta potential is neutralized. Thereafter the particles will no longer repulse each other. Under turbulent conditions coagulation is followed by flocculation whereby phase separation becomes feasible by means of processes such as sedimentation, filtration and flotation.

Although the efficiency of removal of micro-organisms by chemical water treatment attains a two order reduction, the initial number of organisms present in an activated sludge effluent is so high (e.g. coliforms numbering approximately $5 \times 10^4/100$ mℓ), and in many respects so difficult to flocculate effectively, that after such treatment relatively high numbers still remain in suspension. However, at this stage physical protection against disinfection has been largely removed and both bacteria and viruses are much more accessible and therefore vulnerable than before. In this way a situation can be brought about which facilitates effective disinfection to render a water free from pathogens.

7.2 THE EFFICACY OF DISINFECTION

Prerequisite

A prerequisite for the unrestricted reuse of reclaimed water, sometimes even if it is only for industrial or agricultural purposes, is an assurance that the water is wholesome, pure, of unblemished bacteriological and virological charácter and, last but not least, will reliably stay so, at all times. For the production of a potable water it is essential to inactivate all pathogens and to reduce the total plate count to below 100 per mℓ (refer to Part I, section 5.2).

Disinfection of water to render it free from pathogens should, in the context of water reclamation, not be considered in isolation. Today the world is very much aware of the dangers associated with the formation of byproducts such as VHH and other products of oxidation.

Disinfection must therefore produce the safest water with the minimum total risk.

Multiple barriers

One should not rely solely on the final disinfection stage to produce a water of the required bacterial and viral quality and cognisance must be taken of the removal attained through preceding unit operations to ensure that there are at least two barriers against the micro-organisms. For example the Stander Plant in one operational mode used at least four barriers against micro-organisms: lime treatment, quality equalization, breakpoint chlorination or ozonation and final chlorination.

Mechanism

The efficacy of a disinfectant relates to its oxidizing action. The 'vigour' of present day disinfectants varies considerably and in the case of chlorine, which can exist in many different forms when added to an effluent, the variation in vigour of the various forms results in a concomitant variation in its disinfection abilities.

Adding an oxidant to water to achieve disinfection becomes rather unproductive if that water contains reducing agents other than bacteria and viruses. It then becomes necessary to introduce sufficient oxidant to allow all the oxidation reactions to reach completion before a surplus is available for disinfection.

Whilst the removal of reducing agents has a direct bearing on the required dose of oxidant to effect disinfection, the removal of suspended solids, even if they do not exert a consumptive demand on the disinfectant, is also extremely important as these solids may shield pathogens from the action of the oxidized agent. Fortuitously therefore, the removal of the suspended matter and the reducing agents also results in significant removals of both bacteria and viruses, thereby enhancing the efficacy of the disinfection step.

Ozone

Ozone, O_3, is a highly reactive allotropic form of oxygen and has an electronegative oxidation potential which is exceeded only by that of fluorine. It is extremely versatile in its reactions with molecular organic groupings, to such an extent that many biologically intractable residues become amenable to biodegradation.[60] It therefore has an important role to play in water reclamation (see section 6.1). The introduction of ozone prior to the carbon columns at the Stander Water Reclamation Plant enabled the production of a reclaimed water containing a total organic carbon concentration of less than 1 mg/ℓ to be produced.[72]

Ozone destroys bacteria and viruses by means of rapid oxidation of the protein mass. This is presumably a catalytic oxidation process which has a very rapid effect and whereas disinfection by means of chlorine requires relatively long contact periods, disinfection by means of ozone is achieved in a matter of minutes and contact periods of 10 to 15 minutes have been shown to be adequate.[72]

The effect that water quality has on ozone disinfection is discussed in greater detail in the 'Manual for Water Renovation and Reclamation', Chapter 8, but it should be pointed out that because of its much higher oxidation-reduction potential (2,07 V) compared with that of free chlorine (1,45 V), ozone reacts more rapidly and with more compounds in a given water than does chlorine.[73]

Ozone is probably the best of all virucides. On the other hand, on a weight basis it is not as effective a bactericide as chlorine. This apparent anomaly can be ascribed to the short contact period during which bacterial destruction takes place — before the ozone applied is completely consumed. On the other hand as a virucide, the inactivation of poliomyelitis virus is effected in a clear water of high quality if a free residual ozone dose of 0,4 mg/ℓ is maintained for at least 3 min.[74abc]

Other evidence as to the effectiveness of ozone for various purposes is available and leaves no doubt as to its high reputation as a disinfectant.[75,76,77]

The most serious disadvantage of ozone is its inability to provide a persisting residual and as a result 'aftergrowths' are often formed unless post-disinfection is practised.

Chlorine

Chlorine is probably the most versatile of all the disinfectants. It plays an important role in the removal of iron and manganese and residual chlorine concentrations are easily controlled by dechlorination with sulphur dioxide.

Because of its contribution to the formation of chlorinated hydrocarbons, some of which may be carcinogenic, it has been suggested by some that chlorination should be abandoned. This may be a very premature conclusion as the largest share of objectionable chlorinated hydrocarbons in natural waters could easily come from industrial discharges and from natural runoff (i.e. from pesticide applications). Only a very small percentage of the total chlorine production is actually used for water and wastewater treatment and in the United States this only amounts to some 3 to 4%.[73]

Chlorine has little competition in its ability to control biological slime growths and another of its important attributes is the ability to maintain a biocidal residual over extended periods of time, thereby enabling high quality waters to be available at all times at the extremities of distribution systems.

The reader is reminded that reliance on chlorination alone for the production of a high quality effluent should be avoided. Chlorination is only effective when the following conditions apply,[78] and their implications in water reclamation are obvious:

- The degree of bacteriological pollution is moderate and reasonably uniform, and the bacteria to be destroyed are not shielded from the chlorine by being bedded in suspended solids or within the bodies of worms, for example.
- The turbidity and colour of the water do not exceed 5 — 10 JTU units.
- The content of iron or manganese (or both) in the water does not exceed 0.3 mg/ℓ.
- The chlorine demand of the water does not fluctuate so rapidly as to prevent proper adjustment of the chlorine dose.
- Taste and odour-producing substances are absent or do not interfere with the selection of adequate chlorine doses.
- There is a contact period of at least 15 min between the point of chlorination and the house connection of the consumer first supplied with water.

In instances where the distribution network covers a large area it is common practice to maintain the chlorine residual in the chloramine form — the so-called 'combined chlorine residual'.

Chloramines

Chloramines are formed through the action of chlorine on ammonia and they possess disinfecting properties, albeit to a lesser degree than that of free chlorine.

The Rand Water Board in South Africa practises free residual chlorination at its water treatment plants with the objective of achieving fast and proper disinfection and chloramination at its booster pump stations to maintain an acceptable bacteriological quality throughout the distribution network.[79]

The chloramination is achieved through introducing aqueous ammonium hydroxide into the water just upstream of a chlorine injection point.

The use of chloramines as the final disinfection step in a water reclamation plant could be considered, as not only is a disinfectant residual maintained but VHH compounds are not so readily formed.[73, 80]

Chlorine dioxide

Disinfection through the use of chlorine dioxide (ClO_2) is a relatively new development and one that is finding growing support, especially in Belgium where it is now used for pre-oxidation and post disinfection at a number of potable water treatment plants.[70]

Chlorine dioxide is particularly effective in removing phenols from waters and as a disinfectant it is superior to an equivalent concentration of free chlorine in waters with pH values in excess of 7,5.

Pure chlorine dioxide does not form VHH in a potable water supply and, indeed, pretreatment of a raw water by chlorine dioxide appears to destroy the precursors to the formation of these compounds.[70]

Post disinfection through the use of chlorine dioxide is based on rapid disinfection with the dioxide followed by maintained bactericidal action of the chlorite, which results from the reduction of the dioxide. However, care should be taken in this regard as the chlorite ion is reportedly toxic to infants.[80]

Other disinfectants

Other disinfectants such as ultraviolet irradiation, heat or gamma irradiation and chemicals such as bromine, bromide chloride, iodine, hydrogen peroxide etc. have been considered for disinfection. However, for reasons outlined in the 'Manual for Water Renovation and Reclamation', Chapter 7 and the literature,[73] these disinfectants are considered impractical for use at a water reclamation plant.

CHAPTER 8

THE REMOVAL OF METALS IN WATER RECLAMATION

The siting of industry in relation to a water reclamation scheme has been covered in Part 1, section 2.4, which recommends that industries that produce wastes that are prejudicial to the production of a reclaimed water of required quality, be so sited that their wastes receive separate treatment.

The above recommendation relates more to the synthetic chemical industry than to those industries that discharge significant quantities of heavy metals into the sewers. It is possible through careful in-house practice to reduce the metal concentrations in discharges to acceptable levels (refer to Part I, section 2.3). As, furthermore, there are unit operations capable of metal reduction at the reclamation plant, the aspect of acceptance into or diversion from the municipal sewers should be carefully analysed for each particular situation. Obviously where such metal discharges form a significant fraction of the total sewage flow, there would be merit in diverting the wastes discharged by the heaviest polluters.

This section is written to assist in the decision as to whether to accept or to divert, and it considers the efficacy of a number of unit operations commonly found in water reclamation plants in removing metals. In addition, the effect of metals on the biological treatment stage and the problem of sludge disposal are discussed.

8.1 REMOVAL OF METALS IN SEWER SYSTEMS

Experience in South Africa has indicated that sulphide generation in outfall sewers, due to excessive sewage retention periods, results in the formation of insoluble heavy metal sulphides which are precipitated from the flow in primary settling tanks.[81] Table 2.16 shows the reduction of heavy metals achieved through primary sedimentation at the Johannesburg Northern Sewage Works.[81]

The potential toxic effect of the accumulation of metals in anaerobic digesters (to which primary sludges are usually discharged) is largely counteracted by their reaction with the sulphide originating from the reduction of sulphates, but cognisance should be taken of the heavy metal concentration limits proposed by the Water Research Centre, U.K.[82]

TABLE 2.16 REDUCTION OF METALS BY PRIMARY SEDIMENTATION AT THE JOHANNESBURG NORTHERN SEWAGE WORKS, AVERAGE OF 7 SAMPLES[81]

	Cu	Cr	Ni	Mn	Pb	Fe
Screened sewage	0,10	0,12	0,16	0,11	0,06	2,20
After primary settling	0,04	0,05	0,09	0,07	0,03	0,84
% Reduction	60	58	44	36	50	62

8.2 EFFECT OF METALS ON BIOLOGICAL TREATMENT PROCESSES

Metals can disrupt the biological treatment of a sewage, resulting in the production of a substandard secondary effluent. Indications of metal inhibition are sudden cessation of nitrification and the formation of a stable pin-point floc that is carried over in the secondary clarifier effluent.[83]

Table 2.17 lists the threshold concentration of metals considered to be inhibitory to the activated sludge process.[84]

TABLE 2.17 THRESHOLD CONCENTRATIONS OF HEAVY METALS[84]

Metal	Concentration (mg/ℓ)	
	Carbonaceous removal	Nitrification
Arsenic	0,1	–
Boron	0,05 to 100	–
Cadmium	10 to 100	–
Chromium (VI)	1 to 10	0,25
Chromium (III)	50	–
Copper	1	0,005 to 0,05
Cyanide	0,5 to 5	0,34
Iron	1 000	–
Lead	0,1	0,5
Mercury	0,1 to 5,0	–
Nickel	1,0 to 2,5	0,25
Silver	5	–
Zinc	0,08 to 10	0,08 to 0,5

The Table indicates that in certain instances the threshold concentration shows wide variation. This may be attributed to the fact that the make up of the heterogeneous activated sludge culture can vary from plant to plant and as such will exhibit different inhibition patterns. In addition, activated sludge systems operating with long SRT values appear to be less readily inhibited than their short SRT counterparts.[85]

Total metal concentrations of 13 to 14 mg/ℓ in the Johannesburg raw sewages have had no ill-effect on the performance of the biofilter and activated sludge plants.[81] These values are in line with the results of a study conducted in the USA which indicated that total heavy metal concentrations of 10 mg/ℓ can be successfully accommodated by activated sludge plants.[86]

Experience in Pretoria, has indicated that attached growth reactors, such as biological filters and rotating disc units, are more prone to inhibition than the long SRT activated sludge system and that the heterotrophic organisms recovered more rapidly than the autotrophic nitrifiers.[8]

Biological treatment plants are capable of removing significant quantities of most metals, with nickel being least removed.[81,87,88] The poor removal of nickel would indicate that discharges containing this element should be carefully controlled.

8.3 REMOVAL OF METALS IN LIME TREATMENT

Lime treatment of a wastewater is purported to affect substantial metal reductions. Experience at the Stander plant has indicated that metals are indeed precipitated as their hydroxides but that removals are inhibited by the formation of complexes. Table 2.18 summarizes the results obtained and indicates that copper, when complexed with cyanide, was poorly removed.[89]

Lime treatment of oxidation pond effluent is practised in Israel with the purpose of producing a water suitable not only for irrigation but also for ultimate potable reuse. The results indicate that lime treatment reduces the heavy metal concentrations and that recarbonation of the lime treated effluent in shallow lagoons generally improves the overall removal. Table 2.19 summarizes the median concentrations of the metals at the various stages of treatment[90] and it is of interest to note that the metal concentrations complied with standards for drinking water promulgated by the World Health Organisation in 1971.[91]

The removal of heavy metals appears to be dependent upon the specific metal, the influent concentration of the metal, redox potential, pH, ionic strength of the carrier water and other operating and environmental factors.[34] It has been observed that as the influent metal concentration decreases so does the removal efficiency.

TABLE 2.19 MEDIAN CONCENTRATION OF METALS AT VARIOUS TREATMENT STAGES[90]

Metal	Median concentration, µg/ℓ		
	SE	HLE	TE
Cd	5	3	2
Cr	16	9	6
Zn	70	36	28
Ni	60	45	40
Pb	30	23	20
Cu	18	9	8
Fe	140	56	73
Mn	28	5	4

SE — Secondary effluent from oxidation ponds
HLE — High lime effluent, after high lime-magnesium treatment
TE — Tertiary effluent, after high lime-magnesium treatment and detention of the effluent in recarbonation ponds

A survey of six advanced water treatment plants in the USA indicated that selenium appeared to be the most persistent trace metal.[34]

8.4 REMOVAL OF METALS BY CARBON ADSORPTION AND ION EXCHANGE

Activated carbon

Activated carbon is generally adopted as a polishing or safeguard step for micro-organic compounds but it also has an affinity for certain metals such as chromium (VI), mercury, silver and cadmium.[92,93]

Activated carbon is seldom employed as the first line of defence against metals because breakthrough can occur rapidly if the metals are present in significant quantities and the spent carbon requires acid leaching to remove the adsorbed metals prior to regeneration. It

TABLE 2.18 REMOVAL OF HEAVY METALS[89]

Test No.	Element	Compound used used	Concentration in the influent (mg/ℓ)	Concentration in the clarified effluent (mg/ℓ)	Mean removal %
1	Cu	$Cu(Cl)_2$	2,2	1,8	18
	Zn	$ZnCl_2$	2,2	<0,025	100
	*CN	NaCN	3	3,0	0
2	Cu	$CuSO_4$	0,85	<0,025	100
	Zn	$ZnCl_2$	1,36	0,10	93
	Cd	$CdCl_2$	2,7	0,04	99
3	Pb	$Pb(NO_3)_2$	5 to 8	<0,025	100
	Hg	$HgCl_2$	19,0 µg/ℓ	2 µg/ℓ	89

*Shown although not a heavy metal

is rather positioned where its beneficial removal of trace quantities of metals can be fully exploited. For example, the activated carbon stage at the Stander plant is positioned near the end of the treatment train for the main purpose of micro-organic removal, but it also acts as a second barrier against heavy metals — lime treatment being the first.

Ion exchange

A combination of cation-anion exchangers has been successfully employed as a polishing step in the removal of heavy metals. The results indicated that metals such as silver, cadmium, chromium and selenium could be successfully removed.

8.5 OCCURRENCE OF HEAVY METALS IN SLUDGES

The heavy metals originally present in the sewage influent invariably end up in the sludge discharged from the plant. Heavy metal contents of sludges vary widely, being greatly dependent upon the quantity and nature of industrial wastes discharged into the sewers. Table 2.20 summarizes values reported for sludges derived from municipal sewage works in the Johannesburg area[94] as well as the U.K.[95]

It will be appreciated that chemical precipitation of heavy metals will result in sludges with higher metal contents than those shown in Table 2.20.

A common form of final sludge disposal is that of land treatment, either for crop production or as land fill (of strip mines for example). In such cases cognisance should be taken of the heavy metal content of the sludge and the potential toxic effects of excessive applications thereof. In this regard it is recommended that the application limits stipulated for the elements arsenic, boron, cadmium, chromium, copper, mercury, molybdenum, nickel, lead, selenium and zinc in the guidelines published by the Department of the Environment,[96] U.K. be initially adhered to.

TABLE 2.20 HEAVY METAL CONTENTS OF MUNICIPAL SLUDGES[94,95]
(all figures in mg/kg dry mass)

JOHANNESBURG WORKS (Annual Averages 1976/77)

	Northern works: Digested sludge	**Olifantsvlei**		**Klipspruit: Digested sludge**	**Alexandra: Waste activated sludge**	**United Kingdom**
		Digested sludge	**Waste activated sludge**			
Cadmium	60	50	40	20	120	7 — 50
Copper	600	500	380	890	480	100 — 1 000
Mercury	—	—	—	—	—	3 — 5
Nickel	240	470	440	470	500	50 — 1 000
Lead	1 580	390	270	470	800	200 — 700
Zinc	2 500	1 800	1 900	3 600	3 200	100 — 10 000
Iron	15 000	2 500	2 300	20 000	9 800	—
Manganese	310	1 600	1 240	840	240	—
Chromium	570	700	600	630	1 000	100 — 400
Cobalt	20	10	10	80	20	—
Silver	6	20	10	4	5	—
Aluminium	6 600	13 000	10 000	6 100	4 000	—
Potassium	2 500	2 600	4 600	5 200	4 500	—
Molybdenum	—	—	—	—	—	1 — 5
Boron	—	—	—	—	—	50 — 100
Selenium	—	—	—	—	—	1 — 5
Arsenic	—	—	—	—	—	6 — 8

CHAPTER 9

WATER STABILIZATION

The final step in a reclamation plant is usually concerned with stabilizing the water prior to its discharge to the distribution system.

9.1 THE IMPORTANCE OF WATER STABILIZATION

Discharge of an unstable water from the reclamation plant to the distribution system may result in a variety of serious problems. A water supersaturated w.r.t. calcium carbonate ($CaCO_3$) will precipitate this mineral resulting in a turbid water, deposits and/or scale.

Turbid water is undesirable from a health point of view, since the turbidity may act as a carrier for microbial life. Deposits and scale may cause blockages in pipes, which could result in considerable expense. Deposits further encourage pitting corrosion resulting in reduced pipeline life and unexpected failure.

Discharge of a water undersaturated w.r.t. $CaCO_3$, on the other hand, will result in enhanced corrosion with similar effects as those described above.

The importance of stabilization is to a large degree governed by the chemical make-up of the feed water to the reclamation plant. Soft and low alkalinity waters, hard and high alkalinity waters and those waters high in chlorides and sulphates but low in alkalinity require particular attention.

9.2 CRITERIA FOR WATER STABILITY

Parameters with which the corrosive or scale forming nature of an effluent may be gauged include the Langelier Index, the Ryznar Stability Index and the Corrosivity Ratio, all of which are detailed in the 'Manual for Water Renovation and Reclamation', Chapter 12.

Water stabilization generally involves adjusting pH, alkalinity, Ca^{2+} and Mg^{2+} to values which will minimize the possibility of corrosion occurring in the pipelines and providing a water not too hard for the intended form of reuse and one which will not quickly encrust warm water fittings. A usual requirement is that the treated water be saturated or slightly oversaturated with respect to calcium carbonate ($CaCO_3$) and that the Ca^{2+} concentration not be too high.

9.3 THE STABILIZATION OF TREATED EFFLUENTS

Chemicals usually used to stabilize effluents include lime, carbon dioxide, sodium hydroxide, sodium carbonate and acids such as sulphuric or hydrochloric.

Stabilization involves the adjustment of pH, alkalinity and/or calcium hardness, such that the combination of these parameters in the treated effluent renders the water stable with respect to $CaCO_3$.

Chemical dosages to achieve stability may be assessed by the method proposed by Loewenthal and Marais[25] and which is outlined in the 'Manual for Water Renovation and Reclamation', Chapter 12.

CHAPTER 10

NUTRIENT REMOVAL IN WATER RECLAMATION

The removal of nitrogen and phosphorus is of particular importance in water reclamation for reasons of health effects of nitrates, adverse effect of ammonia on final chlorination costs and the prevention of algal growths in storage impoundments.

This section discusses the biological and chemical methods that are available for the removal of these elements as well as referring the reader to certain publications for further details.

10.1 THE REMOVAL OF NITROGEN

Nitrogen may be removed from a wastewater by biological nitrification/denitrification, breakpoint chlorination, ammonia stripping or ion exchange. These systems are all adequately described in the literature[11,97,98,99,100,101,102,103] and only the salient points of each method are discussed below.

Biological nitrogen removal

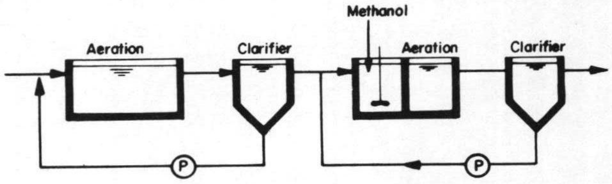
Biological removal of nitrogen incorporates the nitrification (the oxidation of free and saline ammonia to nitrite and nitrate) and denitrification (the reduction of nitrite and nitrate to nitrogen gas) phenomena.

Nitrification has long been a requirement of sewage works in South Africa and as such most process designers are aware of the factors that effect the nitrification kinetics, such as the activated sludge solids retention time (SRT), pH, level of dissolved oxygen and the presence of toxic substances.[104,105] Although denitrification is not at present a requirement of sewage works design, it has already been incorporated in a number of sewage works in South Africa, both in certain catchment basins for reasons of eutrophication control and on the coast for reasons of alkalinity correction.

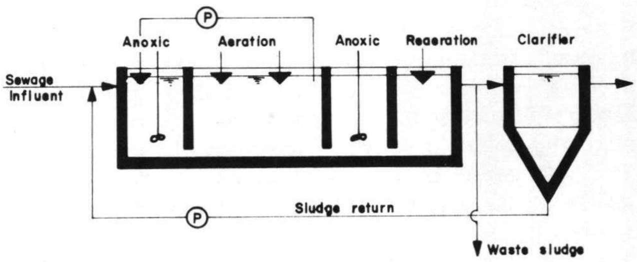
Denitrification is achieved by contacting a nitrified effluent with activated sludge in an environment devoid of dissolved oxygen and into which a carbon source is introduced. In such conditions, the organisms utilize the 'bound' oxygen (that in the nitrite and nitate) to assist in their synthesis of the carbon 'food' source.

The carbon source may be raw or settled sewage[11] or a non-nitrogenous chemical such as methanol, ethanol or acetate[106] and Figure 2.18 indicates typical process configurations that can be employed to achieve biological nitrogen removal.

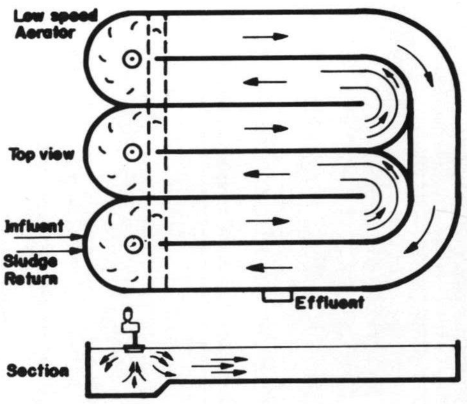
The two sludge system (Figure 2.18(a)) utilizes an external carbon source for denitrification which will increase the overall operating costs appreciably. Although Figure 2.18(a) shows the denitrification stage as being of the suspended media form it can also be of



(a) Two sludge system employing an external, non-nitrogenous chemical carbon source.



(b) Single sludge system employing an internal carbon source — The Bardenpho system.



(c) Single sludge system employing an internal carbon source — The Carrousel system, typical of all channel systems.

FIGURE 2.18: Process configurations employed for biological nitrogen removal

the fixed media form such as anaerobic filters[99] or submerged rotating biological contactors.[107]

The two and three sludge systems* are easy to operate and control but suffer from high chemical costs and the necessity to oxidize residual methanol prior to discharge.

The Bardenpho system (Figure 2.18(b) developed in South Africa, makes use of the carbon present in the raw or settled sewage to achieve denitrification. The process involves a single sludge system, i.e. there is no intermediate clarifier as in the two sludge system (Figure 2.18(a)) and the recycling of nitrified mixed liquor at high rates back to the primary anoxic zone in which the bulk of the denitrification occurs.[11] An inherent advantage of this process is that the carbonaceous load to the aeration zone is reduced (by the requirements for denitrification) with the result that the energy requirements of the system are also reduced.

The Carrousel[97] (Figure 2.18(c)), the Pasveer Ditch and the Huisman Orbal systems are essentially channel-type activated sludge plants whose aeration devices not only introduce oxygen into the liquor but also propel the liquor around the channels. As the oxygen level in the liquor can decrease to very low levels between the points of aeration, zones are created in which denitrification occurs, with the degree of denitrification being dependent upon the extent of these 'anoxic' zones — not an easy factor to control.

A survey of plants of the channel-type that remove nitrogen, concludes that the degree of nitrogen removal can vary greatly, being dependent not only on the pollution load arriving at the plant but also on the diurnal variations of the load.[108] Removals of 50 — 90% with an average of 65% have been reported,[108] whereas the two sludge and the Bardenpho systems are capable of achieving nitrogen removals of 85 — 90%.[11]

Whereas the total nitrogen is minimized by striking a balance between ammonia and nitrate nitrogen in channel systems, the Bardenpho system can be controlled to produce a consistently low ammonia nitrogen concentration coupled with a variable nitrate concentration. For water reclamation, a low ammonia concentration has the advantage that breakpoint chlorination can be achieved at a low dosage of chlorine.

Breakpoint chlorination

Breakpoint chlorination of a wastewater will oxidize ammonia to nitrogen gas but with chlorine dosages of 8 — 10 mg per mg of ammonia (as N). This high dosage would indicate that breakpoint chlorination of an untreated sewage would be economically prohibitive and that only when used as a 'polishing' step for low ammonia concentrations (as practiced at the Stander Plant, Pretoria[101]) could this process perhaps become economically feasible.

In addition to the above cost factors, cognisance must also be taken of the inherent disadvantages of breakpoint chlorination, such as the formation of VHH, the increase in dissolved solids and the necessity for alkalinity correction (refer to section 3.5).

Ammonia stripping

The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 4 for details of the experience gained from stripping towers installed at the Windhoek and Stander Plants.

Ammonia stripping in essence involves raising the pH of the wastewater to values greater than 11,0, whereupon the ammonia is in the free molecular form and can be transferred from the liquid to the gas phase through contacting the liquid with large quantities of air in a correctly designed stripping tower.

The process has a number of failings however, of which the following are perhaps the most important:

- The stripping process is very temperature dependent, becoming less efficient as the temperature decreases.

- The large volumes of air passing through the tower result in a cooling effect which reduces the stripping efficiency.

- The high pH of the wastewater together with the carbon dioxide in the air result in the formation of a calcium carbonate 'scale' on the tower packing media. This scale reduces the stripping efficiency through causing liquid short circuiting and must thus be periodically removed — a high maintenance cost and a temporary termination of ammonia removal.

- Effluent ammonia levels vary between 1 and 7 mg/ℓ as N[100] (as opposed to the trace values discharged from the biological nitrogen removal processes). This ammonia residual can only be efficiently removed through breakpoint chlorination.

- Ammonia stripping of a lime treated raw wastewater should not be considered, as the organic nitrogen fraction will not be removed, whereas in the biological system this component is hydrolysed to ammonia which is then removed in the nitrification/ denitrification stage.

- The ammonia concentration in a wastewater changes throughout the day and the effluent from a stripping tower will show a similar variation. In order to reduce this effluent variation, an equalization basin has been positioned ahead of the stripping tower at the Stander Plant.[100,109]

Ammonia removal from ponds

Ammonia may also be removed from high pH waters by means of stirred lagoons or ponds and the reader is referred to the "Manual for Water Renovation and Reclamation", Chapter 3, as well as the literature[110,111] for further discussion on this subject.

Ammonia removal by ion exchange

Ammonia may be removed from a wastewater through ion exchange using the natural zeolite Clinoptilolite.[99]

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*The three sludge system has separate carbonaceous removal and nitrification stages.

The process requires an influent pH of 4 to 8 and the columns are regenerated by a brine solution from which the ammonia is stripped at high pH by means of steam.

This process has not found wide application and suffers from high capital and operating costs.[99,102]

General discussion

Nitrogen can exist in more than one form in a wastewater and it is therefore essential that the process selected for optimum nitrogen removal (while also being cost effective) be able to 'manage' these different forms.

Physico-chemical methods are only able to remove inorganic nitrogen whereas the biological nitrification/denitrification system is able to convert both the inorganic nitrogen and most of the organic nitrogen to one predominant species (nitrates) and then to remove it (denitrification). The biological system can therefore be expected to offer a greater overall nitrogen removal.

The biological system can be designed and operated to produce an effluent so low in ammonia that breakpoint chlorination (for purposes of disinfection) can be achieved at chlorine doses as low as 5 mg/ℓ, as opposed to values as high as 50 mg/ℓ for effluents from ammonia stripping towers.

Operational characteristics of biological processes are simpler and less dynamic than the operation of the physico-chemical processes and this leads to less maintenance requirements and more reliable, stable results.[112]

10.2 THE REMOVAL OF PHOSPHORUS

Phosphorus may be removed from a wastewater by either biological, chemical or combined biological-chemical means.

Traditionally, phosphorus was removed by the addition of chemicals after the biological plant. However, although this method is effective, one now has the further option of incorporating biological phosphorus removal into the activated sludge process.

Biological phosphorus removal may seem unnecessary in those instances where the secondary effluents are chemically coagulated, as in the production of cooling, general industrial and potable water. However, by incorporating the biological removal step, one can possibly achieve reduced chemical doses.[113] In addition the secondary effluents themselves may be safely discharged into water bodies in the event of the advanced treatment plant being shut down for maintenance and repair.

The low phosphorus level required in many reclaimed waters can thus be achieved by a combination of biological and chemical methods or by purely chemical means.

The former is less costly[114] and, in fact, it can be incorporated at little extra cost into the biological nitrogen removal process that is required for reclamation. The biological nitrogen and phosphorus removal process will of necessity employ a long SRT, and by so doing produce an effluent that is low not only in carbonaceous content (in terms of say the COD) but also in low molecular mass carbonaceous material. This aspect is of great significance in the case of subsequent treatment by activated carbon, as is discussed in sections 5.2 and 6.1.

Biological Phosphorus Removal

A portion (some 15 — 35%) of the phosphorus present in a wastewater is removed for organism growth purposes by the biological filtration and conventional activated sludge processes. However, a substantially improved phosphorus removal can be achieved by a modification to the activated sludge process and this enhanced removal, without the addition of chemicals, has been shown to be mainly biological, in that the phosphorus is incorporated into the micro-organisms' cells, although a small proportion is chemically removed in the form of calcium precipitates.[115]

The biological removal entails inducing the micro-organisms, through manipulating the activated sludge process, to incorporate phosphorus, in the form of polyphosphate, into their cells at rates far in excess of that required for normal growth.

The reader is referred to the literature for further details of the biological phosphorus removal process.[108,114,115,116,117] Suffice it to say at this stage that although the actual mechanism of uptake is not clear, it may be concluded that a prerequisite for biological P removal is that the sludge or mixed liquor must pass through a stage of anaerobiosis prior to an aerobic stage. The term anaerobiosis must be seen in the context of a fermentation pathway as opposed to anaerobic respiration (as occurs in the anoxic zones of the nitrification/denitrification system).

The implication of the above is that nitrates formed in the process must be removed to less than 5 mg/ℓ (as N), as higher values could well result in nitrates being returned to the anaerobic (or fermentation) zone where the bound oxygen will prevent the initiation of the fermentation process required for phosphorus removal to commence.

The previous section has indicated that the most reliable method of nitrogen removal is through biological nitrification and denitrification, employing either internal or external carbon sources. Figure 2.19 shows the configuration of a plant designed for both

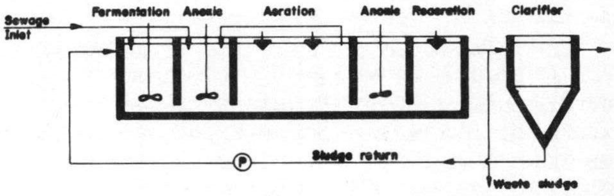


FIGURE 2.19: **Single sludge activated sludge plant for biological N and P removal**

biological nitrogen and phosphorus removal, using an internal carbon source; a number of such plants are either under construction or operational in South Africa.

Biological phosphorus removal has been shown to be unaffected at mixed liquor temperatures of between 30 and 6°C.[114]

There is a possibility that at temperatures approaching 6°C the volume of fermentation zone required for phosphorus removal can adversely affect the nitrification step of the nitrification/denitrification process. As the alternative forms of nitrogen removal are either costly or unreliable, preference may therefore be given to chemical phosphorus removal under such circumstances so that the nitrogen removal step may be optimized. A study should therefore be made of prevailing sewage temperatures and other relevant factors so as to enable the most economical method of combining nitrogen and phosphorus removal to be ascertained.

In the event of an alternative form of nitrogen removal, such as ion exchange or breakpoint chlorination, being selected, biological phosphorus removal could be incorporated into the low SRT (high rate) activated sludge system that would invariably precede the nitrogen removal step. Similarly, the biological phosphorus removal step could be incorporated into the first stage of the two and three sludge systems (refer to the previous section).

The biological removal of phosphorus from normal domestic sewages will generally produce effluents with P concentrations of 1 — 2 mg/ℓ as opposed to values as low as 0,1 mg/ℓ in effluents discharged from combined biological-chemical phosphorus removal systems.

Chemical Phosphorus removal

The removal of phosphorus through chemical precipitation is practised in many parts of the world today. Chemicals such as lime and the mineral salts (alum, sodium aluminate, ferrous sulphate, ferric chloride and sulphate) have all found wide use in this respect.

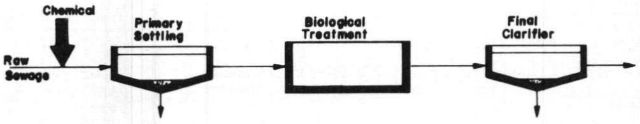
The use of these chemicals in water reclamation is discussed in chapter 3 and systems for their handling and dosing are discussed in Part III, section 3.

The addition of chemicals to a raw sewage and to a biological system will give rise to an increased mass and volume of sludge to be disposed of. Typical sludge production figures together with dewatering properties are discussed briefly in chapter 3 and in more detail in chapter 12.

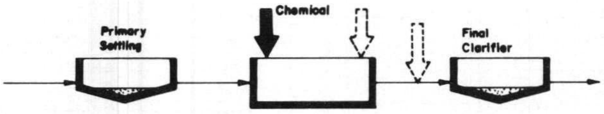
The chemicals can be added at various stages in the overall treatment process, as shown in Figure 2.20, albeit with differing results as regards phosphorus removal.

The reader is referred to the literature for further discussion on the merits and demerits of the various dosing positions[16,23,108,118,119] and a few of the salient points relating to each of the positions are presented below:

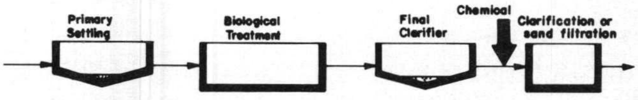
- The degree of P removal achieved by pre-precipitation is limited by the fact that a significant portion of the influent phosphorus is in the organic and polyphosphate form, with such forms not being readily precipitated.[119]



Pre-precipitation



Simultaneous precipitation



Post-precipitation

FIGURE 2.20: Possible positions of chemical addition for phosphorus precipitation

- The point of chemical addition to the biological unit is dependent upon the chemical added and should be carefully ascertained.[119]

- Mineral salt addition to an activated sludge plant has been shown to adversely affect the higher forms of life (protozoa etc.) but not the effluent quality.[119,120,121,122]

- Simultaneous precipitation will generally yield an average P residual of 0,5 mg/ℓ at molar ratios, i.e. moles of cation (Al^{3+}, Fe^{3+}, Fe^{2+}) to moles of phosphorus (as P), of 2 — 3.[119]

- Ferric iron is less effective than aluminium, therefore requiring a higher Fe^{3+}: P mole ratio for the same effluent P concentration.[119]

- Post-precipitation appears to produce the lowest P residuals, being less than 0,5 mg/ℓ.

'Contact filtration', a form of post-precipitation, incorporates the addition of a mineral salt (usually alum or ferric chloride) and a polyelectrolyte to the secondary

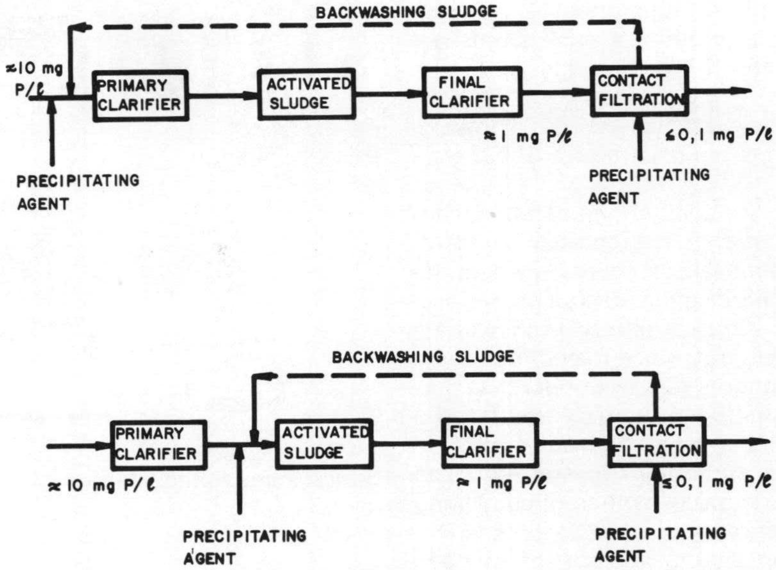


FIGURE 2.21: A combination of contact filtration with pre- and simultaneous phosphorus precipitation.

effluent, just upstream of a dual or multi-media filter. Figure 2.21 shows two overall plant configurations investigated in Switzerland, where effluent phosphorus residuals of less than 0,1 mg/ℓ were consistently achieved.[123,124]

Post-precipitation is generally only used in those specific instances where phosphorus residuals of less than 0,5 mg/ℓ P are required, whereas simultaneous precipitation would be used where effluent phosphorus levels of less than 1,0 mg/ℓ P would be acceptable.

Simultaneous precipitation from a biological filter effluent (i.e. chemical dosing point between the filter and the humus tank) should produce an effluent phosphorus residual of less than 1,0 mg/ℓ P at a mineral salt cation to phosphorus (as P) mole ratio of 1,5 — 2,0 to 1,0.[122] However, when used in conjunction with an activated sludge plant that incorporates biological N and P removal, a similar phosphorus residual should be produced at an approximate stoichiometric chemical dose.[125]

Alternative Phosphorus Removal Processes

There are alternative processes available for the removal of phosphates from wastewaters, and perhaps the best known is the 'Phostrip process', which is shown in Figure 2.22.

The reader is referred to the literature for further details of the process as well as full scale plant results.[126,127,128]

The 'Phostrip' process, as patented, does not include biological nitrogen removal, but experiments conducted in South Africa have indicated that the inclusion of a biological nitrification and denitrification step in the process does not interfere with its ability to remove phosphorus.[129]

The modified LFB process, an integrated biological-chemical process developed in South Africa, utilizes ferric chloride to precipitate phosphorus. The reader is referred to the literature[13] and to Part VI for further details of this process.

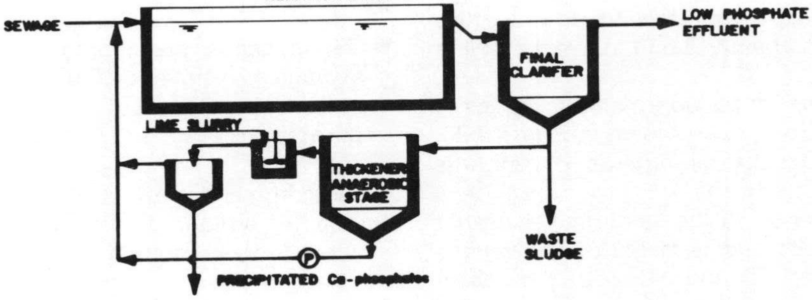


FIGURE 2.22: The Phostrip process

CHAPTER 11

THE PROSPECTIVE USE OF MEMBRANES AND ION-EXCHANGE PROCESSES IN WATER RECLAMATION

The total dissolved solids (TDS) of a sewage is primarily dependent upon the characteristics of the fresh water supply. In addition, salt water infiltration into sewers laid in coastal areas can greatly add to the mineral content of the wastewater flow arriving at the biological and advanced treatment plants.

As the TDS content of a water increases by 300 to 400 mg/ℓ for each cycle of domestic use, the quality of water reclaimed from the resulting sewage, in terms of TDS, may not be suitable for the intended form of reuse.

Demineralization processes have been developed whereby the TDS of a reclaimed water may be reduced to acceptable standards. Such processes include reverse osmosis, ultrafiltration, electrodialysis and ion-exchange.

A classification of the three membrane processes, namely reverse osmosis, ultrafiltration and electrodialysis, according to their type of driving potential and their general behaviour with respect to a municipal secondary sewage effluent is presented in Table 2.21.

11.1 REVERSE OSMOSIS

Reverse osmosis makes use of a selectively permeable membrane across the surface of which flows the polluted water stream at a pressure of between 2 000 and 6 000 kPa. The demineralized water (or permeate) passes through the membrane while the concentrate is retained by the membrane and discharged by a separate route. Figure 2.23 shows a typical schematic of a reverse osmosis system.

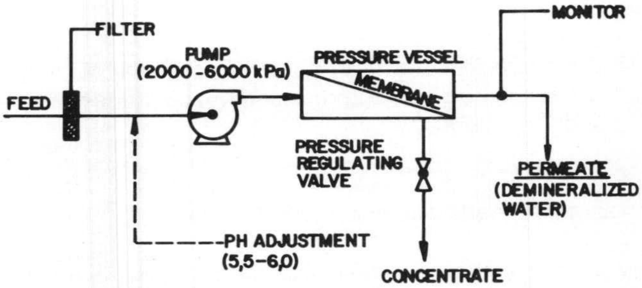


FIG. 2.23: Schematic of a reverse osmosis system

Reverse osmosis is capable of removing more than 90% of inorganic salts and organic solutes having molecular masses of greater than 150 – 200. Oxidized nitrogen and certain phenolic compounds are less well removed, whereas suspended and colloidal matter, bacteria and viruses are practically completely removed.[131]

TABLE 2.21 CLASSIFICATION OF MEMBRANE PROCESSES

Process	Driving potential	Constituents removed from wastewater	Constituents remaining in product (besides water)	Possible size ranges of permeable species (A°)
Reverse osmosis	Pressure (high ~ 4 000 kPa)	Dissolved and non-dissolved inorganic and organic constituents	Little salt (due to membrane leakage (BO_3^-, NO_3^-, urea, low molecular mass organics	4 – 300
Ultrafiltration	Pressure (low ~ 1 000 kPa)	Dissolved and non-dissolved organic constituents	All the salt and low molecular mass organics	300 – 10^5
Electrodialysis	Electrical	Dissolved inorganics	Little salt, all the organics (dissolved and non-dissolved) including viruses, bacteria, etc.	4 – 300

Note: Data abstracted from Table 1 of Reference 130

Solute rejection trends observed from experimental results may be summarized as follows:[132]

- Multivalent ions are rejected more effectively than univalent ions.
- Undissociated or partially dissociated substances are poorly rejected.
- Acids and bases are rejected to a lesser extent than their salts.
- Co-ions affect the rejection of a particular ion (e.g. sodium is better rejected as sodium sulphate than as sodium chloride).
- In general, low molecular mass, water soluble organic molecules are poorly rejected.
- Undissociated low molecular mass organic acids are poorly rejected, while their salts are well rejected.
- Trace quantities of univalent ions are in general poorly rejected.

Dissolved gases, such as chlorine, oxygen, carbon dioxide, hydrogen sulphide, and sulphur dioxide are poorly rejected as gases. If they react with water, their neutralized salts are rejected — for example, sodium bicarbonate and sodium sulphite. Free chlorine, present as the hypochlorite ion, OCl^-, is rejected above pH 7 but is poorly rejected below that pH as the equilibrium distribution shifts toward HOCl.

Water recovery (i.e. permeate volume as a percentage of feed water volume) usually varies from 50 — 85%.[131]

The recovery obtained is influenced by the type of membrane in use, the feed water quality, the working pressure and the temperature of the feed water. Both the quality and quantity of the purified water rise with the working pressure. As temperature rises the viscosity of water decreases, and its coefficient of diffusion through the membrane rises. Permeate flows are defined at 25° C and they increase by about 3% for each degree above 25°C, and decrease by 2,8 to 3% for each degree below 25° C. The quality of the purified water is little affected by the temperature.[133]

Membrane Types

Modified cellulose acetate is presently the most widely used reverse osmosis (RO) membrane, although it does have the drawback of a limited operating pH range (3,5 to 7,5) and susceptibility to biological attack.

Membranes of polyamide and polysulphone construction are rapidly gaining popularity through their higher flux capabilities, greater resistance to chemical and biological degradation, wider operating temperature tolerances and wider operating pH range (3 to 11).

Polyamide membranes have the major drawback in that they are readily degraded by free chlorine residuals.[130,134] This drawback is of great significance as disinfection to the free chlorine stage is frequently employed upstream of an RO unit in order to reduce or prevent biological growths forming on the membranes.

Some materials frequently present in wastewaters are poorly rejected by both cellulose acetate and polyamide membranes. These include phenols, aldehydes, urea, methanol and methyl acetate.[130]

Membrane support systems (Permeators)

The membrane support system is of great importance to the performance of an RO unit in that it must give adequate mechanical support to the membrane whilst providing suitable hydrodynamic conditions for the process water to reach and be collected from the membrane surface.

Several membrane support systems are commercially available, such as tubular, spiral wrap, hollow fine fibre, flat plate and dynamic.[130,132]

Flux decline

'Flux' is a term used to express the water permeation rate through a membrane and usually has the units of $m^3m^{-2}d^{-1}$ ($m\ d^{-1}$).

The most serious problem encountered in the application of RO to wastewaters is that of membrane fouling which leads to flux decline. The fouling usually takes the form of a gel layer which collects at the surface of the membrane, generally attributable to organic and inorganic precipitates, organic interaction with the membrane and/or deposition of suspended particulates.

Flux decline due to membrane compaction is a well-known phenomenon but in general the flux decline rates for secondary sewage effluents are at least five times greater than the decline due to membrane compaction under non-fouling conditions.[135]

Several approaches have been adopted in attempts to reduce the flux decline rate in RO systems treating secondary sewage effluents.

These approaches may be sub-divided as follows:

- Prevention of fouling: by additions to the feed, pretreatment of feed or increased turbulence in the feed flow.
- Removal of the deposit: by flushing with chemicals, use of foam swabs or high velocity flushing.

High turbulence (i.e. Reynolds number of greater than 5 000) across the surface of the membrane and acid addition to the feed water to control the pH in order to prevent membrane hydrolysis (in the case of cellulose acetate membranes only) have proved fairly effective in the prevention of fouling. Other feed additions such as sodium hexametaphosphate to prevent scaling or sodium silicate to disperse the 'gel' have not proved particularly effective.[136]

The three methods listed under 'removal of deposit' have all proved to be effective. Care must however be taken with the foam swab method to ensure that no abrasive material is present during the swabbing operation.

The degree of pretreatment afforded to a sewage

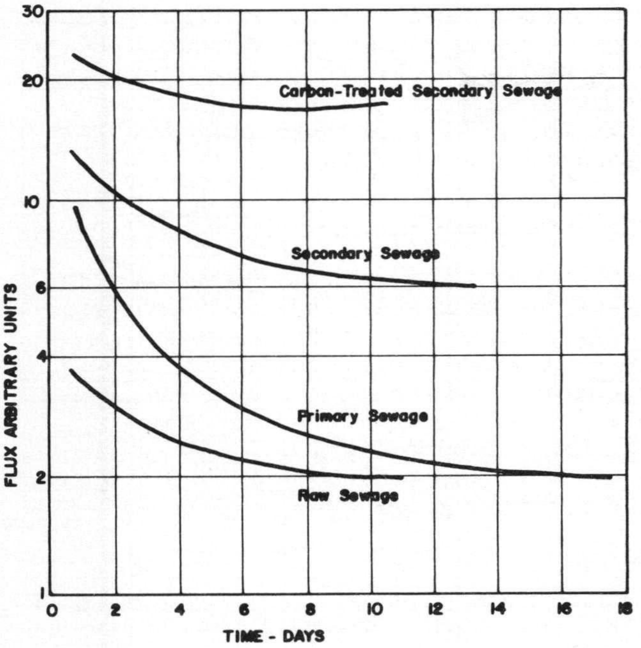


FIGURE 2.24: Flux decline on sewage effluents[135]

clearly influences the initial attainable flux as well as the flux decline rate. The effect of degree of pretreatment on the flux decline rate is shown in figure 2.24.[135]

The flux decline rates obtained with sand-filtered secondary effluent and with sand-filtered plus activated carbon treated secondary effluent have been compared for tubular RO units and it was found that after 160 days of operation there was no significant difference between the two, the fluxes generally being in the range of 0,4 to 0,5 $m^3m^{-2}d^{-1}$.[136] Sand filtration of a well treated secondary effluent prior to RO treatment would therefore appear sufficient pretreatment for a secondary effluent when a tubular type RO unit is used.

Research work in general has shown that using membranes capable of high selectivity (i.e. high rejection characteristics) reduces occurrence of surface fouling, although such membranes will operate at a lower flux than the less selective counterpart.[137] Intermittent flushing with detergent results in fluxes of 0,3 to 0,6 $m^3m^{-2}d^{-1}$ being maintained over long periods of time when secondary and tertiary sewage effluents are passed through an RO unit.[135]

TABLE 2.22 RESULTS OF RO INSTALLATIONS IN SOUTH AFRICA[131]

	Pretoria	Cape Town
Configuration	**Spiral**	**Rod**
Pretreatment	**Sand filtered**	**Sand filtered**
Test period (days)	25	17
Pressure (kPa)	2 965	4 000
Recovery (%)	75	80
Rejection (%)		
– COD	> 89	> 90
– Conductivity	95	94
– Sulphate	> 99	> 95
– Chloride	94	96
– $Ca^{++} + Mg^{2+}$	> 97	> 95

Typical results

Table 2.22 summarizes results obtained at RO installations at Pretoria and Cape Town.[131] The rejections shown compare favourably with those reported elsewhere for the treatment of a sand filtered secondary effluent.[130]

Concentrates

The disposal of the concentrate resulting from the RO process is a factor that is seldom discussed or even included in the economics of the scheme.

The concentrate which contains the material that does not pass through the membrane usually has a volume of 15 to 50% of the feed flow and it is therefore imperative that a form of effective concentrate disposal be carefully investigated prior to commencement with the overall RO scheme.

The concentrate may well be discharged to the sea at coastal or estuarine installations whereas disposal at in-land installations may take one of the following forms:

- Recirculation of the concentrate back to an earlier point in the overall treatment cycle. This possibility obviously depends upon the percentage of effluent to be subjected to RO treatment as there is a limit to which recirculated flows can be absorbed in a treatment process without treated water quality deterioration occurring. This limit should be carefully evaluated.

- Subject the concentrate to a form of treatment in order to reduce the organic and colloidal content.

- Dispose of the concentrate as it is. Little work has been published on this form of concentrate disposal, apart from discharge to the sea. However, the use of mechanical evaporators followed by evaporation ponds or injection into geological formations could receive consideration.

11.2 ULTRAFILTRATION

Ultrafiltration is very similar to Reverse Osmosis, differing only in the operating pressure of less than 1 000 kPa and the use of a more 'open' form of membrane. As a result of the 'open' membrane, most inorganic salts are poorly rejected whereas colloidal and other species with molecular mass of greater than 1 000 are well rejected. As with RO, bacteria and viruses are completely rejected.

The ultrafiltration (UF) membrane support structures or permeators, together with their associated operational characteristics, are similar to those for RO.

On account of the fact that in UF the bulk of the material retained by the membrane is of the macromolecular mass form, problems with concentration polarization may be experienced, leading to an abnormally high rate of flux decline. Concentration polarization in UF is minimized by operating at high feed velocities parallel to the membrane surface and by utilizing thin channel designs.

Membranes

A variety of synthetic polymers, such as polycarbonate resins, substituted olefins and polyelectrolyte complexes have been employed for UF membranes. Many of those membranes can be handled dry and used with a variety of organic solvents. Temperature and pH resistance are often superior to those of conventional cellulose acetate membranes.[132]

Results

A hollow fibre UF unit has been operated with sand-filtered secondary effluent at Daspoort, Pretoria. The membranes were of polysulphane construction and Figure 2.25 shows the variation of COD and permeate flux over a 100 h operating period.[131]

Ultrafiltration has found applications in wastewater treatment as a substitute for thickeners, clarifiers and flocculation.[132,135] In addition, it is considered that in instances where desalination is not a prerequisite UF could well find application as a final polishing stage.

11.3 **ELECTRODIALYSIS**

In electrodialysis an electric current induces partial separation of the components in ionic solution. The separation is accomplished by alternately placing cation and anion selective membranes across the current path. When current is applied, the electrically attracted cations pass through the cation exchanger membrane (anion selective membrane) in one direction, and the anions pass through the anion exchanger membrane (cation selective membrane) in the other direction. The net result is that in alternative spaces between the membranes, salinity decreases in one space and increases in the next, throughout the stack of parallel membranes. Water can then be passed through several such stacks until the desired salinity reduction is accomplished.

Electrodialysis would be expected to remove salts only and thus leave the concentrations of the majority of soluble organic species unaltered. The various inorganic ions are removed to different extents depending on the types of membranes being used and the solution composition. The reported results indicate that the best removals were for calcium and chloride and the worst for sodium and phosphate. Nitrate and ammonium are among the better removed ions.[135]

Membranes

Electrodialysis membranes are manufactured from synthetic polymers. They have the ability to discriminate between oppositely charged ions, they have a low water transport number and in addition are reasonably effective electrical conductors.

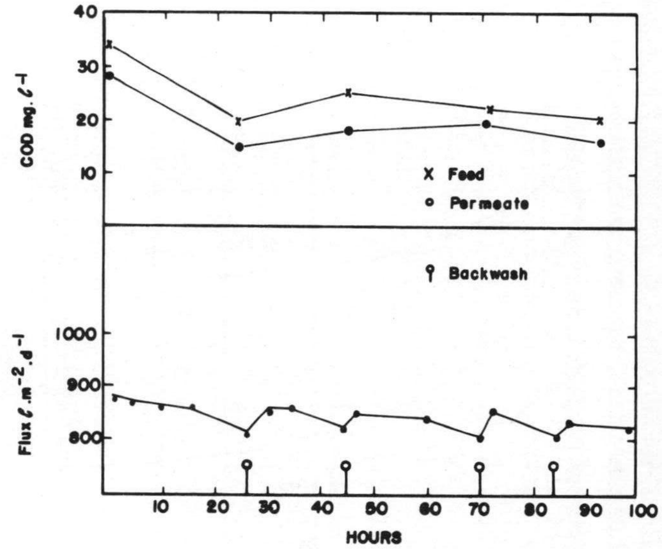


FIGURE 2.25: Performance of UF unit at Daspoort, Pretoria.[131]

Membrane fouling

Membrane fouling does occur, as in RO and UF, but it can be controlled by frequent cleaning in conjunction with ensuring that the feed water is of a reasonable quality. A filtration stage upstream of the electrodialysis stack is normally a prerequisite of the scheme.

As with most chemical processes, electrodialysis demineralization processing is either continuous or batch. Power requirements for each mode of operation vary but are generally in the range 0,75 to 2,2 kW.h m^{-3} product water.[132]

Application

Desalination of brackish water (TDS less than 10 000 mg/ℓ) is the principal use of electrodialysis and many plants have been constructed and are now operating throughout the world.

Research is being undertaken into the demineralization of secondary sewage effluent while electrodialysis has also been investigated as a method of denitrifying agricultural runoff waters.[132]

11.4 **ION EXCHANGE**

The ion exchange process has found extensive use in high-pressure boiler feed water systems, in water softening, industrial waste treatment (for example the recovery of hexavalent chrome from plating wastes) and municipal wastewater treatment.

Nearly all cation exchangers used in water and waste treatment operations are strongly acidic, that is, they contain strongly ionized groups and are thus capable of exchanging all cations. However, two forms of anion exchanger have found application; the strong and weakly basic forms. Strongly basic anion resins are capable of exchanging all anions, including weakly ionized materials such as silicates and dissolved carbon dioxide, while weakly basic resins exchange only strongly ionized anions such as chloride and sulphate.

Ion exchange utilizing a strong base resin has been used for nitrate and phosphate removal and ammonia has been effectively removed through the use of the ammonia-selective zeolite, clinoptilolite.[132]

A continuous counter-current strong acid, weak base ion exchange process has been developed in South Africa for the simultaneous removal of organic and inorganic compounds from secondary sewage effluents. Operation of a 6 m^3/day pilot plant has confirmed that:

- The ion exchange system could be effectively employed for simultaneous desalination and removal of residual dissolved organics contained in purified sewage effluents providing that the total chemical oxygen demand (COD) of the feed-water to the system did not exceed 80 mg/ℓ.

- Counter-current ion exchange (CCIX) columns operating on a continuous liquid up-flow, resin down-flow cycle, can be linked together as required and operated under stable conditions for long periods.

- The control of such columns can be easily effected with relatively unsophisticated and inexpensive hardware.

- The resin, both anion and cation, has long life in terms of ion exchange capacity and mechanical strength.

CHAPTER 12

SLUDGE TREATMENT AND DISPOSAL IN BIOLOGICAL AND ADVANCED TREATMENT PLANTS

Sludge is a by-product of biological and advanced treatment plants and is produced in biological and combined biological-chemical forms.

Correctly designed sludge treatment facilities can account for 30—40 per cent of the plant capital cost and 40—50 per cent of the operating costs of a biological treatment plant.[138]

Inadequately designed sludge treatment facilities can create environmental hazards, such as unpleasant odours, which in turn can adversely influence the public attitude to the plant and involve substantial capital outlays in process modifications.

Preliminary design of the sludge handling and disposal facilities should therefore be carried out in conjunction with the overall design of the reclamation plant and should not be left until the plant is operational.

Design approach

The large variety of treatment and disposal equipment, together with the variety of sludges that can be produced render the design of the sludge treatment facilities no easy task. This is further compounded by the fact that *accurate* designs of sludge treatment facilities can only be carried out once pilot scale tests have been performed on the sludge(s) actually produced by the particular plants.

This approach can be readily applied to existing plants but in the case of those still being designed, sludge characteristics and equipment performances reported in the literature and/or experienced at similar plants have to be used for the preliminary design.

This presents no problem for plants which are to be built in modules, as the sludge produced from the first modules can be used to design the sludge treatment facilities for the subsequent modules.

However, in instances where the plants are not built in modular form, the preliminary design of the sludge treatment facilities should include a 'preferred' scheme together with an emergency 'back-up' scheme.

The emergency scheme would only be used in the initial stages of plant operation should the 'preferred' scheme prove inadequate and it would usually take the form of lagoons, ploughed fields etc.

As soon as sludge is produced, the 'preferred' sludge disposal scheme should be carefully evaluated and if necessary modified. At this stage a decision should be taken whether or not to retain the emergency 'back up' scheme. As this scheme would most likely involve a tract of land, there would be some merit in retaining it as a form of buffer strip.

The aim of this section is to highlight the different forms and quantities of sludge that can be formed in the plants as well as briefly discussing sludge characteristics and possible treatment alternatives.

A more detailed analysis of the sludge treatment and disposal equipment is presented in Part III, sections 2.9 and 2.10.

12.1 SLUDGES PRODUCED IN BIOLOGICAL AND ADVANCED TREATMENT PLANTS

Sludges are dilute solid suspensions, of which water is the largest component. The initial stages of sludge treatment generally involve the separation of the solid and liquid (water) phases and it is thus important to have some knowledge of the nature of the components of the water phase. The water phase can be classified into four categories:

- *Free water* which is not attached to the solid particles in any way and as such can be readily removed by simple gravitational separation.
- *Floc water* which is trapped within the flocs and can be removed by mechanical dewatering.
- *Capillary or bound water* which is held in small capillaries and crevices throughout the solids particles or is otherwise adsorbed upon the surface. Such water will be released if the particles are forced out of shape and compressed.
- *Particle water* which is chemically bound to the individual particles.

Sludges produced in a biological treatment plant are referred to as biological sludge, while the combined biological-chemical sludge produced in a reclamation plant is referred to as chemical sludge.

12.1.1 Biological sludges

These sludges may be classified into three categories, namely primary sludge, digested sludge and waste activated sludge (also referred to as excess activated sludge) depending upon point of production.

Primary Sludge

Primary sludge is that removed from the raw sewage by the primary settling tanks.

Primary sludges include inorganic detritus and silty organic solids, organic and inorganic colloids, vegetable and animal fibres and greases and fats of mineral, animal and vegetable origin. Their dry solids have a specific gravity range of 1,26 to 1,34 with particles ranging in size from below 1 μm to over 100 μm.

The sludge is offensive in nature, high in pathogens and viruses and when stored for any time gives rise to putrescent odours. These sludges are generally anaerobically digested prior to disposal.

Digested sludge

Digested sludge is discharged from anaerobic digesters which stabilize either primary sludge alone, or a mixture of primary and waste activated sludges.

Anaerobic digestion reduces fats, proteins, carbohydrates, other organics and pathogenic organisms by a complex biochemical process in which several groups of organisms decompose the organic matter in the absence of free oxygen.

In the process, a mixed environment of microorganisms achieves gas formation and the release of bound water accompanied by complex structure reductions, biomass stabilization and a tendency to pH stabilization.

The resulting reduced volume of sludge still thickens and dewaters comparatively easily but is considerably less odorous and putrescible than raw primary sludge and is generally suitable for restricted direct land application or general composting. The methane gas resulting from the process has a useful fuel value and can be utilized as an energy source.

Waste activated sludge

Waste activated sludge is that discharged from the activated sludge process, either from the reactor or from the clarifier.

The sludge is far more variable in character than primary sludge due to the variation in nature of the biological process. It is mainly organic and is of much smaller particle size than primary sludge.

Primary and digested sludge quantities

Table 2.23 indicates average quantities of primary and digested sludges expected from the treatment of normal domestic sewage under dry weather conditions in the UK and USA. There are a number of factors that can influence the sludge production, such as temperature, industrial contents, return liquors, living standards, high or low rate settling etc. and it is imperative that the sludge handling equipment (e.g. pumps, pipes etc.) be sized for a range of sludge productions, rather than one arbitrarily selected value.

Experience in South Africa indicates that conventional primary settlement will result in a dry solids production of 35 — 40 g/cap/d with a concentration of 1,5 — 2,5% dry solids, when no return liquors are added to the raw sewage flow. The dry solids production can be expected to increase to some 50 g/cap/day when return liquors (e.g. digester and thickener supernatants) are incorporated into the inflow to the settling tank. Both dry solids production and concentration are reduced when high rate settling is employed.

Digested primary sludge production can be 60 — 66% of the raw primary sludge, in terms of g dry solids/cap/day, while the concentration can vary from 3,0 — 6,0% dry solids.

Anaerobic digestion of a mixture of primary and waste activated sludges is seldom employed in South Africa because (i) the waste activated sludges generally derive from long SRT (15 — 25 d) systems and as such are relatively stable, and (ii) a digested mixture of primary and waste activated sludges dewaters less readily than digested primary sludge alone.

However, it is likely that an increasing number of

TABLE 2.23 PRIMARY AND DIGESTED SLUDGE QUANTITIES

Type of sludge	Dry solids		Quantity ℓ/cap/d	Reference
	g/cap/d	%		
Primary sludge	55	3,5	1,5	139
	54	2,5 — 5,0	1,1	140
	37	2 — 7	1,1	15
	44	—	—	141
	54	—	0,7	141
	—	5,6	1,5	141
	53	5,3	1,0	141
Digested primary sludge	32	8,0	0,4	139
	35	10	0,3	140
Digested primary and activated sludges	55	7,0	0,8	139
	54	6 — 8	0,8	140

treatment plants will in the future incorporate joint digestion facilities, with the increased gas production being used to reduce the imported energy requirements of the plants.

Waste activated sludge production

Figure 2.26 indicates the production of waste activated sludge, in terms of kg dry solids/kg COD removed/day, as a function of the system solids retention time (SRT).[105.142.143]

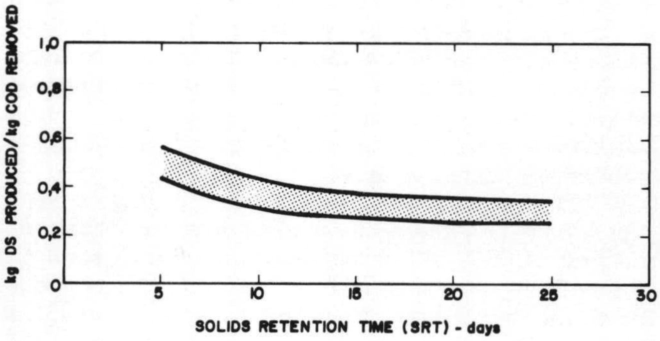


FIGURE 2.26: Production of waste activated sludge

The lower line of the band shown in the figure refers to the treatment of a settled sewage. The presence of inorganic and unbiodegradable organic solids in the influent will result in an increased waste sludge production at any given SRT. The upper line on the band therefore refers to the treatment of a raw sewage with a 250 — 300 mg/ℓ suspended solid content and the shaded area between the two lines refers to influents with different concentrations of suspended solids.

12.1.2 Chemical sludges

Chemical addition to raw sewages, to activated sludge reactors and to secondary effluents gives rise to chemical sludges which can be of the following forms:

Lime sludges

Lime sludges result from the addition of lime to raw sewage (primary lime sludge) and secondary effluents (tertiary lime sludges). The two sludges exhibit different dewatering and settling characteristics which could be attributed to the differing organic contents.

Alum sludges

Alum sludges result from the addition of aluminium sulphate (alum) to raw sewages, activated sludge reactors and secondary effluents. The most common form of alum sludge is that resulting from the addition to secondary effluents to precipitate phosphorus and coagulate any remaining suspended solids.

Iron sludges

Iron sludges result from the addition of iron salts (usually in the form of ferrous sulphate or ferric chloride) to raw sewages, biological reactors and secondary effluents. Iron salts are often added in conjunction with lime, albeit at concentrations very much lower than that of lime.

Chemical sludges generally contain two groups of solids: chemical solids which result from the reaction of the chemical with the inorganic components of the waste and biological solids which were present in the waste and which were either flocculated or enmeshed in the chemical solids precipitate. The properties of the resulting sludges is therefore heavily dependent upon the nature of the wastewater.

Primary chemical sludge production

Table 2.24 indicates typical increases in sludge production in terms of both dry solids and volume, resulting from chemical addition to raw sewages.

Secondary chemical sludge production

Table 2.25 indicates typical increases in sludge production resulting from chemical addition to the activated sludge process.

Tertiary chemical sludge production

Table 2.26 indicates the increase in sludge production resulting from chemical addition to secondary effluents.

TABLE 2.24 SLUDGE PRODUCTION DUE TO CHEMICAL ADDITION TO RAW SEWAGE

Sludge Production Parameter	Conventional Settlement	Low lime addition	High lime addition	Aluminium addition	Iron addition
Chemical dose (mg/ℓ)	0	350 — 500	800 — 1 600	13 — 23	26
Sludge solids content (%)	5,25	11,1	4,4	1,2	2,25
g dry solids/cap/day	23,6	168,8	286,8	39,7	83,2
ℓ/cap/day	1,1	2,2	7,1	5,8	5,5

Note: Data published by the US EPA[15] and a per capita sewage flow of 250 ℓ/cap/day were used in compiling the table.

TABLE 2.25 SLUDGE PRODUCTION DUE TO CHEMICAL ADDITION TO BIOLOGICAL REACTOR

Sludge Production Parameter	**Aluminium addition**		**Iron addition**	
	No aluminium	**With aluminium**	**No iron**	**With iron**
Chemical dose (mg/ℓ)	0	9 – 23	0	10 – 30
Sludge solids content (%)	0,91	1,12	1,2	1,3
g dry solids/cap/day	20,1	35,4	31,7	51,1
ℓ/cap/day	2,3	3,4	2,7	4,7

Note: Data published by the US EPA[15] and a per capita sewage flow of 250 ℓ/cap/day were used in compiling the table.

TABLE 2.26 SLUDGE PRODUCTION DUE TO CHEMICAL ADDITION TO SECONDARY EFFLUENTS

Sludge Production Parameter	**Lime addition**	**Aluminium addition**	**Iron addition**
Chemical dose (mg/ℓ)	268 – 450	16	10 – 30
Sludge solids content (%)	1,1	2,0	0,29
g dry solids/cap/day	139,4	60,0	15,2
ℓ/cap/day	13,4	3,0	5,5

Note: Data published by the US EPA[15] and a per capita sewage flow of 250 ℓ/cap/day were used in compiling the above table.

Sludge production resulting from high lime treatment (pH 11,2 to 11,5) of a secondary effluent at the Stander Plant, Pretoria has been reported as being 0,4 kg m^{-3} of effluent[18] (approximately 100 g/cap/day).

Summary

The effect of chemical addition on sludge production may be summarized as:

- Lime addition to raw sewage causes the greatest increase in sludge mass and volume production.
- Alum addition to activated sludge reactors results in a greater increase in sludge mass but a smaller increase in volume production.
- The sludge mass and volume are critically dependent upon the wastewater characteristics.
- The extra sludge production must be taken into account at the design stage.

12.2 PROPERTIES OF SLUDGES

The variety of sludges that are formed at biological and advanced treatment plants usually undergo further treatment prior to final disposal and the characteristics of the sludges greatly influence the form that the subsequent treatment will take.

Information available as to the basic properties or characteristics of the various sludges is limited. Values reported in the literature vary considerably and all relate to specific and usually different experimental conditions. The properties can however be divided into the following categories:

- Dewatering properties
- Settling properties
- Rheological properties

12.2.1 Dewatering properties

Many factors that influence the dewatering characteristics of sludges have been reported in the literature. However sludge particle size distribution appears to be the most important[144] and changes in dewaterability that are attributed to changes in pH, biological degradation, mixing and chemical conditioning may be explained by the changes these parameters impose on the overall particle size distribution.

Particle size shape and distribution depend on the nature of the wastewater as well as the process from which the sludge originates.[18] These particle characteristics change with time, especially in the case of biological sludges, which explains the spectrum of results reported in the literature relating to these particular sludges. Chemical sludges however are different in that they consist of one or two chemical precipitates which render the particle size shape and distribution more resistant to change with time.

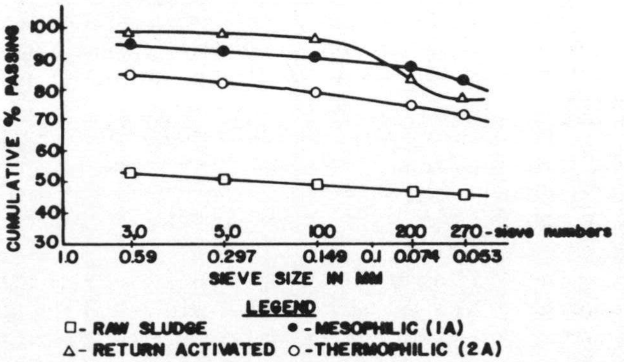


FIGURE 2.27: Sludge particle size distribution[145]

Biological sludges

Figure 2.27 indicates biological sludge particle size distributions reported from dewaterability studies conducted at the Hyperion plant, Los Angeles, USA.[145] The plots show that the raw sludge particles were larger than those of both the activated and anaerobically digested sludges, with only 50% of the raw sludge particles passing through a 30 mesh (600 μm) sieve as compared with 80 and 98% for the anaerobic and activated sludges respectively. A conclusion of the studies was that the sludges containing the finer particles were more difficult to dewater.

Further studies into the effect of particle size distribution made use of the 'specific resistance' parameter* to correlate dewaterability with particle size distribution.[144]

Specific Resistance and Capilliary Suction Time

The 'specific resistance' and 'capilliary suction time (CST)' tests have been widely adopted as parameters with which to gauge the dewaterability of sludges. Both tests do however have failings,[18,144] more so the CST test than the specific resistance test, but they do serve to indicate whether or not dewatering problems can be expected.

Chemical sludges

Very little has been reported as to the particle size distribution of chemical sludges. Work performed at the Stander Plant, Pretoria indicated that the tertiary lime sludge particle size was generally in the range of 2 to 50 μm, with a mass median diameter of 11 μm. Microscopic examination showed that the sludge was composed largely of discrete particles.

Conditioning of Sludges

The dewaterability of sludge can be improved through conditioning by chemicals such as aluminium chlorohydrate, ferric chloride, lime, copperas (ferrous sulphate) and polyelectrolytes or by heat treatment such as the low temperature Zimpro or Porteous processes.

12.2.2 **Settling properties**

Settling properties relate directly to the thickening potential of sludges. The evaluation of thickener area requirements is discussed in Part III, section 2.9.1.

Raw primary sludges exhibit settling properties that are superior to those of both activated and anaerobic sludges.[39] Settling velocities of waste activated sludge improve with increased SRT values — see section 4.2).

The settling properties of primary lime sludges are generally superior to those of the normal primary sludges while primary alum and iron sludges exhibit inferior properties.[15] However, primary lime sludges resulting from waters with high magnesium and low alkalinity contents will exhibit poor settling properties.[14]

Chemically treated activated sludges exhibit settling properties that are dependent upon the nature of the activated sludge component, i.e. whether it is from a low or high SRT system, whether the sludge is generated from a raw or a settled sewage etc. In general, settling properties of chemical/activated sludge combinations are slightly inferior resulting in lower design upflow velocities being required for the clarifiers.[21]

12.2.3 **Rheological properties**

All fluids can be classified in terms of their flow properties, or their 'rheology'. A rheogram defines the rheological properties of a fluid by establishing the relationship between shear stress and shear rate. The dynamic viscosity is the slope of the line defining this relationship.

A Newtonian fluid is one in which the viscosity remains constant as the shear rate is increased. Water is an example of a Newtonian fluid while most sludges, both chemical and biological, exhibit non-Newtonian flow properties in that the viscosity varies. Figure 2.28 illustrates rheograms for various fluids.

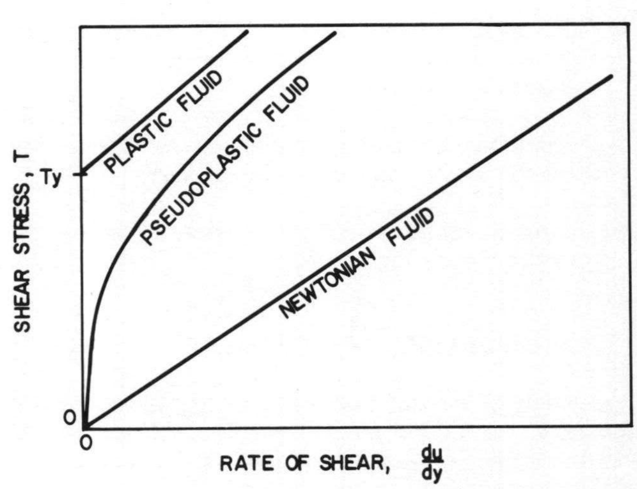


FIGURE 2.28: Rheograms for various fluids

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*Readers referred to ref. 138 for method of 'specific resistance' determination.

Figure 2.28 indicates that plastic fluids require a certain finite shear before they can be displaced. This shear is called 'yield stress' and represents a further rheological property of non-Newtonian fluids. Most sludges however have properties that fall between those of Newtonian and those of plastic and they are accordingly referred to as 'pseudo-plastic' fluids.

The rheological properties of slurries and suspensions have received considerable attention throughout the years, this being in contrast to sewage sludge. The limited data that is available on sludges show a wide variation in rheological properties for the different types of sludge.

Rheological properties play an important role in the design of sludge pumping schemes and as such are further discussed in Part III, chapter 4.

12.3 SLUDGE TREATMENT ALTERNATIVES

12.3.1 Biological sludges

There are a number of treatment stages through which biological sludges usually pass prior to final disposal. Figure 2.29 indicates the various stages together with the alternative forms of treatment pertaining to each stage.

The first stage usually comprises thickening to remove 'free' water and reduce the volume of sludge to be handled by subsequent stages of treatment, thereby reducing dewatering costs. Gravity thickening of primary sludges and dissolved air flotation thickening of waste activated sludges are the preferred processes.

Thickened primary sludges are usually stabilized by anaerobic digestion prior to dewatering but in some instances the stabilization step can be omitted and the thickened sludges immediately dewatered.

Thickened activated sludges resulting from long SRT systems can be immediately dewatered whereas those sludges with low SRT values are usually stabilized by anaerobic or in some instances aerobic digestion prior to dewatering.

The dewatering stage represents the crux of the entire sludge handling facility as the moisture content of the resulting dewatered cake can have tremendous cost implications on the selected form of final disposal. This is due to the fact that the moisture content not only governs the sludge volume, thereby affecting transport costs, but it can also render a sludge non-autothermic and thereby affect the fuel cost in thermal disposal processes.

Sludge dewatering can be attained by land methods, i.e. lagoons and drying beds, or by mechanical means. The various systems are briefly discussed in section 12.4 and in more detail in Part III, section 2.10.

The 'reduction and disposal' stage comprises reduction steps such as composting, incineration and pyrolysis while final disposal usually takes the form of soil conditioning or landfill.

12.3.2 Chemical sludges

The degree of treatment afforded to chemical sludges depends not only on their nature, i.e. primary or tertiary, but also on the size of plant. At the larger plants it

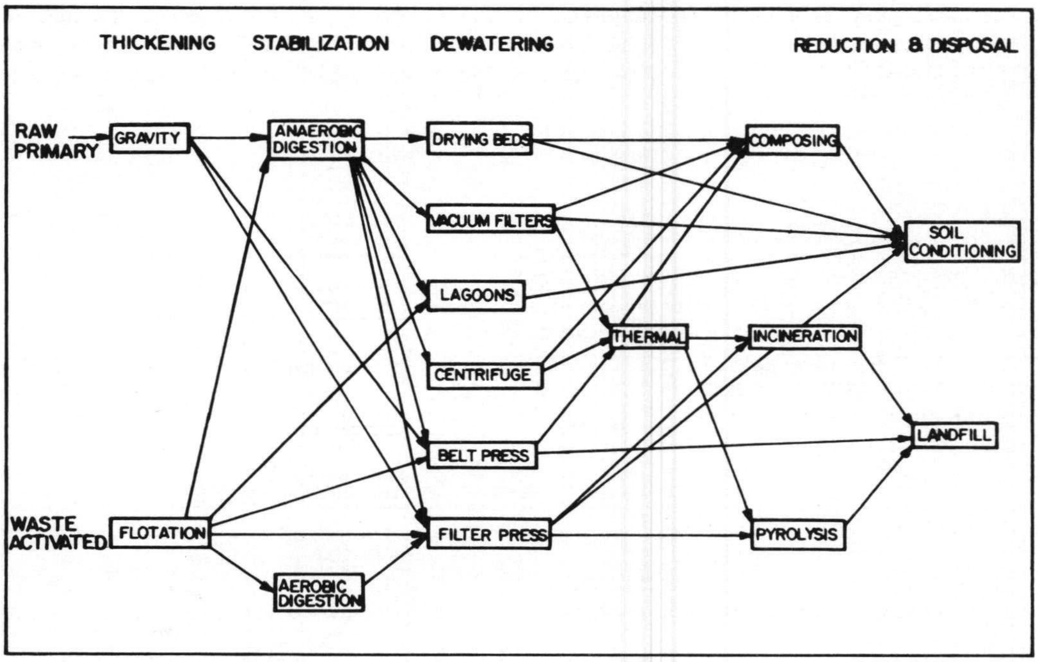

FIGURE 2.29: Alternative stages and forms of treatment for biological sludges

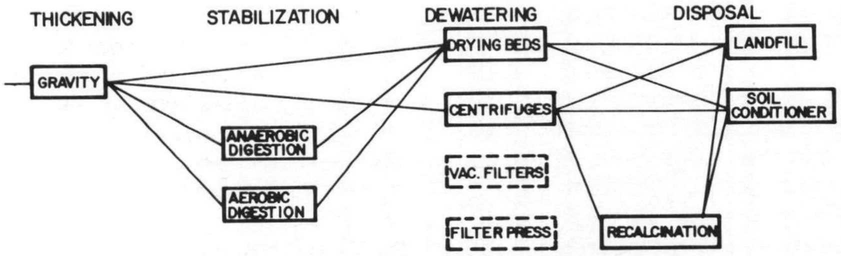

FIGURE 2.30: Treatment and disposal of lime sludges

is fairly common to incorporate a chemical recovery stage, thus not only reducing the initial raw chemical input but also reducing the volume or mass of sludge to be finally disposed of.

Lime sludges

Figure 2.30 indicates the various stages of treatment generally afforded to lime sludges.

All lime sludges, be they from primary or tertiary treatment, undergo gravity thickening prior to further treatment.

In the case of small plants that incorporate primary lime treatment, it is generally not economically feasible to recover the lime, with the result that the sludge undergoes stabilization by either anaerobic[146] or aerobic[147] digestion followed by dewatering on drying beds and final disposal as land fill or soil conditioner.

Lime Recovery

In large scale plants where lime recovery is practised, it is usual for the thickened primary sludge to undergo wet classification, usually by means of centrifuges, to separate the biological and chemical sludges, whereafter the biological sludge is processed by anaerobic digestion, and the chemical sludge is transferred to the chemical recovery stage. Ash from the recovery furnaces is generally disposed of to land while the recovered chemical is recycled to the lime reactor upstream of the primary clarifier. Lime recovery is further discussed in Part III, section 2.11.1.

Tertiary lime sludges are of such a nature that they can be dewatered on drying beds and disposed of to land without the stabilization step. In instances where lime recovery is feasible, the thickened tertiary sludge is further dewatered, usually by means of centrifuges, before being transferred to the recovery furnaces. Classification is not generally practised with these sludges.

Alum sludges

Sludges resulting from the addition of aluminium sulphate (alum) to raw sewages, to biological reactors or to secondary effluents are usually disposed of to land. Alum recovery is being investigated at a number of installations throughout the world but mainly for the sludges resulting from the treatment of secondary effluents[148] and surface or ground waters.[138]

Figure 2.31 indicates the various forms of treatment that can be afforded to alum sludges.

Primary alum sludges are usually stabilized

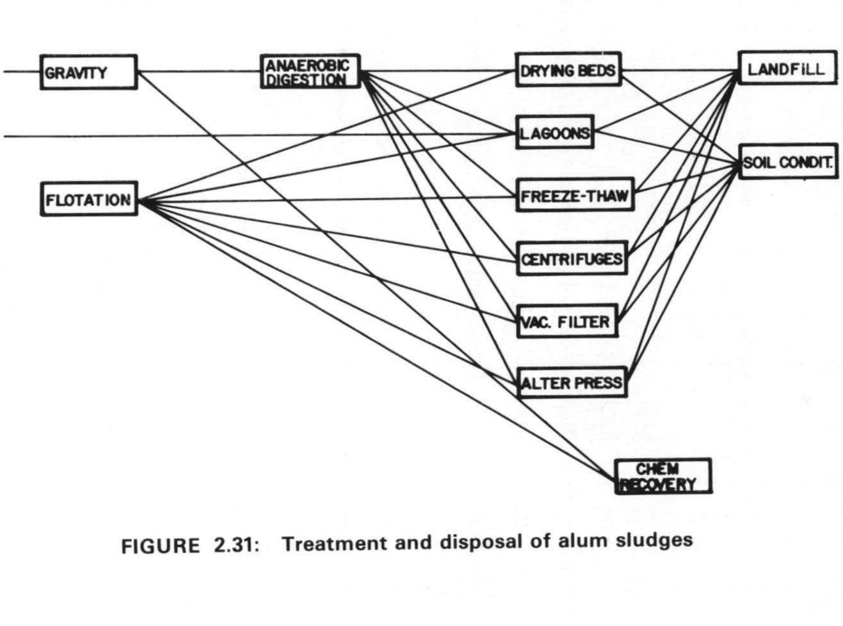

FIGURE 2.31: Treatment and disposal of alum sludges

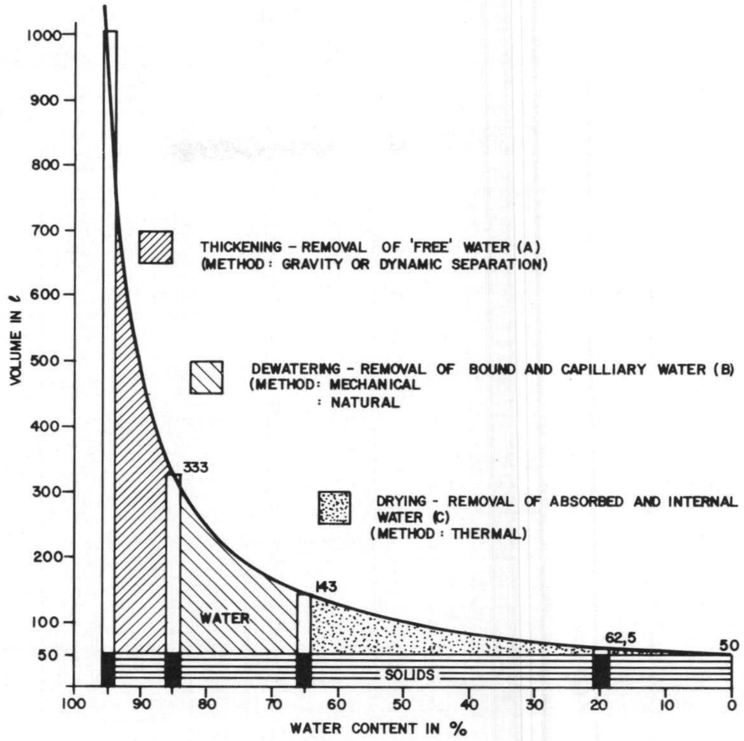

FIGURE 2.32: Reduction in sludge volume at various stages of water removal. (Assumed a m^3 of sludge at 95% moisture from liquid/solids separation)

through anaerobic digestion before dewatering and disposal to land. However, the economics of attaining a satisfactory degree of dewatering are so poor that alum addition to raw sewages is seldom employed.[149]

Sludge resulting from the addition of alum to the biological reactor of an activated sludge process is usually processed by means of flotation (or in some instances gravity) thickening, followed by mechanical dewatering and final disposal to land.

Tertiary alum sludges are processed in much the same way although chemical recovery could be considered for this type of sludge. The normal form of chemical recovery, that of acidification to dissolve the aluminium precipitates that constitute the alum fraction of the sludge, should however not be considered for systems in which the alum is originally added for phosphorus removal.

Iron sludge

Primary treatment by iron salts alone is seldom employed for reasons similar to those discussed above for primary alum sludges. However, iron salts are often added as a 'floc-aid' to primary lime treatment installations and as such are processed with the resulting primary lime sludges.

Iron sludges resulting from the addition to biological reactors and secondary effluents are processed in similar fashions to those described for the corresponding alum sludges. The recovery of iron from such operations is theoretically possible but at this stage is not economical.[143]

12.4 DEWATERING OF SLUDGES

Dewatering may be defined as the treatment stage that reduces the water content of a sludge from that achieved by thickening to that required for the selected form of final disposal. Figure 2.32 shows the degree of water removal that may be achieved by various processes, with thickening and dewatering being responsible for the bulk of the removal.

Thickening is usually achieved by gravity or flotation, although dynamic thickeners are being developed and should be considered at the process evaluation stage. Dewatering may be achieved by the natural forms of lagoons and drying beds or by the mechanical forms of vacuum filters, centrifuges, filter presses and belt presses.

12.4.1 **Biological sludges**

Figure 2.33 shows *typical* thickening and dewatering performances of the various treatment alternatives for both waste activated and primary sludges.

The alternative forms of mechanical dewatering all require a degree of chemical conditioning in order to produce cakes with the optimum solids content. These chemical costs contribute greatly to the overall operating costs and in some instances can be as high as 50% of the total dewatering costs of both the biological and chemical sludges. Table 2.27 compares four alternative forms of mechanical dewatering for a waste activated sludge with an SRT of 15 — 20 days and which has previously undergone flotation thickening to some

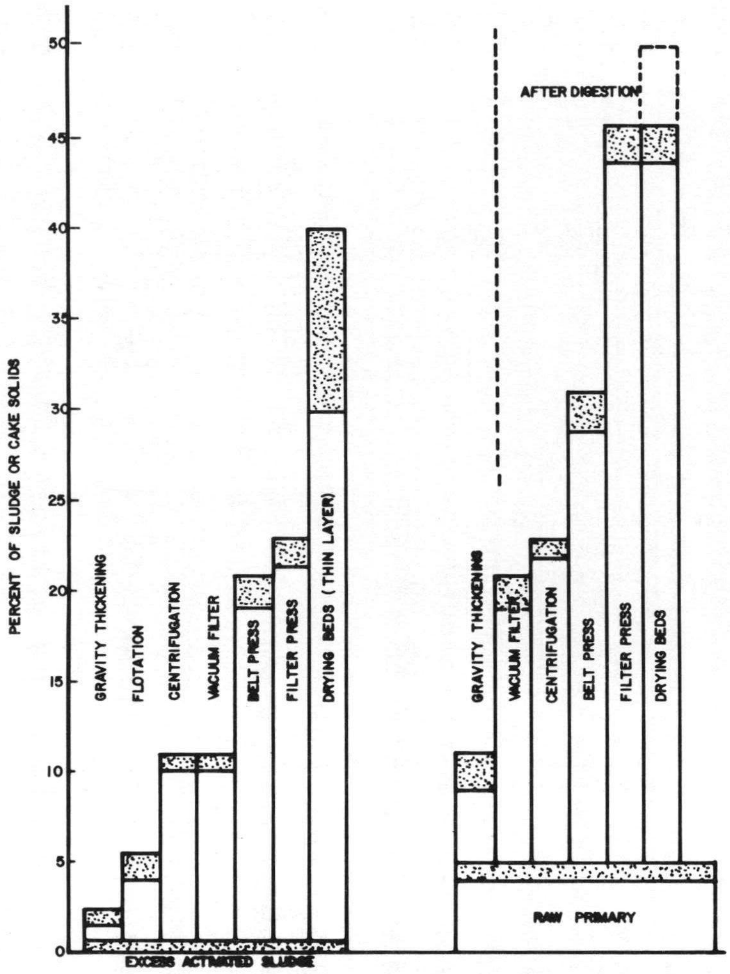

FIGURE 2.33: Degree of thickening and dewatering attained by various techniques

TABLE 2.27 COMPARISON OF DEWATERING ALTERNATIVES

	Filter plate press	Vacuum filter	Centrifuge	Filter Belt Press
Design Paramter	6,5 — 7,0 kg m^{-2} of plate/h	7,0 — 20,0 kg $m^{-2}h^{-1}$	Volume throughput depends on size of machine	4,5 $m^3h^{-1}m^{-1}$ belt width 180 kg $h^{-1}m^{-1}$ belt width
Chemical Addition				
● Lime	± 200 kg/t DS (can be 500 kg/t DS)	—	—	—
● $FeCl_3$	40 g/t DS (can be 200 kg/t DS)	—	—	—
● Polyelectrolyte	—	2,5 — 4,0 kg/t DS	3,5 kg/t DS	2,5 kg/t DS
Cake Solids	25 — 40%	15 — 20%	13 — 14% DS	18 — 22% DS
Advantage	High cake solids Clear filtrate High solids capture	Continuous operation Visible dewatering Low maintenance cost	Continuous operation High solids capture Clear filtrate Low space requirement	Low energy cost Continuous operation High solids capture Clear filtrate Easy to operate — low labour cost
Disadvantage	Batch operation High labour cost High chemical cost High inert solids content of cake	Cloth life limited High energy cost	High energy cost Low cake solids High polyelectrolyte cost High maintenance cost (bearings, scrolls) High noise levels	Belt life limited Large moving part content

4% dry solids by weight. The table highlights typical chemical requirements as well as operational advantages and disadvantages.

12.4.2 **Chemical sludges**

Lime sludges

Lime sludges may be dewatered on drying beds or by mechanical means such as vacuum filtration, filter presses or centrifuges. However, due to the variable nature of the sludges, particularly those from primary lime treatment, centrifugation is usually preferred. Cake solids of 30 — 40% by weight can be obtained by the three forms of mechanical dewatering mentioned.

Alum and iron sludges

Alum and iron sludges may be dewatered to 8 — 10% in lagoons[149] to 15 — 25% by centrifugation and to 20% by vacuum filtration,[15] albeit with high chemical conditioner requirements.[151]

More detailed discussions on each of the abovementioned forms of thickening and dewatering, together with design details, are presented in Part III, section 2.10.

12.5 REDUCTION AND ULTIMATE DISPOSAL OF SLUDGE

The decision as to the most acceptable method of disposal for the sludges generated at biological and advanced treatment plants should be based on social, environmental, political, economical and technical considerations. All disposal methods involve both capital and recurring expenditures and the most economical method is not necessarily the one finally adopted.

Final disposal usually takes one of two forms; either as an inert material (e.g. ash) or in such a form that the organic matter can be utilized (e.g. soil conditioning).

Disposal as inert material

Disposal as an inert material involves Incineration or Pyrolysis which of necessity are both preceded by chemical conditioning and dewatering stages. The ashes that result from the process are usually disposed of as landfill or as construction material.

Incineration reduces the sludge dry mass by approximately 70% and the volume by at least 95%. Multihearth, rotary hearth and fluidized bed furnaces are commonly used for sludges and as a result of high exhaust gas temperatures, 800 — 1 000°C, it is possible to recover significant amounts of energy.

Pyrolysis, whilst not being an incineration process *per se* also serves to reduce the sludge mass and volume. The process involves the destructive distillation of the sludge in the absence of oxygen and it has an advantge over incineration in that useful byproducts in the form of gas and char are formed. The gas can be fired for electricity generation and the char is a storable fuel which also has application as an adsorbent.

The largest recurring cost of both incineration and pyrolysis is that of auxilliary fuel consumption. It is therefore essential that the conditioning and dewatering stages that precede the processes are such that an autothermic sludge cake is fed to the furnaces. The percentage dry solids content at which a sludge becomes autothermic appears to be dependent upon its volatile matter content, such that the higher the volatile content the lower the dry solids content need be. Table 2.28 illustrates this relationship.[15]

TABLE 2.28 INFLUENCE OF VOLATILE CONTENT ON DRY SOLIDS CONTENT FOR AUTOTHERMICITY[15]

Sludge Parameter	**Case 1**	**Case 2**
Gross Calorific Value	17 400	29 100
% Volatiles in Solids Mass	60	75
% Dry Solids	41,8	18,5

Combination of reclamation plant sludge with domestic refuse prior to incineration or pyrolysis is practiced in the U.K. and U.S.A. This aspect has the advantage in that the sludge need not be dewatered to the same degree as that required in straight sludge incineration applications, thereby reducing the dewatering costs.

The overall design of a sludge conditioning and dewatering scheme can fall within the responsibilities of the process designer but in the case of incineration or pyrolysis plants the overall design should be left to the equipment supplier. Prospective suppliers should therefore be made fully aware of the performance requirements of their plant, such as capacity, compliance with air pollution regulations, form of final disposal, whether energy recovery is required or not etc.

Disposal as organic matter

Disposal in such a form that the organic matter present in the sludge can be utilized refers mainly to biological or predominantly biological sludges. This category consists of composting with domestic refuse or application to land in such a manner that not only is the soil conditioned but crops are grown, harvested and sold to realise an economic return.

Composting

Most mechanical composting plants require a water addition to produce optimum conditions within the drum. The amount of water added obviously depends on the moisture content of the incoming domestic refuse, which varies seasonally. The water addition can take the form of moisture present in the biological sludge emanating from the reclamation plant. In such instances, it is usual for the sludge to undergo a degree of dewatering prior to its addition, with the actual degree being dependent on the mass ratio of sludge to refuse as well as the optimum moisture content for the composting process.

Land application

Land application requires extensive collaboration between health officials, agriculturalists and public representatives. Decisions to be taken include the choice of site, method and rate of application of sludge, whether or not to lagoon before application and selection of vegetation.[150]

Health aspects of land application of sludges are discussed in the following section.

12.6 HEALTH ASPECTS OF LAND DISPOSAL OF SLUDGE

Use of untreated biological sludge on land may present an appreciable health hazard. Viral, bacterial and parasitic organisms are present in all sewages and the purification of the liquid phase tends to concentrate these in the sludges. Therefore, most health authorities consider it necessary to implement controls on the use and disposal of these waste materials.

The potentially pathogenic microbes found in sludges from a given population will, in a general measure, parallel the infective disease pattern, active or latent of that population. Consequently, any guidelines proposed should be discussed fully with the local Health Authority and modified to suit their particular requirements.

Guidelines on hygienically acceptable land-use for sludges have been proposed in Europe, United States and South Africa and agree in general.

Ideally, to decide on the most suitable processes for treating a sludge before agricultural use, one should have full information on:

- The levels of pathogenic organisms in raw sludges.
- The fate of these organisms during treatment (and consequently the concentrations of organisms in treated sludges).
- The incidence of infection in humans and animals arising from the use of sludges with known pathogen contents in agriculture.

From a literature survey, it would appear that there is little information available in any of these categories.

An expert committee of the Public Health Service of the Federal Republic of Germany has made recommendations as to the treatment of sludge before disposal to agriculture, and Table 2.29 summarizes their recommendations.[152] It can be seen that account is taken of the type of sludge, the type of land use and the season of application.

In the United Kingdom, the Department of the Environment is preparing similar guidelines but these are not expected to be published for some time yet. However, interim advice has been given as to the options available for the treatment of sludge to avoid *undue* risk of infection as a result of land use.[153]

It is believed that disinfection of all sludges before use on land cannot be justified in view of the few problems which have arisen over the many years during which unsterilised sludges have been employed as fertilisers. Similarly, the indiscriminate use of raw sludge on land cannot be advocated since in some circumstances, significant risks of animal infection cannot be ruled out.

In South Africa, guidelines have been suggested for the uses of sludges deriving from municipal sewage, stressing that these should be flexible and subject to the conclusion of on-going research. These are presented in Table 2.30.[154]

The preceding paragraphs seek to summarize the safeguards recommended in Europe and South Africa for sewage sludge usage and to act as a preliminary guide in drafting disposal standards. It is felt that the drafting of any such standards can only be carried out in consultation with the local Health Authorities and only after a period of research into the infective disease pattern and incidence of parasitic organisms of the contributing population has been conducted.

TABLE 2.29 HYGIENIC CONSIDERATIONS FOR AGRICULTURAL UTILIZATION OF SEWAGE SLUDGE[152]

Type of sludge	Fallow or barren land	Arable land	Pasture & fodder crop	Vineyard	Orchard	Tree nursery	Horticulture & vegetable cultivation
Raw, unstabilised	+	—	—	—	—	—	—
Anaerobically or aerobically stabilized	+	+	(+)—	+	+	+	—
Chemically conditioned	+	+	(+)—	+	+	+	—
Treated by heat or composted	+	+	+	+	+	+	+

\+ permissible (after harvesting)
— objectionable

TABLE 2.30 MICROBIOLOGICAL GUIDELINES FOR THE USE OF SLUDGES (SOUTH AFRICA)[154]

Purpose	Recommendations
1. LAND CONDITIONING	
A. Crops for human consumption which are eaten raw —	No sludge receiving less than advanced treatment (Pulverisation preferable)
B. Marketed as a domestic garden conditioner	
C. Golf courses, parks and sports fields —	
D. Crops for human consumption, not likely to be eaten raw —	The sludge to have received secondary treatment
E. Fruit trees and trellised vines —	
F. Grazing (excluding dairy cows)	
G. Vegetation not intended for grazing but utilized as dry fodder	No microbiological limits prescribed. Odour nuisance to be avoided. Lands fenced to prevent the access of livestock
2. DISPOSAL TO —	
A. Rivers, streams, etc.	Not permitted
B. The sea, (i) surf zone	Not permitted
(ii) Beyond surf zone	The degree of treatment required as well as the microbiological standard will be determined according to conditions prevailing in each case

NOTES: For the purpose of these recommendations:

- "Sludge" is derived from conventional treatment works adequately designed and properly operated and controlled.
- Secondary sludge treatment refers to any or a combination of approved treatment processes of sludge, e.g. composting, pasteurization.
- Advanced sludge treatment refers to physical and/or chemical processes which produce a quality sludge containing no viable Ascaris ova, and no E. coli per 100 g final product.

CHAPTER 13

PROCESS CONFIGURATIONS IN WATER RECLAMATION

This chapter describes possible process configurations that could be utilized to produce a reclaimed water of a desired quality. The configurations proposed should not be viewed as being the optimum for all conditions but rather as a guide to assist in the final selection thereof.

The reader is referred to the various sections that relate to the various unit processes mentioned for details of their efficacies in the context of water reclamation.

13.1 PROCESS CONFIGURATIONS FOR INDUSTRIAL REUSE

Figure 2.34 shows a possible process configuration for the production of an effluent suitable for cooling and general industrial purposes.

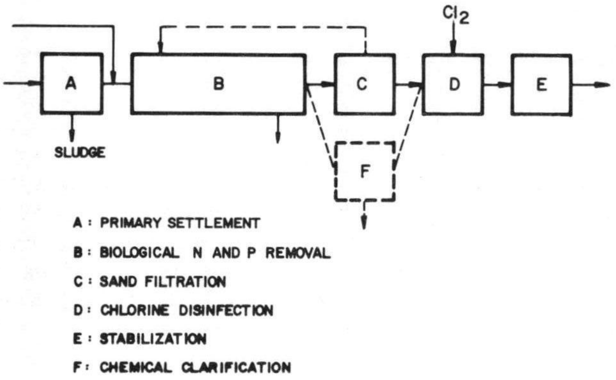

FIGURE 2.34: Possible process configuration for cooling water and general industrial reuse

13.2 PROCESS CONFIGURATIONS FOR POTABLE SUPPLY SYSTEMS

The quality of effluent for potable reuse is discussed in Part I, section 5.3 and Figure 2.35 shows various process configurations that could be used to comply with these requirements.

Extensive worldwide research is still being conducted into process configurations for potable reuse, particularly with respect to the positioning of the sand filtration, ozonation, breakpoint chlorination and activated carbon adsorption stages. The process configurations shown in Figure 2.35 are based on present day pilot and full-scale plant findings, both from South Africa and overseas and it may well be possible that they will require modification as future research findings are published. It is therefore imperative that the process engineer keep abreast of the latest developments in this field.

Configuration I could be employed in instances where the heavy metal content of the sewage is such that the biological process will not be inhibited but the final product water will be sub-standard with respect to its heavy metal content. Configurations II, III and IV could be employed where no heavy metal interference is expected and configuration V could be employed either when the heavy metal content of the sewage will inhibit the biological process or the dissolved solids of the sewage is so high that softening is required.

In the latter instance the lime could be added to the settled sewage in order to eliminate the problem of handling the lime/organic sludge mixture that would result if the lime were added to the raw sewage.

In addition, in the case of a relatively fresh raw sewage it may be necessary to incorporate an acid fermentation step (block P in Figure 2.35) in order to ensure that there is sufficient COD available in the influent to the biological reactor to ensure optimum denitrification (refer to section 10.1).

Configurations I, II, IV, V and VI could contain a quality and hydraulic equalization stage (block C in Figure 2.35) between the biological treatment and reclamation plants. However, as the biological plant would receive a constant flow of sewage, it may be decided not to include this stage particularly as such a storage stage would be expensive on large scale plants. Suffice it to say that the aspect of quality and hydraulic equalization should be carefully considered for each reclamation project.

Configurations I, II, III and V each contain a disinfection stage upstream of carbon adsorption that could be either ozonation or breakpoint chlorination (blocks H and I respectively in Figure 2.35). The selection of which to use should be based on aspects such as capital and operating costs, quality of operating personnel, carbon regeneration costs, virgin carbon costs, VHH formation etc.

Configuration IV could be used in instances where optimum disinfection through ozonation alone would be too costly. The ozone dose would be just sufficient to 'condition' the water before the carbon adsorption stage and disinfection would be achieved through breakpoint chlorination which would be positioned after the first carbon adsorption stage (refer to sections 6.1

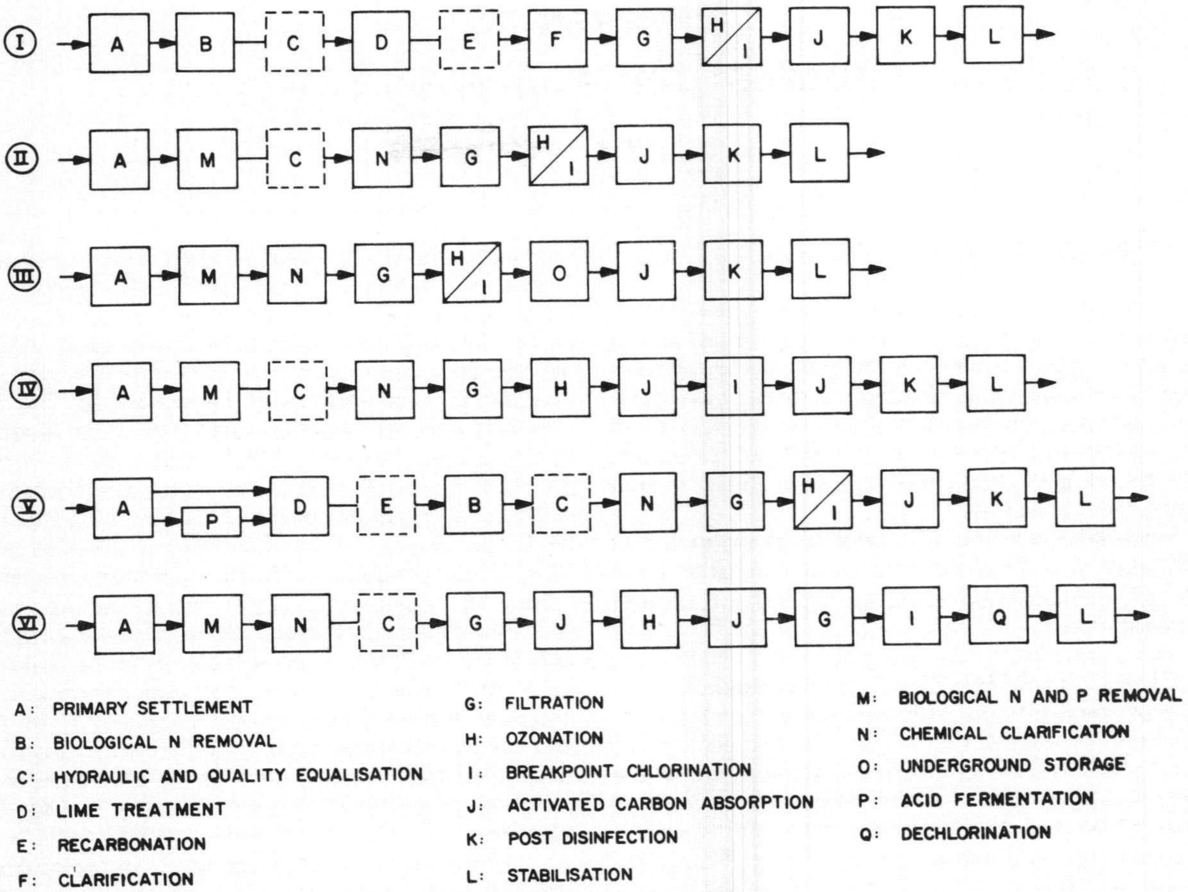

FIGURE 2.35: Possible process configurations for potable reuse

and 6.3). This system, however, could produce a high VHH concentration in the distribution system.

Post-disinfection (Block K in Figure 2.35) to maintain a bactericidal residual in the distribution system could be achieved through the use of chlorine, chlorine dioxide or chloramines although at present chlorine dioxide costs render this alternative unattractive.

Configuration VI could be used where a higher ozone dose than in configuration IV could be tolerated and where breakpoint chlorination would be required as a final safety barrier. This configuration is likely to result not only in a minimum dissolved TOC in the final effluent but also minimum VHH formation in the distribution network.

CHAPTER 14
PROCESS CONTROL STRATEGY

14.1 AIMS OF PROCESS CONTROL

The need for skilled operation of water reclamation plants, particularly those for potable water production, is frequently greater than that of industrial processes because of the temporal variation in wastewater flow and composition. Improved operation can be obtained by increasing the quantity and quality of personnel and/or by using modern instrumentation similar to that currently used in industry.

In areas where there is a dearth of operators of high quality, it is consequently usual for reclamation plants to be constructed with a considerable degree of instrumentation.

The usual aims of an instrumentation programme are to automatically control process parameters considered essential for the efficient operation of the individual unit processes that constitute the reclamation plant, e.g. pH in the lime treatment section, DO in the activated sludge section, etc., while at the same time relaying parameter status to indicators, recorders or data processors in a central control room. The works manager will, through this relayed information, be able to gain an overall picture of the reclamation plant's performance and make adjustments accordingly.

The *overall* aim of the process instrumentation is to ensure that a high state of 'operational efficiency' is at all times maintained. 'A high state of operational efficiency' can be taken to describe the situation in which operational errors are quickly detected and immediately rectified, thereby ensuring that an effluent with the desired quality is continually discharged.

Process control and instrumentation are discussed in more detail in Part 3, section 5.

14.2 CONTROL AND MONITORING AT VARIOUS REUSE LEVELS

The degree of instrumentation, for control or monitoring, installed in a reclamation plant is obviously dependent upon the effluent quality and reliability requirements of the plant. Reclamation for potable purposes therefore requires the greatest degree of instrumentation but care must be taken not to 'over-instrument' the plant. This could result not only in the keenness and iniative of the operating staff being adversely affected but a large and competent instrument maintenance force would be required.

The Stander plant has a minimum of automated control loops, primarily because this plant was intended as a research and demonstration facility. However, years of research and development have shown that a plant which is orientated towards operator control can supply a fail-safe product on a continuous basis.

At the Stander plant, pH, turbidity and the free chlorine residual are used as key control parameters. These parameters are monitored automatically on a continuous basis as well as manually on an intermittent basis while automatic control loops are used to control pH after lime treatment and recarbonation as well as the free chlorine residual at the disinfection step. The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 13 for further discussion and details of the monitoring and control instrumentation installed at the Stander plant.

The degree of instrumentation installed at the Stander plant together with the instruments required to control the dissolved oxygen, and to monitor the pH and nitrates, in the biological N and P removal stage as well as ozone at the ozonation stage can be considered to be the minimum for an operator orientated plant designed to produce a potable quality effluent. It is possible to increase the degree, and form, of instrumentation installed to such an extent that the entire plant is computor controlled, as at the Central Contra Costa Plant.[155]

There is however great merit in designing for operator participation in the overall control and installing a computor (or microprocessor) to record data and abstract figures at preselected time intervals, e.g. monthly record sheets etc. In such instances, the computor should be so sized that control functions may be added in the future.

Reclamation plants designed for the production of an effluent suitable for unrestricted agricultural reuse, general industrial reuse and reuse as cooling water would contain a lesser degree of instrumentation, but would still retain automatic DO and free chlorine residual control plus regular monitoring of turbidity, pH, nitrogen etc. There is however little justification for computor control in such instances.

It is essential that the degree of instrumentation to be installed in a reclamation plant be carefully considered at an early stage of the overall design, irrespective of the intended form of reuse. Factors such as availability of skilled operating and instrument maintenance personnel, proximity of instrument spare parts and degree of quality reliability required should be considered.

14.3 THE ROLE OF BIOMONITORING IN RECLAMATION FOR PUBLIC SUPPLY SYSTEMS

The increasing presence of potentially toxic elements or compounds in effluents, and indeed some fresh water supplies, has emphasized the need for sophisticated analytical tools with which such compounds can be detected and hence prevented from gaining access to potable water supplies.

Continuous physical and chemical monitoring systems provide a partial answer to these problems in that they are able to detect single toxic elements which have reached reportedly lethal levels. However, aquatic organisms respond to the collective effect of such environmental factors and among the most effective techniques for the detection of toxic substances is that of monitoring the respiration and movement of fish.

Municipalities and industries can employ biomonitoring systems as a safeguard against accidental sub-quality discharges, be it to a watercourse, direct to a public supply system or just into the municipal sewerage system.

Extensive research is being carried out in South Africa into the most effective form of biomonitoring system.

REFERENCES

1. Article 8 of Title 22, Division 4, Sections 60301 — 60357 of the California Administrative Code, U.S.A.
2. Article 10 of Title 22, Division 4, Sections 60301 — 60357 of the California Administrative Code, U.S.A.
3. Stander G.J. Modern Thinking in Wastewater Management. *Prog. Wat. Tech.*, **10** (1/2) 9, (1978).
4. Hart O.O. Contribution to a Debate at the 50th Annual Conference of the California Water Pollution Control Association, April, 1978.
5. Fish H. and Torrance S. Control of Specific Industrial Pollution of Water Sources. Paper presented at International Water Supply Congress, Kyoto, Japan, 1978.
6. Venter S.L., Halliday J. and Pitman A.R. Optimization of the Johannesburg Olifantsvlei Extended Aeration Plant for Phosphorus Removal. *Prog. Wat. Tech.*, **10**, (1/2) 279, (1978).
7. Kim B.R. and Snoeyink V.L. Influence of Activated Sludge CRT on Adsorption. *J. Env. Eng. Div., ASCE, Feb.*, **55** (1976).
8. Cillie G.C., Davies T.R., Hart O.O. and Hassett A.J. The Effect of Toxic Loads on Effluent Purification Systems. *Water S.A.*, **3**(2) 83, (1977).
9. Horstkotte B.A., Niles D.G., Parker D.S. and Caldwell D.H. Full-Scale Testing of a Water Reclamation System. Proc. 45th Ann. Conf., WPCF, Atlanta, USA (1972).
10. Barnard J.L. Discussion on paper Centrifugal Dewatering of Lime Sludges from Water Reclamation Plants, by Ronen M. and van Duuren F.A. *Prog. Wat. Tech.*, **10**, (1/2) 656 (1978).
11. Barnard J.L. The Bardenpho Process. Chapter 6 of 'Advances in Water and Wastewater Treatment — Biological Nutrient Removal'. Edited by Wanielista M.P. and Eckenfelder W.W. and published by Ann Arbor Science, (1978).
12. Van Vuuren L.R.J. and Wiechers S.G. Nitrification and Denitrification of Lime Treated Wastewaters. *Prog. Wat. Tech.*, **10**, (1/2) 185, (1978).
13. Van Vuuren L.R.J. and Taljard M.P. The Reclamation of Industrial/Dometsic Wastewaters. Paper presented at Water Reuse Symposium, Washington, March, 1979.
14. Minton G.R. and Carlson D.A. Primary Sludges Produced by the Addition of Lime to Raw Wastewater. *Wat. Res.*, **7**, 1821, (1973).
15. United States EPA, Process Design Manual for Sludge Treatment and Disposal. EPA 625/1-74-006, October, 1974.
16. Matthews P.J. Application of Physico-Chemical Treatment as a Method of Achieving Partial Standards on Sewage Effluents Discharged into Estuarial and Coastal Situations. *Pub. Health. Eng.*, **5**, 31 (1977).
17. Ronen M. Clarification. Chapter 2 of the 'Manual for Water Renovation and Reclamation. CSIR Technical Guide K42, Pretoria, (1978).
18. Ronen M. The Characterization, Processing and Recycling of Lime Sludges. CSIR Special Report WAT 49, Pretoria, (1976).
19. Ronen M. and Halbertal Y. Operational Experience in the Lime Treatment of Effluent from Oxidation Ponds. *Prog. Wat. Tech.*, **10**, (1/2) 565 (1978).
20. Minton G.R. and Carlson D.A. Combined Biological-Chemical Phosphorus Removal. *J. WPCF* **44**, 1736, (1972).
21. Schmidte N.W. Coagulation and P-Removal. Wastewater Technology Centre, Environmental Protection Service, Ontario, Canada, (1973).
22. Cooper P.F. and Thomas E.V. Recent Developments in Sewage Treatment based on Physico-Chemical Methods. *Wat. Polln, Cont.* **73**, 505, (1974).
23. United States EPA. Process Design Manual for Phosphorus Removal. October, 1971.
24. Jakowkin A.A. Notes on the Hydrolysis of Chlorine. *Z Phys. Chem.*, **29** 624 (1899).
25. Loewenthal R.E. and Marais G.v.R. Carbonate Chemistry of Aquatic Systems: Theory and Application. Ann Arbor Science, (1976).
26. Van Vliet B.M., Active Carbon Adsorption. Chapter 9 of the 'Manual for Water Renovation and Reclamation', CSIR Technical Guide K42, Pretoria, (1978).
27. American Waterworks Association, AWWA Standard for Granular Activated Carbon: AWWA Standard No. B604-74 (first edition). *J. Am. Wat. Wks. Ass.*, **66**, 672, (1974).
28. White M.J.D., Baskerville R.C. and Day M.C. Increasing the Capacity of Sedimentation Tanks by Means of Sloping Plates. *Wat. Polln. Cont.*, **75**(1), 21, (1976).
29. White M.J.D. Design and Control of Secondary Sedimentation Tanks. *Wat. Polln. Cont.*, **75**, (4) 459 (1976).
30. Dick R.I. *et al.* Discussion on Low Temperature Activated Sludge Settling. *J. Sanit. Eng. Div.*, ASCE, April, 638 (1969).
31. Pitman A.R. Bioflocculation as a Means of Improving the Dewatering Characteristics of Activated Sludges. *Wat. Polln. Cont.* **74**, (6), 688.
32. Nicholls H.A. Full Scale Experimentation on the New Johannesburg Extended Aeration Plants. Paper presented at the 'Workshop on New Aspects of Biological Treatment', Pretoria, February, 1975.
33. Halliday J. Discussion on: Bioflocculation as a Means of Improving the Dewatering Characteristics of Activated Sludges. *Wat. Polln. Cont.*, **74**, (6) 688, (1975).
34. Englande A.J., Smith J.K. and English J.N. Potable Water Quality of Advanced Wastewater Treatment Plant Effluents. *Prog. Wat. Tech.* **10**, (1/2) 17, (1978).
35. O'Farrel J.P. and Bishop D.F. Lime Precipitation in Raw, Primary and Secondary Wastewater. Water 1971, Am. Inst. Chem. Engrs. Symposium Series, **68**, 43.
36. Parker D.W., Carthew G.A., Horstkotte G.A. Lime Recovery and Reuse in Primary Treatment. *J. Envir. Eng. Div., ASCE*, December, 985, (1975).
37. Leentvar J., Werumeus Buning W.G. and Koppers H.M.M. Physico-Chemical Treatment of Municipal Wastewater. Coagulation-Flocculation. *Wat. Res.*, **12**, 35 (1978).
38. Rebhun M. and Streit S. Physico-Chemical Treatment of Strong Municipal Wastewater. *Wat. Res.* **8**, 195 (1974).
39. United States EPA. Process Design Manual for Suspended Solids Removal. EPA 625/1-75-003a, January, 1975.
40. Bébin J. and Jacquart J.C. Pilot Studies on the Utilization of Flotation and Accelerated Clarification Units for the Direct Physico-Chemical Treatment of Domestic Wastewaters. *Prog. Wat. Tech.*, **10**, (1/2) 205, (1978).
41. Van Vliet B.M. The Efficacy of Inclined Tube and Plate Modules in a High Lime Clarification Process. *Wat. Res.*, **11**, 78 (1977).
42. Ronen M. Private Communication, 1977.
43. Painter H.A. Wastewater Characterization. Int. Assoc. Wat. Polln. Res. Short Course, Birmingham, U.K., September, 1974.
44. Painter H.A. Organic Compounds in Solution in Sewage Effluents. *Chemistry and Industry*, September, 818, 1973.
45. Painter H.A. Biodegradability. Proc. R. Soc. London., **185**, 149, (1974).
46. Notes on Water Research. Published by the Water Research Centre, U.K., No. 14, February, 1978.
47. Roberts M.R. Sizing of Basic Units in Activated Sludge Plants. Paper presented at Inst. Wat. Polln. Cont. (SA Branch) meeting, Johannesburg, September 21st, 1978.
48. Weber W.J. Adsorption. Chapter 5 of 'Physico-chemical Processes for Water Quality Control'. Edited by Weber W.J. and published by Wiley Interscience (1972).

49. Rebhun M., Narkis N. and Sheindorf C. Combination of Physico-Chemical and Biological Processes for Wastewater Treatment and Reuse. *Prog. Wat. Tech.,* **10**, (1/2) 173, (1978).
50. Van Rensburg J.F.J., Van Rossum P.G. and Hattingh W.H.J. The Occurrence and Fate of Organic Micropollutants in a Water Reclaimed for Potable Reuse. *Prog. Wat. Tech.,* **10**, (1/2) 41, (1978).
51. Hart O.O. The effect of various process configurations of a water reclamation plant on the composition of the organic compounds in the reclaimed water with special reference to molecular mass distribution and halogenated hydrocarbons. D.Sc. Thesis, University of Pretoria (1979).
52. Metzler D.F., Culp R.L., Stoltenberg H.A., Woodward R.L., Walton C., Chang S.L., Clarke N.A., Palmer C.M. and Middleton F.M. Emergency Use of Reclaimed Water for Potable Supply to Chanute, Kan. *J. Am. Wat. Wks. Ass.* **50**, 1021, (1958).
53. United States EPA, Federal Register, February 9th, 5756, (1978).
54. Ford D.L. Carbon Adsorption as an Advanced Wastewater Treatment Process. *Prog. Wat. Tech.,* **10**, (5/6) 1, (1978).
55. De Walle F.B. and Chian E.S.K. Removal of Organic Matter by Activated Carbon Columns. *J. Sanit. Eng. Div., ASCE* **100**, October, 1974.
56. Stopka K. Ozone-Activated Carbon Can Remove Organics. *Wat. and Sew. Wks.* May, 66, 1978.
57. Weber W.J. and Ying W-C. Integrated Biological and Physical-Chemical Treatment for Reclamation of Wastewater. *Prog. Wat. Tech.,* **10**, (1/2) 217, (1978).
58. Sontheimer H., Heilker E., Jekel M., Nolte H. and Volmer F.H. The Mulheim Process — Experience with a New Process Scheme for Treating Polluted Surface Waters. (1978).
59. Rice R.G., Miller G.W., Robson C.M. and Kuhn W. Biological Activated Carbon. Paper presented at Symposium on Advanced Ozone Technology, Toronto, Canada, November 17th, 1977.
60. Mignot J. Application of Ozone with or without Activated Carbon for Drinking Water Treatment. Proc. First Int. Symp. on Ozone for Water and Wastewater Treatment. Edited by Rice R.G. and Browning M.E., published by Hampson Press, (1975).
61. Zellman G. Summarized Description of the Treatment of Potable Water Using Ozone. Technical Application, Demag Metallgewinnung.
62. Ross W.R., Van Leeuwen J. and Grabow W.O.K. Studies on Disinfection and Chemical Oxidation with Ozone and Chlorine in Water Reclamation. Proc. Second Int. Symp. Ozone Tech., Montreal, May 11th — 14th, 497, (1975).
63. Van Leeuwen J. Discussion on 'Ozonation in Water Reclamation'. Paper presented at Symposium on 'Disinfection of Water', Pretoria, November, 1978.
64. Guirguis W. Cooper T., Harris J. and Ungar A. Improved Performance of Activated Carbon by Pre-ozonation. *J. WPCF* **50**, February, 308, (1978).
65. Weissenhorn F.J. Private Communication, 1978.
66. Hart O.O. Operational and Control Aspects in Water Reclamation. *Prog. Wat. Tech.,* **10** (1/2), 65, (1978).
67. Gomella C. Micropollution in Water Treatment, *Aqua,* **2**, 19 (1978).
68. Zoetman B.C.J. Sensory Assessment and Chemical Composition of Drinking Water. Doctoral Thesis, Rÿksuniversiteit, Utrecht, (1978).
69. Nasionale Instituut vir Waternavorsing, 'Die Gesondheidsaspekte van Watervoorsiening'. Vyfde Jaarverslag, 1 Julie 1977 — 30 September 1978, Pretoria, (1978).
70. Masschelein W.J. The State of the Art in the Use of Chlorine Dioxide and Ozone in the Treatment of Water. *Water SA* **6** (3) 116.
71. Van Duuren F.A. The Significance of Microparticles in Water Purification. Paper presented at Biennial Conference of Inst. Wat. Polln. Cont. (S.A. Branch), Port Elizabeth, March, 1978.
72. Van Leeuwen J. and Prinsloo J. Ozonation in Water Reclamation. Paper presented at Symposium on 'Disinfection of Water', Pretoria, November, 1978.
73. American Water Works Association, Committee Report on Disinfection. *J. Am. Wat. Wks. Ass.* **70**, April, 220, (1978).
74. a. Coin L. Inactivation par L'Ozone du Virus de la Poliomyelite Present dans les Eaux. *La Presse Medicale,* **72**, 37 (1964).
    b. Coin L., Hannoun C. and Gomella C., *Ibid,* **72**, 2153 (1964).
    c. Coin L. *et al. Ibid,* **72**, 1833 (1967).
75. Gomella C. Ozone Practices in France, *J. Am. Wat. Wks. Ass.* **64** (1) 39 (1972).
76. Schalekamp M. Experience in Switzerland with Ozone, particularly in connection with the Neutralization of Hygienically Undesirable Elements Present in Water. Presented at Int. Symp. on Ozone and Water, 'Wasser Berlin', Berlin, West Germany, May 16, 12 (1977).
77. Kühn W. Sontheimer H. and Kurz R. Use of Ozone and Chlorine in Water Works in the Federal Republic of Germany. Presented at Workshop on Ozone/Chlorine Dioxide Oxidation Products of Organic Materials, Cincinati, Ohio, (Nov. 1976). Int. Ozone Inst., Cleveland, Ohio.
78. Cox C.R. Operation and Control of Water Treatment Processes, W.H.O., Geneva, 143 (1964).
79. Van der Merwe S.W. Chlorine Disinfection in a Large Potable Water Treatment Plant. Paper presented at Symposium on 'Disinfection of Water', Pretoria, November, 1978.
80. Siemak R.C., Trussel R.R., Trussel A.R. and Umphres M.D. How to Reduce Trihalomethanes in Drinking Water. *Civil Engineering — ASCE,* February, 49, 1979.
81. Funke J.W. Metals in Urban Drainage Systems and Their Effect on the Potential Reuse of Purified Sewage. *Water SA* **1** 36 (1975).
82. Mosey F.E. Assessment of the Maximum Concentration of Heavy Metals in Crude Sewage which will not Inhibit the Anaerobic Digestion of Sludge. *Wat. Polln. Cont.* **75** (1) 10 (1976).
83. Neufeld R.D. Heavy Metals-Induced Deflocculation of Activated Sludge. *J. WPCF.* **48** (8) 1940 (1976).
84. Water Pollution Control Federation. Wastewater Treatment Plant Design. A Manual of Practice. Washington D.C., (1977).
85. Poon C. and Bhayani E.R. Metal Toxicity to Sewage Organisms. *J. Sanit. Eng. Div ASCE,* **97**, April, 1971.
86. Barth E.F., Ettinger M.B., Salotto B.V. and McDermott G.N. Summary Report on the Effects of Heavy Metals on the Biological Treatment Processes. *J. WPCF.* **37** (1) 86 (1965).
87. Olivier B.G. and Cosgrove E.G. The Efficiency of Heavy Metal Removal by a Conventional Activated Sludge Treatment Plant. *Wat. Res.,* **8**, 869 (1974).
88. Roberts P., Hegi H.R., Weber A. and Krähenbuhl H.R. Metals in Municipal Wastewater and Their Elimination in Sewage Treatment. *Prog. Wat. Tech.,* **8** (6) 301 (1977).
89. Smith R., Siebert M.L. and Hattingh W.H.J. Removal of Inorganic Pollutants from Wastewater during Reclamation for Potable Use. *Water SA* **6** (2) 92.
90. Idelovitch E. and Michal M. Trace Metal Removal from Secondary Effluent by Two-Stage High Lime-Magnesium Treatment. *Prog. Wat. Tech* **10** (5/6) 832 (1978).
91. World Health Organization. International Standards for Drinking Water, 3rd Edn., Geneva. (1971).
92. Huang C. and Wu M. Chromium Removal by Carbon Adsorption. *J. WPCF* **47** (10) 2437 (1975).
93. Linstedt K. and Houck C.P. Trace Element Removals in Advanced Wastewater Treatment Processes. *J. WPCF* **43** (7) 1507 (1971).
94. Osborn D.W. — presented in discussion at Symposium on 'The Treatment and Disposal of Sludges Deriving from Municipal Sewage', Pretoria, October, 1977.
95. Unit Processes, 'Sewage Sludge III: Utilization and Disposal', Manual of British Practice in Water Pollution Control. *Inst. Wat. Polln. Cont.,* London (1978).
96. Standing Committee on the Disposal of Sewage Sludge. 'Report on the Working Party on the Disposal of Sewage Sludge to land', Dept. of the Envir/Nat. Wat. Council (Standing Technical Committee Report No. 5) London. (1977).
97. Stensel H.C., Refling D.R. and Scott J.H. Carrousel Activated Sludge for Biological Nitrogen Removal. Chapter 4 of 'Advances in Water and Wastewater Treatment — Biological Nutrient Removal'. Edited by Wanielista M.P. and Eckenfelder W.W. and published by Ann Arbor Science. (1978).
98. Bouck D.W. Nutrient Removal In Three-Stage Processing. Chapter 5 of 'Advances in Water and Wastewater Treatment — Biological Nutrient Removal'. Edited by Wanielista M.P. and Eckenfelder W.W. and published by Ann Arbor Science. (1978).
99. United States EPA. Process Design Manual for Nitrogen Con-

trol. October, 1975.

100. Van Vuuren L.R.J. Ammonia Stripping. Chapter 4 of the 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42, Pretoria. (1978).

101. Van Leeuwen J. Chlorine Disinfection. Chapter 7 of the 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42, Pretoria. (1978).

102. Barnard J.L. and Van Vuuren L.R.J. Removal of Nitrogen from Sewage. Presented at Birmingham Post IAWPR-Conference lecture series, September, 1974.

103. Marais G.v.R., Van Haandel A. and Ekama G.A. The Present Status of Research on Nitrogen Removal: A Model for the Modified Activated Sludge Process. Presented at Seminar on 'Nutrient Removal from Municipal Effluents'. Pretoria, May, 1979.

104. Downing A.L. Nitrification in the Activated Sludge Process. *J. Inst. Sew. Purification* 130 (1961).

105. Marais G.v.R. and Ekama G.A. The Activated Sludge Process Part I — Steady State Behaviour. *Water SA,* **2** (4) 163 (1976).

106. McCarty P.L., Beck L. and St. Amant P. Biological Denitrification of Wastewater by Addition of Organic Materials. Proc. 24th Ind. Waste Conf., Purdue University, 1271 (1969).

107. Antonie R.L. Nitrogen Control with the Rotating Biologial Contactor. Chapter 13 of 'Advances in Water and Wastewater Treatment — Biological Nutrient Removal'. Edited by Wanielista M.P. and Eckenfelder W.W. and published by Ann Arbor Science. (1978).

108. Memorandum on Current State of the Art of Nutrient Removal. Compiled by the IWPC Nutrient Removal Working Committee, Inst. Wat. Polln. Control (SA Branch), Pretoria, June, 1977.

109. Van Vliet B.M. Quality Equalization. Chapter 3 of the 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42, Pretoria. (1978).

110. Ronen M. and Van Vuuren L.R.J. Ammonia Removal in a Ponds System and in a Stripping Tower. *Prog. Wat. Tech.,* **10** (1/2) 293 (1978).

111. Wachs A.M., Folkman Y. and Shemesh D. Use of Surface Stirrers for Ammonia Desorption from Ponds. Applications of New Concepts of Physical-Chemical Wastewater Treatment. Edited by Eckenfelder W.W. and Cecil L.K. and published by Pergamon Press. (1972).

112. Barth E.F. Implementation of Nitrogen Control Processes. Chapter 2 of 'Advances in Water and Wastewater Treatment — Biological Nutrient Removal'. Edited by Wanielista M.P. and Eckenfelder W.W. and published by Ann Arbor Science. (1978).

113. O'Melia C.R. Coagulation and Flocculation. Chapter 2 of 'Physico chemical Processes for Water Quality Control'. Edited by Weber W.J. and published by Wiley Interscience. (1972).

114. Barnard J.L. Biologische Phosphor- and Stickstoffbeseitigung — Paper presented at Essener Tagung, West Germany, March, 1979.

115. Hoffman R.J. and Marais G.v.R. Phosphorus Removal in the Modified Activated Sludge Process. Research Report No. W22, University of Cape Town. (1977).

116. Simpkins M.J. and McLaren A.R. Consistent Biological Phosphate and Nitrate Removal in an Activated Sludge Plant. *Prog. Wat. Tech.,* **10** (5/6) 433 (1978).

117. Osborn D.W. and Nicholls H.A. Optimization of the Activated Sludge Process for the Biological Removal of Phosphorus. *Prog. Wat. Tech.* **10** (1/2) 261 (1978).

118. Wuhrman K. Objectives, Technology and Results of Nitrogen and Phosphorus Removal Processes. 'Advances in Water Quality Improvements'. Edited by Gloyna E.F. and Eckenfelder W.W. and Published by Univ. of Texas Press, 21 (1968).

119. Minton G.R. and Carlson D.A. Combined Biological-Chemical Phosphorus Removal, *J. WPCF* **44**, 1736 (1972).

120. Anderson D.T. and Hammer M.J. Effects of Alum Addition on Activated Sludge Biota. *Wat. and Sew. Wrks.,* **120**, Jan., 63, 1973.

121. Zenz D.R. and Pivnicka J.P. Effective Phosphorus Removal by the Addition of Alum to the Activated Sludge Process. Proc. 24th Ind. Waste. Conf. Purdue University 273 (1969).

122. Wiechers H. and Van Vuuren L.R.J. A Review of Applied Technology for Nutrient Removal from Municipal Effluents. Presented at Seminar on 'Nutrient Removal from Municipal Effluents'. Pretoria, May, 1979.

123. Boller M.A. Contact Filtration for Additional Removal of Phosphorus in Wastewater Treatment. Paper presented at IAWPR Workshop on 'Design-Operation/Interactions at Large Treatment Plants'. Vienna, September, 1975.

124. Pelloni L. Removal of Residual Phosphorus and Suspended Solids by Contact Filtration. *Prog. Wat. Tech.* **10** (5/6) 255 (1978).

125. Marais G.v.R. Discussion on 'Comparison of Cost and Energy Requirements for Alternative methods of Sewage Treatment'. Seminar on 'Nutrient Removal from Municipal Effluents'. Pretoria, May, 1979.

126. Levin G.V., Topol G.J. and Tarney A.G. Pilot Plant Tests of Phosphate Removal Process. *J. WPCF* **44**, 1940 (1972).

127. Levin G.V., Topol G.J. and Tarney A.G. Operation of Full Scale Biological Phosphorus Removal Plant. *J. WPCF.* **47**, 577 (1975).

128. Matsch L.C. and Drnevich R.F. Phostrip: A Biological-Chemical System for Removing Phosphorus. Chapter 7 of 'Advances in Water and Wastewater Treatment — Biological Nutrient Removal'. Edited by Wanielista M.P. and Eekenfelder W.W. and published by Ann Arbor Science, (1978).

129. McLaren A.R. Simultaneous Biological Nitrogen and Phosphate Removal from Wastewater in a modified Phostrip Process. *Water SA* **5** (3) 144 (1979).

130. Belfort G. Pressure-Driven Membrane Processes and Wastewater Renovation, Chapter 6 of 'Water Renovation and Reuse'. Edited by Shuval H.I. and published by Academic Press. (1977).

131. Botha G.R. and De Villiers H.A. The Application of Reverse Osmosis and Ultrafiltration in the Reclamation of Water from Purified Sewage Effluents. Presented at the Biennial Conference of the Inst. Wat. Polln. Cont. (SA Branch), Port Elizabeth, March, 1978.

132. Cruver J.E. Membrane Processes. Chapter 7 of 'Physicochemical Processes for Water Quality Control'. Edited by Weber W.J. and published by Wiley-Interscience. (1972).

133. Degremont. Technical Publication on Reverse Osmosis (1976).

134. Quinn R.M. and Hendershaw W.K. A Comparison of Current Membrane Systems Used in Ultrafiltration and Reverse Osmosis. *Ind. Wat. Eng.,* June/July, 12 (1976).

135. Sammon D.C. and Stringer B. The Application of Membrane Processes in the Treatment of Sewage. *Process Biochem.,* March, 4 1975.

136. Bailey D.A., Jones K. and Mitchell C. The Reclamation of Water from Sewage Effluents by Reverse Osmosis. *Wat. Polln. Cont.* **73** (4) 353 (1974).

137. Lim H.S. and Johnston H.K. Reverse Osmosis as an Advanced Treatment Process. *J. WPCF* **48** (7) 1804 (1976).

138. Vesilind P.A. Treatment and Disposal of Wastewater Sludges. Published by Ann Arbor Science. (1974).

139. Imhoff K., Müller W.J. and Thistlethwayte D.K.B. Disposal of Sewage and other Waterborne Wastes. Published by Butterworths, 2nd edition, London (1971).

140. Fair and Gayer. Water Supply and Wastewater Disposal. Published by John Wiley and Sons, New York (1966).

141. Institute for Water Pollution Control — Unit Processes. Primary Sedimentation. Manual of British Practice in Water Pollution Control. IWPC London (1973).

142. Van der Emde W. Private Communication. (1976).

143. Hopwood A.P. and Downing A.L. Factors Affecting the Rate of Production and Properties of Activated Sludge in Plants Treating Domestic Sewage. *J. Proc. Inst. Sew. Purif.* **5** 435 (1965).

144. Karr P.R. and Keinath T.M. Influence of Article Size on Sludge Dewaterability. *J. WPCF,* **50** 1911, August, 1978.

145. Ohara G.T., Raksit S.R. and Olson D.R. Sludge Dewatering Studies at Hyperion Treatment Plant. *J. WPCF* **50** 912, May, 1978.

146. Walton E. Practical Aspects of Primary Lime Treatment. *Wat. Polln. Cont.,* **75** (3) 353, (1976).

147. Huang J. and Tsai K. New Design Criteria for the Aerobic Digestion of Sewage Lime Sludge. *Prog. Wat. Tech.* **10**, (1/2) 615 (1978).

148. Shelef G., Moraine R. and Sandbank E. Physico-chemical Treatment of Pond Effluents for Unrestricted Agricultural Reuse with Recovery of Algae as Protein Source: Pilot and Field Scale Experiments. *Prog. Wat. Tech.* **10** (1/2) 91 (1978).

149. Adams C.E. Disposal and Recovery of Sludges from Physical-Chemical Processes. Applications of New Concepts of Physical-Chemical Wastewater Treatment. Edited by Eckenfelder W.W. and Cecil L.K., and published by Pergamon Press Inc. (1972).

150. Engenheiros Consultores Projetistas, Ninham Shand and Partners, P.G.J. Meiring and Partners. Report on Proposals for Treatment and Disposal of Sewage Works Sludges. Report submitted to CAESB, Brasilia, February, 1978.

151. Westerhoff G. and Daly M. Water Treatment Plant Wastes Disposal — Part 2. *J. Am. Wat. Wks. Ass.* **66** (6) 379 (1974).

152. Obrist W. Cost and Hygienic Necessity of Sludge Pasteurization in Switzerland. Proc. Int. Atomic Energy Agency Symp. on 'Radiation for a Clean Environment', Munich, West Germany, 1975.

153. Burley M.J. and Bayley R.W. Sludge Disposal Strategy: Processes and Costs, *Wat. Polln. Cont.*, **76** (2) 205 (1977).

154. Smith L.S. Can Sludge Be Used Hygienically? *IMIESA*, **3** (1) 27 (1978).

155. Flanagan M. Direct Digital Control of Contra Costa Sanitary District Water Reclamation Plant. *Prog. Wat. Tech.*, **6** 550 (1974).

PART III
PLANT DESIGN GUIDELINES

CONTENTS

CHAPTER Page

CHAPTER 1

PLANT DESIGN AND ERECTION SEQUENCE

Laboratory and/or pilot plant scale experiments often comprise the initial step in the design of a water reclamation scheme but their necessity is questionnable for those areas in which *similar* reclamation schemes are already operational and from which design data may be obtained.

This chapter has nevertheless been included in the event that such experiments or studies are required.

1.1 LABORATORY AND PILOT PLANT SCALE EVALUATION

The process designer should ensure that, before the commencement of laboratory or pilot plant experiments, the wastewater to be treated is thoroughly characterized with respect to its organic, inorganic and microbiological constituents.

Once the wastewater has been so characterized, the process designer should draw up a rational but tentative combination of unit operations to produce a product water of the required quality. The configurations discussed in Part II, section 13 should assist in this regard when the wastewater is predominantly of domestic origin.

Laboratory experiments

Laboratory scale experiments generally have a threefold purpose:

- Evaluation of the treatability of the wastewater by biological and chemical means, separately and in combination.
- Evaluation of the efficacy of selected unit operations in the treatment of the waste (e.g. biological N and P removal, chemical flocculation and clarification).
- Establishment of preliminary design data for pilot plant design.

Simulation of complete process trains is seldom performed at laboratory scale but rather the performance efficacy of the more salient unit operations are assessed. The performance of these units over a range of influent hydraulic, organic and suspended matter loadings will enable an optimum operational range to be selected for the preliminary design of a pilot plant.

The frequency of sample collection and the range of analyses performed should be carefully controlled as meaningless samples and analyses result in unwarranted expense and effort.

The laboratory scale units (reactors, clarifiers etc.) should be robust, easy to maintain, be of transparent material construction and should be positioned in such a way that they are readily accessible.

Pilot plant experiments

Pilot plant experiments have a sixfold purpose:

- To evaluate and collect design data for the full scale reclamation plant.
- To establish the most cost effective combination of unit operations required to produce an effluent of the required quality.
- To assure the prospective users of the treated effluent, be they from industry, agriculture or members of the public, that a water of the required quality can indeed be produced.
- To train staff at the operating, maintenance and managerial level.
- To evaluate the authenticity of equipment suppliers' claims as to their products' performance. This information will be invaluable at the full scale plant tender adjudication stage (refer to section 1.4).
- To enable capital and running cost estimates to be made for the full scale plant for budgetary or loan purposes.

Capacity

Pilot plants should have capacities of greater than 50 m^3/d in order to reduce the problems frequently encountered in scaling up the results to full scale requirements.[1] There are obviously no limitations to maximum capacity, apart from funds and land area available.

Good results are not necessarily dependent on sophisticated instrumentation or on the use of expensive construction materials. Before deciding therefore upon the exact form of the plant, a basic decision as to its life expectancy should be made. If the pilot plant is to be used for only several months to a year prior to the design of the full scale plant, less expensive and less durable materials of construction should be considered.

However, if the pilot plant is to be maintained as a 'testing ground' for new operating procedures and/or treatment processes once the full scale plant is operational, then there is definite merit in considering the more expensive and durable materials.

Flexibility

The emphasis on the overall design of the plant should be one of 'flexibility', in that facilities to reroute liquor and sludge flows (i.e. by-passes etc.) and to adopt new or additional processes to the treatment sequence should be included.

An inherent failing of a great number of pilot plants is that the attention of the designer, and hence the operators, is generally focused only on the production of an effluent with a required quality, while the characteristics and disposal of the sludge by-product are virtually ignored.

As discussed in Part II, section 12, the treatment and disposal of sludges can account for a substantial portion of the overall costs of biological and advanced treatment plants. This, together with the fact that inadequate sludge handling facilities at the full scale plant stage may jeopardize its very existence, renders pilot scale sludge treatment experiments extremely important.

Pilot plants should therefore include selected unit operations for sludge thickening and dewatering studies.

Flow modes

The flow mode through a pilot plant should receive careful consideration at the design stage. Ideally provision should be incorporated in the design for steady rates of flow to be attained at the outset of the investigations, followed by variable rates at a later date for the purpose of establishing the flexibility in performance of the individual unit processes and operations.

1.2 PRELIMINARY PLANT LAYOUT

A number of factors require consideration before a preliminary layout of the biological and advanced treatment plants can be drawn up, namely:

(i) Selection of the site(s): The site should be carefully chosen and consideration given to the following aspects:

- Area available for future plant expansions.
- The proximity of the site to residential areas, particularly from an aesthetic and environmental point of view.
- The distance that the wastewater has to be conveyed together with the degree of complexity in establishing the conveyance system i.e. pumpstations, river crossings, road crossings etc.
- The distance the treated effluent has to be conveyed to the point(s) of reuse.
- The cost implications involved in supplying year round access and services (such as water, electricity etc.) to the site.
- The cost implications of providing communication facilities between the site and central offices situated off site.
- The ease with which the site can be fenced to deter would-be vandals. Security services will have to be planned and they are to a certain extent influenced by the topography of the site.
- The susceptibility of the site to natural disasters such as floods, earthquakes etc.

(ii) Soil conditions: The initial step in evaluating soil conditions is to consult a geological map of the area in which the site falls. Geological abnormalities or uncertainties should be followed up by either randomly selected 'trial pits' or a detailed geological survey of the site undertaken by a qualified geologist. Accurate assessment of soil conditions is of the utmost importance as they influence the founding of the civil structures.

(iii) Survey of site: The survey should be such that contour spacings are not greater than 0,5 m.

(iv) Sizing of units: This stage is based on the laboratory and/or pilot plant experiments or on data from existing plants.

(v) Hydraulic design: This stage involves the selection of pipe sizes, pipe routes and pump duties for transporting liquors and sludges to and from the components of the plant. This aspect is dependent not only upon the unit operations but also upon the soil conditions (i.e. the avoidance of poor soil areas, rock etc.) and the fall on the site.

(vi) Liaison with authorities: The authorities that are involved, either directly (e.g. municipalities) or indirectly (e.g. Department of Water Affairs), should be regularly informed of the progress on the preliminary layout.

1.3 CONSIDERATION OF TURN-KEY CONTRACTS

A 'turn-key' contract may be defined as a contract under which a single contractor undertakes to design and provide a complete operational plant. The single contractor is usually an equipment supplier and by subcontracting the construction side to a civil consultant and/or contractor he retains overall responsibility for the entire project.

The 'one-step' design and construct method should be viewed with great reservation when planning a dynamic, industrial type venture such as a water reclamation plant. Detailed process and operational considerations are of overriding importance to the subsequent performance of such a plant and it is therefore desirable that these considerations be the common point on which all tenders be based.

There is therefore definite merit in having a concise, well defined equipment specification prepared by an independent designer who has studied and optimized the specific process with its associated engineering and operational aspects. Such optimization would be achieved by visits to similar plants or through laboratory and/or pilot plant scale experiments.

1.4 TENDER ENQUIRY AND SUBSEQUENT ADJUDICATION

The tender enquiry document would contain the detailed specification for the equipment required for the reclamation plant and would list the relevant standards to which the equipment to be supplied must comply.

Adjudication of the completed tenders generally involves considerations of aspects such as:

- mechanical soundness
- efficiencies
- process guarantees
- operational complexity
- spare parts availability
- locally manufactured content
- delivery and erection periods
- civil structure costs
- elelctricity consumption related to present day worth
- commissioning

There are few suppliers in a position to offer the full range of equipment required for a water reclamation plant and as such it is very likely that there will be more than one successful tenderer. However, there is definite merit, from an administrative, financial and contractual point of view, in limiting the number of successful tenderers.

Having completed the adjudication the process designer should write his 'adjudication report' in which he motivates his recommendations and summarizes the financial implications thereof and recognises all qualifications by tenderers

The completed report is then submitted to the body who control the allocation of funds. This body generally comprises non-technical personnel and as such the report should be clear in both recommendations and financial implications.

1.5 FINAL PLANT LAYOUT

The final plant layout stage usually follows the formalizing of the contract between the client and the successful suppliers (the contractors).

The contractors should then be called upon to supply drawings detailing the geometric and foundation requirements for their equipment. These details are then incorporated into the preliminary plant layout (section 1.2), the hydraulic design is rechecked and the final plant layout is drawn up.

The detailed civil design stage now begins, including such items as roads, structures, services etc.

CHAPTER 2

UNIT OPERATIONS AND PROCESSES

2.1 THE BIOLOGICAL UNIT

The form of biological treatment that is either integrated with or precedes a physico-chemical plant is dependent not only upon the quality of secondary effluent required but also upon the configuration of the physico-chemical plant.

For example, should the biological treatment unit precede chlorine disinfection and activated carbon adsorption stages there is definite merit, both in terms of economics and effluent quality, in employing a long SRT activated sludge system that incorporates the biological removal of nitrogen (refer to Part II, sections 5.2, 6.1, 6.2 and 10.1).

The biological removal of phosphorus need not be incorporated (in the biological treatment unit) in those instances where chemical clarification of the raw sewage, or lime treatment of the secondary effluent, is to be practised. However, it should be considered where secondary effluent coagulation and clarification is achieved through the use of mineral salts, as the chemical cost could be reduced by so doing (refer to Part II, section 10.2).

The design of the biological treatment unit has been well documented in the literature referring to sewage treatment and as such only the more salient points that should be considered in the design of an activated sludge plant incorporating both nitrogen and phosphorus removal are listed below:

- necessity of sewage flow balancing
- necessity of primary sedimentation
- temperature dependency of the nitrifying organisms
- selection of the system solids retention time (SRT)
- method of SRT control
- methods of aeration and the corresponding efficiencies (in terms of kg oxygen transferred/kW.h electricity consumed)
- mixed liquor recycle rate and methods of achieving same
- selection of method of mixing for anaerobic and anoxic zones
- sizing of clarifiers
- sludge treatment and disposal

2.2 CLARIFIERS

Primary biological settling tanks

Primary settling tanks preceding biological systems are generally of the scraped, sloping floor type although the Dortmund type does find application on small scale plants. Suction type sludge removal mechanisms are never used on account of the nature of the primary sludge.

Rectangular tanks are used extensively overseas for primary settlement but there appears to be a preference in South Africa for circular primary tanks.

Area requirements for low rate, conventional primary settlement (i.e. 60 — 65% suspended solid removal) may be based on the hydraulic loadings of 1,2 $m^3\ m^{-2}h^{-1}$ at average dry weather flow or 2,4 $m^3\ m^{-2}h^{-1}$ at peak dry weather flow, whichever results in the largest area.

When primary settling tanks are followed by an activated sludge system, it is common for the tanks to be sized with higher hydraulic loadings (2,0 $m^3\ m^{-2}h^{-1}$ and 4 $m^3\ m^{-2}h^{-1}$ at average and peak weather flow conditions respectively) than usual — the so-called 'high rate' settling tanks. This is due to the fact that the added cost of the larger conventionally sized settling tanks usually cannot be offset against the slight decrease in installed aeration capacity (in the activated sludge system) resulting from the increased efficiency of these larger tanks.

Side wall depths of primary settling tanks are usually 3—4 m and the settled sludge is discharged intermittently, usually at a concentration of 1,5 — 2,5% dry solids.

Activated sludge clarifiers — area requirements

Clarifiers in a long SRT activated sludge system, that incorporates biological N and P removal, may be sized on an upflow velocity of 1,5 $m\ h^{-1}$ at peak plant inflow conditions or a maximum solids loading of 9,5 $kg\ m^{-2}h^{-1}$ based on peak plant inflow plus peak recycled sludge flow, whichever results in the greater area. (Sludge recycle rates of 0,5 to 1,5 times the average daily design flow are usually employed).

Clarifier area requirements for low SRT systems may be sized on a peak upflow velocity of 1,0 $m\ h^{-1}$ and/or a solids loading of 5,0 $kg\ m^{-2}h^{-1}$.

Chemical clarifiers — area requirements

Chemical clarifier area requirements may be sized on an upflow velocity of 1,5 — 2,0 $m\ h^{-1}$, the lower value referring to mineral salt applications and the higher value to lime applications.

Clarifier depth

Clarifiers for both activated sludge and chemical sludge applications are generally 3 to 4 m deep at the vertical side wall.

Rectangular clarifiers

Rectangular clarifiers have found application, albeit on a lesser scale than circular tanks, in activated sludge and chemical applications.

They generally require less gross land area than circular tanks and although the rectangular tanks are simpler to construct they are less suitable than circular tanks when poor soil conditions pertain.

The tanks generally have length to width ratios of not less than 6:1 and depths of 3 — 4 m.

Sludge collection and removal in rectangular clarifiers have presented serious problems through the years, particularly where the scrapers are chain-driven. However, recent developments have eradicated a number of the faults but great care should still be attached to this aspect of rectangular clarifiers.

A further problem arises in the case of rectangular suction-type clarifiers in activated sludge applications in that the 'lifts' cannot be arranged to vary the lifting of the sludge according to the distribution of the deposited sludge on the floor. Most of the sludge will be deposited in the first third of the basin and very little near the end. In circular tanks, it is possible to adjust the lift from each of the down pipes so that the maximum quantity of sludge is returned at the shortest possible retention in the clarifier. Once the lift pipes are adjusted, correctly, little further adjustment will be required. This adjustment is not readily achieved in a rectangular tank and two or three sweeping mechanisms may be required, each desludging a different zone of the clarifier.

Narrow rectangular tanks will not be unduly influenced by wind action, provided that they are orientated cross-wind. Wind blowing along the length may cause wave action, stirring up the solids and preventing good sedimentation.

In order to keep weir velocities within reasonable limits, overflow weirs for rectangular clarifiers are usually placed along the downstream two thirds of the basin, plus another one in the centre of the basin. It is therefore virtually impossible to install scumboards in this type of tank, this being a disadvantage in activated sludge applications treating unsettled sewage.

Inlets — circular tanks in biological sludge applications

The inlet arrangement to a circular clarifier usually takes one of two forms: a central stilling well or peripheral inlets — the so-called 'Rimflow' system. Both systems have been used for activated sludge and can be expected to produce similar results but the peripheral feed system does have some advantage in high wind applications.

Stilling wells should be so designed that they dissipate the energy of the incoming stream, distribute the flow evenly over the entire area of the tank and thereby reduce short-circuiting. This well should occupy at least 15% of the overall surface area of the tank and should have slots with baffles to distribute the flow.

Inlets — circular tanks in chemical sludge application

Central stilling wells are generally employed for chemical clarifiers and there does not appear to be any hard and fast rule as to their size, apart from a 15% minimum relative surface area. Some clarifiers have a very large well to serve not only as an energy dissipator but also as a flocculation zone.

While submerged inlets may be suitable for those applications in which mineral salts are the coagulants, an open launder discharging into the top of the stilling well is preferred for lime treated effluents — particularly in the high lime treatment process — as scale formation can be readily controlled in this instance.

Inlets — rectangular tanks

Submerged slots and/or weirs appear to afford the best results for rectangular tanks.

Scum collection and removal

Experience in South Africa indicates that activated sludge clarifiers should be equipped with scum collection and removal facilities but that such facilities are not required for chemical clarifiers.

The facilities include peripheral scum baffles, radial scum sweepers and scum discharge boxes. The discharge boxes should be mounted just below minimum top water level and should be connected by means of a suitably sized pipe to a control valve which is activated automatically by electronic or pneumatic means or by an actuator arm mounted on the scraper mechanism. On each actuation the flow of effluent through the pipe should be such as to draw the collected scum into the box and away from the tank.

Weirs and launders

It is common practice for launders on very large activated sludge clarifiers to be inset from the periphery of the clarifier, with 'V-notch' weir plates mounted on each side.

The shallow depth of flow in the launders render them ideal algal growth sites and steps such as covering or brushing the launders are usually taken to reduce such growths. Brushing may be carried out by labourers or by attachiung suitably sized and positioned brushes to the scraping mechanism, usually the bridge.

High rate chemical clarifiers are often equipped with radial launders and weirs, thereby enabling higher hydraulic loadings to be applied.

Sludge collection and removal — activated sludge

Settled activated sludge is either gently scraped along the clarifier floor to a central hopper from where it is discharged hydrostatically or it is 'lifted' from the floor by suction-type scrapers which operate on a siphon principle.

Scraped tanks generally have floor slopes of 1:6 — 1:12, sloping from the vertical side walls to a hopper which is centrally situated in the case of circular tanks or at the inlet in the case of rectangular tanks while suction lift tanks generally have flat floors.

Circular tanks of up to 30 m diameter are usually of the scraped form, while larger diameter tanks are generally of the suction form. A disadvantage of the suction type tank is that the sludge underflow concentration is generally low (i.e. below 0,75% dry solids) whereas in a scraped tank, following a biological N and P removal plant, sludge concentrations of up to 1,5% can be obtained.

Settled activated sludge is continuously discharged from the clarifier and returned to the biological reactor.

Sludge collection and removal — chemical sludges

Scraped tanks are preferred for chemical clarifiers and they have much the same design as for activated sludge systems.

Chemical sludges resulting from the treatment of raw sewage or secondary effluents should be recycled, either internally or externally, in order to reduce the coagulant dosages.

Experience gained at the Stander Plant indicates that both external recycling and operating the clarifier on the sludge blanket principle offer distinct operational advantages.

The design of the actual sludge draw-off system should be carefully considered as, in the case of the high lime treatment process, the draw-off pipe should be accessible for regular removal of any scale or deposits.

The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 2 for further discussion on the sludge removal system of chemical clarifiers.

Drive mechanism

The drive motor and gearbox must be rated for the intended duty. Although similar clarifiers may be used for activated and chemical sludges, cognisance should be taken of the increased quantities of chemical sludges which in some instances (e.g. lime sludge) can compact to a higher solids content than activated sludges.

All drive mechanisms should be equipped with a form of overload protection.

Two forms of circular tank mechanism drives are available, one in which the motor is situated in the centre of the tank (a centre drive unit) and the other where the motor drives a wheel around the periphery of the tank (a peripheral drive unit).

A centre drive unit usually comprises a fixed access bridge with the rotating collection mechanism being suspended from a centrally situated rotating cage, while a peripheral drive unit usually comprises a rotating bridge, which can span either the radius or diameter of the tank, and from which the mechanism is suspended. A centre drive unit is generally more expensive on account of increased torque loads.

Scraper speed

The peripheral speed of the sludge collection mechanism in a circular tank, and the longitudinal speed in a rectangular tank, should not be greater than 1,5 to 2,0 m min^{-1} for both activated and chemical sludges as speeds greater than 2,0 m min^{-1} may well lead to resuspension of the settled sludge particles.

2.3 FILTERS

The filtration step can be achieved by slow sand filters, rapid gravity filters, pressure filters, dual or multimedia filters, upflow sand filters and micro-straining.

The theory of filtration, together with typical details and design criteria of slow sand, rapid gravity, pressure, dual and multimedia filters are covered in the 'Manual for Water Reclamation and Renovation', Chapter 6 and as such are not reproduced here. Upflow filters and micro-strainers are however discussed and the data presented should be regarded as a supplement to the above-mentioned reference.

The reader is referred to the literature for further details such as the underdrainage system for rapid gravity filters, backwashing requirements, filter flow control systems etc.[2,3,4]

Upflow filters

Upflow filters generally contain filter media consisting of anthracite and sand, graded with the coarser particles at the bottom. The influent to the filter passes up through the coarser media then through the fine media before being discharged via suitably positioned troughs.

Hydraulic loadings are usually 15 m^3 m^{-2}h^{-1} for a good quality secondary effluent. Filter media cleaning is achieved by lowering the water level to a point just above the sand surface and vigorously aerating the bed, thereby releasing the organic material retained in the interstices of the media. The wastewater flow is then increased to some 35 m^3 m^{-2}h^{-1} whereupon the filter 'bed' expands to 1,2 times its normal volume. As the incoming wastewater is utilized as washwater, no separate washwater tanks or pumps are required.

Suspended solids and BOD removals of 80 and 60% respectively have been reported for such installations.[5]

Microstrainers

Microstrainers consist essentially of a rotating drum, the surface of which is formed by a stainless steel or polymeric fabric of very fine mesh. The wastewater is discharged inside the drum and flows radially outward through the fabric. Provision to backwash the fabric continuously with high pressure jets of clean water is incorporated, with the backwash water and displaced solids being collected by a trough suitably positioned in-

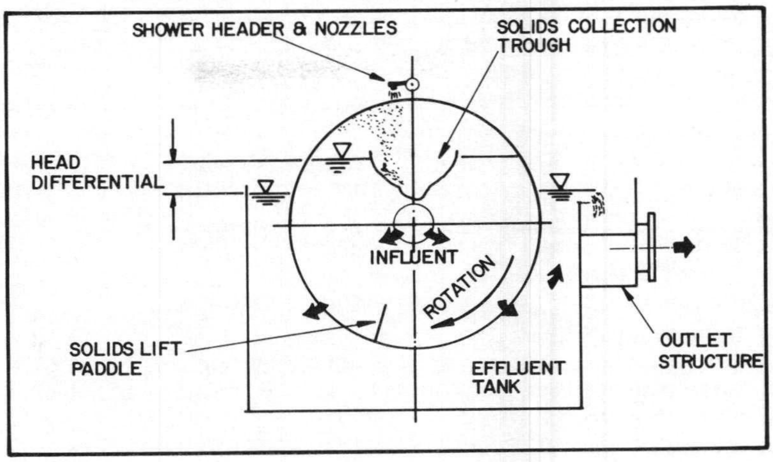

FIGURE 3.1: Details of a typical microstrainer[6]

side the rotating drum. Figure 3.1 indicates details of a typical microstrainer.

Microstrainers are usually designed on the basis of a maximum hydraulic loading which can range from 300 to 700 m^3 m^{-2} of fabric per day depending upon the grade of fabric used. Factors that affect the selection of mesh size and hydraulic loading are:[6]

- required effluent quality, and
- characteristics of the feed.

Microstraining drums range in diameter from 1 to 3 m and in length from 0,3 to 4,5 m. Fabric is available in mesh sizes ranging from 90 to 390 apertures per mm^2 (65 — 15 μm openings) and should be protected against hydraulic overloading by an overflow weir linking the inlet channel to the effluent chamber. This weir should come into operation if the differential head rises to above 150 mm, so that the removal efficiency and effluent quality is not affected.

Results from the UK[5] and USA[7] indicate that suspended solid removals of 30 — 80% and BOD removals of 27 — 70% have been achieved. The use of microstrainers to remove suspended matter from humus tank and maturation pond effluents was investigated at Windhoek, SWA/Namibia and the results indicated that microstraining was not particularly effective, especially when treating maturation pond effluent.[8] Microstrainers would seldom be considered for the filtration stage in a physico-chemical reclamation plant.

2.4 RECARBONATION UNITS

The recarbonation step serves to reduce the high pH values of high and low lime treated effluents to values acceptable for discharge not only to the reticulation system but also to the subsequent forms of treatment.

This pH reduction is achieved through the addition of carbon dioxide (CO_2) to the effluent, either by artificial means in stirred reactors or by natural means in shallow lagoons or ponds.

Artificial recarbonation offers more control opportunities than the natural form and as such has found a greater application.

Artificial recarbonation

Artificial recarbonation may be achieved by one or two stages of CO_2 addition. The latter form is generally only used in instances where effluent softening is required and consists of two CO_2 reactors with an intermediate settling tank.

The single stage installation reduces the pH to the desired value in one step whereas in the two stage setup the pH is initially reduced to 9,5 in the first stage, the precipitated $CaCO_3$ settled out in the settling tank (usually with the aid of a coagulant) and the pH then further reduced to the desired value in the second stage where bicarbonates are formed.

The final pH should be such that the product water is in equilibrium with respect to calcium carbonate for a stable effluent.

Single stage recarbonation has been installed at the Stander Plant, Pretoria and consists of a continuously stirred tank with a hydraulic retention time of 15 min, during which time the pH is reduced from 11,0 to 8,5. Bottled CO_2 is introduced into the effluent by means of a static mixer positioned just upstream of the tank.[9,10]

Typical hydraulic retention times for two stage recarbonation installations have been reported as being 5 to 15 min for the two CO_2 reactors and 30 to 50 min for the settling tank.[11,12]

The settling tank should receive a hydraulic loading not exceeding 4 m^3 $m^{-2}h^{-1}$ and should be equipped with continuous sludge collection and removal equipment.[12]

CO_2 can be produced *in situ* by burning hydrocarbons or purchased in bulk pressurized containers (refer to Part 2, section 3.8), with the latter form gaining popularity for reasons of cost and operational simplicity. A serious disadvantage of the former alternative, particularly when dieselene is burnt, is that the combustion byproducts are also dispersed into the water and taste, odour or toxicity problems could result.

When bulk CO_2 is used, it should be borne in mind that the storage vessels are under high pressure and should be protected from fire and impact. In addition, they should be situated on the perimeter of the plant both for ease of accessibility, and as an extra safety precaution against the discharge of CO_2 on site. CO_2 is not poisonous, but, since it has a higher density than air, it can displace air and cause suffocation. For this reason, these vessels should not be built in confined quarters. (When ammonia stripping towers were used at the Stander Plant, CO_2 in the atmosphere also had to be limited to the very minimum to minimize the scaling effect on the packing material).

The CO_2 dosage rate should be automatically controlled, usually by means of suitably positioned and selected pH sensors and associated equipment. Bulk CO_2 storage and feeding is more amenable to automatic control than the alternative of burning hydrocarbons.

The quantity of CO_2 required for recarbonation may be estimated by graphical means[9,13] (the modified Lawrence-Caldwell diagram) once the initial parameters of pH, calcium, alkalinity and total dissolved solids have been determined.

The reader is referred to the literature for details of CO_2 contacting systems, CO_2 pipework and diffusion systems.[2]

Natural recarbonation

Natural recarbonation of high pH effluents has been investigated at reclamation plants in Israel, where it was found that significant pH reductions could be achieved after a 14 day retention in shallow ponds.[14]

The pond effluents did however still require artificial recarbonation to achieve the pH values required for stability (pH 8,0 — 8,5), but with CO_2 doses of only about one third of those required when the ponds were excluded.

2.5 ACTIVATED CARBON ADSORPTION

The important role that activated carbon adsorption plays in a water reclamation plant designed for integration with potable supplies is discussed in Part II, section 6.1.

The process design of a carbon adsorption system entails establishing the following process parameters:

- The type of contacting system (i.e. granular or powdered carbon).
- The mode of operation of the contacting system (i.e. counter-current moving bed, expanded bed upflow, packed bed upflow, upflow—downflow, fixed bed downflow).
- The type of activated carbon.
- The contact time required to ensure that the desired product quality is attained, the carbon loading rate attainable and the corresponding carbon exhaustion rate.

Type of contacting system

The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 9 for a discussion on the merits and demerits of the granular and powdered carbon contacting systems. However, suffice it to state that at present granular carbon systems appear to be the most cost effective form of contacting for water reclamation plants.[15]

Mode of operation

There are a number of modes of operation for granular carbon systems, all of which have been operated at various plants throughout the world.

Countercurrent moving bed

The countercurrent moving bed mode involves passing the process water up through either a slightly expanded or a packed bed of carbon. Fresh carbon is fed intermittently to the top of the bed, while spent carbon is withdrawn in slugs from the bottom. The density of the carbon increases as it becomes more saturated with adsorbed organic material and only the most saturated carbon is withdrawn from the column. This countercurrent flow results in the lowest carbon dosage rate of all the modes of operation, but it does have some disadvantages with respect to water reclamation.[15]

- The column effluent contains carbon fines after each pulsing operation.
- The columns are not emptied during normal operation; therefore inspection or repairs can only be carried out by taking an adsorber off line.
- No significant filtration effect is obtained during normal operation when the carbon bed is slightly expanded.

Figure 3.2 shows details of normal flow paths through the countercurrent flow adsorbers installed at the South Tahoe PUD Water Reclamation Plant.[11] Backwash facilities are generally also incorporated and are used after a major transfer of carbon to clear the carbon bed of excessive fines which would otherwise be discharged with the carbon column effluent.

Expanded bed upflow

The expanded bed upflow mode involves process water upflow through an expanded bed which remains in the column until it is exhausted and breakthrough occurs, at which time the carbon is removed for regeneration.

Upflow expanded beds have advantages over the upflow packed bed and fixed bed downflow alternatives, namely:

- Waters with relatively high suspended solids contents can be treated.
- Finer carbons can be used without creating excessive headloss.[16]

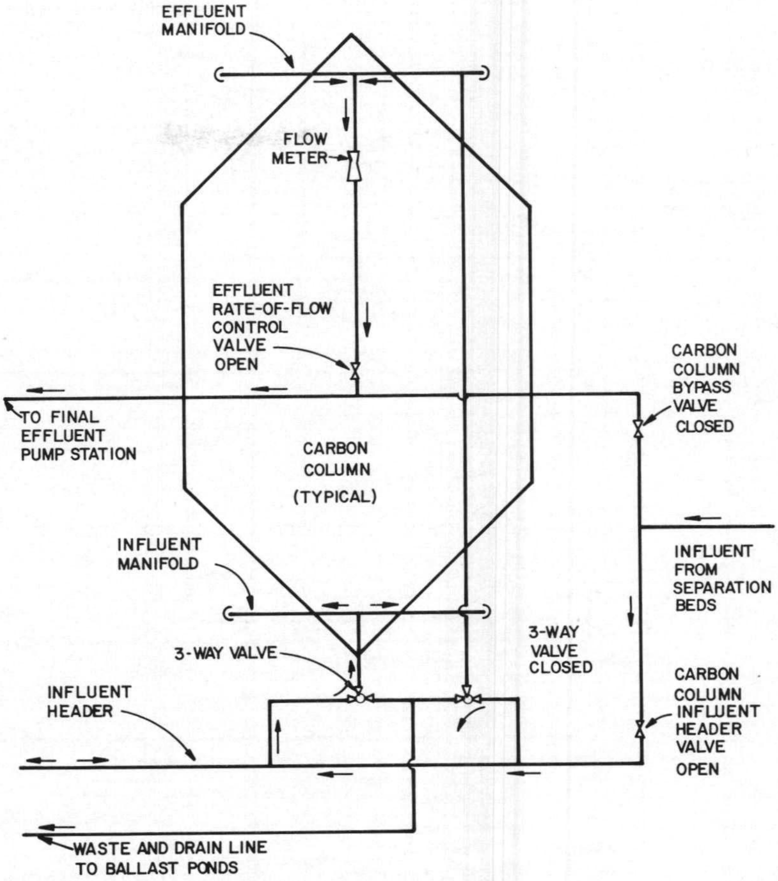

FIGURE 3.2: **South Tahoe carbon columns — normal upflow operation**[11]

- The finer carbons enable a reduced contact time to be used.[16]
- Frequent backwashing is not required.[15]

However, the fact that a significant filtration effect is not included represents a serious disadvantage when applied in the water reclamation context.

Packed bed upflow

The packed bed upflow mode is similar to that of the expanded bed upflow, except that the carbon bed is not expanded (i.e. hydraulic loading is not sufficient to create bed expansion).

This mode of operation is only suitable for waters of low turbidity (less than 2,5 JTU[2]) and it requires the use of a coarser carbon than is used in the expanded bed form.[16]

Sufficient freeboard of at least 40 per cent should be left above the top surface of the carbon bed to enable the bed to be occasionally expanded (through imposing higher hydraulic loads) to dislodge any material collecting at the bottom of the bed.[16] Separate backwashing facilities are occasionally also provided.

Fixed bed downflow

The fixed bed downflow mode differs from the upflow modes in that the process water is passed downwards through a compacted bed of carbon. Accordingly a substantial filtration effect is obtained in addition to the adsorption of the organic material.

Biological growths develop on the carbon, especially if the carbon is preceded by an ozonation step, (refer to Part II, section 6.1 and 6.2) and these growths together with the filtering effect of the compact carbon bed necessitate frequent backwashing in order to prevent excessive head losses being created. Experience at the Stander Plant has shown that backwashing at weekly intervals is sufficient.[15]

Figure 3.3 indicates the proposed mode of operation of the fixed bed downflow carbon adsorption columns installed at the Cape Flats Reclamation Plant, where each column will be used alternatively as a secondary (polishing) unit, a primary (roughing) unit and eventually as the unit to be regenerated.

Single stage adsorption is seldom used as the carbon cannot be operated to saturation but rather to breakthrough of a relevant control parameter; thereby resulting in under utilization of the adsorptive capacity of the carbon.

In a two or multi-stage system, the first stage can be operated beyond breakthrough until saturation of the carbon is attained, thus utilizing the full capacity of the carbon for the given feed condition. In this mode the saturated first stage is then regenerated and the partially saturated second stage becomes the first stage.

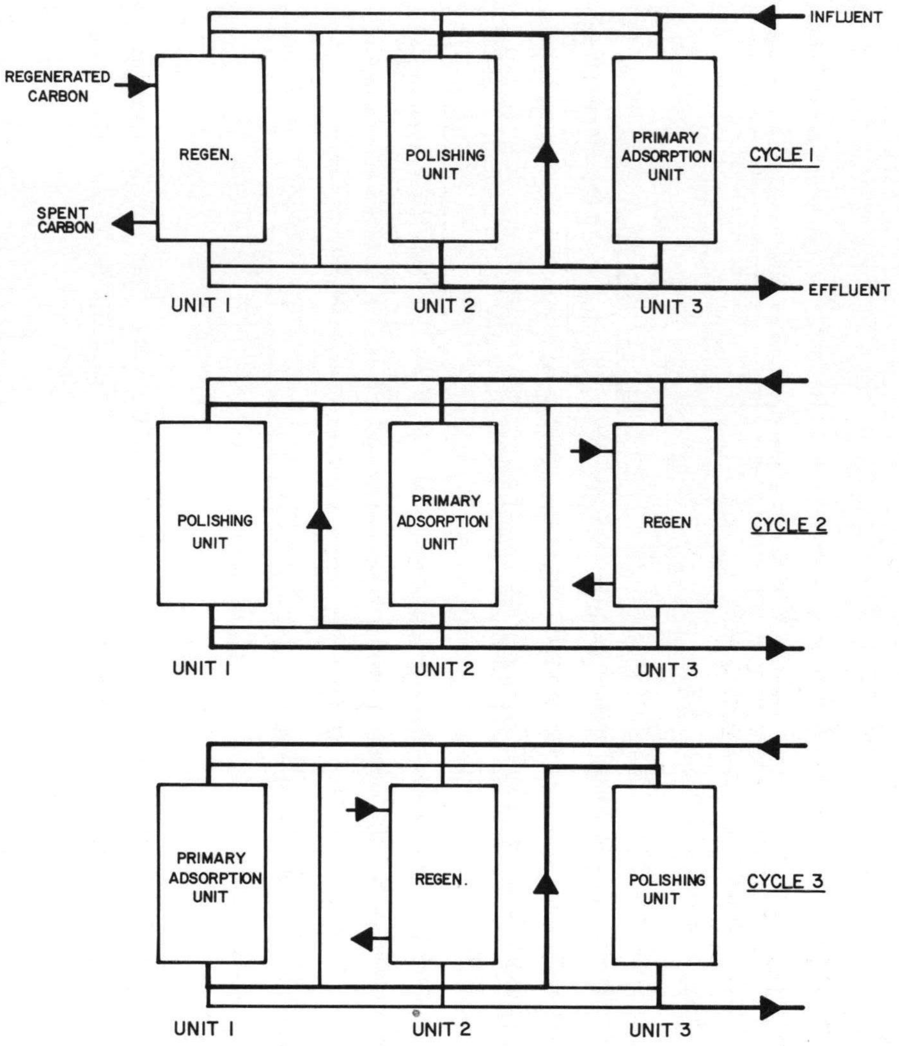

FIGURE 3.3: **Proposed mode of operation of granular carbon contacting system**

As many options are open, the optimization will take into account operating ability and flexibility in addition to capital and operating costs.

Upflow-downflow

The upflow-downflow mode of operation involves preceding a fixed bed downflow polishing stage with an expanded bed upflow roughing stage. Figure 3.4 indicates a layout of a typical upflow-downflow system.[17] Once breakthrough occurs in the downflow polishing column, the pair of columns are taken off line, the spent upflow column regenerated and the unused capacity of the downflow column is used by reversing the flow and employing it as the upflow reactor, using the former upflow column containing regenerated carbon as the downflow polishing unit.

The expanded bed roughing unit provides more particle movement and therefore less accumulation of biological growths on the activated carbon, while the fixed bed downflow polishing unit will retain growths that are carried over from the primary unit, while at the same time adsorbing residual organic compounds.

Backwashing of carbon columns

The frequency of backwash is dependent upon the column hydraulic loading, the nature of the process water influent (i.e. organic matter content, suspended solids content, turbidity etc.), the carbon particle size and the mode of operation (i.e. fixed bed downflow invariably requires more frequent backwashing than expanded bed upflow).

Backwashing serves the purpose of controlling the head loss through the carbon bed through removing captured solids, carbon fines and excessive biological growths.

Experience in the USA has indicated that where biological growths are encouraged on the activated carbon, a vigorous air scour before the backwash is required to prevent adverse build-up of such growths.[18]

However, as the air scour can cause carbon parti-

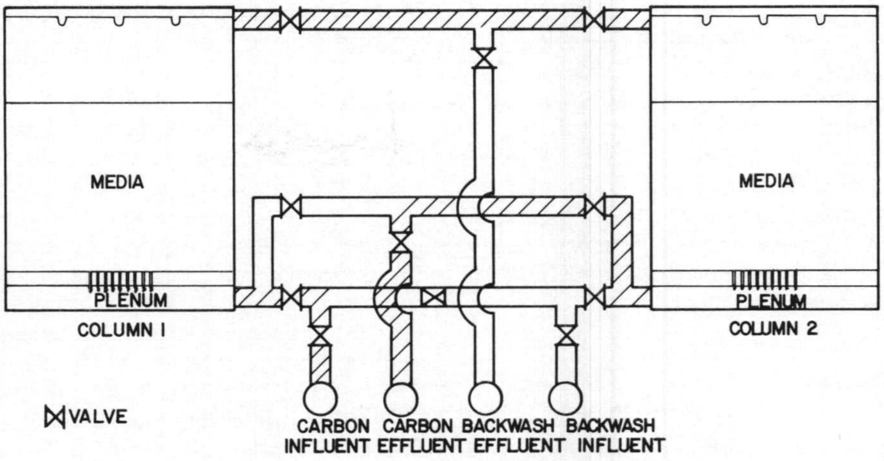

FIGURE 3.4: Typical upflow-downflow mode of contacting[17]

cle attrition, care must be taken in the selection of the type of carbon to be used (refer to discussion below).

The reader is referred to the literature[15,16] for further details of carbon column backwashing.

Discussion on the mode of operation

Conclusions reached from South African experience is that fixed bed downflow contactors are best suited for water reclamation, due primarily to their capacity to both adsorb and filter.[15]

These findings, however, are based on experience gained from relatively small scale plants (i.e. 5 Mℓ/d) and it is possible that continuous or pulsed countercurrent systems may find favour in large scale applications on account of the reduced carbon inventory.

The advent of preozonation and controlled biological growths also suggest that the upflow-downflow system may find favour for future applications.

Type of activated carbon

The correct application of activated carbon as a unit process in a water reclamation plant requires the selection of a carbon suited for the intended duty.

The most important test parameters for the initial screening of a number of prospective carbons, together with the minimum requirements thereof, are listed in Part II, section 3.9 and the 'Manual for Water Renovation and Reclamation', Chapter 9.[15]

For those applications in which a vigorous air scour will be used (refer to the foregoing discussion on column backwashing), cognisance should be taken of the abrasion resistances of the carbons and experience has shown that bituminous-coal based carbons are clearly superior for such applications.[18]

Required contact time

The required contact time, the carbon loading rate and the corresponding exhaustion rate should be evaluated through extensive laboratory and/or pilot scale experiments.

Methods for conducting these experiments and for analysing the results are adequately described in the literature and as such are not reproduced here.[2,15,16]

Specific adsorber height, adsorber diameter, number of adsorbers and number of trains are normally established after consideration has been given to hydrodynamic and economic factors.

A method for obtaining the most cost effective combination of carbon columns is presented in Chapter 9 of the 'Manual for Water Renovation and Reclamation'.

Carbon loadings

Carbon loadings and exhaustion rates attained in the

TABLE 3.1 CARBON LOADINGS AND EXHAUSTION RATES ATTAINABLE IN THE TREATMENT OF HIGH LIME TREATED BIOFILTER HUMUS TANK EFFLUENT AND LOW LIME TREATED ACTIVATED SLUDGE EFFLUENT AT THE STANDER PLANT[15]

Parameter	High lime treated biofilter humus tank effluent	Low lime treated activated sludge effluent
Carbon loading, kg COD removed per kg carbon (minimum)	0,12	0,12
Carbon exhaustion rate, kg carbon per 1 000 m^3 water treated	65	65
Typical percentage COD reduction through two stages (e.g. 20 down to 12 mg/ℓ COD)	40	40

treatment of high lime treated biofilter humus tank effluent and low lime treated activated sludge effluent at the Stander plant, Pretoria are given in Table 3.1.[15]

The results shown in Table 3.1 were obtained with a Type A, 8 x 30 mesh carbon (refer to Part II, section 3.9). Should a substantially different type of water be considered (e.g. alum or ferric chloride flocculated secondary effluent) or should the use of a lower grade carbon be envisaged, a new set of process design parameters (i.e. contact time and carbon exhaustion rate) will have to be developed.[15]

Carbon column design

Table 3.2 summarizes typical carbon column design criteria of a number of tertiary treatment installations in the USA and South Africa.[15.16.17]

Materials of columns construction and corrosion protection

Carbon columns are usually fabricated from mild steel with a suitable internal corrosion protection coating or lining, as partially dewatered carbon is extremely corrosive (as well as being abrasive).

Epoxy tar was applied to the interiors of the original columns at the South Tahoe plant to a dry film thickness of some 200 μm[11] but after a three year period serious pitting of the steel was observed.[11.19] The column interiors were again sand blasted and then coated with an improved epoxy tar to a dry film thickness of 450 — 600 μm,[2.11] which proved adequate protection.

Hard rubber linings have been successfully used[15] but such linings can become brittle after prolonged exposure to ozone in installations where ozonation precedes the carbon adsorption stage.

TABLE 3.2 CARBON COLUMN DESIGN CRITERIA[15.16.17]

Site	Contactor Type	No. of Contactors in series	Total Empty Bed Contact Time (min)	Hydraulic Loading $(m^3\ m^{-2}h^{-1})$	Total Carbon Depth (m)	Carbon Size	Effluent Requirements (Oxygen Demand)
Arlington, Virginia	Downflow Gravity	1	38	7,1	4,6	8 x 30	BOD < 3 mg/ℓ
Colorado Springs, Colo.	Downflow	2	30	12,2	6,1	8 x 30	BOD < 2 mg/ℓ
Dallas, Texas	Upflow Packed	1	10	19,6	3,0	8 x 30	BOD < 10 mg/ℓ BOD < 5 mg/ℓ (by 1980)
Fairfax County, Va.	Downflow Gravity	1	36	7,3	4,6	8 x 30	BOD < 3 mg/ℓ
Los Angeles, Calif.	Downflow Gravity	2	50	9,8	7,9	8 x 30	COD < 12 mg/ℓ
Montgomery County, Md.	Upflow Packed	1	30	15,9	7,9	8 x 30	BOD < 1 mg/ℓ COD < 10 mg/ℓ
Occoquan, Va.	Upflow Packed	1	30	14,2	7,3	8 x 30	BOD < 1 mg/ℓ COD < 10 mg/ℓ
Orange County, Calif.	Upflow	1	30	14,2	7,3	8 x 30	COD < 30 mg/ℓ
Piscataway, Md.	Downflow Pressure	2	37	15,9	9,8	8 x 30	BOD < 5 mg/ℓ
St. Charles, Missouri	Downflow Gravity	1	30	9,0	4,6	8 x 30	
South Lake Tahoe, Calif.	Upflow Packed	1	17	15,2	4,3	8 x 30	BOD < 5 mg/ℓ COD < 30 mg/ℓ
Garland, Texas	Upflow Downflow	2	32	11,5	3,0	—	COD < 15 mg/ℓ BOD < 10 mg/ℓ
Windhoek, South Africa	Downflow Pressure	2	30	9,3	4,6	12 x 40	COD < 10 mg/ℓ
Stander Plant, South Africa	Downflow Pressure	2	30	15	4,0	8 x 30	COD < 12 mg/ℓ

The carbon columns at the Stander Plant are lined with an abrasion resistant epoxy enamel (Copon), but to date no attempt has been made to assess whether this form of coating is adequate.

Glass fibre reinforced polyester (bis-phenol A type) has been found to be particularly effective.[15]

Flow distribution and collection system

Screens of type 304 or 316L stainless steel and nozzles of polypropylene or ABS manufacture have found use in column flow distribution and collection systems.

Nozzles of both materials have been used in the collection system of the columns of the Stander plant where it has been found that the polypropylene nozzles tend to become brittle after some 5 — 6 years of operation.[20]

The reader is referred to the literature for further discussion on this important facet of activated carbon column design.[2,15,16]

Further discussion

Factors such as carbon transportation, carbon inventory, pipeline material, valve selection, personnel requirements etc. are all adequately covered in the 'Manual for Water Renovation and Reclamation', Chapter 9,[15] and the literature[2,16,19] and as such are not repeated in this guide.

Typical carbon handling schemes

Although the abovementioned references do consider carbon storage and handling systems, Figure 3.5 has been included to indicate the carbon handling scheme installed at the Cape Flats reclamation plant.

Virgin or regenerated carbon is transferred by means of a bucket elevator to a mild steel storage hopper which discharges via a vibrating screw feeder into a mild steel carbon slurry sump. The screw feeder is hydraulically operated and has a variable output.

The virgin or regenerated carbon is transferred to the carbon columns in slurry form (100 g carbon per ℓ water) by a centrifugal pump having a rubber lined casing and impeller. Spent carbon is transferred by means of the same pump to a vibrating dewatering screen after which it is stockpiled.

The carbon columns are internally lined with hard rubber laminated sheet while the other storage tanks are all internally coated with epoxy tar to a total dry film thickness of some 325 μm.

2.6 CHLORINATORS

This section should be read in conjunction with Chapter 7, of the 'Manual for Water Renovation and Reclamation'.[21]

The extensive use of chlorine for disinfection and ammonia removal purposes has resulted in the development of reliable feeders (chlorinators) and methods of contact and dosage control.

Chlorine containers

Chlorine for commercial use is liquified under pressure and transported in 68 kg cylinders or one ton containers. Cylinders are of seamless steel with a valve con-

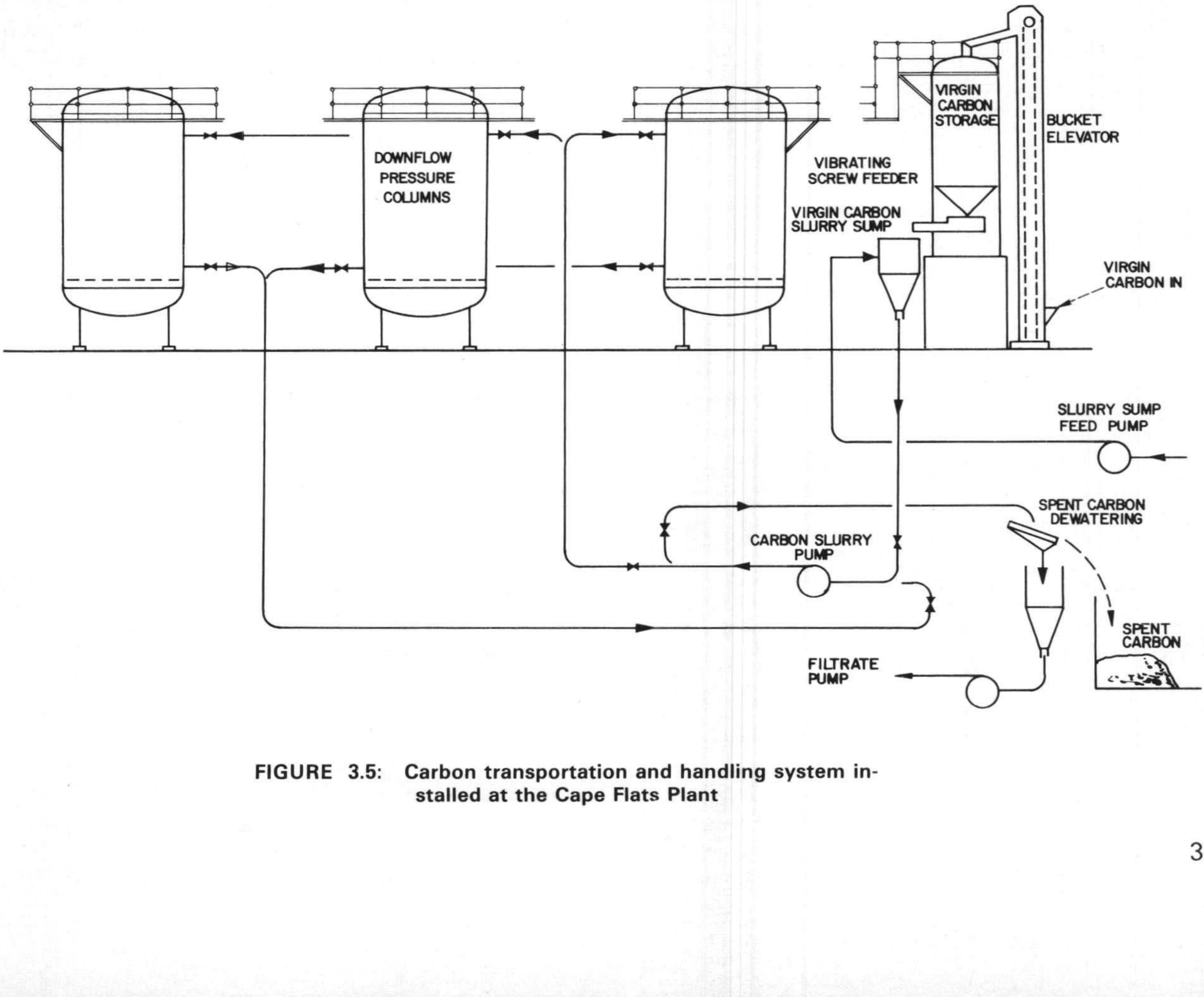

FIGURE 3.5: Carbon transportation and handling system installed at the Cape Flats Plant

taining a fusible metal safety plug designed to soften and melt between 70 and 74°C and fitted with a bonnet designed to protect the valve from impact.[22]

Cylinders should be stored upright and one ton containers cradled horizontally in a cool, dry place, which should be well ventilated and away from heat sources, walkways, elevators, stairways and ventilating system intakes. Indoor storage should be above ground and fireproof whereas outdoor storage should provide protection from direct sun.

Ton containers require a hoist and lifting clamp for handling whereas cylinders may be clamped to a balanced hand truck for moving.

Chlorine feeders

Chlorine may be delivered from a feeder by one of two methods:

- Solution feed, commonly practiced in which the chlorine gas is metered and introduced into a stream of make-up water, and then conducted as a solution to the point of application.

- Direct feed, in which the gas is introduced directly through a suitable diffuser at the point of application. This method is infrequently used because of operating difficulties and hazards.

Figure 3.6 shows details of a typical vacuum type chlorinator in which a vacuum created by a suitably sized ejector, draws the chlorine gas through a rate controlling valve into a stream of water, which is drawn from the main effluent flow just upstream of the chlorinator and reintroduced just upstream of the contact tank.

Other types of vacuum chlorinator are available in which the gas flow is regulated either by a positive acting, spring opposed diaphragm regulator or by a V-notch variable orifice, both of which can be controlled manually or automatically under a vacuum.

Chlorinators may either be cylinder mounted or housed in a separate building or room to that of the storage cylinders. The latter case may be preferred for convenience and/or safety.

Mechanical operation, control and maintenance of chlorine feeders should be in accordance with the manufacturer's instructions.

Chlorine leaks

Leaks from chlorine feed lines call for safety precautions and immediate repair, as serious physiological damage may result from breathing chlorine contaminated air.

Chlorine leaks may be detected by the use of a rag soaked in ammonia solution, which when placed near to a leak will give rise to dense white funes (ammonium chloride).

Chlorine can be absorbed in caustic soda, soda ash or a hydrated lime solution. When dealing with a leaking container, water should never be applied because the corrosive conditions will aggravate the leak and the heat supplied, even by cold water, will cause the liquid chlorine to vaporize faster. Water may be sprayed on non-leaking containers in a fire to help prevent build-up of hydrostatic pressures and possible rupture of the containers.

Respiratory protective devices should be readily available where chlorine is being stored or used. They should be located outside of the chlorinator or storage room.

Contacting channels

Adequate contacting time to ensure pathogenic organism inactivation is essential for complete disin-

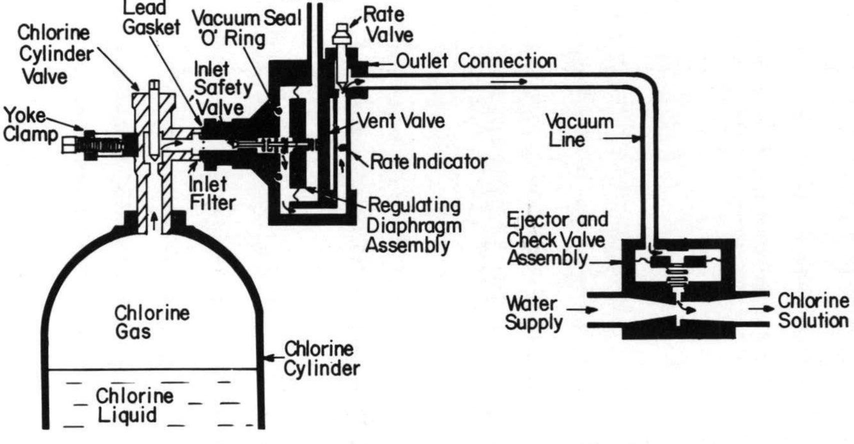

FIGURE 3.6: Typical vacuum type chlorinator

fection. Retention times of a minimum of 45 min are usually required in a water reclamation scheme.

A contacting channel usually consists of a long, narrow channel to provide the best approximation to plug flow.[21] The most practical layout of a covered channel with a length to width ratio of more than 30 to 1 is a spiral or a cylindrical tank with concentric baffled compartments. To ensure sufficient contact the nominal retention time (i.e. volume of contacting chamber divided by flow rate of water through the chamber) should be some 50 per cent greater than the desired contacting time.[21]

Sampling points should be provided at different positions along the contacting channel to check the progress of disinfection and obtain a continuous analysis of chlorine levels.

Dosage control

Effluents from correctly designed and operated biological treatment plants should contain only trace concentrations of ammonia. In such cases, chlorine-sensitive measuring cells may be utilized with automatic dosage adjustments and/or an alarm system to control the chlorine dosage rates.

Chlorinator sizing

The chlorinator should have a maximum capacity of some 25% greater than the maximum expected chlorine demand.[21]

2.7 OZONATORS

Ozone is an unstable gas and as such cannot be stored or bottled for any length of time and must be generated on site for immediate use.

Ozonators

Commercially available ozonators are basically very simple. A current flow is established between two parallel surfaces acting as electrodes and to insure uniformity of inter-electrode discharge, a dielectric material is placed in intimate contact with one or both surfaces. Air (or oxygen), flowing through an air gap between the electrodes is excited to the proper energy level and ozone is formed.

A number of parameters have an effect on the efficiency of operation of an ozonator namely: air gap, pressure, temperature, dielectric material, electric power, feed gas and flow rate.[23] Obviously therefore, an ozonator must be designed (or selected) for each specific application.

Large scale ozonators can be divided into two types — the concentric tube (the system first devised by Siemens) or the flat plate type (the so called Otto system). Currently the flat plate type is being phased out and the tubular type, operating at voltages of between 12 and 20 kV, is finding increasing applications.[23,24]

Today a large number of ozonators are commercially available which are very competitive in price. Customizing an ozonator to a particular application may give rise to a sharp variation in price from the standard models available.

Each particular design has its advantages and disadvantages. For instance, water cooling is more costly than air cooling but many years of experience with water cooling has led to the development of systems that are relatively trouble free. Dielectric materials vary in cost and life expectancy and have different characteristics. Since they do fail, replacement cost and downtime are factors to be considered.

With proper instrumentation and controls an ozonation system should operate continuously and automatically. However, the controls and safety devices of each system should be carefully engineered and all potential hazards fully evaluated. It is of vital importance that each system be engineered to the particular application and designed to operate properly within all expected load conditions.

Feed gas

Water vapour in the feed gas to an ozonator must be removed as it can reduce the ozone production and through the formation of nitric acid give rise to corrosion of generator components and ozone handling equipment.[25,26]

Air drying is usually achieved by one of two methods — a low pressure, two-stage system in which the air is first cooled then dried and a high pressure, single stage system in which the air is compressed and fed to the drier.

In each case the drying can be achieved through the use of active alumina or molecular sieves[25] and the overall aim is to produce an air with a very low dew-point (−35 to −60°C)[25,27] on a continuous basis.

The high pressure (500 — 700 kPa) drying system can be some 50 — 85% more expensive than the low pressure (70 kPa) alternative.[28] However, the more compact nature of the former can result in the overall installation costs being only 10% more for ozone production rates of 1 — 2 kg O_3 per hour.[28]

Small installations are therefore often equipped with the high pressure drying system as it is not only compact but also easy to operate and maintain.

The feed gas must also be dust free and have a low temperature to improve the efficiency and service life of an ozonator. Low temperatures greatly improve the energy efficiency of the overall plant and especially that of the service life of the dielectric.

Ozone production and energy consumption

Typical economic yield from commercially available ozonators are 12 to 20 g O_3/Nm^3* of air with that from oxygen being approximately 50 to 100% greater. Energy demand for the production of ozone from air is 12 to 17 W.h/g O_3 and that for production from oxygen 9 to 12 W.h/g O_3. These energy demand figures are for the ozonator only and do not include that for the blowers, compressors and drying units, which can have a demand ranging from 30 to 60% of that of the ozonator,

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*Nm^3 ≡ 'Normal' cubic metre, measured at 760 mm Hg and 273 K.

being dependant upon the size of installation. Approximately 90% of the energy supplied to an ozonator is used to produce light and heat rather than the desired ozone.

A 1% concentration of ozone in air (i.e. 15 g O_3/Nm^3 of air) is generally considered to be the most economical production rate for an ozonator operating on air feed.[28]

Safety requirements

Ozone is very toxic to man. Ozone equipment should, therefore, be housed only in well ventilated rooms, taking into consideration the fact that ozone is heavier than air. The amount of ozone in the atmosphere surrounding the equipment and arising from a leak in the generators or piping system can be monitored and safety devices set to turn off the generator if necessary.

An emergency hand-operated switch should nevertheless be strategically positioned.

Breathing masks, and possibly compressed-air breathing apparatus, should be available for operating personnel. No grease or oils should be used for lubricating valves or other fittings which may come into direct contact with ozone, as even at low temperatures, oils and greases can lead to spontaneous combustion.

Ozone off-gases

The gas stream leaving an ozone contacting unit invariably contains small concentrations of ozone. With the short half life of ozone it is possible that these gases will cause no problems but in certain instances steps may have to be taken to 'destroy' the ozone residuals.

This destruction can be achieved by the following methods:[28]

- Thermal destruction, which involves heating the 'off-gases' to about 150°C, whereupon the ozone rapidly breaks down. It is possible to install a form of energy-recovery on this system and utilize the recovered heat in the air drying cycle.

- Destruction by catalytic action, which involves the use of a material that is catalytic to the breakdown of the ozone such as activated carbon.

- Route the off-gases to a pretreatment stage, for example upstream of a sand filtration stage.

Material of construction

Aluminium and a stainless steel containing molybdenum, for example type 316, have a high resistance to ozone, both in the gaseous state and in the dissolved form. Some polymers, particularly unplasticized PVC and ABS, are highly resistant to ozone. Flexible materials, like nylon and natural and synthetic rubbers, have a very low resistance to ozone, but nitrile rubber can be used for gaskets. Silicone pastes can be used as sealants, whereas most commercial carbon-based sealants are severely attacked.

The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 8[29] for further details of materials of construction.

Contacting system

The design of the gas/liquid contacting system is of primary importance and has a decisive effect on the efficiency of the scheme and as such should be performed by an experienced and knowledgeable person.

There are basically four types of gas/liquid contact systems:[24,26,30,31]

- Spray towers (liquid dispersed in a gas)
- Packed beds
- Bubble plate or sieve plate towers
- Units for dispersing gas bubbles in a liquid

The last mentioned is the most common and is accomplished by introducing gas bubbles of the correct size into the water (through diffusers) or by the disintegration of a massive bubble or gas stream (by injectors or turbines). Table 3.3 compares the energy requirements for six systems concerned with dispersing gas into a liquid,[24,31] and the reader is referred to the literature for discussion on the advantages and disadvantages of these systems.

TABLE 3.3 COMPARATIVE ENERGY REQUIREMENTS OF DISPERSING SYSTEMS[24,31]

Injection through porous pipe	2 — 3 W.h/g ozone
Total injector system	4 — 5 W.h/g ozone
Rapid mixers	7 — 10 W.h/g ozone
Recirculation turbine	5 — 7 W.h/g ozone
Gas dispersor	2 — 3 W.h/g ozone
Turbine circulating water and air	5 — 6 W.h/g ozone

In designing an ozone contacting system, it is important to determine the specific purpose for which the ozone is to be used e.g. colour removal, disinfection, or reduction of COD. It is also important to know whether the kinetics of the reaction are fast or slow, and whether the reactions are highly dependent on the ozone concentration. For disinfection of water, a contactor producing rapid mass transfer of ozone is required, whereas the reaction of acetic acid, urea and ammonia is very slow, even in the presence of large excesses of ozone.

Figure 3.7 shows the ozonation process unit at the Stander Plant indicating that a packed bed contactor is mounted on top of a horizontally and vertically baffled tank which provides a 15 min retention.[29] The ozonation facilities are capable of dosing ozone at 10 mg/ℓ into a nominal flow of 4 500 m^3/d (i.e. 45 kg ozone/day).

The off-gases from the packed bed reactor are recycled to the water pipeline ahead of a small stirred tank, from which the system waste gas flow emanates.

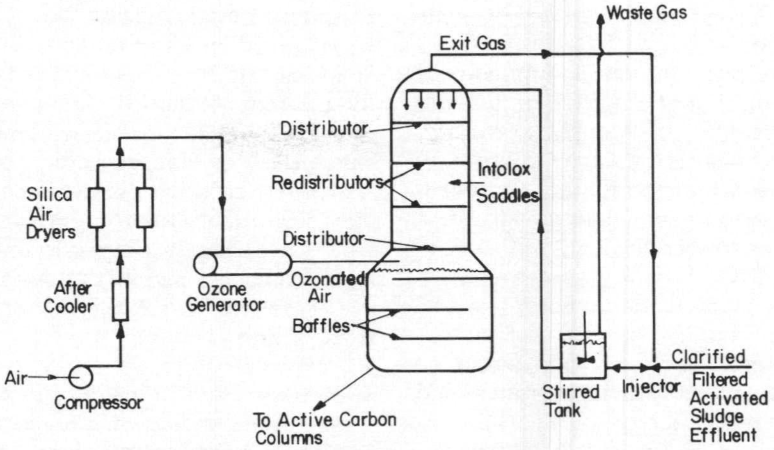


FIGURE 3.7: The ozonation process unit at the Stander Plant[29]

Control

For efficient manual operation of contacting systems, the operator must be able to monitor the ozone, both in the gas phase as it leaves the generator and in the liquid phase after contacting. The most widely used technique has been the starch-KI-iodine method in which the iodide is oxidized to iodine, starch added, and the blue colour intensity measured colorimetrically.

Automatic process control of modern ozonation systems can be readily achieved by monitoring residual total oxidants in the water just after the contacting chamber exit. The analyser is coupled to an automatic control system which varies the voltage input to the ozone generator, thus effecting variations in ozone dosage.[29]

2.8 ACTIVATED CARBON REGENERATION

The regeneration (or reactivation) of activated carbon has been included in many reclamation plants throughout the world. The local on-site costs of virgin carbon and energy, together with the expected spent carbon production, dictate the economics of such systems and should be carefully considered at the design and planning stage.

Typical regeneration systems

Figure 3.8 indicates the flow diagram of the carbon regeneration system installed at the Stander Plant,[32] showing that the spent carbon is transferred, via a

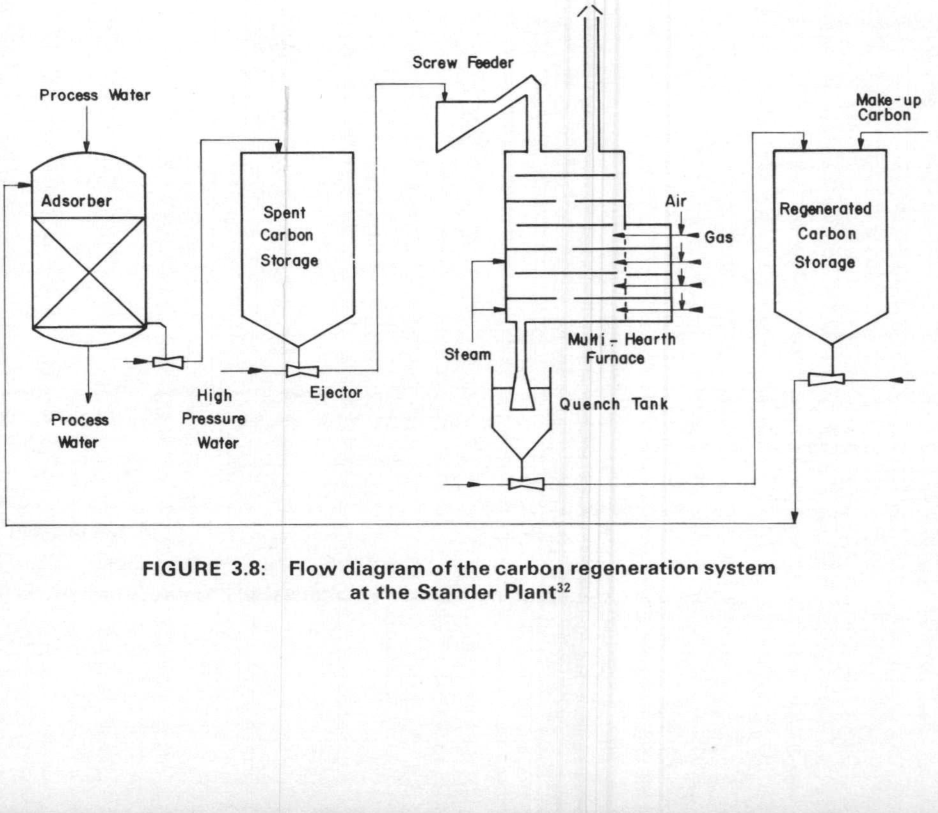


FIGURE 3.8: Flow diagram of the carbon regeneration system at the Stander Plant[32]

carbon storage tank, to a screw feeder situated on the top of a multi-hearth furnace.

The screw feeder has the dual function of dewatering the spent carbon prior to transferring it into the furnace and of also providing a water seal at the top.

The spent carbon, with a moisture content of some 45% flows by gravity into the furnace, is reactivated and passes out of the furnace under gravity into a quench tank which serves to wet and cool the carbon.

The regenerated carbon is then transferred via a storage tank, into which virgin make-up carbon is also added, back to the adsorbers.

Regeneration furnaces are generally equipped with afterburners and scrubbers to reduce organic and particulate contents of the furnace off-gases.

Carbon make-up

Make-up carbon is perhaps the single most important cost element of a regeneration facility. Carbon losses in the adsorbers, in the carbon transfer and handling systems and in the carbon storage and regeneration systems can be held to the 5 — 7% range by proper design.[33]

Regeneration furnaces

Regeneration involves drying the carbon, followed by vaporization of the volatile adsorbates followed by pyrolysis of the non-volatile adsorbates and finally oxidation of the pyrolysed adsorbates. Steam is added to control the final step, ensuring that optimum activation occurs with the minimum loss of carbon.

Regeneration furnace sizing and the results to be expected from regeneration are a function of the adsorbate, the char left by pyrolysis of the adsorbate, initial or added mineral constituents which may catalyse or suppress reactions, the type of active carbon used, and the feed moisture content.[34]

Three types of furnace have found application at commercial installations; the fluidized bed, the rotary kiln and the multi-hearth. Of the three, the multi-hearth has found the widest application.[35]

Fluidized bed furnaces

Fluidized bed furnaces have recently found application for the regeneration of activated carbons primarily for their ability to regenerate all types of carbon and their suitability for intermittent operation. They have, however, not found the wide acceptance that the multi-hearth or indeed the rotary kiln furnaces have.

The reader is referred to the literature for details of typical fluidized bed installations.[36,37]

Rotary kiln furnaces

The rotary kiln furnace, a refractory-lined steel cylinder closed at the ends by stationary hoods and mounted on two or three sets of trunnions so as to slope downward from inlet to outlet (Figure 3.9)[33] passes the carbon granules either cocurrent or countercurrent to combustion gases and steam.

A variable speed drive, coupled to a speed reducer and pinion gear meshing with a girth gear on the shell, rotates the kiln. Wet spent carbon enters onto flights through a feed-screw or chute, and regenerated carbon at 870 — 980°C discharges from the lower end to fall down a chute into a quench tank, which also acts as a seal over the lower end of the chute.

Multihearth furnaces

The multiple-hearth furnace consists of four to eight hearths which are contained in a cylindrical refractory-lined steel shell, one above the other, and a central rotating shaft that drives rabble arms across the hearths (Figure 3.10).[34] Nozzle mix type burners using either fuel, oil or natural gas are mounted on the shell so as to direct their flames tangentially into the space above the hearths. Steam for controlling the reactivation stage i.e. optimum char gasification with minimum loss of carbon granules, is added through ports into the selected hearths.

The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 11[32] for details of the multihearth furnace installed at the Stander Plant.

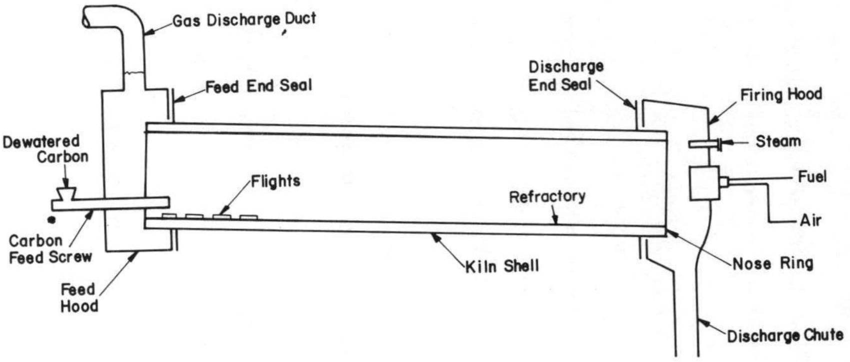


FIGURE 3.9: Details of a countercurrent rotary kiln furnace[33]

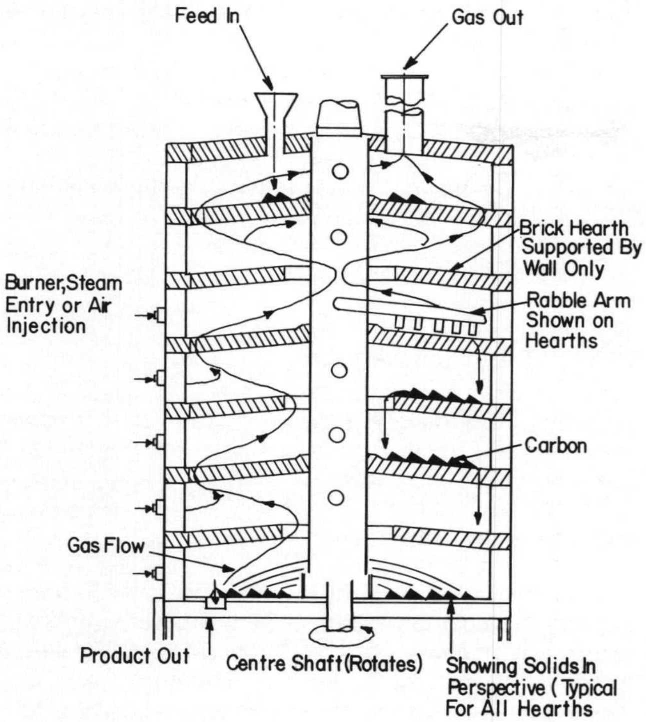


FIGURE 3.10: Details of a typical multihearth furnace[34]

Comparison of rotary kiln and multihearth furnaces

The following discussion compares the rotary kiln and multihearth furnaces:

Installed cost

Total installed costs are very much the same for both.[33]

Area required

A rotary kiln furnace has a smaller 'reaction surface area to furnace volume ratio' than a multiple hearth furnace, and as such requires a larger area for installation. Site preparation, foundation and structural costs are therefore higher for a rotary kiln than for a multiple hearth.[33]

Fuel consumption

The larger surface area and less effective thermal insulation of a rotary kiln furnace results in its fuel (or energy) consumption being higher than that of the multihearth counterpart, with typical values being presented below:[32.33]

	Energy consumption (MJ/kg carbon)
Multiple-hearth	5,8 — 11,0
Rotary kiln	8,1 — 18,6

Capacity turndown

Because of the greater control possible in the various zones of the multiple-hearth furnace, the ratio of minimum to design capacity, at equivalent reactivated carbon quality, is about 35%. As the rotary kiln has only one burner and one point of steam addition, rotational speed is the major element of control and maximum turndown is approximately 50%.[33]

Control

The distinct zones of a multiple-hearth furnace, each equipped with the means to regulate combustion, steam concentration and air concentration, offer better control over the reactivation process than does the rotary kiln. However, for a properly sized kiln, this is not a distinct advantage.

Corrosion and slag

The multiple-hearth furnace has more exposed parts and is therefore more susceptible to corrosion.

Slag build-up in a multiple-hearth furnace will require periodic shutdowns, whereas in a rotary kiln the slag is discharged along with the carbon.[33] However, when the temperature is not accurately controlled in a rotary kiln, slag can build up on the refractory lining and has to be chiselled off with the associated high risk of lining damage.

Maintenance

Experience has indicated that multiple-hearth furnaces have higher maintenance costs, for the following reasons:[33]

- Corrosion and slag cause shutdowns for repairs.
- Rabble teeth and arms are more expensive to replace than kiln flights.
- Multiple-hearth furnaces are difficult to work on, so that it takes more manhours to rebuild a hearth than to replace brick in a kiln.
- More instrument components are required for a multiple-hearth furnace.

Feed variations

Although periodic planned shutdowns can be carried out without damaging the multiple-hearth furnace, the upper hearths can be damaged by temperature cycling caused by fluctuations in the feed flow and the degree of dewatering thereof. In a rotary kiln, feed interruptions are not much of a problem, since the refractory is less affected by temperature cycling.

Operating factors

Due to the above considerations, the operating factor for the rotary kiln is generally 85 to 95% compared to 75 to 90% for the multiple-hearth furnace in industrial-wastewater applications.

Quality of regenerated carbon

The quality of regenerated carbon is discussed extensively in the literature, and the results show that high quality reactivated carbon can indeed be produced, at particle mass losses of 5 – 7%.[32,33,34,36]

Studies have shown that the quality of regenerated carbon can also be improved by:[38]

- Employing a slow, rather than a fast, drying period (i.e. greater than 20 min.).
- Employing an activation temperature of between 898 and 926°C.
- Applying a metal-ion leach to the spent carbon prior to regeneration in cases where the wastewater contains organo-metallic compounds of Fe, Ca, Mg, Na and K, as the studies indicated that the adsorption of such ions contributes to a decreased recovery of the iodine number (i.e. a decrease in the carbon's ability to adsorb molecules of low molecular weight).

Sizing of multihearth regeneration furnaces

Figure 3.11 presents a nomogram that has been developed for preliminary sizing of multihearth regeneration furnaces.[39] The inputs required are the flow to the carbon adsorbers, the COD removed across the adsorbers, the carbon loading and the required furnace utilization.

Another procedure to be followed in the sizing of a multihearth furnace is presented in the 'Manual for Water Renovation and Reclamation', Chapter 11[32] and is summarized below:

Step 1: Internal furnace area

$A_i = (re.Q_c)/180$

where:

A_i = internal furnace area (m^2)

re = carbon exhaustion rate (kg carbon/1 000 m^3 water)

Q_c = water treatment capacity (1 000 m^3/day)

Step 2: Regeneration rate

$r_r = 15.A_i$ (kg carbon/h)

Step 3: Number of hearths and furnace diameter

The number of hearths and furnace diameters are fixed for most commercial units. Final selection should therefore be the least cost combination such that the resulting internal furnace area is equal to or marginally greater than that actually required (A_i)

Step 4: Thermal energy requirements (excluding those for flue gas afterburners)

$E_t = 330.A_i$ (MJ/h)

Step 5: Electrical energy requirements (excluding those for steam raising)

$E_e = 7{,}5\ A_i$ (kW)

Step 6: Steam requirements

$S = 15.A_i$ (kg steam/h)

Equipment design consideration

The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 11[32] for details of refractory linings, materials of construction for rabble arms, combustion equipment, control equipment and ancilliary equipment such as dewatering screws, afterburner, scrubbers, quench tanks etc.

It should be appreciated by the process designer that once the initial requirements of the regeneration system have been finalized, contact should be made with furnace suppliers, who have experience in such systems, in order to define more clearly the overall design requirements.

2.9 SLUDGE THICKENING OPERATIONS

The production of sludges at biological treatment and advanced treatment plants as well as their possible treatment and disposal routes, are discussed in Part II, Chapter 12.

This section considers those items of equipment that could find application in the thickening of the various sludges. The thickening stage generally precedes a mechanical dewatering stage as it is a particularly cost effective method of reducing the volume of sludges to be treated and disposed of.

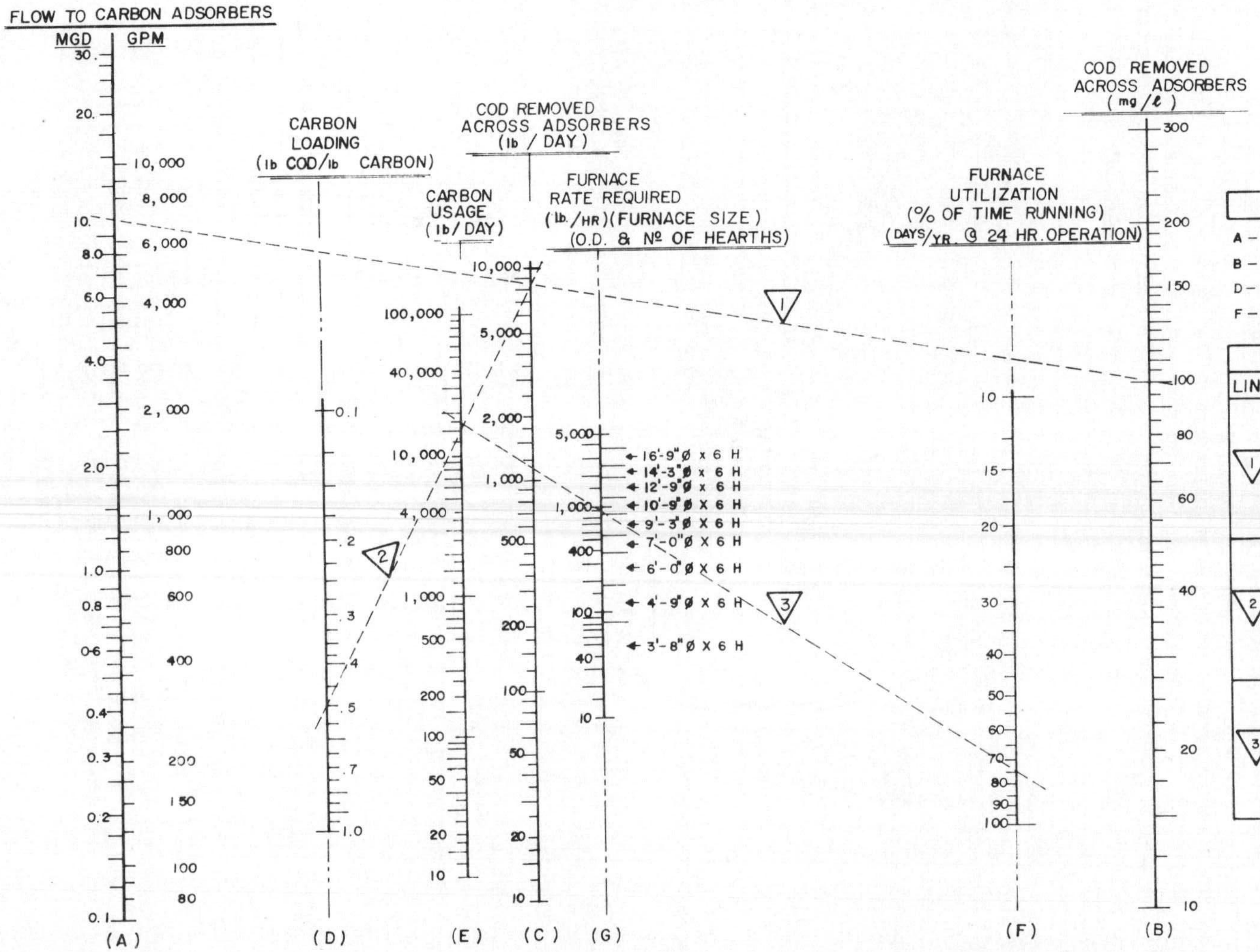
2.9.1 Gravity thickening

Gravity thickening is at present used extensively for primary, digested primary and primary chemical sludges, but is seldom used for excess activated sludge and tertiary chemical sludges.

Gravity thickener design

Laboratory methods of gravity thickener design based on the mass flux theory, have been adequately reported[40,41] and readers are referred to these publications should they require a wider understanding of the gravity thickening mechanism.

Gravity thickeners can be designed with laboratory methods or on experience with similar instal-



CARBON FURNACE SELECTION

REQUIRED INPUTS

A – FLOW TO CARBON ADSORBERS(MGD or GPM) ______

B – COD REMOVED ACROSS ADSORBERS(mg/ℓ) ______

D – CARBON LOADING(lb COD/lb CARBON) ______

F – FURNACE UTILIZATION (% OF TIME RUNNING days/YR 24 HR OPERATION ______

NOMOGRAPH CALCULATION EXAMPLE

LINE	INPUTS	READ OUT	EXAMPLE
1	A FLOW TO CARBON ADSORBERS(MGD) B COD REMOVED ACROSS ADSORBERS (mg/ℓ)	C COD REMOVED ACROSS ADSORBERS (lb / DAY)	A = 10 MGD B = 100 mg/ℓ C = 8,340 lb/DAY
2	C COD REMOVED ACROSS ADSORBERS (lb / DAY) D CARBON LOADING (lb COD/lb CARBON)	E CARBON USAGE (lb/ DAY)	C = 8,340 lb / DAY D = 0,5 lb COD / lb / CAR E = 16,680 lb / DAY
3	E CARBON USAGE (lb./ DAY) F FURNACE UTILIZATION (% OF TIME RUNNING Days/Yr. @ 24 HR. OPER)	G FURNACE RATE REQUIRED(lb/ HR) AND FURNACE SIZE (DIA & HEARTHS)	E = 16,680 lb / DAY F = 75% G = 927 lb / HR
			10' 9"Ø x 6H.

FIGURE 3.11: Multiple-hear. . furnace sizing guide (courtesy of Envirotech)

lations, with the solids loading rate (kg $m^{-2}d^{-1}$) being the usual design parameter.

Biological sludges

Gravity thickening of primary and digested primary sludges is a reliable and efficient process at application rates of 100 to 120 kg $m^{-2}d^{-1}$, at which loadings thickened sludges of 6 to 8% by weight are produced.

Chemical sludges — lime

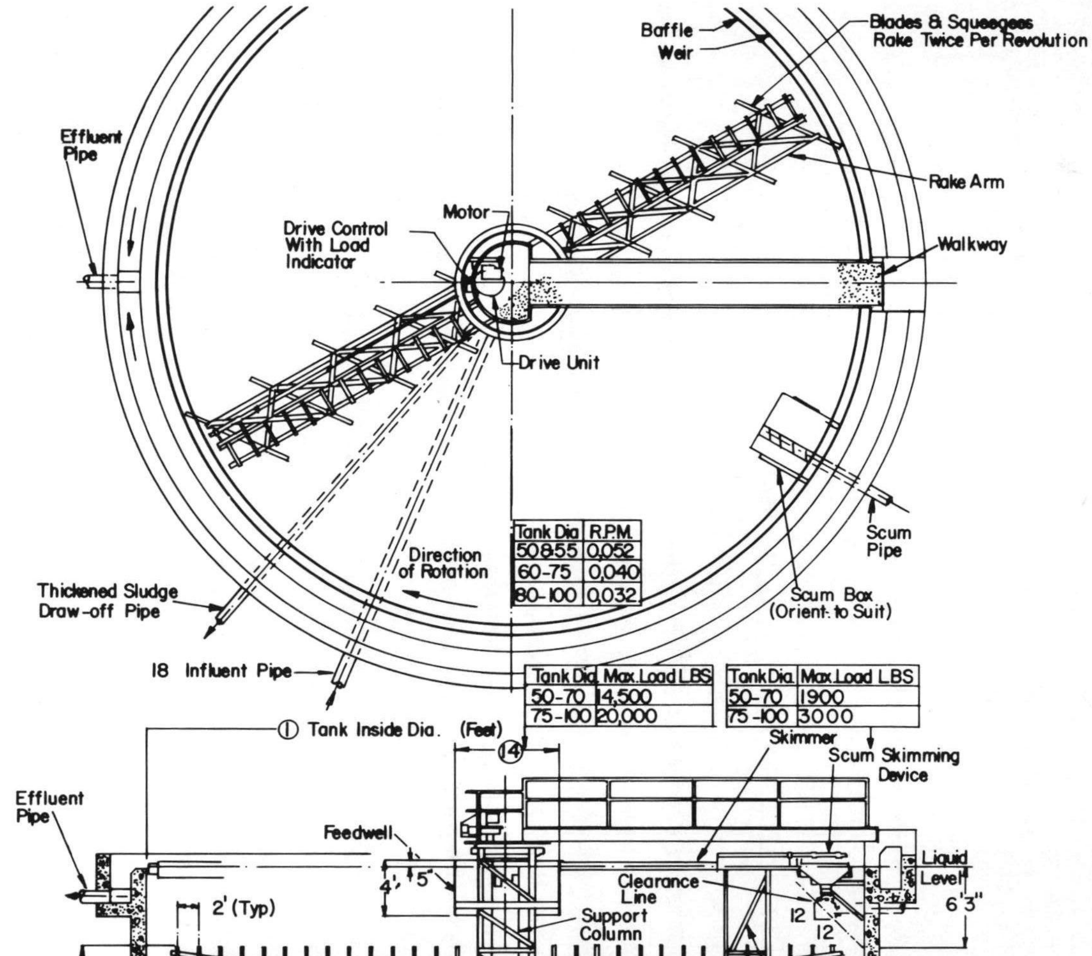
The magnesium ion concentration of the wastewater and the pH/alkalinity relationship influence the thickening characteristics of lime sludges (refer to Part II, section 3.1) and for these reasons the design of lime sludge gravity thickeners is usually based on laboratory studies. Thickener rates of 160 to 200 kg $m^{-2}d^{-1}$ are commonly used, producing thickened sludges of 10 to 20% dry solids.[42]

Alum and iron sludges

Gravity thickening has found application for primary alum and primary iron sludges, and as the thickening characteristics of these sludges are inferior to those of primary biological and primary lime sludges, the thickeners are loaded at rates of 25 to 75 kg $m^{-2}d^{-1}$.[40] Gravity thickening is seldom applied to secondary and tertiary alum and iron sludges.

Diameter side wall depth

The diameter of the thickener is obtained from the area required that relates to the design loading rate and the side wall depth (SWD) is in most cases 3 to 3,5 m.



Tank Dia	R.P.M.
50&55	0,052
60-75	0,040
80-100	0,032

Tank Dia	Max.Load LBS
50-70	14,500
75-100	20,000

Tank Dia	Max.Load LBS
50-70	1900
75-100	3000

FIGURE 3.12: A typical gravity thickener (Courtesy Envirotech)

Floor slope

The floors slope at gradients of 1:5 to 1:8 towards a central cone from which the thickened sludge is withdrawn.

Scraper mechanism and drive

The design of the scraper mechanism (and associated drive motor) should take cognisance of the maximum sludge concentration at the thickener floor. The concentration of the sludge will determine the torque required to effectively transfer the sludge solids towards the central collecting cone. The drive unit should have a torque rating of at least five times the maximum required and due to the thixotrophic nature of the sludge (pseudoplastic behaviour – refer to Part II section 12.2.3) the rake should be equipped with pickets (or thixoposts) to assist the dewatering and resulting compaction (refer to Figure 3.12).

It is usual practice to add polyelectrolyte or other floc aids (e.g. ferric chloride in the case of lime addition) to accelerate the chemical sludge settling rates and thereby decrease the size of thickener.

The reduced size of thickener can only be determined through laboratory tests.

In some instances, particularly in primary lime treatment, the sludge discharged from the clarifier can be of such a high solids content that the installation of a gravity thickener between the clarifier and the dewatering stage cannot be justified. This aspect should be carefully evaluated at the laboratory and/or pilot plant stage.

Figure 3.12 shows details of a typical gravity thickener.

2.9.2 **Dissolved air flotation thickening**

Flotation thickening may be achieved by dissolved air flotation, electrolytic flotation and dispersed air flotation. Dissolved air flotation has found extensive use whereas the latter two methods have yet to be proved in large scale applications.

Dissolved air flotation

Dissolved air flotation (DAF) thickening has found wide application for excess activated sludge for two reasons:

(i) The poor performance of gravity thickeners.

(ii) The activated sludge resulting from systems designed to biologically remove phosphorus must be maintained in an aerobic state in order to suppress phosphorus release to the liquid phase (refer to Part II, Chapter 10).

The most common form of DAF thickening involves partial pressurization of the clarified underflow from the flotation unit. Systems involving total or partial pressurization of the flotation unit inflow are available but are not considered suitable for sludge thickening applications. Figure 3.13 indicates a typical DAF installation and Figure 3.14 shows details of a rectangular flotation unit.

The pressurized recycle flow is depressurized at a point near the sludge inlet to the flotation unit, resulting in the formation of clouds of fine air bubbles which become attached to the sludge particles and buoy them up to the surface.

Sludge consolidation takes place at the surface

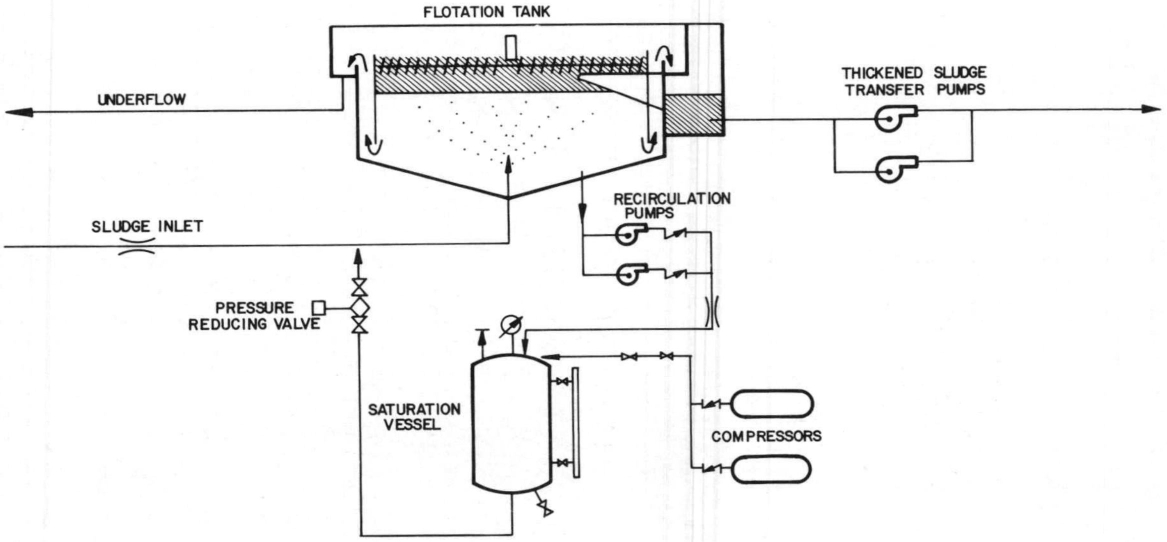


FIGURE 3.13: Typical dissolved air flotation thickening installation

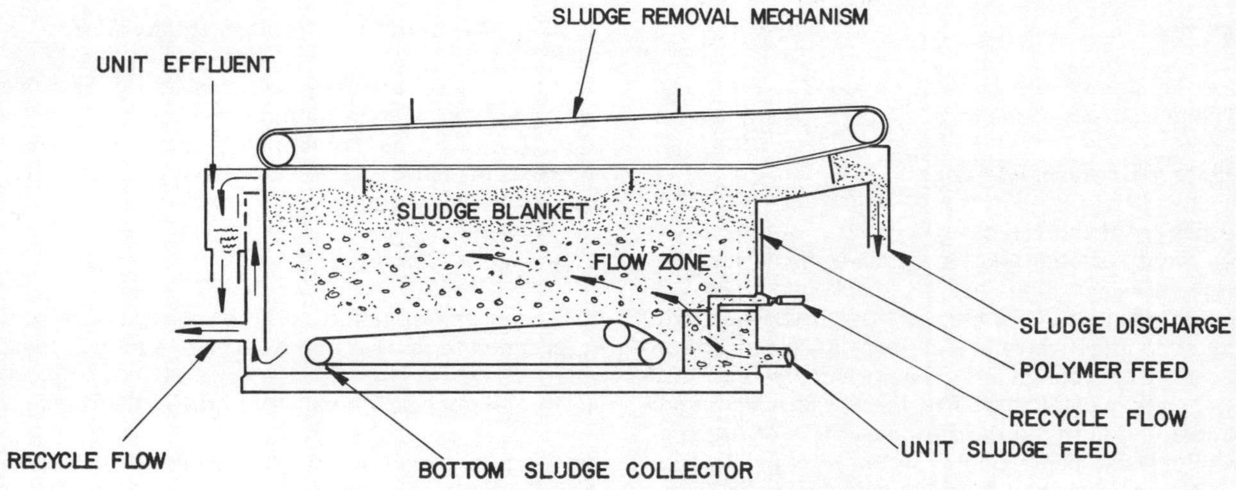


FIGURE 3.14: Typical rectangular flotation unit

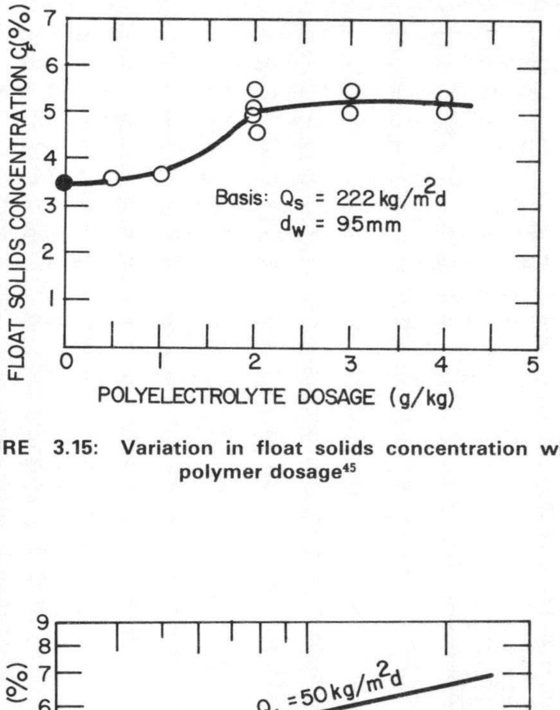


FIGURE 3.15: Variation in float solids concentration with polymer dosage[45]

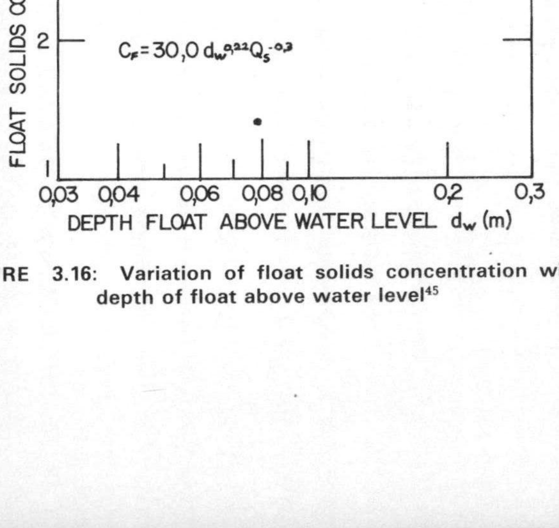


FIGURE 3.16: Variation of float solids concentration with depth of float above water level[45]

and the thickened sludge is removed by suitably designed scrapers.

Design of DAF units

The parameters that affect the performance of a DAF system have been clearly set out in the literature,[43,44,45,46] the most important being the flotation unit solids loading rate (in terms of kg dry solids (DS) $m^{-2}d^{-1}$)[44], the depth of float above the water level,[44] the nature of the excess activated sludge,[45,46] and the degree of polyelectrolyte addition.[45]

Solids loading rates

Solid loading rates of 60 to 300 kg $m^{-2}d^{-1}$ for activated sludges with SRT values of 15 to 20 days, with SVI values of less than 150 mℓ/g and which result from the treatment of unsettled sewages, can be expected to result in float concentrations of 5 to 3,5% respectively, without the addition of polymer.[45,47]

Sludges with similar SRT and SVI characteristics but resulting from the treatment of settled sewages, form floats of slightly lower solids concentrations for the same solids loading rate range.

Activated sludges with low SRT values invariably require polymer doses (0,5 to 2,5 kg dry polymer/ton DS) to achieve similar performances.[48,49]

Figure 3.15 indicates the effect of polymer addition in the case of a long SRT excess activated sludge.[45] Further experiments indicated that the optimum polymer dose (usually 2 kg/ton DS) increased the float solids concentration by a factor of 1,35.

Depth of float above water level

Figure 3.16 indicates the effect the depth of float above the water level has on the float concentration.[45]

Provision to vary the skimming depth of the float removal equipment is therefore generally incorporated in most equipment designs.

Effluent quality

Clarification of underflow is especially important when thickening waste sludges from activated sludge plants where enhanced phosphate removal is effected. Since adsorbed or precipitated phosphorus is contained in the solid fraction, a high effluent solids concentration would give rise to a concomitantly high concentration of phosphorus which is invariably recycled back to the plant.

Flotation units treating waste sludges with high SRT values and no polymer addition, generally give rise to underflow solids concentrations of 30 — 120 mg/ℓ,[45,47] representing overall solids captures of approximately 98%. The addition of polymer results in the solids capture being increased to greater than 99%.

Shallow flotation units invariably produce underflows with high solids content on account of the flow scouring the bottom of the float. Depth of flotation unit must therefore be carefully considered and in the case of rectangular units, the use of broad and short units as opposed to narrow and long units is to be preferred. General flow conditions pertaining to circular flotation units suggest that from the viewpoint of scour minimisation these units may be preferable.

Air to solids ratio

An air to solids mass ratio of 0,02 is sufficient for activated sludge thickening. Values below this figure result in float instability while higher values represent unnecessary expenditure. System total costs are not affected by values chosen for saturator pressure and recycle ratio provided that in combination they produce an air to solids ratio of 0,02.[44]

Inlet blending

The blending of the sludge and pressurized recirculant should be carefully considered. The pressure relief valve should be as close as practically possible to the point of blend so as to obtain maximum particle to bubble contact as the bubbles are formed.

Float withdrawal

Large scale flotation units should be equipped with multiple sludge withdrawal points so as to prevent the occurrence of localized sludge build up which can result in high underflow solids contents.[47,50]

Saturation vessels

Contact of the recycled flow with the air in the saturation vessel can be achieved by various means of which water sprays, packed columns and internal recycling are the most common. Saturation vessel operating pressures are usually 400 to 600 kPa and as such the vessels must comply with the local Factory and Safety Act regulations pertaining to pressure vessels.

Compressors

The air compressors are usually sized at 4 to 5 times the required duty and discharge into suitably rated air receivers. The apparent 'over-sizing' results from the fact that in most instances the compressors are of the air-cooled variety and require standing time.

System flexibility

The design of the flotation system should incorporate a degree of operational flexibility in that provision should be made for variable recycle rates (against a fixed saturation vessel pressure), for different depths of float removal and variable scraper speed.

2.9.3 **Dynamic thickening (centrifuges)**

Disc and basket centrifuges have recently been used for thickening excess activated sludges in the U.S.A. with cake solids of 5 — 10% and solids captures of 80 — 95% being achieved without the use of polyelectrolyte.[51]

Descriptions of both types of centrifuge may be found in "Chemical Engineers' Handbook" edited by J.H. Perry, "Unit Operations in Chemical Engineering" edited by McCabe and Smith and in various articles on the applications of centrifuges.[52,53]

Experiments conducted at Johannesburg into the thickening of long SRT excess activated sludge by means of a basket centrifuge indicated that cake solids of 10 — 12% and high solids captures could be achieved with no polyelectrolyte addition.[47] However, the apparent advantage of this equipment is at present offset in the South African context by the high capital cost.

Solid bowl centrifuges are generally employed to dewater previously thickened sludges (refer to following subsection) but they have also been applied to the thickening of excess activated sludges at installations in South Africa[54,55] and the USA.[51]

The South African experience indicates that cake solids of 10 to 11%[54,55] and overall solids capture of 99% can be achieved with polyelectrolyte doses of 5 kg/ton DS.[55] Solids capture decreased to 75% when no polyelectrolyte was added, with the cake solids remaining at 10%.[55] The experience gained at one installation indicated that solid bowl centrifugation should only be performed on previously thickened excess activated sludges.[54]

2.10 SLUDGE DEWATERING OPERATIONS

Sludges can be dewatered by numerous methods of which those discussed below are perhaps the most common.

2.10.1 **Centrifuges**

The advent of effective polyelectrolytes has resulted in centrifugal dewatering of sludges becoming competitive with the other methods.

Centrifugation is essentially a form of sedimentation in that the solid/liquid phase separation is achieved by greatly increased gravitational forces induced by high rotational speeds.

Centrifuges can be applied for all types of sludges,

TABLE 3.4 GENERAL PERFORMANCE OF THREE TYPES OF CENTRIFUGE

Type of centrifuge	Dewatering performance	Clarity of centrate
Solid-bowl decanter	good	good
Basket type	good	poor
Disc type	poor	good

both biological and chemical, albeit with a scatter of results. They have the advantage of being totally enclosed, simple to operate, compact in installation and are not as sensitive to influent quality fluctuations as are other items of dewatering equipment. However, chemical, maintenance and energy costs are frequently relatively high.

There are many types of centrifuges on the market and Table 3.4 indicates the general performance of the three types that are suitable for biological and/or chemical sludges.

Countercurrent and Cocurrent

The solid bowl decanter has found wide application in sludge dewatering installations as it can be used for sludges containing 25 to 400 g/kg and having a solids particle diameter ranging from 4 to 20 000 μm. Both 'counter-' and 'cocurrent' decanters are available: countercurrent refers to the opposite flow directions taken by the cake and centrate while cocurrent indicates that the two flows are in the same direction. Cocurrent centrifuges are usually used on light sludges.

Figure 3.17 depicts details of a typical solid bowl countercurrent decanter.

Sludge is fed into the centrifuge bowl through a pipe located inside the hollow shaft. Owing to the centrifugal force created by rotation of the bowl, the sludge is separated into a sludge cake and water, the cake settles against the inside of the bowl and is moved by a screw conveyor (the scroll) up the conical section (the beach) where it drains prior to being discharged. The liquid level (pool depth) in the bowl is controlled by adjustable outlets and these make it possible to control the capacity, degree of clarification and dryness of cake. The scroll generally rotates in the same direction as the bowl but at a slightly slower speed (5 — 30 r/min slower).

Dewatering performance

The dewatering performance of a centrifuge is usually expressed in terms of cake dryness, centrate clarity and percentage of solids recovered. Two groups of variables influence the performance, namely machine variables and process variables[56] with each of these groups being subdivided as follows:

- Operational variables which relate to the centrifuge and which can be changed according to the process requirements.
- Independent variables which are primarily functions of the treatment sequence and mode of sludge production.

Table 3.5 summarizes the more important of these variables.[56]

The effect of these variables on the performance of a solid bowl centrifuge is extensively covered in the literature but Table 3.6 summarizes the more important effects.[40,56]

Perhaps the most important relationship pertaining to centrigure performance is that of cake dryness and solids recovery. Figure 3.18 shows a general solids recovery-cake solids curve for a centrifuge, indicating that a high solids recovery (usually attained through polyelectrolyte addition) is associated with a wet cake.[40]

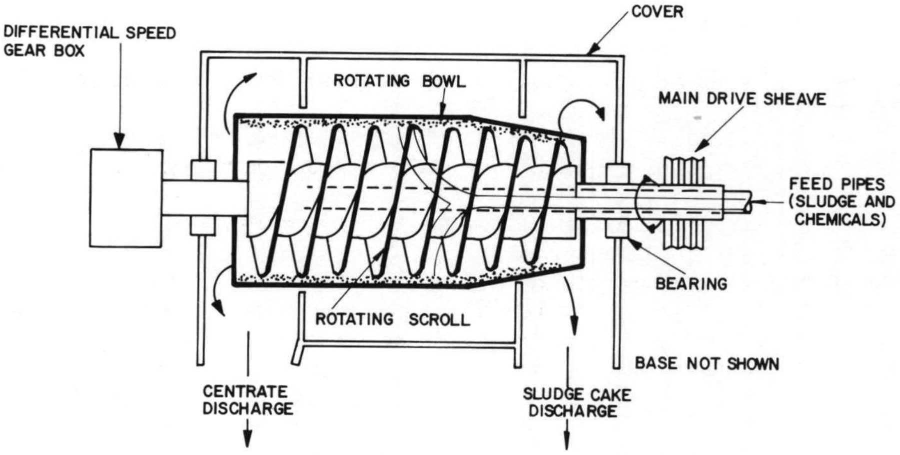


FIGURE 3.17: Typical solid bowl countercurrent decanter (Courtesy Sharples)

TABLE 3.5 VARIABLES INFLUENCING SOLID-BOWL CENTRIFUGE PERFORMANCE DURING LIME SLUDGE DEWATERING[56]

Machine variables	Process variables
Operational Variables	
Bowl speed (gravitational force)	Hydraulic flow rate of feed sludge
Pool depth	Solids load on the centrifuge
Scroll differential speed	Polymer dosage and point of addition
	Consistency of feed
Independent Variables	
Bowl configuration (e.g. conical or cylindrical-conical)	pH and chemical composition of the sludge
Length of bowl	
Diameter of bowl	Physical characteristics of the sludge (such as particle properties, viscosity, compressibility and temperature)
Beach angle and length	
Scroll type and configuration	

TABLE 3.6 EFFECTS OF OPERATIONAL VARIABLES ON CENTRIFUGE PERFORMANCE[40.56]

Parameters	To increase the cake dryness	To increase the solids recovery
Bowl speed	Increase*	Increase*
Pool depth	Decrease	Increase
Scroll speed	Decrease	Decrease
Feed rate	Increase	Decrease
Feed consistency	Decrease	Increase
Use of flocculant	Do not use	Use

*Bowl speed increase above a certain value can result in the settling force exceeding the mechanical cohesion of the particles, leading to total rejection of the solids in the centrate.

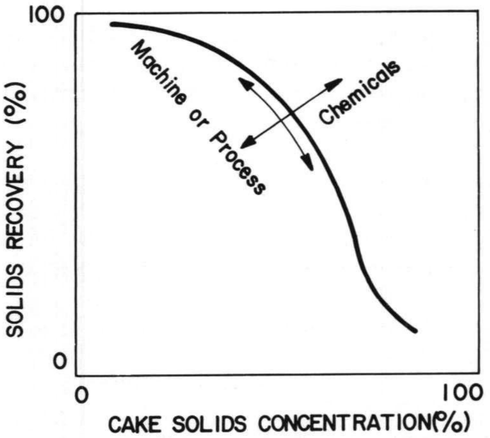


FIGURE 3.18: General solids recovery-cake solids curve

The hydraulic retention time of the sludge in the centrifuge has recently found greater application in describing the performance of a centrifuge.[40.56]

Evaluating the performance of a centrifuge

The sizing of centrifuges for a particular application should be based on pilot scale (and preferably full scale) experiments on the sludge actually produced or on a sludge produced from a similar reclamation plant.

Scale up from pilot (or laboratory) scale centrifuge tests to full scale requirements is usually carried out by the use of the sigma and beta concepts which are adequately described in the literature.[56]

Biological sludges

Solid bowl centrifuges have been used for some years to dewater biological sludges in South Africa and Table 3.7 summarizes the results from a number of these installations.

Chemical sludges — lime

The solid bowl centrifuge is the most suitable for dewatering lime sludges generated at water reclamation plants and when correctly operated can produce relatively dry cakes that can be mechanically conveyed and stacked on site prior to further treatment.

Cake solids of 20 to 40% can be achieved on wastewater lime sludges with solid recoveries of 95 to 99% being achieved at polymer dose levels of 1,0 — 2,0 kg/ton dry solids.[61] The coagulation pH appears to affect the cake dryness in that at values above 11,0 the precipitated magnesium hydroxide (if magnesium was present in the wastewater) which is gelatinous in nature will usually reduce the cake dryness.

Classification

Centrifuges are also used to 'classify' lime sludges. This

TABLE 3.7 BIOLOGICAL SLUDGE DEWATERING BY SOLID BOWL CENTRIFUGE

Nature of Sludge	Feed solids %	Cake Solids %	Recovery %	Polymer kg/ton	Reference
TPS	4 — 6	25 — 30	98	1,5 — 2,0	(57)
EAS	0,5 — 1,0	10	75	Nil	(55)
EAS	0,5 — 1,0	10	99	5	(55)
T(PS + EAS)	4,5	22	90	4	(58)
T(PS + EAS)	—	—	99	3,8	(59)
EAS	4,0	15	99	3,5	(47)
Dig S	6,0	25	90	1,5 — 2,0	(58)
Dig S	6,0	26	90	2,5 — 3,0	(58)
Dig S	3,6	20	94	3,4	(60)
HTS	10,0	27	94	0,5	(58)

Note:

TPS = Thickened primary sludge
EAS = Excess activated sludge
Dig S = Digested sludge
HTS = Heat treated sludge
T(PS + EAS) = Thickened mixture of primary and excess activated sludges

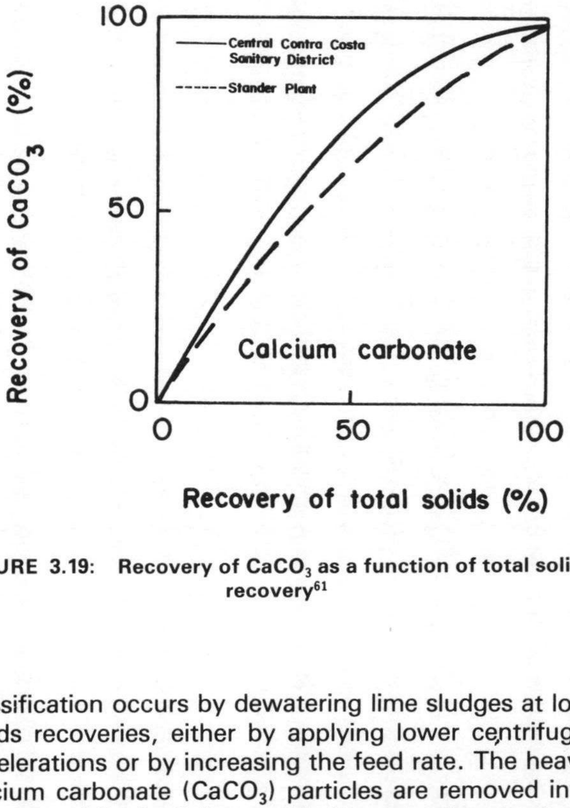


FIGURE 3.19: Recovery of $CaCO_3$ as a function of total solids recovery[61]

classification occurs by dewatering lime sludges at low solids recoveries, either by applying lower centrifugal accelerations or by increasing the feed rate. The heavy calcium carbonate ($CaCO_3$) particles are removed into the cake while the lighter solids (the organics plus inorganic fines) are discharged with the centrate which is usually then dewatered by a further centrifuge. It is therefore possible to obtain a cake of fairly pure $CaCO_3$ but cognisance should also be taken of the requirement of further treatment of the centrate prior to its return to the process. This requirement arises not only from the necessity to reduce fines build-up in the system but also to reduce return phosphorus loads in the case of plants designed for biological phosphorus removal. Section 2.11 covers the chemical recovery systems and outlines typical lime sludge classification process sequences.

Classification of tertiary lime sludge has been performed at the Stander Plant, Pretoria.[61] Figure 3.19 compares the results with those obtained from the initial experiments run at the Central Contra Costa Sanitary District Plant.[61] Usual total solids recovered lie in the 45/50% range while cake dryness is approximately 60%.[61]

Alum and iron sludges

Alum sludges generated at waterworks in the UK and USA are frequently dewatered by solid bowl centrifuges, resulting in cakes of 15 to 30% with recoveries of 95 to 98% at polymer doses of 1,5 to 3,0 kg/ton.[40.62.63]

Waterworks sludges may be considered indicative of sludges resulting from alum addition to secondary effluents.

Sludges deriving from iron salts can be expected to result in similar performances.

Polyelectrolyte addition

Polyelectrolyte can be added to the sludge prior to entrance into the centrifuge or directly to the contents in the bowl. The optimum position can only be ascertained through experimentation as it is not only dependent upon the sludge characteristics but also upon the type of polyelectrolyte.

Maintenance

In order to minimize maintenance problems, it is recommended that the following precautions be taken at the design stage of a centrifugal dewatering-classification system:

- Maximum use of non-corrosive materials.
- Judicious selection of hardened surfaces for critical areas subject to erosion.

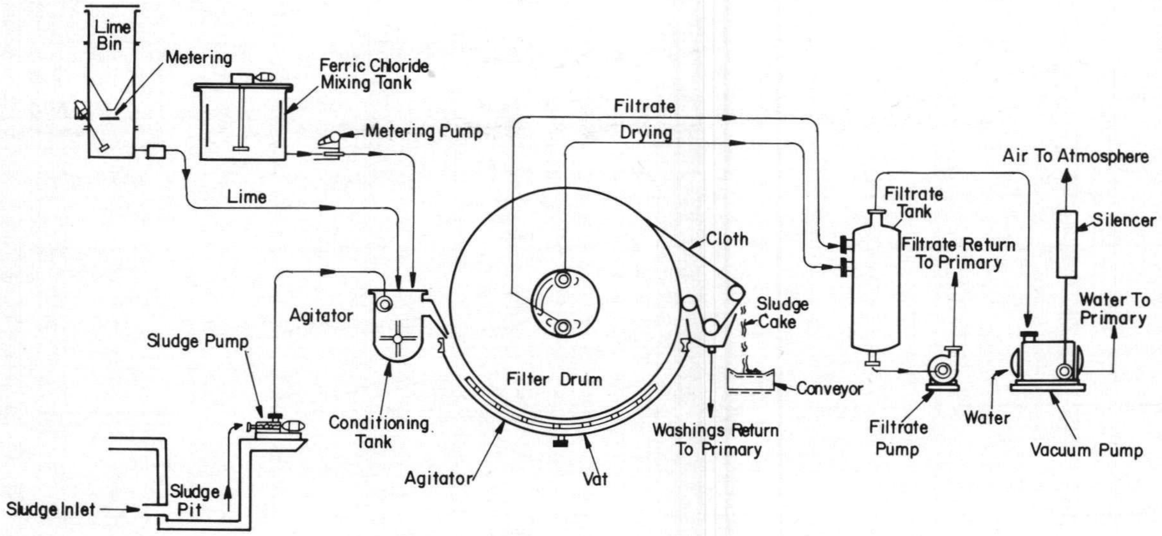


FIGURE 3.21: **Typical rotary vacuum filter system**[51]

specific resistance, upon cake yields of vacuum filters may be estimated by an approach proposed by Gale in 1971.[65]

Readers are referred to the Water Pollution Control Federation Manual of Practice No. 20, 'Sludge Dewatering', for detailed description of the various components of a vacuum filtration installation.

Conditioning

Sludges are generally chemically conditioned prior to vacuum filtration as a means to improve the cake yield and solids capture. Cationic polymers appear to be the most common conditioner although there are installations using aluminium chlorohydrate and ferric chloride together with lime.[40.51]

Polyelectrolyte doses range from 0,5 to 2,2 kg/ton dry solids for digested sludges but can be as high as 4 kg/ton for excess activated sludges.[66]

Performance

Vacuum filtration is generally applied to primary and digested sludges, seldom to excess activated sludges. Typical performance figures are cake solids of 15 — 20% dry solids, solid captures of 85 — 95% and yields of 10 — 50 kg dry solids per m^2 per h at the polyelectrolyte doses mentioned above; the higher yields relating to the filtration of raw sludges.

Vacuum filtration can find application for the chemical sludges, particularly lime sludges.

Operation and maintenance

Vacuum filters have been installed at treatment works in South Africa, primarily for the dewatering of digested sludges, and in certain instances they have not proved particularly successful.[66.67] However, the extensive use of vacuum filters in the mining industry, under relatively unskilled operating conditions, would indicate that they are simple to operate.

Maintenance is generally concerned with the upkeep of the filter cloth which is in turn influenced by the conditioning of the sludge (prevention of blinding etc.). A cloth life of 12 — 18 months can be expected.

2.10.3 **Filter belt presses**

The belt press has been under development for nearly two decades and many variations have been evolved by machinery suppliers. In essence, they all consist of a horizontal perforated or woven belt onto which the conditioned sludge is fed, and a press belt which bears on the other, the belts being kept in contact by a series of individually adjustable rollers. Dewatering is carried out in three separate stages, an initial gravity draining zone followed by a pressure zone and finally a shear zone. In the pressure zone, the sludge is subjected to mechanical pressure between press belt and filter belt, while in the shear zone a shear force is imposed on the sludge as the belts pass around a set of rollers.

Figure 3.22 indicates the configuration of a typical filter belt press. After the dewatered cake is separated from the belts by means of suitably positioned 'doctor blades', the belts are spray-washed with high pressure water jets.

Filter belts

Belts can be polyester or stainless steel mesh fabrication and their alignment on the press is maintained by hydraulically actuated centralizing rollers (refer Figure 3.22).

Belt speeds are variable in the 0,1 — 10 m/min range by suitably geared electric motors which have power ratings of 1 — 1,5 kW/m belt width.

Belt tension are adjustable in the 0 — 6 kg/cm belt

TABLE 3.8 FILTERING CENTRIFUGES[64]

Basic Type	Feed	Separating compartment	Method of discharging solids	Method of separation
Pusher	Continuous	Cylindrical perforated single or multi-stage	Oscillating pusher	Filtration
Peeler	Batchwise	Perforated or solid Horizontal basket	Plough or knives	Filtration or sedimentation
Pendulum	Batchwise	Perforated or solid vertical basket	Knives or manual	Filtration or sedimentation

TABLE 3.9 BASIC DATA RELATING TO FILTERING CENTRIFUGES[64]

Centrifuge	Pusher	Peeler	Pendulum
Centrifugal force	400 — 1 400 g	500 — 1 500 g	up to 1 250 g
Feed particle size	100 μm — 40 mm	5 μm — 10 mm	5 μm — 10 mm
Cake solids content	20 — 75%	5 — 60%	5 — 60%
Capacity	0,8 — 35 ton/h	0,07 — 3 ton/charge	0,08 — 0,5 ton/charge

- Use of a proper lubrication system. It is recommended that a separate oil-circulating, automatically controlled system be used.

- Automatic torque protection and vibration cut-off should be an integral part of the system.

Filtering centrifuges

Filtering centrifuges describe a group of machines designed to handle slurries or suspensions containing a relatively large amount of solids. These centrifuges generally find application in the chemical and pharmaceutical industries.

Table 3.8 lists the three basic types of filtering centrifuges together with their main distinguishing features while Table 3.9 compares the basic data relating to their performances.[64]

The feed particle size and solids content requirements of the pusher type, together with the batchwise nature of the peeler and pendulum types render these filtering centrifuges unsuitable for reclamation plant applications.

2.10.2 **Vacuum filters**

Vacuum filtration consists essentially of an internally partitioned drum, rotating partially submerged in a sludge trough. The filter media, usually in the form of a synthetic cloth is positioned over the drum and rotates with it. Vacuum is applied to the internal partitions of the drum in such a manner that a sludge layer forms on the media and the filtrate passes through the media into the drum and is subsequently discharged. The belt is washed on both sides after cake discharge prior to reimmersion in the sludge. Figure 3.20 shows details of a typical belt-type vacuum filter and Figure 3.21 details of a typical vacuum filtration installation.[51]

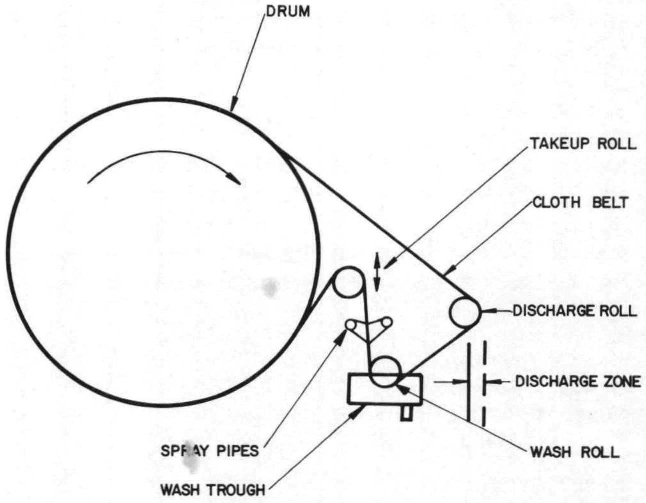


FIGURE 3.20: Typical details of a belt-type vacuum filter[51]

A number of factors affect the performance of vacuum filters (in terms of cake solids content, cake solids yield and solids capture) of which depth of submergence, speed of rotation, filter media, feed sludge solids content and filterability are the most important.

Filterability is dependent upon the characteristics of the sludge and can be gauged by the 'filter leaf' and 'specific resistance' tests, the methods for which are adequately described in the literature.[40,51,61]

The influence of sludge filterability, in terms of

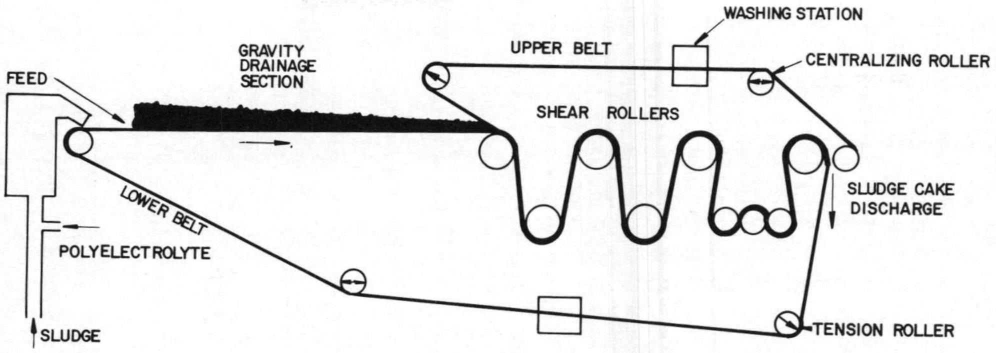


FIGURE 3.22: Configuration of a typical filter belt press (Courtesy of Simon-Hartley S.A.)

width range by means of hydraulically or pneumatically actuated tensioning rollers. Average belt life at normal tension levels is approximately 2 years.

Washwater

Washwater flows are usually such that the ratio of washwater:feed is maintained in the 2 — 3:1 range, the actual value being dependent on the type of press.

Washwater pressures are generally around the 600 kPa level and the use of final effluent is acceptable provided the suspended solids content does not exceed 100 mg/ℓ.

Performance

Experience in South Africa with the dewatering of waste activated sludges resulting from long SRT systems has indicated that cake solids of 16 — 19% can be obtained at polyelectrolyte doses of 2,5 — 3,0 kg/ton dry solids. Solid recoveries reported lie in the 96 — 99% range.[68.69]

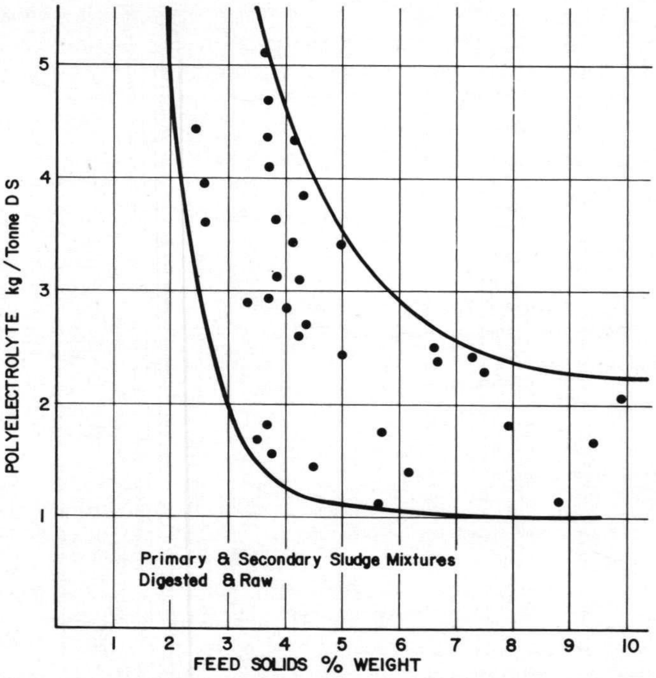


FIGURE 3.23: Influence of feed sludge solids content on polyelectrolyte usage.[70]

The waste activated sludge was previously thickened to 3 — 4% by dissolved air flotation resulting in belt press volumetric application rates of 4 — 5 m^3 $h^{-1}m^{-1}$ effective belt width (equivalent to 160 — 200 kg $h^{-1}m^{-1}$ width).

The filter belt presses operate more effectively with a prethickened sludge. A further benefit of prethickening the feed sludge is that of reduced polyelectrolyte requirements — as indicated by Figure 3.23.[70]

Experience in both South Africa[68] and overseas[70] indicates that primary, digested primary and a digested mixture of primary and waste activated sludges are more amenable to dewatering by the belt filter press than waste activated sludge alone.

Operation

Filter belt presses operate at low speeds, are quiet and easy to operate and hence are amenable to operation by unskilled personnel.[68]

In practice the required cake dryness is dictated by the form of final disposal and where a wetter cake than the 16 — 19% mentioned above is acceptable considerable savings can be realised through operation at reduced polyelectrolyte levels. It is not feasible however to run filter belt presses without polyelectrolyte addition.

Evaluation

There is no better alternative to pilot scale experiments for evaluating the performance of filter belt presses, but a laboratory technique has recently been developed to predict the performance of a filter belt press on a particular sludge.[71]

General

As the final dewatering stage of a filter belt press involves the sludge being sheared between two belts, there is the possibility that small, hard, sharp objects (such as razor blades, buttons etc.) present in the sludge may damage the belts. This possibly has been cited as one of the reasons for installing fine screens at the inlet to a reclamation plant.

2.10.4 **Filter presses**

Filter pressing is an effective means of dewatering conditioned sludges to a higher degree than is normally possible with vacuum filters. Filter presses consist of a series of parallel plates covered on both sides with filter cloths and shaped to permit drainage. Sludge is introduced under pressure (400 – 650 kPa) into the spaces separating successive plates, and water is forced through the filter cloths, leaving behind the solids. After a period of time (the "pressing time"), the press is opened and the accumulated dewatered solids are discharged.

Pressing time varies considerably with the sludge characteristics and can be from 3 h to 3 days, with 6 h being the norm for a well conditioned, previously thickened biological sludge.

Press plates used to be manufactured in cast iron which often cracked due to unequal feed distribution and as a result they are now manufactured in GRP, polypropylene or moulded rubber.

Figure 3.24 shows a section of a filter press[51] while Figure 3.25 indicates the layout of a typical filter press installation, showing the various components thereof.[72]

Installation

Filter presses are normally installed above floor level so that the cakes can drop into trailers (or similar) positioned underneath. Conveyors can be installed under presses to transport the cake to the storage area.

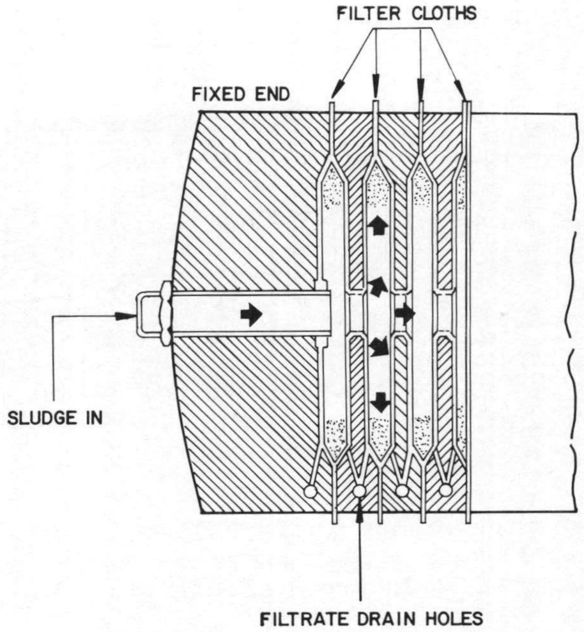


FIGURE 3.24: **Section through a filter press[51]**

Operation

Filter pressing is inherently a batch operation, and high labour costs have been associated with the periodic discharge of dewatered cake. Because of this disadvantage, there is a trend toward automation to make filter pressing a mechanized semi-continuous process.

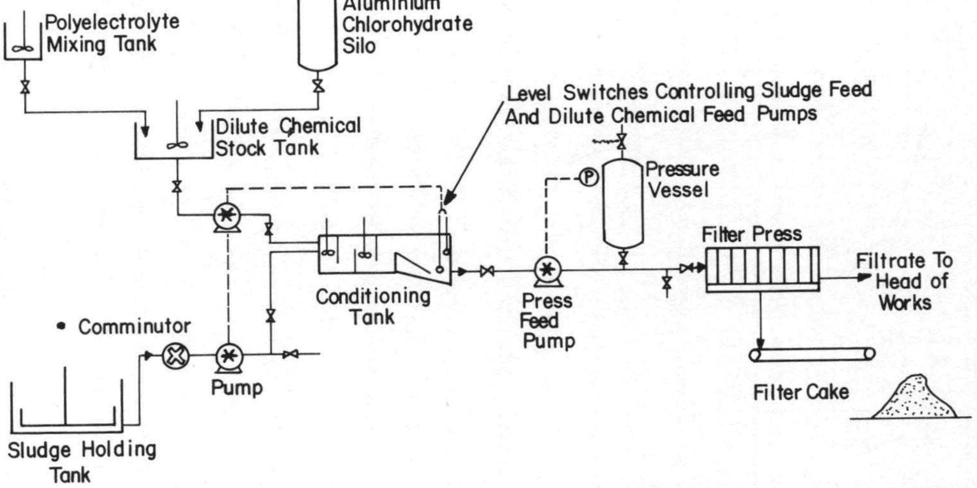


FIGURE 3.25: **Layout of a typical filter press installation[72]**

Conditioning

Chemical conditioning of the sludge prior to filtration plays an important role in the performance of filter presses.

Chemicals such as lime, in conjunction with copperas (ferrous sulphate) or ferric chloride, aluminium chlorohydrate and occasionally polyelectrolytes, are used to reduce the specific resistance of the sludge to the 0,1 — 0,4 x 10^{13} m/kg range which is considered adequate for filter presses.[73]

The type and dosage of chemical to be applied can only be ascertained through laboratory experimentation but Table 3.10 summarizes the doses that have been applied in practice. These figures should be used as a guideline for the laboratory (or full scale) experiments.

TABLE 3.10 TYPICAL CHEMICAL DOSAGES

Chemical	**Dose ($^{w}/w$ on dry solids) %**
Lime	10 — 20
Ferrous sulphate Ferric chloride	4 — 10
Aluminium chlorohydrate (as Al_2O_3)	1 — 4
Polyelectrolyte	1 — 4

Ash can also be used for conditioning, with typical dosages being 100 — 200%.[51,74]

A disadvantage of the lime plus iron salts and the ash is the amount of inert matter added to the sludge, thereby increasing the mass of sludge cake that will eventually have to be disposed of.

Performances — biological

Filter presses are generally able to produce cakes of 40 — 50% dry solids from primary and digested primary sludges with chemical dosing rates approaching the lower values shown in Table 3.10.

The incorporation of waste activated sludges in a sludge blend will generally result in wetter cakes and higher chemical consumptions.[75]

Performances — chemical

Dewatering of waterworks' alum sludges by means of filter presses can produce cakes of 40 — 50% dry solids with the addition of 5 — 12% lime and 3 — 5% ferric chloride.[76]

2.10.5 **Sludge drying beds**

Drying beds are widely used for dewatering both biological and chemical sludges. Their design should be based on climatic factors such as rainfall and evaporation, physical factors such as specific resistance and origin of the sludge and construction factors, whether underdrained or in an impermeable evaporation basin.

Simple manually desludged beds are generally only installed on small works or where labour is plentiful and cheap, their dimensions being often calculated on the basis of a day's sludge discharge. Mechanically desludged beds are considerably larger, their length being as great as possible with the width being suited preferably to a bridge structure carrying a removal mechanism or alternatively to a vehicular form of removal (e.g. front end loader with wide rimmed tyres). Sludge drying beds with mechanical cake removal can therefore be incorporated in large works although the area of land required may prove to be prohibitive.

Drying beds are usually constructed with compacted soil bases overlain by an underdrainage collection and removal system. The underdrainage flow deriving from plants that incorporate biological phosphorus removal, will contain phosphorus which should be chemically removed prior to returning the flow. Drying beds with concrete slabs or strips of concrete in sand bases have also been used, particularly in applications where cake removal is by means of front end loaders entering the beds. However, drying beds with sand bases appear to perform in a superior manner to beds with impervious bases.[77]

The effectiveness of a drying bed system depends on several factors:

- The efficiency of the media to readily drain the free water without blinding.
- A comprehensive underdrainage system and a means of decanting supernatant water.
- The ease of applying the wet sludge and lifting the dried sludges.

A considerable improvement can be made in drying bed capacity in wet weather by covering them to exclude rainfall. In the past, this necessitated an expensive structure but recently in areas where snow and hail do not constitute a threat, ventilated enclosures can easily be constructed with translucent plastic sheeting and light frames similar to the plastic "tunnels" used in horticulture.

Construction

Readers are referred to the literature[51,78,79] for typical constructional details of drying beds suitable for most types of sludges, including mixed liquor discharged directly from the activated sludge reactor.[79]

All drying beds comprise an upper layer of fine sand which should be free of clay particles and should have an effective size of 0,3 — 0,8 mm with a uniformity coefficient of less than 4,0. This sand layer should be at least 200 mm deep and as sand particles adhere to the sludge cakes a reserve quantity of sand should be available on site so that the 200 mm depth may be maintained.

Underdrains usually take the form of open joint pipes or plastic pipes with suitably spaced slots surrounded by a coarse stone media (nominal size 37,5 mm). It is good practice to extend the upstream end of the underdrainage pipe through the bed wall for rodding purposes.

Drying beds that receive mixed liquor or activated sludge from final clarifiers should be provided with means of supernatant withdrawal. Figure 3.26 shows one such system which incorporates a number of weirs set at different levels.[79]

Theoretical bed area requirements

A graphical method that takes into account evaporation and rainfall has often been used to size drying beds.[80] This method makes use of two factors that were experimentally established in the U.K.; one being that the average evaporation rate from a wet sludge surface was 75% of that from a free water surface and the other being that 57% of the rainfall was absorbed by the sludge.

This method has a serious drawback in that it takes little account of the particular sludge characteristics and although the evaporation correction factor of 75% for free surface evaporation is reasonable for most sludges, the percentage of absorption varies considerably and therefore the factor of 57% for rainfall absorption cannot be assumed with any degree of confidence.

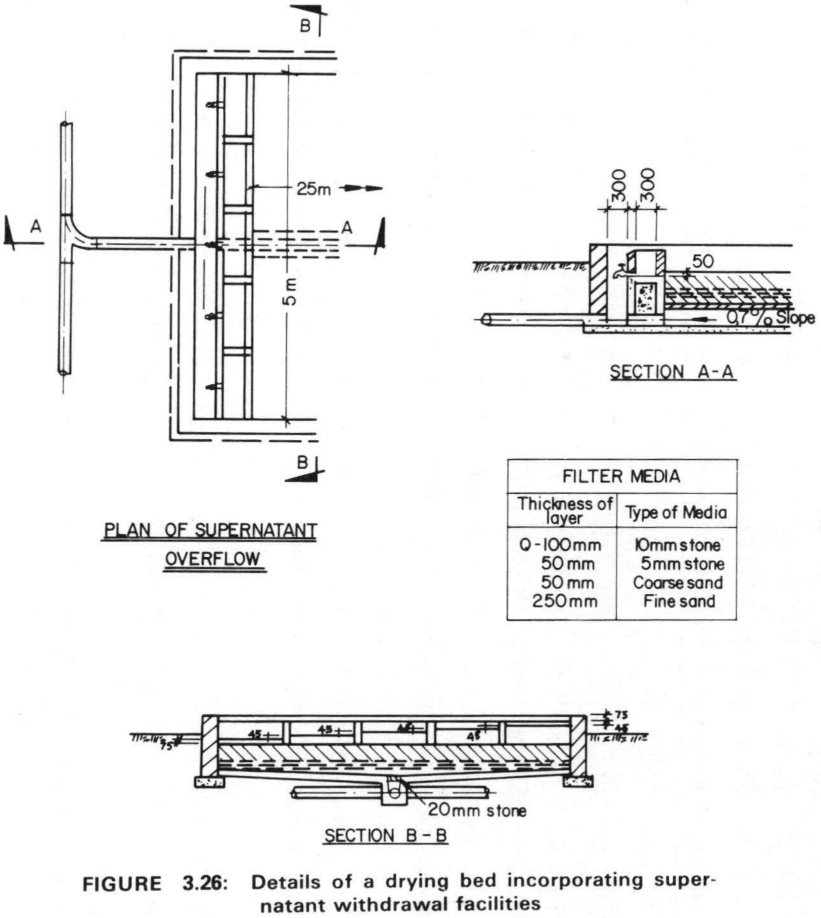
Very little factual information on this aspect of sludge drying is available in literature and pilot scale tests show that the range of rainfall absorption correction factors for the drainage characteristics of the sludge vary from 30% to 85% for normal wastewater sludges.[81]

A more acceptable method of design is to place model beds out in the field in the actual climatic conditions. Such beds with various types and depths of sand and with various depths of sludge applications can yield the best possible information for the design of drying beds.

Area requirements based on experience

Sludge bed area design is frequently based on a per capita requirement which has resulted from reported experience with the different sludges. Table 3.11 indicates the area requirements for digested sludges under conditions pertaining in the U.S.A.

Climatic conditions and sludge characteristics are



FILTER MEDIA	
Thickness of layer	Type of Media
0-100mm	10mm stone
50 mm	5mm stone
50 mm	Coarse sand
250mm	Fine sand

FIGURE 3.26: Details of a drying bed incorporating supernatant withdrawal facilities

TABLE 3.11 SLUDGE DRYING BED AREA REQUIRED FOR DEWATERING DIGESTED SLUDGE*

Type of Sludge	Area (m^{2}/cap.)	
	Open Beds	Covered Beds
Primary digested	0,09 to 0,14	0,07 to 0,09
Primary and humus digested	0,12 to 0,16	0,09 to 0,12
Primary and activated digested	0,16 to 0,23	0,12 to 0,14
Primary and chemically precipitated digested	0,19 to 0,21	0,12 to 0,14

*Data presented in WPCF Manual of Practice No. 2078 has been metricated.

not mentioned in the table and as such the figures should be used as guidelines only.

Table 3.11 highlights the effect of waste activated sludge on the dewatering properties of digested sludge in that the area requirement for digested primary plus activated sludge is some 75% greater than for digested primary sludge alone. The incorporation of activated with primary sludge in an anaerobic digester should therefore be carefully considered. The necessity to further treat waste activated sludges is dependent upon their 'activity', in that activated sludges emanating from high rate systems (i.e. low SRT, 2—5 days) will create odours if dewatered on beds while sludges from low rate systems (SRT of 15 — 25 days) can be readily dewatered without further stabilization, with an area requirement of some 0,09 m^{2}/capita.[79]

The table also indicates the adverse effect that a chemically precipitated sludge has on the area requirements. This is thought to be due to accretion of the chemicals on to the sand particles which results in the upper sand layer becoming 'blinded'.

As the 'specific resistance' test is often used to gauge the dewaterability of sludge, attempts have been made to correlate this parameter, which can be readily measured for all sludges, with an area requirement and Figure 3.27 shows one such preliminary correllation,[81] making use of the area requirements presented in Table 3.11 and typical values of specific resistance reported in the literature.[51,82]

Expressing sludge bed area in terms of per capita area requirements poses problems where industrial wastes are concerned. A rational basis for design is therefore the solids loading, in terms of kg dry solids/m^{2}/day (or month, year). Figures reported in the USA indicate loadings of 0,4 kg m^{-2}d^{-1} for covered beds and 0,3 kg m^{-2}d^{-1} for open beds for 'any sludge with dewatering characteristics comparable to digested primary wastewater sludge'.[78]

South African experience at the coast[55] and on the highveld[79] indicates that long SRT activated sludges have a drying time of 4 — 6 days when applied at 1,5 — 2,0 kg m^{-2}d^{-1}.

Chemical sludges

Primary lime sludges are seldom dewatered directly on drying beds on account of odour generation. Tertiary lime sludges contain a lesser degree of potentially putrescible organic matter and as such are commonly dewatered on beds in small installations.

Bed loadings of 0,7 — 0,8 kg m^{-2}d^{-1} result in cakes of 30 — 35% dry solids being achieved within 3 — 8 days under Israeli summer and autumn climatic conditions (evaporation rates being 7 and 4 mm/d respectively).[83]

There is a paucity of literature on results of dewatering alum and iron sludges on drying beds and it is suggested that either Figure 3.27 — the relationship between specific resistance and area requirements — or a loading of 0,4 kg m^{-2}d^{-1} be used for preliminary designs.

Chemical conditioning

Conditioning of sludges prior to discharge to drying beds has been used in instances where the solids loading exceeds the beds' capacity, the sludges' dewatering characteristics suddenly deteriorate or the beds are subjected to a prolonged period of wet weather.[84,85]

Mineral salts such as alum and ferric-chloride have been used but these salts tend to increase the solids

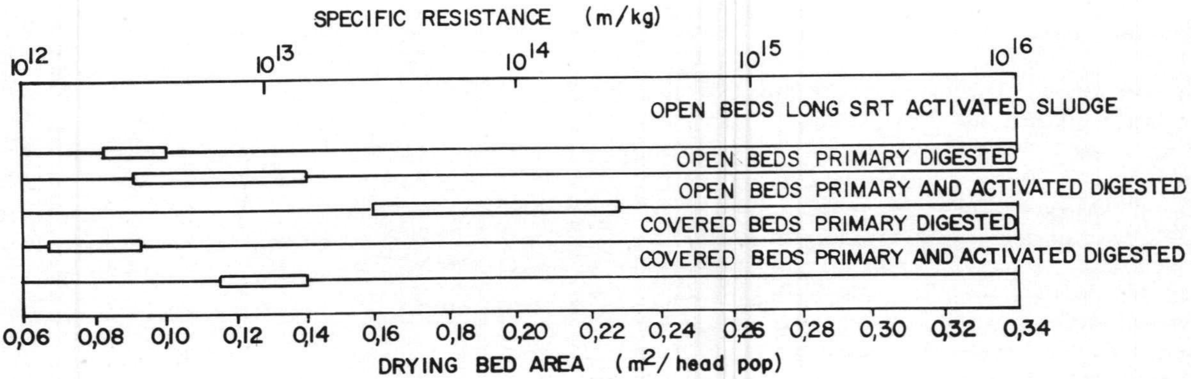


FIGURE 3.27: Relationship between 'Specific Resistance' and drying bed area requirements[51 81 82]

mass to be dewatered and as a result are not widely used.[84]

Cationic polymers are suitable for biological sludges whereas anionic or non-ionic polymers are generally used for chemical sludges.

Polymer addition to an anaerobically digested sludge can result in a floating sludge and provision then has to be made to withdraw the relatively clear water under the sludge if adequate bed underdrainage facilities have not been provided.

Polymer dosing rates of 1,5 — 3,0 kg/ton of dry solids have been found to increase the bed loadings by some 20 — 50% while at the same time reducing the drying time.

2.11 CHEMICAL RECOVERY SYSTEMS

Chemical costs can be a major portion of a reclamation plant's running costs and consequently larger plants are investigating, and indeed some have installed, chemical recovery systems.

In many cases the recovered chemical cost may not be cheaper than that of the fresh chemical but recovery generally reduces the mass of sludge to be disposed of. Reduced sludge handling and disposal costs thus achieved should be considered in the overall economic comparison.

2.11.1 **Lime recalcination**

The most common method of lime recovery is that of recalcination which involves incineration of the sludge at temperatures of 900 to 1 100°C to convert the carbonates (and hydroxides) to calcium oxide (quicklime) which is subsequently slaked prior to return to the process. The high energy requirements of the process must be considered at an early stage of the investigation.

Multihearth, fluidized bed and rotary kiln furnaces can be used for the recalcination process. The former two are the major incineration systems employed for sewage sludges while the latter is widely used in the quicklime production industry and readers are referred to the literature[51,86] for descriptions of these various types of furnace. It is of importance to note however that the recalcination process is orientated towards production and as such a different design approach may be required to that for a purely combustion process.

Primary lime sludge

Two systems have been developed in the USA for the recalcination of primary lime sludges.[87] One system comprises wet classification of the thickened lime sludge, usually by means of centrifuges, after which the $CaCO_3$ rich cake is recalcined, with the product being air classified prior to slaking and return to the process. The centrate from the classifying centrifuge contains the bulk of the organic matter originally present in the lime sludge and undergoes further thickening and dewatering before final disposal, usually by incineration. Figure 3.28 indicates a layout of such a system installed at the Contra Costa Plant in the USA.[87]

The second method involves dewatering the

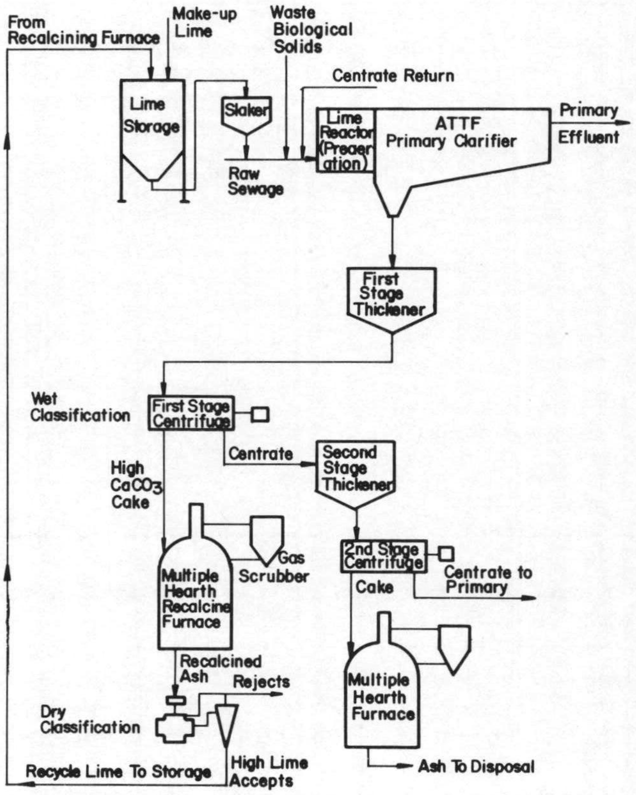


FIGURE 3.28: **Recalcination system employing wet classification[87]**

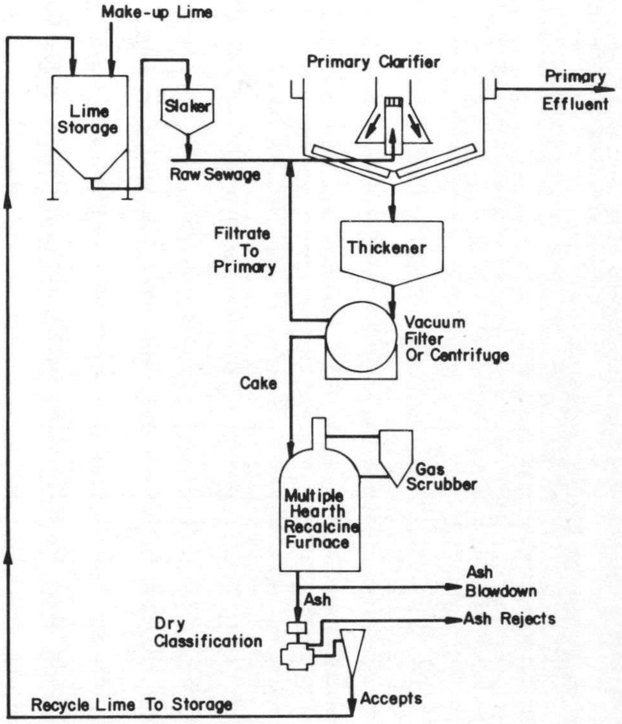


FIGURE 3.29: **Conventional single furnace recalcination system[87]**

thickened lime sludge by vacuum filter or centrifuge after which the dewatered 'mixed' cake is incinerated. The recalcined ash discharged from the furnace undergoes dry classification which separates the quicklime from the ash. The quicklime is returned to the process while the ash is disposed of to landfill. Figure 3.29 shows details of such a system.[87]

Experiments conducted in the USA[87] into the effectiveness of the two methods have indicated that the second method (Figure 3.29) results in a high recycle solids load which can be reduced to the level resulting from the first system (Figure 3.28) by incorporating a racalcined ash blowdown, which can be up to 30% of the total recalcined ash flow. However, the blowdown results in a greater proportion of fresh make-up lime being required.

The crux of the first system is the wet classification step which has to be carefully controlled. The slightest wear on the scroll of the centrifuge will result in poor $CaCO_3$ recoveries[88] and for this reason the second method, although it results in a greater fresh lime requirement, may be preferred.

Tertiary lime sludges

Tertiary lime sludges contain less organic material and as such should be easier to classify.

Recovery of lime from a tertiary lime sludge has been practiced at Lake Tahoe, USA since 1968 where the recovered lime accounts for some 72% of the overall requirements and has an average CaO content of 66%.[11]

Figure 3.30 shows details of the recalcination system, indicating that the tertiary sludge can either be dewatered, in which case the centrate is routed back to the primary clarifier, or it can be classified, in which case the centrate is dewatered by a second 'swing' centrifuge.[11] No subsequent dry classification of the recalcined ash has been allowed for.

Effect of lime recycling

Lime recalcination is still under research, particularly the effect that recycling of components such as magnesium, phosphorus compounds, heavy metals and inerts has on the overall plant performance and economics.

The centrifugal classification step at Lake Tahoe is carried out by cocurrent centrifuges which have proved satisfactory for the separation (or classification) of phosphorus rich inerts and magnesium from the reusable calcium carbonate.[11]

2.11.2 **Magnesium**

The important role that magnesium plays in the lime clarification process has been discussed in Part II, section

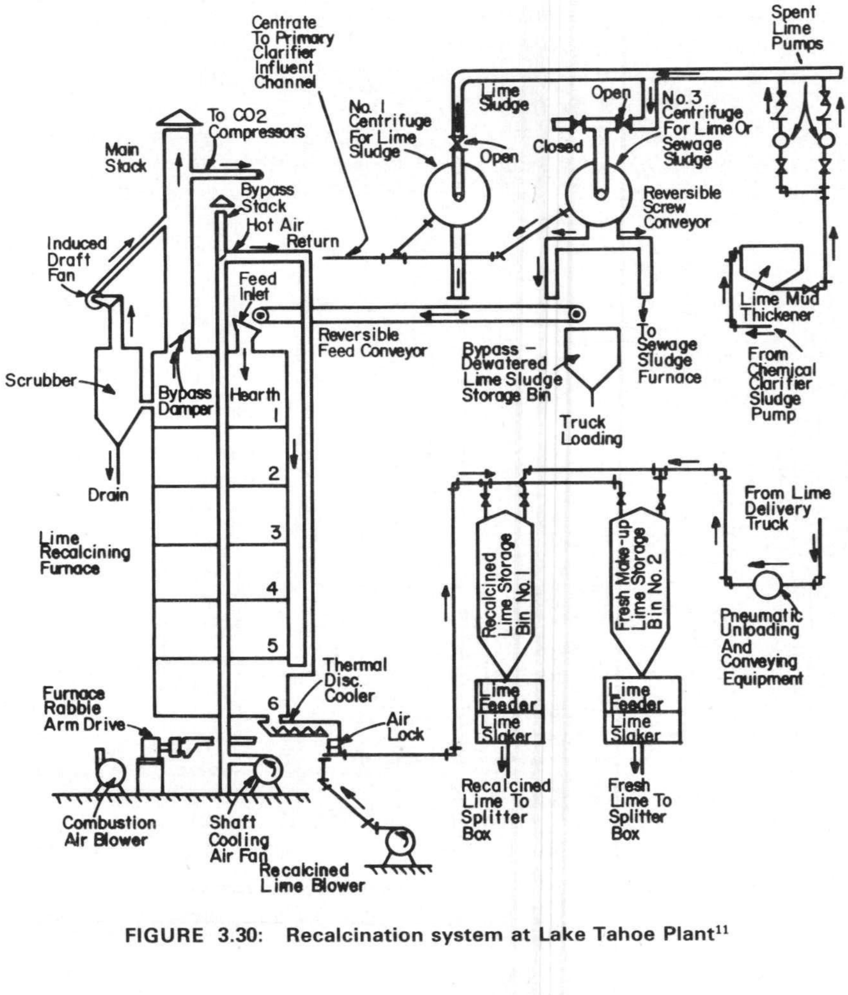


FIGURE 3.30: Recalcination system at Lake Tahoe Plant[11]

3.1. Suffice it to say in this section that magnesium ions are often added to wastewaters low in magnesium in order to achieve the concentration required for optimum clarifier performance.

In these instances, the recovery of magnesium from the resulting lime sludge may prove economically feasible on large scale plants.

Magnesium recovery systems have been developed for sludges resulting from lime softening of potable waters.[89] These sludges contain very little organic matter and it is likely that the recovery systems could be adapted to tertiary wastewater lime sludges.

The magnesium recovery systems involve the dissolution of the magnesium hydroxide precipitate by lowering the pH through carbon dioxide addition. The CO_2 can be generated from a bulk storage facility or flue gases (14 — 20% CO_2) resulting from the recalcination of lime. Lowering the pH to just above the point of calcium carbonate dissolution (i.e. pH 9,3), forms the soluble magnesium bicarbonate which is subsequently separated from the $CaCO_3$ by vacuum filtration or similar. Figure 3.31 indicates a typical magnesium recovery system that utilizes the flue gases from a lime recalcination stage to form the bicarbonate.[89]

Magnesium recoveries of 80 — 100% have been reported for lime softening sludges, while preliminary experiments with wastewater sludges have yielded recoveries of some 25 — 40%.[90]

2.11.3 **Aluminium sulphate (alum)**

Aluminium sulphate may be recovered from alum sludges by methods that involve either raising the pH to the 12,0 region by means of sodium hydroxide or lime or lowering the pH to the 2 — 2,5 region by means of sulphuric acid.[91]

Recoveries range from 50 — 90% depending on the method and purity of chemicals used.[63]

Figure 3.32 shows details of a typical alum recovery scheme using acid.[63] The separator shown in the figure can take the form of a disc centrifuge which has been successfully applied to a system removing aluminium from algae.[92]

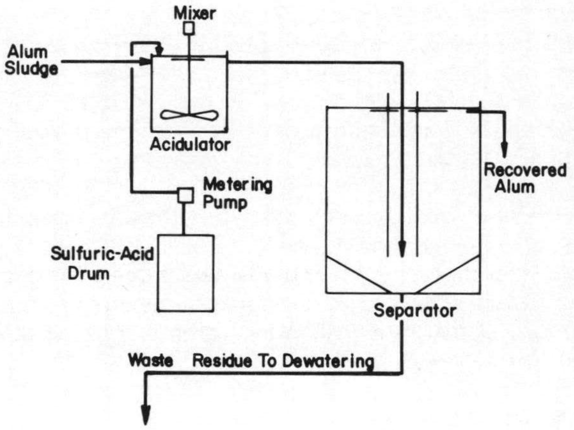


FIGURE 3.32: Typical alum recovery scheme utilizing sulphuric acid[63]

A major disadvantage of the acidic recovery method is the dissolution of phosphorus at the low pH values, which renders this method unsuitable for plants in which chemical phosphorus removal is practised.

2.11.4 **Iron salts**

It is possible to recover iron salts from the sludges but, as mentioned in Part 2, section 12.3.2, recovery is at this stage not economical.

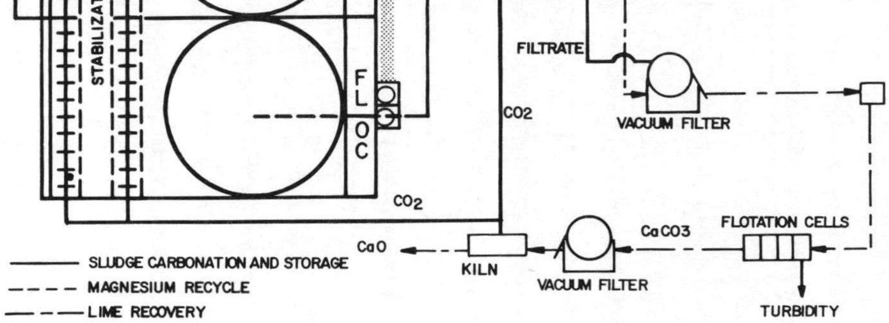


FIGURE 3.31: Typical magnesium recovery system[89]

CHAPTER 3

CHEMICAL HANDLING SYSTEMS

Although the properties of chemicals can vary, the following guidelines can be applied to most chemical feeding systems:

No chemical is harmless

- Operators should be made aware of the nature of the chemicals and should be equipped with protective clothing, gloves, boots and safety glasses.
- Storage areas should be so designed and protected as to prevent spills.
- Ventilation should be provided in all storage areas.

Valves

- The diaphragm valve, suitably lined, is the most satisfactory type of valve for chemical systems.

Pipelines

- Pipes are often of small diameter and as such are relatively fragile. They should therefore be kept out of the way yet be accessible. Walls or trenches are generally used.
- Pipe supports should be carefully designed so as to avoid 'sag'.

Sight glasses on storage and preparation tanks

All sight glasses should be shielded.

3.1 LIME

The basic decision to be taken when designing the lime system is whether to use powdered, hydrated lime or lumped quicklime (to be slaked on site). The decision should not only be based on economics but should also take into account the engineering and operational aspects associated with the use of both types of lime.

For example, the extreme hygroscopic nature of quicklime necessitates great care being paid to storage facilities to ensure that they are watertight.

The on-site quicklime slaking installation adds a degree of operational complexity to the overall system which invariably results in additional maintenance as well as operating costs. A by-product of the slaking process is that of grit production which can amount to 10 per cent of the total mass of quicklime processed. Grit disposal facilities have therefore to be provided.

Quicklime, and the associated slaking installation, would generally only be used in large scale treatment plants in which lime recovery is an integral part.

Figure 3.33 indicates a typical lime slurry preparation and dosing system.

It will be noted that the system comprises a number of stages:

- *Storage*

Hydrated lime is delivered to the works' site either in bulk by special trucks equipped with pneumatic silo loading facilities or in bags in which case the bags are manually unloaded, opened and transferred to the storage silo or, in the case of a small installation, fed direct to the slurry preparation facilities.

Lumped quicklime is generally delivered in bulk, and unloaded into a hopper from where it is transferred to the storage silo.

Bulk lime, both hydrated and quicklime, is usually stored in watertight concrete or steel silos. The lime is

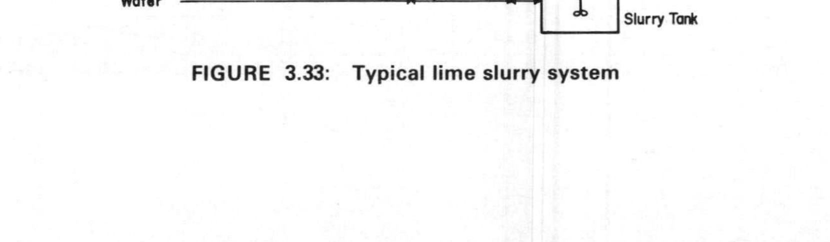


FIGURE 3.33: Typical lime slurry system

transferred to the silos by means of bucket elevators, screw conveyors or pneumatically. Belt conveyors are not recommended; bucket elevators and screw conveyors should only be used when the air is dry and there is little chance of moisture ingress into the lime. Pneumatic loading can be used for both quicklime and hydrated lime but cognisance must be taken of the moisture content of the transport air, particularly in coastal installations. In such humid environments it is usual for air dryers to be provided not only for the transport air but also for all air ingress into the silo.

The discharge end of the feeders, particularly bucket elevators and pneumatic lsystems, should be connected to a dust removal and recovery system mounted on the top of the silo. Such dust recovery systems usually consist of a collection of canvas hoses which trap the dust and are periodically 'shaken' so as to dislodge the trapped dust which falls back into the silo.

The discharge end of silos are generally conical, at an angle of 55 to 60 degrees for quicklime and 60 to 66 degrees for hydrated lime. Take-offs are sometimes eccentric as a means of arching-prevention.

Silos should also be equipped with mechanical vibration or internal air agitation facilities as a further preventative against arching. Air agitation should not be considered for quicklime silos or for silos installed in humid environments.

Storage capacity must take into account the advantage of bulk purchase versus the disadvantage of construction cost and chemical deterioration. Maximum storage period for both forms of lime is 60 days.

Silos should be equipped with content measurement equipment with facilities for high and low level alarms. Such equipment can take the form of ultrasonic level detectors mounted inside the silo, suitably designed load cells positioned on the silo supports or simple capacitance switches.

● *Feeders*

Feeders may be of the volumetric (e.g. rotary vane) or gravimetric form (e.g. beam balance type). Volumetric feeders are less accurate than their gravimetric counterparts, typical accuracies being ± 2 to 7 per cent for the volumetric and ± 1 per cent for the gravimetric feeders but they cost considerably less.

Feeder accuracy requirements must therefore be established before a decision is made as to which form of feeder should be purchased.

● *Slaking unit/slurry tank*

Quicklime is dosed by feeder (usually of the gravimetric form) into the slaking unit which consists of a slaking chamber, followed by dilution compartments. It is essential to ensure that complete mixing takes place in the slaking chamber, and that the proposed mixing equipment can keep the heavy slurry (about 25% dry solids) in suspension. When insufficient mixing is applied, a paste-like deposit develops, which can clog the slaking unit. The slaking unit is equipped with a grit removal facility.

When hydrated lime is used, the slaking unit is replaced by a slurry tank in which a 1 to 6% lime slurry is prepared. (The lower the concentration, the easier the handling characteristics.) In a continuous slurry make-up system the tank would have a retention of some 5 min while in a batch system it would be sized to suit the process and operational requirements, e.g. one batch may be required to be sufficient for one operating shift.

Dilution water flow can be either manually or automatically controlled but provision must be made to automatically stop the flow in the event of a power failure.

A slow, vertical, paddle-mixer should be installed in the sump to keep the slurry in suspension. Figure 3.34 indicates the power required as a function of the slurry solids content.[93]

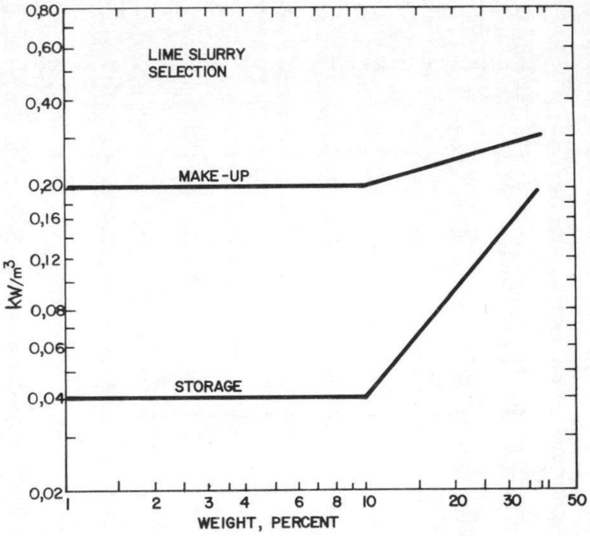


FIGURE 3.34: Power requirements for lime slurry tanks[93]

Suitable baffles should be positioned on the slurry tank walls to a limit vortexing. The mixer shaft and paddles should be coated in a hard rubber for erosion protection.

Overflow and drainage arrangements must be designed for the slurry sump, and high- and low-level alarms installed in it.

In some plants, a 10 per cent slurry is initially prepared in a 'slurry preparation tank' which discharges into the 'slurry tank' in which dilution water is added to produce a slurry with the desired solids content.

● *Dosing pumps*

Lime slurry dosing pumps can be either of the open impeller, centrifugal type with iron body and impeller with bronze trim or rubber lined with rubber covered impellers or they can be of the positive displacement type operating on the 'screw' principle. In each case the pumps should have variable speed drives coupled to the pH control system of the lime reactor, and the pump speed adjusted to compensate for pH fluctuations.

The pump speed range must be such that pipeline velocities are in the 0,8 to 2,5 m/s range and motors should be sized for the maximum envisaged duty. It is recommended that a pump be kept on stand-by to ensure treatment continuity. When a pump is placed on stand-by after being operational it should be thoroughly flushed with clear water. An emergency stop-switch should be installed near every pump.

- *Pipework*

Lime slurry should be transported by gravity in open channels wherever possible. Piping, channels and accessories may be rubber, iron, steel, concrete, and plastics. Glass tubing, such as that in rotameters, will cloud rapidly and therefore should not be used. Any abrupt directional changes in piping should include plugged tees or crosses to allow rodding-out or high pressure flushing of deposits. Long sweep elbows should be provided to allow the piping to be cleaned by the use of a cleaning 'pig'. Daily cleaning is desirable.

Flush-water connections should, within practical limitations, have a cross-sectional area of not less than 25 per cent of that of the slurry pipe.

A minimum pipeline velocity of 0,8 m/s will generally eliminate lime sedimentation within the pipes.

Workmen in the lime handling section should be equipped with protective clothing, masks and goggles as lime dust and hot slurries can cause skin irritations and burns.

Lime quality

Table 3.12 indicates the qualities of high grade quicklime and hydrated lime produced in South Africa.[94] The specification for the quality of lime to be supplied should be based on these tabulated figures. Methods of quality testing should also be specified.

TABLE 3.12 THE QUALITY OF THE TYPES OF LIME AVAILABLE IN S.A.[94]

Type of Lime	Quality I (%)	Quality II (%)
Lumped unslaked lime		
Available calcium oxide	88,0	90,7
Total calcium oxide	94,0	95,2
Magnesium oxide	0,6	1,5
Silicon dioxide	3,0	1,0
R_2O_3*	1,0	1,5
Loss on ignition	1,4	0,8
Hydrated lime		
Available calcium hydroxide	67,7	69,1
Total calcium hydroxide	73,9	72,0
Magnesium dioxide	0,9	1,8
Silicon dioxide	1,4	0,8
R_2O_3*	0,9	1,4
Loss on ignition	22,9	24,0
Screen analysis (plus 0,075 mm)	3	10

*R represents Mn, Al, Fe

Lime dosing system

Figure 3.35 shows details of the lime dosing system installed at the Stander Plant and which enables the pH in the lime clarifier to be controlled to within ± 1,5% of the set point.[95]

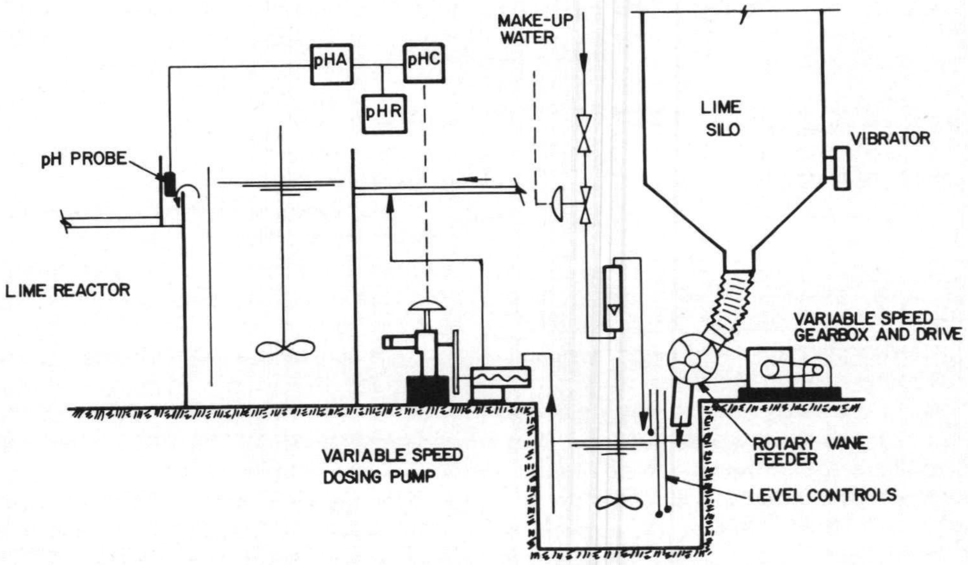


FIG. 3.35: Lime dosing system installed at the Stander Plant[95]

3.2 POLYELECTROLYTES

Polyelectrolytes are available in liquid and powder form. Most polyelectrolyte dosing systems in South Africa are based on the use of powder polyelectrolytes and there has been little use of the liquid form.

In the case of water reclamation for potable supplies, certification must be received from the polyelectrolyte supplier that his product is certified for potable water use. The supplier should also be requested for details of storage life as this factor can vary, being dependent upon the type of polyelectrolyte selected.

Polyelectrolyte solution preparation can be on a batch or continuous basis with the polyelectrolyte powder being added either manually or automatically in the case of the batch system. There are also package, fully automatic systems on the market which should receive consideration for large scale applications.

Figure 3.36 shows a typical batch type polyelectrolyte preparation and dosing scheme.

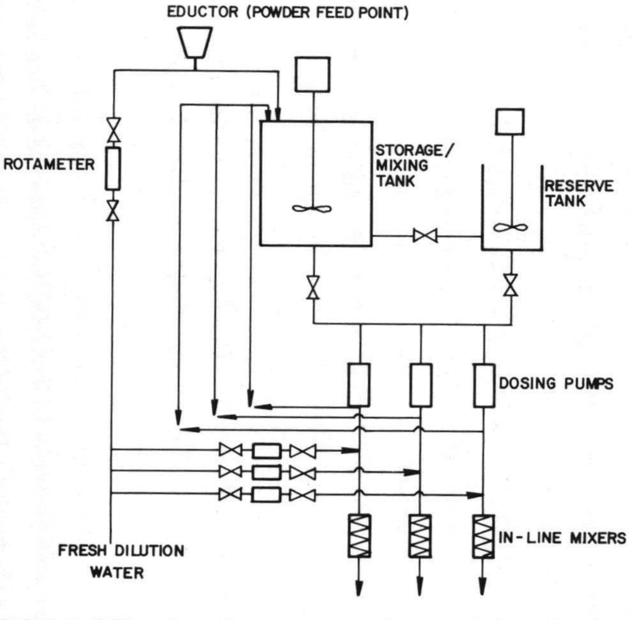


FIGURE 3.36: **Typical batch type polyelectrolyte and dosing schemes**

A 0,5% solution is made up with clean, fresh water in the storage/mixing tank and then diluted to a 0,1% solution just after the pump discharge, with suitably placed rotameters accurately measuring the dilution water flow. In-line mixers should be provided to ensure complete mixing of the 0,5% solution and dilution water prior to discharge at the dosing point.

The in-line mixers should have low shear properties so as not to break up the polymer chains. This form of mixing could be replaced by a separate dilution tank into which the 0,5% solution and fresh water discharge and are thoroughly mixed by means of a slow speed, low shear, inclined mixer.

The storage/mixing tank should have a retention of 12 to 24 h, while the reserve tank should have a retention of at least 4 h. This 4 h period in the reserve tank will cover the time spent preparing a fresh batch as well as imparting at least a 2 h 'age' to the freshly made up solution.

The tanks should be constructed out of stainless steel, GFRP or rubber lined mild steel due to the corrosive nature of the polyelectrolyte solution.

Both tanks should be equipped with low speed, low shear inclined mixers with shafts and impellers of a high grade stainless steel (316L).

The dosing or metering pumps should be of the positive displacement type, either of the plunger or diaphragm type or of the 'mono' type. All moving parts in contact with the polyelectrolyte solution should be of 316L stainless steel or inert material.

All pipework should be of 316L stainless steel or of a non-metallic material.

The most effective results (of the polyelectrolyte addition) will be obtained if the diluted solution (0,1%) is dispersed over the cross-section of the flow to the treated, whether this be the cross-section of a flume, pipe or channel.

Steps should be taken downstream of the point of addition to avoid sudden changes of direction, free discharges etc. which could cause floc break up.

3.3 ALUMINIUM SULPHATE

Aluminium sulphate ($Al_2(SO_4)_3.16H_2O$) is available in the kibbled (lumped) or powdered forms with bulk densities of 1 025 and 670 kg/m^3 respectively. Both forms are delivered in 50 kg bags or in bulk. Storage should take the form of covered areas for the bags and silos for the bulk form and the storage period should be limited to 30 days.

Aluminium sulphate lye at a 50% concentration by weight is also available. Dry aluminium sulphate can be transferred with screw conveyors, pneumatic conveyors or bucket elevators, all of mild steel frame construction. Pneumatic conveyor elbows should be reinforced as alum can be abrasive.

Silo agitation is seldom required with powdered alum as it exhibits less tendency to arch than lime. The discharge ends of the silos should be conical at an angle of 60 degrees.

The feeders may be of the volumetric or gravimetric forms and as discussed earlier (3.1), the volumetric feeder is less accurate than the gravimetric counterpart but it costs considerably less. However, belt-type gravimetric feeders, having an accuracy of ± 1%, are usually used in large scale alum preparation installations. The feeders should be of stainless steel construction, although feed hoppers can be of mild steel, and provision should be made for regular on-site calibration of the installed feeders.

Figures 3.37 and 3.38 show typical aluminium sulphate solution preparation and dosing systems — one continuous (Figure 3.37) and the other batch (Figure 3.38).

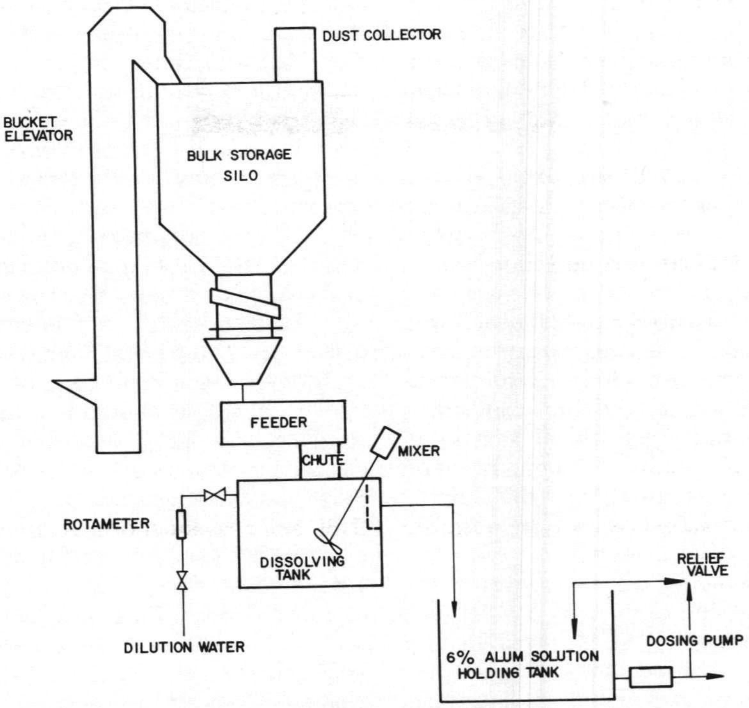


FIGURE 3.37: Scheme for continuous make-up and dosing of aluminium sulphate solution

The aluminium sulphate solution is fairly corrosive so the dissolving and holding tanks in the continuous system (Figure 3.37) and the mixing and holding tanks in the batch system (Figure 3.38) should be constructed of 316L stainless steel, GFRP, rubber lined concrete or glass fibre lined concrete.

A 6% aluminium sulphate solution is usually prepared in both systems, with the dissolving tank in Figure 3.37 being sized for a 5 min detention at maximum solution feed rate and the mixing/holding tanks in Figure 3.38 being sized either to suit shifts (i.e. 8 h) or for 24 h operation.

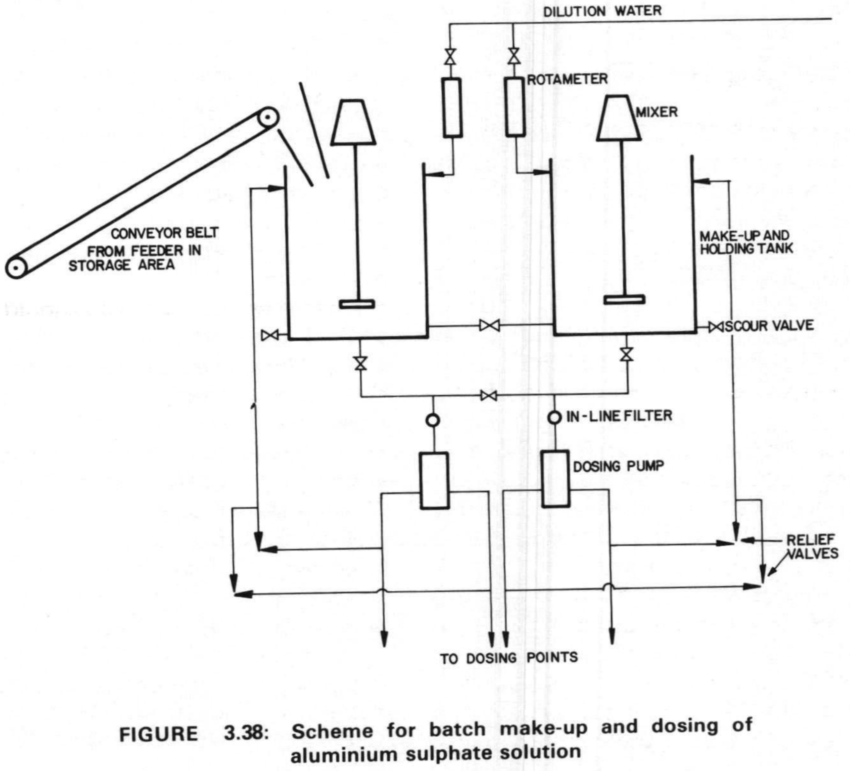


FIGURE 3.38: Scheme for batch make-up and dosing of aluminium sulphate solution

All the tanks should be equipped with suitably designed mixers, all with 316L stainless steel (or rubber lined mild steel) shafts and impellers, and dilution water facilities, which in the case of the continuous system should include facilities for automatic shut-off in the event of power failure.

Consideration should be paid to installing level 'sight-glasses' (with transparent plastic tubes) on the tanks, particularly the larger tanks in the batch system. 'Hi' and 'Lo' alarms would be an optional extra.

All the distribution pipework and associated valves should be corrosion resistant, i.e. of plastic, 316L stainless steel or rubber lined mild steel construction.

The aluminium sulphate solution dosing pumps can be either of the centrifugal or positive displacement metering type. In the case of the centrifugal alternative, the pumps should not be close-coupled to the motor on account of possible leakage occurring and they should be of 316L stainless steel or suitably lined, high quality cast iron construction.

The positive displacement pumps should be of the plunger or diaphragm type and all parts in contact with the alum solution should be of 316L stainless steel or plastic construction. These pumps should be protected from solids ingress by the installation of in-line filters upstream of their intakes.

In large applications, where accurate alum dosing is required, it would be advisable to consider using variable speed motors or variable setting pumps in order to be able to automatically pace alum supply with demand.

Aluminium sulphate powder or dust can cause eye and nose irritation and it is therefore common to ventilate all storage or handling areas as well as providing protective clothing to the operating personnel.

3.4 **IRON SALTS**

Ferric chloride and ferrous and ferric sulphate are available in South Africa.

The iron salts are generally cheaper than aluminium sulphate, in terms of R/kg, but they have the disadvantage of their solutions being extremely corrosive and in some instances resulting in significant iron concentrations in the treated effluents.

Ferric chloride is available in both liquid and powder form. 'Liquid $FeCl_3$ is a dark brown aqueous solution containing 43% by mass $FeCl_3$ with an indefinite storage life. This solution has a freezing point of 0°C and in order to prevent crystallization occurring in pipelines etc. the solution is usually diluted. Although a 39% by mass solution will only freeze at $-13{,}9°C$, solutions of 3 to 15% by mass are commonly dosed.

The materials of tanks, pumps, stirrers, pipelines and valves that were specified for the aluminium sulphate system also pertain to the dosing of $FeCl_3$. In addition, all floor surfaces in the vicnity of the storage and dosing tanks should be treated with a corrosion resistant coating.

Powdered $FeCl_3$ is commonly dosed as a 3 to 6% by mass solution, with equipment as detailed for the preparation and dosing of aluminium sulphate.

Ferrous sulphate is generally in powder form although there are treatment plants that utilize the salt in the form of 'waste pickle liquor' from plating works.

Powder ferrous sulphate generally contains 55 — 58% $FeSO_4$ and has a bulk density of 1 000 — 1 050 kg/m^3. As the composition of the powder does vary, full specifications should be obtained from prospective suppliers prior to the order being placed. When ferrous sulphate is obtained from pickling liquors, guarantees must be obtained as to the absence of heavy metals.

Ferrous and ferric sulphate are usually dosed as 6% by mass solutions and, as for ferric chloride, the solution preparation and dosing equipment are the same as those detailed for aluminium sulphate.

Chlorinated copperas, a solution of ferric sulphate and chloride, is formed by the action of aqueous chlorine on ferrous sulphate. As ferric ions are more effective coagulants than the ferrous ion, there may be some merit in producing the chlorinated copperas at those plants that already incorporate chlorination and which are situated in such an area that ferrous sulphate is not only readily available but is also very much cheaper than the commercial grade ferric chloride.

Due to the corrosive nature of the iron salts, particularly ferric chloride, all operating personnel should be issued with goggles and acid resistant clothing, boots and gloves.

3.5 **SODIUM HYDROXIDE (CAUSTIC SODA)**

Caustic soda is available in lyes of different concentrations. All the lyes crystallize at temperatures approaching 0°C and therefore provision must be made to keep the storage tank above the freezing point by the insertion of stainless steel electric heating elements. Lagging of the storage tank can also be considered as an added measure.

Low carbon steel can be used for the construction of the storage tank.

The dosing pumps can be of the centrifugal or positive displacement type and dilution water is usually added in the same manner as for polyelectrolytes (*vide* 3.2) in order to bring the lye to a concentration of 5% by weight.

Caustic soda can cause severe burns. Operators must therefore be issued with protective clothing, face masks, safety glasses, gloves and boots.

CHAPTER 4
PUMPING AND PIPING

4.1 DESIGN PARAMETERS AND FORMULAE FOR EFFLUENT AND SLUDGE PUMPING

Effluent

The most common formula for assessing the pressure drop due to flow in a pipeline is the 'Fanning' or 'D'arcy' equation:

$$P = \frac{4fL}{D} \cdot \frac{V^2}{2gc}$$

where P = pressure drop (m)
f = Fanning friction factor
L = Pipeline length (m)
D = Pipeline internal diameter (m)
V = Mean velocity (m/s)
gc = 9,81 m $s^{-1}s^{-1}$

The Fanning friction factor, f, is not only dependent on the Reynolds Number of the flow in the pipe but also on the roughness of the interior of the pipe. The reader is referred to the literature for details of the variation of 'f' with both Reynolds Number and roughness.[96]

The apparent roughness of a pipe is dependent upon a number of factors, of which material of construction, age and joint alignment are perhaps the most significant. The reader is referred to the literature for typical surface roughness factors,[97.98] where it will be seen that there can be a great variation in the roughness factor for any particular pipe. Most effluent pumping systems operate in the turbulent flow regime (i.e. Reynolds Number greater than 4000) and, as the effect of roughness becomes more pronounced at the higher Reynolds Numbers, great care should be exercised in selecting the appropriate roughness factor for design.

The pressure drop through fittings such as valves, bends and tees can be expressed either by the equation $\triangle P = K.V.^2/2gc$ or by an equivalent length of pipe and readers are referred to the literature for typical values.[96.99]

In selecting the size of pipe to be used for a particular system, there is frequently a range of permissible diameters encompassing two or more standard sizes of pipe. In such cases the final selection should be made on an economic basis so that the relationship of total operation cost to investment is most favourable.

Economic pipe-diameter charts are available for selection of pipe diameters for the lengths usually encountered within chemical plants or refineries.[96] These charts may also be used for water reclamation plant pipelines.

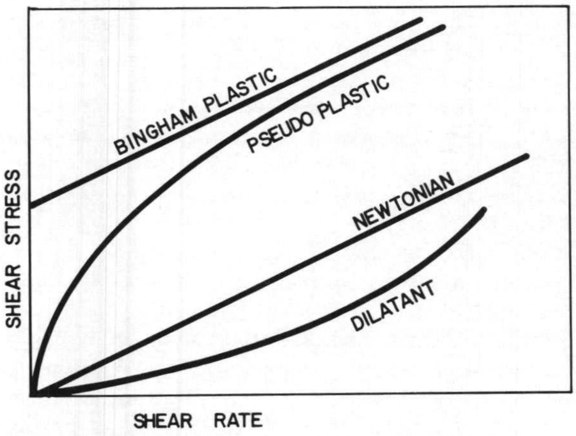


FIGURE 3.39: Non-Newtonian flow characteristics

Sludge

The rheological properties of sludges have been briefly discussed in Part II section 12.2.3. Figure 3.39 is a typical rheogram comparing the various forms of non-Newtonian fluid and highlighting the differences between their characteristics and those of a Newtonian fluid.

The viscosity of Newtonian fluids is defined as follows:

$$\Gamma = \mu . \frac{du}{dy}$$

where Γ = shear stress, which is the shearing force per unit area exerted in the direction of flow (N/m^2)

μ = liquid viscosity (Ns/m^2)

$\frac{du}{dy}$ = shear rate (or velocity gradient)

The value of μ in a Newtonian fluid is independent of shear rate and varies only with temperature, pressure and composition. The flow characteristic of a Newtonian fluid is therefore represented on a rheogram by a straight line passing through the origin, with a slope equal to its viscosity.

Non-Newtonian fluids, however, exhibit flow characteristics with shapes other than straight lines passing through the origin. Such characteristics have been designated as Bingham plastic, pseudoplastic and dilatant (refer Figure 3.39).

The characteristic of a Bingham plastic fluid is expressed as follows:

$$\Gamma - \Gamma y = \eta \frac{du}{dy}$$

where

Γy = 'yield stress', which indicates that unless a stress larger than Γy is applied the fluid will not 'flow' (N/m^2)

η = 'coefficient of rigidity', the value of which is independent of the shear rate, $\frac{du}{dy}$, and is the slope of the line.

The characteristics of pseudoplastic and dilatant fluids may be expressed by a power-law relationship:

$$\Gamma = K'\left(\frac{du}{dy}\right)^{n'}$$

where K' = 'Consistency index' (identical to the viscosity in the case of Newtonian fluids)

n' = 'flow behaviour index' which indicates the degree of departure from Newtonian fluids. For $n' = 1$ the system is Newtonian, for $n' < 1$ the system is pseudoplastic and for $n' > 1$ the system is dilatant. Values of n' for pseudo plastic fluids are usually in the range of $0{,}6 < n' < 1{,}0$.[61]

Sewage sludges exhibit non-Newtonian properties, but there is dispute in the literature as to whether their behaviour is pseudoplastic or Bingham plastic[40,96,100,101] although the difference between the two forms only really becomes significant at low rates of shear.[102] There is consensus, however, that the sludges exhibit thixotropic properties in that their composition changes not only with shear rate but also with time. This results in a concomitant change in rheological properties (for any given value of shear rate). Rheograms of thixotropic fluids generally indicate a hysteresis loop brought about by the time dependence of the rheological properties; Figure 3.40 indicates a typical plot.

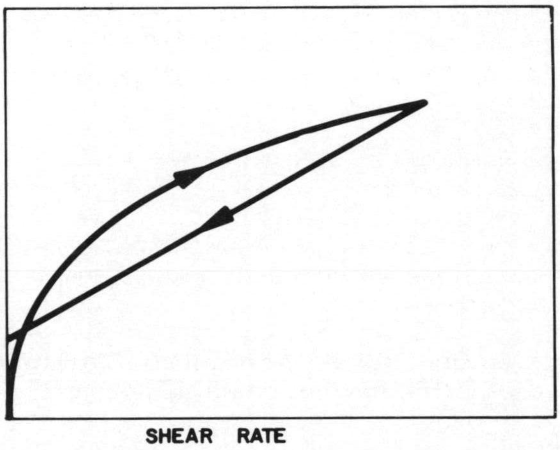


FIGURE 3.40: Typical thixotropic plot

The variation in viscosity with time plus the initial high shear stress required to initiate fluid movement (for both pseudoplastic and Bingham plastic fluids), render the calculation of pipeline friction losses no easy task. The difficulty in calculating pressure loss is highlighted by the fact that it is common practice to take the friction as 1,5 — 4,0 times the friction loss for water.[103] This 'factor application' can lead to sludge pumping systems being incorrectly designed as it underestimates the friction losses under laminar flow conditions but over-estimates them at turbulent flow.

The initial high shear stress (or yield stress) is dependent not only upon the nature of solids in the sludge but also upon the solids content (dry basis).[81] The effect that the nature of the sludge has on the friction loss is highlighted by the fact that pumping anaerobically digested sludge results in a lower friction loss than pumping raw primary sludge of the same solids content and flow condition.[104] Digested and waste activated sludges appear to exhibit similar head losses.[81]

Sludges are generally pumped at velocities of 0,8 to 2,4 m/s which, depending upon the nature and concentration of the sludge, should ensure that the flow is in the turbulent regime.[104,105]

Figure 3.41 which presents a plot of friction loss versus velocity for digested sludges of different solids contents, indicates that as the solids content increases from 0 (i.e. water) to 5%, the velocity at which transition from laminar to turbulent flow occurs also increases.[106]

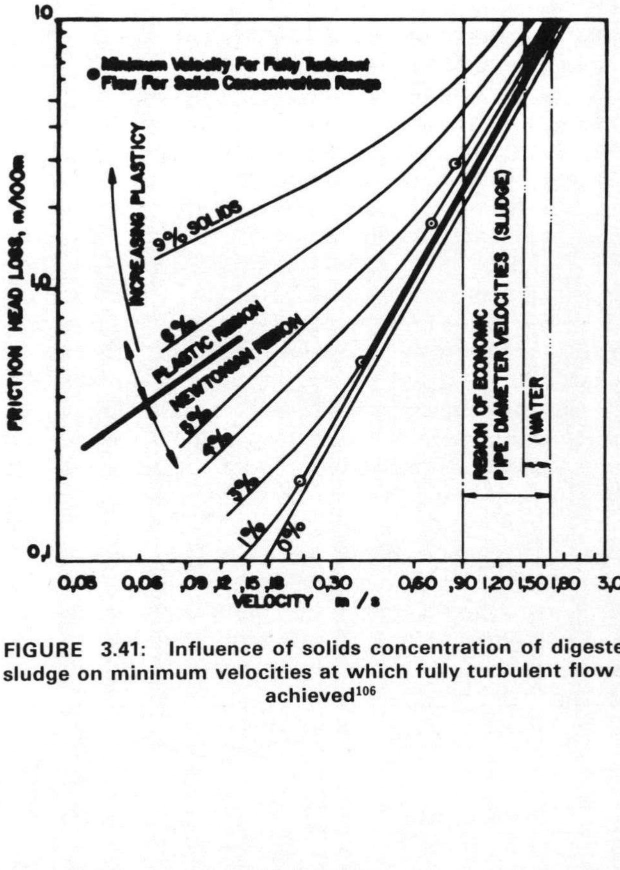


FIGURE 3.41: Influence of solids concentration of digested sludge on minimum velocities at which fully turbulent flow is achieved[106]

Methods for calculating the friction pressure drop are presented in the literature,[40.96.101.102] with the major obstacle in the procedures appearing to be that of collecting reliable rheological data for the sludge to be pumped.

Rheological data is generally obtained through the use of laboratory viscometers which are described in the literature.[61.100] A rheogram relating shear stress to shear rate can then be plotted for the particular sludge and the shape of the line will indicate the non-Newtonian form that the sludge takes.

In order to calculate the pipeline friction loss, the abovementioned data is plotted on a log-log scale and the equation describing the pseudoplastic characteristic is used but in a slightly different form:

$$\frac{\triangle P.D.}{L} = K' \left(\frac{8V}{D}\right)^{n'}$$

In this case K' is the value of $\frac{\triangle P.D.}{L}$ when $\frac{8V}{D} = 1$ and n' is the slope of the line on the log-log plot. The values of K' and n' are inserted into the 'modified' Reynolds Number:

$$N_{RE} = \frac{V^{2-n'} . D^{n'} . \varrho}{K' . 8^{n'-1}}$$

whereupon the Fanning friction factor, f, is obtained from the relationship mentioned earlier.

This method represents a slight modification to the method proposed by Dodge and Metzner[107] who reported that their method resulted in excellent approximations being attained even for non-Newtonian fluids that did not obey the power-law (e.g. Bingham plastics).

In instances where the pumping system has to be designed without there being sludge available with which to ascertain the necessary rheological data, n' values in the range $0{,}6 < n' < 1$ and K' values in the range $0{,}001 < K < 1{,}0$ can be used. K' values are greatly dependent upon the solids concentration of the sludge and Table 3.13[108] can be used as a *rough* guide for K' value selection, with the value adopted requiring verification as soon as the actual sludge is available.

Temperature has a considerable effect on the viscosity of water, oils and other homogeneous fluids but in the case of sewage sludges the effect is not so marked.[101] This has been attributed to the dominant influence of the sludge particles, which are virtually unaffected by temperature, upon the non-Newtonian flow.

TABLE 3.13 RELATIONSHIP BETWEEN 'K' AND SOLIDS CONTENT[108]

K ($Nm^{-2}s^{-1}$)	Dry solids (%)
1,00	10
0,70	8
0,30	7
0,08	5
0,005	3
0,001	water

A consequence of the high 'K' values for sludges of high solids content (say greater than 7%) is that even at velocities of 2 m/s modified Reynolds Numbers are obtained that are still in the laminar flow regime (i.e. below 2 100). This is confirmed by experience at Chicago where experiments into the pumping of sludge with solids content of 8 — 13% indicated that the flow was almost always laminar.[101]

The 'modified' Reynolds Number procedure, which is geared for turbulent flow only, will result in pipeline friction losses being *underestimated* under *laminar* flow conditions. In instances therefore, where the modified Reynolds Number is less than 2100, use should be made of the Poiseuille-Bingham equation to estimate the friction losses:

$$\triangle p = \Gamma \frac{4L}{D}$$

where Γ = the shear stress which is dependent upon the shear rate, $\frac{8V}{D}$, actually pertaining in the system and is ascertained from a rheogram of the sludge or of similar sludges.

Pumping flotation thickened activated sludge

Special care must be exercised when pumping flotation thickened activated sludges due to the presence of entrained air.

The pump suction must always be drowned so as to ensure that the Nett Positive Suction Head (NPSH) is always positive or degassing will occur, leading to air locks, loss of prime and/or pump damage.

The suction piping should be as straight as possible and include a minimum of valves, tees, crosses, reducers etc.

4.2 MAINTENANCE OF EFFLUENT AND SLUDGE PIPELINES

Effluent is generally pumped at velocities high enough to ensure turbulent conditions, which prevent any solids that might be present in the effluent from settling out.

Maintenance of effluent pipelines is therefore usually restricted to that of ensuring that the external corrosion protection is functional.

It is good practice to flush out pipelines when pumping is terminated as the effluent may undergo further biological degradation if left standing within the pipe. This degradation could result in oxygen depletion and possible initiation of internal corrosion.

Sludge pipelines, however, do require a measure of internal maintenance, especially in the case of raw primary sludge pumping systems where grease build up and coarse solid settlement often occur.

Velocities of 1,5 — 2,4 m/s, correct pipe lining selection, effective screening and grit removal facilities and sludge maceration prior to pumping will alleviate these problems but provision must also be made for pipeline flushing, which in any event should be performed as soon as sludge pumping is stopped.

Recirculation of digester supernatant and chemical emulsifiers have been used at various treatment works in the USA to limit the grease build up in primary sludge lines.[104,109]

Anaerobically digested and excess activated sludges contain less grease than raw sludges and as such can be pumped at lower velocities — e.g. 0,6 to 0,8 m/s for activated sludge with a solids content of 0,5 to 1,0%.[104]

Chemical sludge lines, particularly those transporting sludge originating from lime treatment, should always be thoroughly flushed out as soon as pumping is terminated.

4.3 PUMP SELECTION FOR EFFLUENT AND SLUDGE DUTIES

The reader is referred to the literature for detailed discussions on the selection of pumps suitable for effluent and sludge pumping systems.[96,103,110] Table 3.14 is a guide to the types of pumps suitable for the various applications.

TABLE 3.14 SUMMARY OF PUMPS FOR VARIOUS APPLICATIONS

Fluid	Type of pump	Comments
1. Raw sewage	Non-chokeable (open single vane impeller or single port closed impeller) or Archimedean screw.	Pumps must be suitable for handling liquids containing solids *and* rags. Use of Archimedean screws is dependent upon head requirements.
2. Settled sewage and secondary effluents	Semi-non chokeable centrifugal	—
3. Tertiary effluents	Conventional clearwater centrifugal pump	—
4. Raw primary (natural and thickened), digested and primary chemical sludges	Non-chokeable centrifugal or positive displacement	Non-chokeable centrifugal should be specially designed for thicker materials. Positive displacement pump usually adopted operates on the 'screw' principle and must be preceded by a macerator for this application
5. Waste and return activated	Archimedean screw or non-chokeable centrifugal	Archimedean screws preferred for return activated sludge applications owing to their variable output capability. Centrifugals are frequently used for waste sludge applications where head requirements and/or site layout are such that Archimedean screws are excluded
6. Thickened waste activated, secondary and tertiary chemical sludges	Positive displacement	Pump operating on the 'screw' principle. Not necessary to precede the pump with a macerator.

CHAPTER 5
INSTRUMENTATION AND CONTROL

5.1 CLASSIFICATION OF PROCESS INSTRUMENTATION

The purpose of instrumentation is to measure and/or control selected process variables that are associated either with the entire reclamation scheme or with various unit processes that constitute the plants. The decision as to which type of instrument to use should be based upon the intended function, namely for 'monitoring' or 'control', and the reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 13 for discussions on the level of instrumentation installed at the Stander Plant.

Monitoring

'Monitoring' instrumentation is used mainly to detect and prevent process failure and, ultimately, to protect personnel and equipment and to serve as a record of plant performance. In addition, through the use of monitoring instrumentation, operating personnel, maintenance and plant down-time may be minimized.[10]

Control

'Control' instrumentation is required for the efficient operation of the plant. It must provide for both manual and automatic operation. The functions of control instrumentation include the maintenance of operating parameters within preset limits; sequencing of valves and pumps in response to operational commands and modes such as start, backwash and shut down; and automatic variation of parameters to compensate for variations in quality or operating efficiency, e.g. pacing the chlorine dosage according to ammonia concentrations and provision of a safety barrier by directing substandard water to a drain or alternative disposal site.[10]

While there is operational benefit in installing a significant degree of monitoring instrumentation at reclamation plants, the degree of automation should be carefully evaluated. This caution arises from the fact that although automation can offer potential benefits such as improved plant performance, more effective use of operating staff, lower operating costs etc., it also requires sophisticated equipment which in turn requires regular maintenance, which is a definite drawback on the smaller plants. In addition, as automatic control systems may occasionally break down, provision has to be made for manual operation in such instances.

Perhaps the main disadvantages of automatic control is the inevitable loss of direct operator observation and control of the process.

Analogue and digital transmission

The control and monitoring functions of instruments on biological treatment and reclamation plants are generally achieved through the transmission of signals in the analogue form. Such signals are routed to and from a central control room which is equipped with the associated controllers, recorders and/or indicators and perhaps a mimic diagram of the entire plant as well.

The degree of instrumentation installed on a large plant will usually involve substantial lengths of instrument cabling for these analogue signals. In addition, the manual logging of the process variables for the monthly data sheets may become a time consuming exercise which may eventually be neglected.

Data logger

A number of plants have accepted the high cabling costs but have installed a 'data' logger (a minicomputor) in the control room. The analogue signals to be recorded are converted into the digital form and 'fed' to the logger which is then programmed to print out daily, weekly, monthly etc. log sheets from which the plants' performance can be readily gauged.

Multiplexing

The high cabling costs can also be reduced by the installation of remote 'multiplexing' stations where groups of analogue signals are converted to the digital form and relayed to the control room over a single cable (per group of analogue inputs). In such a case the inputs to the control room are in digital form and can be fed directly into a computer or microprocessor which would then serve as the overall control point, the so called direct digital control (DDC) system.

Data loggers and visual display units (VDU) could be connected to the computer, the VDU taking the place of the mimic diagram and being controlled by the computer.

There are many sewage treatment and water reclamation plants, in the USA particularly, that have installed such a direct digital control system, and the reader is referred to the literature for further details.[111,112,113]

5.2 THE MEASUREMENT OF SEWAGE, TREATED EFFLUENT AND SLUDGE FLOWS

Raw sewage

Raw sewages, treated effluents and sludge flows can be readily measured by Parshall or Venturi flumes. Such flumes usually form part of a concrete channel and experience has indicated that the greatest flow accuracies are obtained through the use of glass fibre flumes which are cast into the channels.

Flow measurement with both forms of flume is achieved by either float operated instruments, with the glass fibre or earthenware float being installed in a stilling well sited adjacent to the flumes, or by ultrasonic instruments which are mounted directly over the flumes. Flow accuracies of 1 — 2% can be obtained by both types of equipment.

The ultrasonic instrument obviates the necessity of a side stilling well and has the added advantage that there is no contact between the flow sensor and the flow medium. However, this equipment is more sophisticated than its float operated counterpart and as such could require more attention.

A disadvantage of the float operated equipment is that particularly in the case of sewage or sludge flows, provision must be made for daily flushing of the stilling wells.

Treated effluent and sludge

Both treated effluents and sludge flows can be measured by magnetic or ultrasonic flow meters. This latter form of flow metering is relatively new to the South African market while magnetic flow metering has been well proven.

Provision for cleaning the magnetic flow meter electrodes should be included, either in the form of mechanical cleaning or in the form of in-situ electronic or ultrasonic cleaning.

Mechanical cleaning appears to be more effective for meters installed on secondary effluent lines whereas mechanical or the electronic and ultrasonic alternative are both suitable for biological and chemical sludge applications.

Raw sewage flows should never be measured by magnetic flow meters on account of the rapid fouling of the electrodes by grease and fat deposits.

The decision as to the site of a magnetic flow meter installation should take into account the upstream and downstream pipe conditions required for optimum operation (usually 10 pipe diameters of straight pipe upstream and 5 diameters downstream) as well as ease of access for calibration or electrode replacement purposes. It is good practice to provide a flow by-pass around each meter, to be used when the meters have to be removed. Cognisance must also be taken of the proximity of HT electrical cables as magnetic flow meters are prone to electrical interference.

Treated effluent flows can be measured by normal 'water meters while another common form of flow measurement, particularly for smaller plants, is that of utilizing a pump characteristic together with a running-hour meter.

The form of flow measurement installed should be such that daily, weekly or monthly flow figures can be reasonably accurately obtained (1 — 2%), while at the same time enabling diurnal flow patterns to be established.

5.3 THE MEASUREMENT OF AIR AND GAS FLOWS

Gas and air flows are usually measured by orifice plates and associated differential pressure sensors — either a simple manometer or the more complex pneumatic or electronic sensor transmitters.

Dall tubes (both 'long' and 'short' insert) and forms of Pitot tubes have also been successfully applied in installations where head loss at the point of measurement has to be kept as low as possible.

Flow accuracies of flow sensor plus transmitter is usually in the 1 — 2% range.

5.4 THE CONTINUOUS MEASUREMENT OF SELECTED PROCESS PARAMETERS

Of the myriad of parameters pertaining to the biological and advanced treatment plants, pH, DO, turbidity, residual chlorine and residual ozone are frequently selected for continuous measurement. Electrodes are however also available to continuously monitor nitrates, oxidation-reduction (redox) potential, sludge densities, total organic carbon etc.

A sensor or electrode for continuous measurement duty should be accurate, reliable and require little maintenance. It should be interchangeable with others of the same type without recalibration, and should be unaffected by changes in variables other than the one it is designed to measure. In addition, the sensor should be relatively inexpensive and provide an output which is easy to connect to telemetry systems.[114]

While this sub-section is not concerned with the physical make-up of the electrodes, it is pertinent to mention at this stage that the design engineer should thoroughly aquaint himself with the full range of electrodes available for the intended duty. His final selection should be guided not only by actual installation performance but also by spares and service facilities availability.

The actual siting of electrodes should receive careful consideration. Electrodes that require regular electrolyte refilling should be situated near washing facilities and should be installed in such a way that they can be easily removed for calibration purposes. In instances where the electrodes are to be installed in a continuous flow, there appears to be merit in installing them in 'side chambers' through which a portion of the flow is directed.

Continuous pH measurement is usually associated with the lime treatment, chlorine disinfection and final stabilization steps and experience has shown that electrodes in the lime treatment application soon become coated with a calcium carbonate deposit which impairs their performance; electrodes in the other applications are relatively trouble free.

Ultrasonic cleaning is particularly ineffective in removing the lime treatment deposits[115] and the method employed at the Stander plant to ensure reliable electrode performance involves the alternation, on a daily basis, of two similar pH electrodes. The electrodes are cleaned by dipping into 100 g/kg hydrochloric acid for 10 min and then stored in clean water.[10]

DO measurement is usually associated with the control of oxygen input in an activated sludge works. As fine control of this parameter can reap substantial electricity cost savings it is usual for more than one electrode to be installed and for complete spare electrodes be readily available on site. Calibration facilities should be mounted adjacent to each measuring site.

Turbidity, residual chlorine and ozone measurement are of particular importance to the advanced treatment plant as these parameters are generally associated with the all important disinfection stage.

As mentioned earlier, electrodes are available for the continuous measurement of various other parameters such as nitrate nitrogen, total organic carbon etc. These electrodes or sensors are being continually updated and although some of them have been installed at biological and advanced treatment plants throughout the world, it is considered that unless they be a prerequisite for the effective and safe performance of the process, they be regarded as an unnecessary luxury at this stage. However, there is definite merit in keeping abreast with their development and actual installation performances.

5.5 SAMPLING AND ANALYTICAL EQUIPMENT

The performances of the biological and advanced treatment plants are gauged through sampling at various pre-selected sites throughout the treatment sequence.

Although regular manual sampling does suffice for most plants, there are instances where automatic sampling has been instituted.

There is a range of automatic samplers available on the market, some that proportionate the samples, some that incorporate refrigerators to preserve the samples and some that produce a composite sample over a preselected time interval. No matter what form is selected, experience has shown that such samplers require a considerable degree of maintenance and should therefore be carefully selected.

The samples should be analysed as soon as possible after collection; however, in practice, immediate analysis is seldom feasible and the samples are then preserved until analysis.

The site laboratory should be geared only for the analytical requirements of the plant. Once these requirements have been decided upon, the process designer should consult a specialist who would be able to itemize equipment or instrumentation required for the agreed-upon analyses. If the controlling authority has a number of plants under its auspices, it may well prove advantageous to create a central laboratory at which the more complicated (and hence costly) analyses would be carried out. This would obviate the duplication of expensive equipment at the site laboratories.

5.6 MAINTENANCE OF EQUIPMENT AND INSTRUMENTATION

Perhaps the most important aspect of purchasing instrumentation is the spare part and service back-up offered by the suppliers. It is of the utmost importance that this aspect be carefully evaluated prior to the purchase, as well as ensuring that all instrumentation is compatible with the local electricity network (i.e. voltage, frequency etc.).

A fully descriptive maintenance manual should be included in the purchase agreement. The manual should only be officially submitted by the instrument supplier once it has been approved of by the design engineer and it should consist of detailed maintenance instructions, as well as equipment descriptions, *all in a language* understood by the client.

The spare parts policy should be carefully evaluated. In the case of instruments that form part of essential control circuits it is advisable to hold a full range of spares, while in the case of instruments used solely for monitoring purposes and whose spares are readily available, it may prove preferable to purchase the spare parts as required. The policy adopted at the Stander plant was to maintain duplicates of those items that frequently require replacement.[115]

Large scale, sophisticated advanced treatment plants usually incorporate such a degree of instrumentation that the inclusion of instrument technicians in the operating staff is warranted. This is not the case with small, non-potable reclamation plants but in this instance the installation of instruments that are 'rugged' and require little maintenance — even if they do cost more — is warranted.

CHAPTER 6

NECESSITY FOR 'STANDBY' EQUIPMENT

This chapter considers the necessity of installing standby equipment at those plants that are to produce a water suitable for integration with the public supply system.

There are two main categories of standby equipment that should be considered: one relating to power failures and the other to equipment breakdown and/or maintenance.

6.1 POWER FAILURE

Standby equipment for power failures should ensure that the raw sewage continues to flow through the biological system even though the physico-chemical tertiary treatment stage would be bypassed.

In the event of a power failure, the sludge in the biological reactor and clarifiers will tend to settle to the lower regions and there will be little chance of biomass 'washout' occuring. In addition, the relatively long hydraulic retention times of 15 — 25 day SRT systems will ensure that a degree of 'dilution' is effected, thereby resulting in the discharge of an effluent far superior in quality to a raw or settled sewage but inferior to the normal secondary effluent.

There would be no necessity for primary settling tanks or clarifiers to operate but in the case of diffused air activated sludge plants, it would be necessary to provide a small air blower, usually of the Rootes type, which would have a rating such that water ingress into the diffusers and distribution pipework would be avoided. Such a blower could be directly driven by means of gas, diesel or diesel-gas engines or by indirect means via similarly fueled engine driven alternators. No stand-by is required for surface aeration installations.

Secondary effluent would only be routed back to the tertiary treatment section when its quality complied with the design requirements.

6.2 BREAKDOWN AND/OR MAINTENANCE

Standby for equipment breakdown and/or maintenance has the aim of enabling uninterrupted operation of the plants to be achieved and can take two forms; the first being a separate unit identical to a duty unit such that the maximum duty required of the installation can at all times be met, and the second being when a degree of standby is built into the units of a particular installation, such that when all units operate they account for (say) 120 — 140% of the maximum required duty.

The first form of standby is generally applied to transfer pumps, chemical dosing pumps, filter backwash pumps, instrument air blowers etc. The second form is applied in cases of equipment items that are not only extremely costly but are also essential to the overall performance of the plants, such as the air blowers in a diffused air activated sludge plant and chlorinators and ozonators in an advanced treatment plant.

In general, duties required of unit operations constituting an advanced treatment plant should never fall upon single items of equipment, but rather upon multiple units, such that a degree of operational flexibility is installed in the plant.

There is little justification for installing standby instrumentation, but rather it is advisable to ensure that essential spares are to hand and that each automatic control loop can also be manually operated.

CHAPTER 7

PROCESS ALARMS AND EMERGENCY OPERATIONS

7.1 EVALUATION OF ALARM REQUIREMENTS

Once the configurations of the biological and advanced treatment plants have been decided upon, a decision should be taken as to which process parameters are important, not only to the overall performance of the plants but also to the performance of the individual unit operations that constitute the plants.

Pilot plant studies will assist in the selection of the important variables, but care must be taken not only to ensure that meaningful parameters are selected but also that their numbers are controlled.

In instances where pilot plant studies are not conducted, the 'alarm' parameters should be selected after discussion not only with equipment suppliers but also with personnel (both management and operating) at plants of similar configuration.

Once the parameters have been selected, the necessary degree of instrumentation should be provided for in the full scale plants such that the measured parameters are displayed in a central control room from where management has an overview of both plants.

7.2 EMERGENCY ROUTES FOR EQUIPMENT FAILURES

Emergency operating procedures should be evaluated and decided upon prior to commissioning of the full-scale plant. Such procedures can be drawn up after operation of pilot plants and discussion with personnel at similar plants.

Pilot plants are ideal for such evaluations as various unit operations can be by-passed and the effect of such actions on downstream units and final water quality readily ascertained.

The degree and complexity of emergency procedures is obviously dependent upon the quality of effluent to be produced by the plant, with the plant designed for integration with public supply systems requiring the most stringent procedures.

Emergency operation should receive the attention of top management in the early stages of the planning of the water reclamation scheme as it will be a 'good tool' with which to assuage the public's fears as to final quality upsets.

Operating and maintenance personnel should be instructed in the emergency procedures before they assume responsible roles on the plant — refer to Part IV.

REFERENCES

1. Lund H.F. Industrial Pollution Control Handbook. Published by McGraw-Hill, 15—27 (1971).
2. Culp R.L. and Culp G.L. Advanced Wastewater Treatment. Published by Van Nostrand Reinhold. (1971).
3. Cleasby J.L. Filtration. Chapter 4 of 'Physicochemical Processes for Water Quality Control'. Edited by Weber, W.J. and published by Wiley Interscience. (1972).
4. United States EPA. Process Design Manual for Suspended Solids Removal. EPA 625/1-75-003a, January, 1975.
5. Unit Processes. Tertiary Treatment and Advanced Wastewater Treatment. Manual of British Practice in Water Pollution Control. *Inst. Wat. Polln. Cont.* London (1978).
6. Ewing L. Design Criteria for Microscreening Biological Wastewater Plant Effluents. *Wat. and Sew. Wks 1976 Reference Issue,* April 30th, 94 (1976).
7. Diaper E.W.J. Tertiary Treatment by Microstraining-Case Histories. *Wat. and Sew. Wks.* **120**, August, 42 (1973).
8. CSIR Contract Report No. C WAT 4. Reclamation of Purified Sewage Effluent for Augmentation of Domestic Water Supply of Windhoek. Pretoria, November, 1965.
9. Van Leeuwen J. and Wiechers H. Softening and Recarbonation. Chapter 5 of 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42, Pretoria (1978).
10. Hart O.O. Operational Guidelines. Chapter 13 of 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42, Pretoria (1978).
11. South Tahoe Public Utility District. Advanced Wastewater Treatment as Practised at South Tahoe. Report prepared for the Water Quality Office, EPA, Project 17010 ELQ (WPRD 52-01-67), August, 1971.
12. Preliminary Report on The Hueco Bolson Recharge Project and the Treatment Processes Required. Prepared for the City of El Paso, Texas, by Parkhill, Smith and Cooper Inc., June 1978.
13. Loewenthal R.E. and Marais G.v.R. Carbonate Chemistry of Aquatic Systems: Theory and Application. Ann Arbor Science. (1976).
14. Report on Advanced Treatment and Reuse of Municipal Wastewater, Dan Region Pilot Plant. Prepared by Tahal for Mekorot Water Company Limited, April, 1976.
15. Van Vliet B.M. Active Carbon Adsorption. Chapter 9 of 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42. Pretoria (1978).
16. United States EPA. Process Design Manual for Carbon Adsorption. October, 1973.
17. Ford D.L. Carbon Adsorption as an Advanced Wastewater Treatment Process. *Prog. Wat. Tech.* **10** (5/6) 1 (1978).
18. Weber W.J. and Ying W-C. Integrated Biological and Physical-Chemical Treatment for Reclamation of Wastewater. *Prog. Wat. Tech.,* **10**, 1/2) 217 (1978).
19. Cover A.E. and Wood C.D. Appraisal of Granular Carbon Contacting. Phase III: Engineering Design and Cost Estimation of Granular Carbon Tertiary Waste Water Treatment Plant. FWPCA Report No. TWRC-12, Washington D.C., Federal Water Pollution Control Administration. May, 1969.
20. Van Leeuwen J. Private Communication, July, 1979.
21. Van Leeuwen J. Chlorine Disinfection. Chapter 7 of 'Manual for Water Renovation and Reclamation', CSIR Technical Guide K42, Pretoria (1978).
22. Chemicals and Chemical Treatment. *Water and Waste Treatment,* March, 28 (1977).
23. Klein M.J., Braberts R.I. and Kinney L.C. Generation of Ozone. Proceedings First Int Symp. on Ozone for Water and Wastewater Treatment. Edited by Rice R.G. and Browning M.E. Published by Hampson Press (1975).
24. Masschelein W.J. The State of Art in the Use of Chlorine Dioxide and Ozone in the Treatment of Water. *Water SA* **6** (3) 116.
25. Zellman G. Summarized Description of the Treatment of Potable Water Using Ozone. Technical Application. Demag Metallgewinnung.
26. Rice R.G. Recent Advances in Ozone Technology. *Wat. Poll. Cont.* **77** (1) 51 (1978).
27. Degremont. Horizontal Tube Ozonators. Sales Literature.
28. Paré M. Cost of Utilizing Ozone and Energy Balance Sheet. Paper presented at Int. Symp. on Ozone and Water, Berlin, West Germany, May 16—17, 1977.
29. Van Leeuwen J. Ozone Disinfection. Chapter 8 of 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42, Pretoria (1978).
30. Stahl D.E. Ozone Contacting System. Proceedings First Int. Symp. on Ozone for Water and Wastewater Treatment. Edited by Rice, R.G. and Browning, M.E. Published by Hampson Press. (1975).
31. Masschelein W.J., Fransolet G. and Genot J. Techniques for Dispersing and Dissolving Ozone in Water. *Wat. and Sew. Wks.*, December 1975 and January 1976.
32. Van Vliet, B.M. Carbon Regeneration. Chapter 11 of 'Manual for Water Renovation and Reclamation', CSIR Technical Guide K42, Pretoria (1978).
33. Zanitsch H. and Lynch R.T. Selecting a Thermal Regeneration System for Activated Carbon. *Chem. Eng., January*, 2, 95 (1978).
34. Von Dreusche C. Process Aspects of Regeneration in a Multiple Hearth Furnace Water 1975, *AICHE Symposium Series*, **71**, 151, 432.
35. Waller G. Granular Activated Carbon and its Reuse in Water and Waste Treatment. *Prog. Wat. Tech.*, **8** (2/3) 39 (1976).
36. Schalekamp M. and Bakker S.P. Use and Thermal Regeneration of Activated Carbon in Switzerland. *Effl. and Wat. Treat. J.* January, 28 (1978).
37. Lurgi South Africa (Pty) Limited. Reactivation of Activated Carbon — Thermal Reactivation of Granular Activated Carbon in Two-Stage Fluid Bed. Sales Literature (1979).
38. Juhola A.J. Regeneration of Activated Carbon. Paper presented at the Water Research Association Conference on 'Activated Carbon in Water Treatment', Univ. of Reading, England, April, 1973.
39. Envirotech (Pty) Limited, South Africa. (1978).
40. Vesilind P.A. Treatment and Disposal of Wastewater Sludges. Ann Arbor Science (1974).
41. Dick R.I. Gravity Thickening of Sewage Sludges. *Wat. Polln. Cont.,* **81**, 368 (1972).
42. Minton G.R. and Carlson D.A. Primary sludges Produced by the Addition of Lime to Raw Wastewater *Wat. Res.,* **7**, (12) 1821 (1973).
43. Bratby J. and Marais G.v.R. Dissolved Air Pressure Flotation: An Evaluation of Interrelationships between Process Variables and their Optimization for Design. *Water S.A.* **1** (2) 57 (1975).
44. Bratby J. and Marais G.v.R. A Guide for the Design of Dissolved Air (Pressure) Flotation Systems for Activated Sludge Processes. *Water S.A.* **2** (2) 87 (1976).
45. Bratby J. Aspects of Sludge Thickening by Dissolved Air Flotation. *Wat. Polln. Cont.* **77** (3) 421 (1978).
46. Langenegger O. and Viviers J.M.P. Thickening of Waste Activated Sludge with a Dissolved Air Flotation Unit. *Wat. Polln. Cont.* **77** (1) 79 (1978).
47. Marx C. Johannesburg City Engineer's Department, Private Communication (1978).
48. Ashman P.S. Operational Experiences of Activated Sludge Thickening by Dissolved Air Flotation at the Aycliffe Sewage Treatment Works. Paper presented at Wat. Res. Cent. Conf., on 'Flotation for Water and Waste Treatment, Felixstowe, England (1976).
49. Komline T.R. Sludge Thickening by Dissolved Air Flotation in the USA. Paper presented at Wat. Res. Cent. Conf. on 'Flotation for Water and Waste Treatment', Felixstowe, England (1976).
50. Mulbarger M.C. and Hoffman D.D. Mixed Liquor Separation by Flotation. *J. Sanit. Eng. Div., ASCE,* August, 861 (1970).

51. United States EPA. Process Design Manual for Sludge Treatment and Disposal. EPA 625/1-74-006, October, 1974.
52. Keith F.W. and Little T.H. Contrifuges in Water and Waste Treatment. *Chem. Eng. Prog.* **65** (11) 77 (1969).
53. Ambler C.M. How to Select the Optimum Centrifuge. *Chem. Eng.* October, **20** 96 (1969).
54. Roets S.D. Sekere Oorwegings by die Keuse van Slykontwateringsapparaat. Paper presented at Symposium on 'The Treatment and Disposal of Sludges Deriving from Municipal Sewage', Pretoria, October (1977).
55. Kirk B. Discussion on 'Thickening and Centrifuging of Sludge'. *Wat. Polln. Cont.* **77** (1) 84 (1978).
56. Ronen M. Sludge Dewatering. Chapter 10 of 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42, Pretoria (1978).
57. Lamouche A. Private Communication (1978).
58. Everitt I.E. The Optimized Economic Use of Sludge Treatment Facilities in Durban. Paper presented at Symposium on 'The Treatment and Disposal of Sludges Deriving from Municipal Sewage'. Pretoria, October, 1977.
59. Slim J.A. Sludge Treatment at the Fishwater Flats Water Reclamation Works, Port Elizabeth. Paper presented at Symposium on 'The Treatment and Disposal of Sludges Deriving from Municipal Sewage'. Pretoria, October, 1977.
60. Hellings J.E. and Van der Merwe P.H. Sludge Treatment and Disposal at Germiston. Paper presented at Symposium on 'The Treatment and Disposal of Sludges Deriving from Municipal Sewage'. Pretoria, October, 1977.
61. Ronen M. The Characterization, Processing and Recycling of Lime Sludges. CSIR Special Report Wat 49, Pretoria (1976).
62. Ford J. The Sludge Dewatering Centrifuge. *Inst. Chem. Eng. Symp. Series,* No. 41, Q1 (1975).
63. Westerhoff G.P. and Daly M.P. Water Treatment Plant Wastes Disposal — Part 2, *J. Am. Wat. Wks. Ass.* **66** (6) 379 (1974).
64. Alfa Laval S.A. Centrifugal for Chemical and Process Industries. (1978).
65. Gale R.S. The Calculation of Theoretical Yields of Rotary Vacuum Filters. *Wat. Polln. Cont.* **70** 114 (1971).
66. Voysey J.A. Sludge Dewatering by Vacuum Filtration. Paper presented at Symposium on 'The Treatment and Disposal of Sludges Deriving from Municipal Sewage'. Pretoria, October, 1977.
67. Mansfield R.A. Vacuum Filtration, with Particular Reference to Operational and Maintenance Problems. *Wat. Polln. Cont.* **77** (1) 61 (1978).
68. Davis C. Dissolved Air Flotation and Belt Filter Pressing of Activated Sludge in Johannesburg, Paper presented at Sympsoium on 'The Treatment and Disposal of Sludges Deriving from Municipal Sewage'. Pretoria, October 1977.
69. Davis C., Halliday J. and Marx C. Experience with Thickening and Dewatering Surplus Activated Sludge of Long SRT in Johannesburg. Paper presented at Biennial Conf. of Inst. Wat. Polln. Cont. (S.A. Branch), Port Elizabeth, March, 1978.
70. Simon Hartley S.A. Sales Literature. (1977).
71. Baskerville R.C., Bruce A.M. and Day M.C. Laboratory Techniques for Predicting and Evaluating the Performance of a Filterbelt Press. Paper presented at Filtration Society Symposium on 'Design and Application of Belt Filters'. London, February, 1978.
72. White M.J.D. and Baskerville R.C. Full Scale Trials of Polyelectrolytes for Conditioning of Sewage Sludges for Filter Pressing. *Wat. Polln. Cont.* **73** (5) 486 (1974).
73. Water Pollution Research 1964. Ministry of Technology. Published by Her Majesty's Stationery Office, London, Page 70.
74. Vater W.A.G. European Practices in Sludge Digestion and Disposal. Page 421 of 'Water Quality Improvement by Physical and Chemical Processes'. Edited by Gloyna E.F. and Eckenfelder W.W. Published by University of Texas Press (1970).
75. Brade C.E. and Sambridge N.E.W. The Effect of Surplus Activated Sludge on Filter Press Performance. *Wat. Polln. Cont.* **73** (2) 138 (1974).
76. Satec Hudamech. Sales Literature (1978).
77. Randall C.W. Are Paved Drying Beds Effective for Dewatering Digested Sludge? *Wat. and Sew. Wks.* **03** 10 (1969).
78. Water Pollution Control Federation Manual of Practice No. 20. Sludge Dewatering. (1969).
79. Vosloo P.B.B. Design of Drying Beds for Surplus Activated Sludge. *Wat. Polln. Cont.* **77** (1) 71 (1978).
80. Swanwick J.D. Sludge Dewatering on Drying Beds. *J. Proc. Inst. Sew. Purif.* **2** 153 (1966).
81. Engenheiros Consultores Projetistas S.A. Ninham Shand and Partners Inc. and P.G.J. Meiring and Partners Inc. Report on Proposals for Treatment and Disposal of Sewage Works Sludges. Submitted to CAESB, Brasilia, February, 1978.
82. Pitman A.R. Bioflocculation as a Means of Improving the Dewatering Characteristics of Activated Sludges. *Wat. Polln. Cont.* **74** (6) 668 (1975).
83. Tahal, Water Planning for Israel Limited. Advanced Treatment and Reuse of Municipal Wastewater, Dam Region Pilot Plant. Prepared for Mekorot Water Co. Ltd., Tel Aviv, April, 1976.
84. Beardsley J.A. Sludge Drying Beds are Practical — Parts I and II, *Wat. and Sew. Wks.* 123. July, 82 (1976) and *123*, August, 42 (1976).
85. Jacke R. Polymer Cuts Disposal Costs. *Wat. and Sew. Wks,* **123**, June, 99 (1976).
86. Unit Processes. Sewage Sludge III: Utilization and Disposal. Manual of British Practice in Water Pollution Control. *Inst. Wat. Polln. Cont.* London (1976).
87. Parker D.S., Niles D.G. and Zadick F.J. Processing of Combined Physical-Chemical-Biological Sludge. *J. WPCF* **46** (10) 2281 (1974).
88. Parker D.S., Carthew G.A. and Horstkotte G.A. Lime Recovery and Reuse in Primary Treatment. *J. Env. Eng. Div., ASCE* December, 985 (1975).
89. United States EPA. Technology Transfer Capsule Report: Magnesium Carbonate — A Recycled Coagulant for Water Treatment'. Washington D.C. Date unknown.
90. Mulbarger M.C., Grossman E., Dean R.B. and Graneto L. Lime Clarification Recovery, Reuse and Sludge Dewatering Characteristics. *J. WPCF* **41** (12) 2070 (1969).
91. Adams C.E. Disposal and Recovery of Sludges from Physical-Chemical Processes. Applications of New Concepts of Physical Wastewater Treatment. Edited by Eckenfelder W.W. and Cecil L.K. Published by Pergamon Press Inc. (1972).
92. Shelef G., Moraine R. and Sandbank E. Physico-chemical Treatment of Pond Effluents for Unrestricted Agricultural Reuse with Recovery of Algae as Protein Source: Pilot and Field Scale Experiments. *Prog. Wat. Tech.* **10** (1/2) 91 (1978).
93. Adams C.E. Pretreatment Procedures. Paper presented at Post IAWPR Conference Study Course, Birmingham, September 16—21, 1974.
94. Ronen M. Clarification. Chapter 2 of 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42, Pretoria (1978).
95. De Wind H. and Prinsloo J. Improved Lime Dosing System at the Stander Water Reclamation Plant. Paper in print, (1979).
96. Perry J.H. Chemical Engineers Handbook. Section 5. 4th Edn., Published by McGraw-Hill, Tokyo, 5—1 (1963).
97. Seeley E.E. Data Book for Civil Engineers — Design. Published by John Wiley and Sons, 18 (1960).
98. Rause H. Engineering Hydraulics. Published by John Wiley and Sons 115 (1950).
99. McCabe W.L. and Smith J.C. Unit Operations of Chemical Engineering. Published by McGraw-Hill, 159 (1956).
100. Dick R.I. and Ewing B.B. The Rheology of Activated Sludge. *J. WPCF* **39** (4) 543 (1967).
101. Rimkus R.R. and Heil R.W. The Rheology of Plastic Sewage Sludge.
102. Dick R.I. Sludge Treatment. Chapter 12 of 'Physicochemical Processes for Water Quality Control. Edited by Weber W.J. Published by Wiley Interscience (1972).
103. Water Pollution Control Federation. Manual of Practice 'Sewage Treatment Plant Design' (1959).
104. Sparr A.E. Pumping Sludge Long Distances. *J. WPCF* **435** *(8) 1702 (1971).*
105. Raynes B.C. Economic Transport of Digested Sludge Slurries. *J. WPCF* **42** (7) 1379 (1970).
106. Figure 3.41 taken from Ref. (105) and metricated.
107. Dodge D.W. and Metzner A.B. Turbulent Flow of Non-Newtonian Systems. *J. Am. Inst. Chem. Engrs.* **5** 2 (1959).
108. Selby A. Values abstracted from: A Method of Assessing Friction Losses for a Non-Newtonian Fluid, such as Sewage Sludge, under Laminar Flow Conditions. *Inst. Publ. Health Engrs.,* March (1976).

109. Fisichelli P. Raw Sludge Pumping — Problems and Interdisciplinary Solutions. *J. WPCF* **42** (11) 1916 (1970).
110. Hicks T.G. and Edwards T.W. Pump-Application Engineering. Published by McGraw-Hill (1971).
111. Flanagan M. Direct Digital Control of Central Contra Costa Sanitary District Water Reclamation Plant. *Prog. Wat. Tech.* **6** 550 (1974).
112. Schratz J.P. and Preszler H.D. Multilevel Digital Control of the Hyperion Treatment Plant. Paper presented at IAWPR Workshop on 'Instrumentation and Control for Water and Wastewater Treatment and Transport Systems', London and Stockholm, May, 1977.
113. Cotton P. and Latten A. Acquisition and Use of Data in Wastewater Treatment Plants. Paper presented at IAWPR Workshop on 'Instrumentation and Control for Water And Wastewater Treatment and Transport Systems', London and Stockholm, May, 1977.
114. Briggs R., Page H.R.S. and Schofield J.W. Improvements in Sensor and System Technology. Paper presented at IAWPR Workshop on 'Instrumentation and Control for Water and Wastewater Treatment and Transport Systems'. London and Stockholm, May, 1977.
115. Hart O.O. Private Communication, 1979.

PART IV
OPERATION AND MAINTENANCE

CONTENTS

Page

INTRODUCTION

The process designer, as part of his responsibilities, should draw up detailed operating and maintenance manuals to cover the various unit operations that constitute the treatment plants.

The manuals should be submitted in draft form, after consultation with the relevant representatives of the controlling authority and just prior to the commissioning stage. As the plant's running-in period progresses, their contents should be continually reviewed and any changes deemed necessary made. The completed manuals should be submitted officially when all contracts with equipment suppliers have lapsed, and as the operating experience of the authority's personnel increases over the years, they would be further modified or updated.

As no two reclamation schemes are the same, it is difficult to list the contents of operating and maintenance manuals that can be applied for all plants. It is therefore the intention that this section deal with operation and maintenance in the broad sense, while at the same time furnishing guidelines from which such manuals may be compiled.

The essentials for proper operatioon of biological and advanced treatment plants include the following:[1]

- A complete understanding of the various unit processes, their theory and operation.
- The performance of the necessary laboratory tests, together with the practical interpretation and application of the data.
- Proper equipment operation and adequate maintenance.
- Cleanliness in and about the plant and grounds.

These standards of plant operation in turn call for experienced planning both in the organizing and scheduling of work for plant personnel, and in the recording of operation and maintenance information.

The guidelines are therefore written not only for the process designer, to enable him to draw up his manuals, but also for the controlling authority's maintenance and operating personnel who will in the long term be responsible for all maintenance and operational aspects.

CHAPTER 1
OPERATION

1.1 THE OPERATING MANUAL

The operating manual informs the operating personnel of the correct operational procedure to be followed in order that the quality of water produced will at all times comply with the requirements.

The manual should be clearly indexed and should begin with an introductory section which describes the treatment plants, including such items as which areas contribute the wastewater flow, the destination and quality requirements of the product water, the design flows and pollution loads, the treatment sequence together with typical liquid and mass balances, the names of the consultants, equipment suppliers and civil contractors, the total overall cost etc. Clearly marked flow diagrams and schematic sketches of the individual unit processes should be bound into the manual.

The manual should then proceed to discuss the operation of each unit process in the overall treatment sequence. These sections should not only indicate how the various unit processes are operated but also the steps that should be taken in the event of equipment breakdown or an emergency, alternative routing of process liquors, the degree of maintenance, if any, expected from the operator, the safety and health hazards associated with each unit process etc.

TABLE 4.1 START-UP PROCEDURE FOR OZONATORS AT PALO ALTO PLANT, CALIFORNIA[1]

1. Check oil level on compressor.
2. Check that compressor turns freely.
3. Check rubber connection and tighten.
4. Check that cooling supply water is on.
5. Check for main power to be ON.
6. Check discharge valve to be OPEN.
7. Check inlet and outlet air filters.
8. Start Ozonator. Turn switch (under control panel) ON.
9. Check cooling water to be flowing.
10. Check auxiliary air compressor to be running and drain condensation.
11. Check refrigeration unit to be operating.
    a. Within 30 min. exchange temp should be 40°F
    b. Within 30 min. outlet temp should be 40°F to 36°F
12. Adjust air flow valve to give 11 PSI back pressure.
13. After 10 min, of operating at zero voltage power (on control panel) increase to 250 V.
14. Thereafter power may be turned up 50 V every 15 minutes until desired voltage is reached — maximum voltage setting is 450 V.

Lengthy narratives should be avoided and an effort should rather be made to supply the operating personnel with clean and concise instructions suitable for everyday use.

The manual should also highlight the control strategies for the various unit processes, laboratory analyses and their interpretation, the preparation of records and reports.

Abridged Operating Manual

The operating manual that is drawn up in the above manner will inevitably be a bulky document and there is definite merit in drawing up an 'abridged manual' for ready reference by operating personnel.

The manual would highlight the sequence of actions to be followed in the operation of the various unit processes. This may be achieved by either tabulating a sequence of actions or by a flow prescription which would lead the reader from a collection of input data to the desired result through a succession of small directed steps.[2]

Table 4.1 is an example of the former method and lists the start up procedure to be followed for the ozonators at the Palo Alto Reclamation Plant in California,[1] while Figure 4.1 shows a portion of the flow prescription for the lime clarifier at the Stander Plant.[3]

Sample calculations of for example the chlorine dosing rate, the make-up carbon etc. are often useful aids for the operators.

1.2 EMERGENCY OPERATION

The process designer should be in a position at the commissioning stage to provide a preliminary list of possible plant or equipment failures, together with associated remedial actions to reduce the impact of the failure on the performance of the biological and advanced treatment plant (refer to Part III, section 7.2).

As the operating personnel gain experience and confidence so the emergency operating procedure would be updated.

No matter how small or insignificant an equipment or system failure may appear it should be reported, especially in the initial stages of operation of the plant.

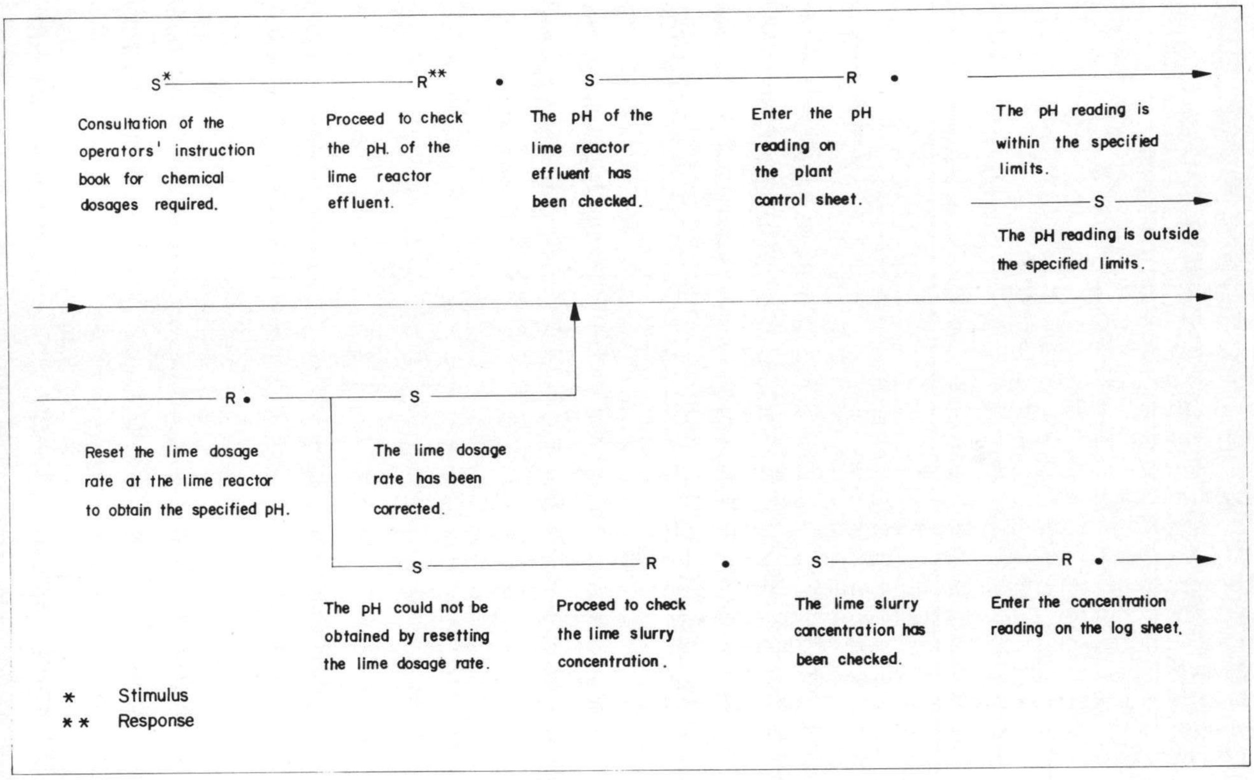


FIGURE 4.1: Flow prescription for lime clarifier at the Stander Plant[3]

The report should include the following:

- description of failure together with apparent reasons,
- whether or not there were signs prior to the failure that would have indicated the deteriorating situation;
- the actions taken by both operating and maintenance staff, for comparison with the preprepared emergency routines;
- the damage caused; and
- the conclusions drawn.

The reports should be drawn up by the plant superintendent in conjunction with the relevant section's operator and maintenance personnel.

1.3 CONTROL STRATEGY

A control strategy should be drawn up and implemented for the overall reclamation scheme. Provision should be made for aspects such as individual unit process control strategies, sampling points, frequency of sampling, visual observations and a product assurance programme.

The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 13 for details of the control strategy adopted at the Stander plant.

1.3.1 The monitoring programme

A monitoring programme has the purpose of enabling the controlling authority (and the process designer) to evaluate the performance of the treatment plants.

Initially a monitoring programme tends to be intensive as the performance of the individual units and the plant as a whole are still very much unknown quantities. The programme is revised from time to time as the more salient and meaningful parameters with which to accurately assess the plants' performance are identified.

The major aims of a monitoring programme may be defined as:

- To ensure that the quality of the treated effluent complies with that required and that the individual units that constitute the plants perform within their design criteria.
- To ensure that the operating personnel's expertise develops in the correct manner.
- To ensure that there is little danger of health or environmental hazards being created at or by the biological and advanced treatment plant.
- To enable conclusions to be drawn from the plant performance in order that design criteria for future plants may be evaluated.

A monitoring programme for the plant should consist of, but not necessarily be limited to, the following:

- *Climatic conditions:* Rain, wind and ambient temperature measurement. Maximum and minimum ambient temperatures should be recorded daily.
- *Flow conditions:* Daily flows should be recorded. Weekly average flows together with maximum and minimum weekly flows should be reported. Annual figures should be abstracted at the end of each year.
- *Mass balances:* Should be drawn up initially at the end of each week and then at the end of each month after one year's operation.
- *Solids or sludge production:* The quantities of the various sludge by-product streams should be recorded daily, with weekly and annual figures being abstracted as required.
- *Energy consumption:* Daily, monthly and yearly consumptions of electricity and other forms of energy (e.g. oil, gas etc.) should be recorded and reported.
- *Equipment running time:* Minimum time between failures (MTBF) should be annually recorded. More detailed equipment running time evaluation will be carried out by the maintenance personnel under their maintenance programme (refer to section 2.1.2).
- *Process parameter analyses:* All parameters that are measured in a laboratory at a predetermined frequency should be recorded daily and reported monthly. Those parameters that are measured continuously, such as dissolved oxygen, turbidity, residual chlorine etc. should be recorded every hour with the daily averages together with minimum and maximum values being reported. The reader is referred to the 'Manual for Water Renovation and Reclamation' Chapter 13 for details of the frequency of sampling employed at the Stander Plant, although it must be remembered that this is an experimental plant and as such the frequency of sampling as well as the number of samples could well be reduced for a full scale production installation.

1.3.2 **Product assurance programme**

In considering a potential control strategy, a distinction should be made between control strategies for individual processes and an overall strategy for the plant. The overall strategy should be aimed at obtaining a reliable, fail-safe, product water. If the objectives of each unit process are achieved, the progressive improvement in quality through the consecutive processes will yield an acceptable final product. To attain these objectives, a product assurance programme must be developed to aid the operator in keeping the control parameters strictly within their limits.[3]

The product assurance programme is aimed at detecting system failures, evaluating proper reliability and providing a means to reduce equipment down-time by isolating the cause of failure. It entails daily scrutiny of certain critical operational parameters which quantify satisfactory plant operation. For each of the critical control parameters, a POTOL value (percentage of time outside limits) is calculated on a weekly basis. Average values for the week are then compared with those of the previous week and the maximum allowable values. A recurrence of high values for any parameter is traced back either to system failure, equipment malfunction or incorrect or negligent control by the operator.

This system has several advantages. The operator and superintendent can immediately isolate problem areas and system failures. Negligent operator control can easily be detected if a certain operator consistently produces bad results. The system also provides a record of improvement or deterioration in both operator and plant performance.

1.3.3 **Plant records**

Performance records of plants are important as they not only enable operational changes to be equated with process results and serve as a history of treated effluent quality but they also enable a record to be kept of the overall reclamation costs.

One serious limitation with plant records is that of administration, in that it is sometimes difficult to initially decide which are the important ones. As a result there is the danger of accumulation of superfluous information. Parameters to be recorded should therefore be carefully selected.

The recording of a plant's performance will usually comprise the following three categories:

- *Data collection:* This includes the recording of process variables, be they indicated in the plant or analysed in the laboratory, equipment running hour meters etc. and any special events (such as breakdowns).
- *Weekly or monthly operating logs:* This entails transferring the recorded data to log sheets so arranged or drawn up that a week's or a month's performance can be readily ascertained.
- *Annual reports:* This will include a summary of the weekly or monthly log sheets so that the annual performance of the plants can be easily reported.

The latter two categories are usually carried out by the plant superintendent (or his aids) while the first is carried out by the operators of the individual sections.

In many plants throughout the world all three categories are carried out by computers. All variables are frequently 'read' by the computer which prints out the required log sheets at programmed intervals.

It will be appreciated that in these instances the labour required for the data processing is drastically reduced. Experience has indicated that should management have to reduce their personnel for economic reasons one of the first areas of neglect is that of data processing and recording — a disadvantage not suffered by computerized processing.

However, computerized processing is generally only applicable to large scale plants and/or to plants which have ready access to qualified computer personnel. For these reasons the balance of this sub-section relates to manual data processing.

Data collection

The data collection sheets should be clear in their requirements and after each set of data recording the operator should sign in a space specially set aside for his signature. The signature has more of a psychological effect than practical value and thereby hopefully ensures that no fabricated data are recorded.

Once the data has been transferred to the weekly or monthly log sheets, the data collection sheets should be stored for approximately six months and then discarded.

Weekly or monthly sheets

The weekly or monthly log sheets will be viewed by top management and they should thus be of such a form that they are easily legible. All figures should be typed in and space should be allowed for comments and additional data.

The format of the log sheet should be reviewed at regular intervals and in the event of the controlling authority's operating and management personnel having little experience in drawing up both the data collection forms and the weekly, monthly log sheets, the onus will be on the process designer to put forward preliminary proposals which would be a basis for future sheets.

Annual reports

The preparation of the annual reports is usually the responsibility of the plant superintendent or manager, who makes use of the abovementioned weekly or monthly log sheets. The report will be to the controlling body or authority and should reflect the annual performance of the plant.

1.3.4 **Laboratory facilities**

The size of the laboratory is obviously dependent upon the nature of the work or analyses required. The controlling authority may have little or no experience as to laboratory requirements, in which case the onus would be on the process designer to recommend instruments, equipment and manpower requirements as well as recommending which tests be sent to external laboratories.

In sizing the laboratory, the following guidelines should be followed:

- The laboratory should be so sized that routine analyses of a predetermined number of samples may be performed at least on a daily basis. Infrequent analyses should rather be performed at external laboratories — possibly at a Central Laboratory belonging to the Authority.
- A room for the calibration and adjustment of automatic and manual instrumentation should be provided.
- There should be facilities for the professional staff to carry out special tests but there should be no allowance for ongoing research work.
- There should be no facilities for carrying out analyses for external concerns.

The laboratory personnel should have ready access to external specialists for such matters as methods of analysis, purchase of instrumentation and the maintenance thereof.

1.3.5 **Central control and monitoring room**

Many plants have central control rooms in which selected parameters or variables relating to the various unit processes are displayed. In plants containing automatic control loops it is usual to find the controllers situated in this room as well.

This centralized form of display and/or control enables the works superintendent to have his 'finger on the pulse' by being in this one room as he is able to gauge the performance of the entire plant and to check on the efficacy of the operating staff in the various sections.

The choice of variable to be displayed should receive careful consideration. The running state (i.e. whether running or standing idle) of all equipment should be indicated, preferably in a mimic diagram or similar form of display such as computer operated visual display units (VDU's). Variables which tend to fluctuate if not controlled, either manually or automatically, should also be displayed — such variables being tank levels, controlled discharges, DO contents etc.

Additional variables should be screened to assess which one (or ones) would transfer the most information relating to the performance of each unit process by being displayed in the control room.

The stop/start control of all equipment should not be mounted in the central control room unless the site conditions are such that there is no alternative. In general stop/start functions are initiated from electrical panels housed in switchrooms adjacent to the equipment served.

Multiple control rooms may be justifiable on large sophisticated plants in which physical distances between the various units are large. However, in most cases a single central control room, situated if possible in such a position so as to ensure a panoramic view of the plant, is sufficient.

Central control rooms tend to require regular maintenance and as such the process designer should carefully consider the maintenance facilities available for all the instruments etc. installed in the control room.

1.4 **OFFICE FACILITIES**

The design of the administration offices should form a part of the overall plant design sequence and the offices should also be constructed at the same time as the rest of the plant. The offices should have sufficient lighting, should be adequately sized and should be comfortably and tastefully furnished.

A conference room, which could also act as a lecture room, and a small library should be provided. The library should contain books and periodicals that relate to the function of the treatment plants and there should be readily accessible to all operating personnel.

CHAPTER 2

MAINTENANCE

Every item of operating equipment requires frequent attention to ensure maximum performance, minimum maintenance costs and a long useful life. Neglected equipment will almost always fail, often resulting in needless expense and reduction in overall efficiency.

It would therefore appear justified to invest sums of capital in maintenance, equivalent to the anticipated capital outlays and inconvenience should equipment fail.

Maintenance can generally be divided into two categories:

- Preventative maintenance — which covers the activities concerned with forecasting and preventing mechanical breakdown or failure. This includes regular maintenance of all items of equipment (instrumentation included) carried out to a predetermined programme which should be initially drawn up in conjunction with, and repeatedly reviewed by, qualified maintenance engineers.

- Breakdown maintenance — which covers the activities concerned with repairing and reinstating equipment that has broken down or failed. The aim of this activity should be to restore normal operation in as short a time as possible by the most efficient method.

Although equipment may be regularly maintained under a preventative maintenance programme, it may well be found that the standard of maintenance is of poor quality, leading to subsequent equipment failure outside the programme. In instances where equipment failures occur regularly, each breakdown should be carefully analysed and conclusions formed.

As the quality of the maintenance staff is of the utmost importance to the efficient operation of the water reclamation scheme, it is good practice to regularly bring to their attention the analyses of and conclusions drawn from equipment failures — especially in the case outlined above.

2.1 THE MAINTENANCE MANUAL

The maintenance manual is drawn up to inform the maintenance personnel of the degree and frequency of maintenance required to ensure not only that all equipment operates effectively, but also that the equipment has a long useful life. The manual should be clearly indexed and should contain a proposed preventative maintenance programme, a proposed breakdown maintenance programme, a list of lubricants required and detailed electrical and instrumentation wiring diagrams. Each manual should be issued with a set of 'as-built' drawings of the treatment plants, and it is imperative that these drawings be kept up to date.

The reader is referred to the 'Manual for Water Renovation and Reclamation', Chapter 13 for further details of maintenance manuals.

2.1.1 **Preventative maintenance programmes**

The preventative maintenance programme should include the following items:

- The maintenance of all mechanical and electrical items of equipment, including instrumentation, which should initially be based on the manufacturers' instructions and thereafter on on-site experience.

  It is imperative that the process designer studies equipment manufacturers' recommendations on maintenance closely, since manufacturers are often over-optimistic about duty cycles and the amount of maintenance required to ensure smooth operation of their equipment. Based on his own experience as well as that of others using similar equipment, the process designer should be able to provide a realistic and practical system of maintenance.

- The maintenance of all process sub-systems. A process sub-system should be taken to describe equipment that is designed to operate under abnormal conditions, for example stand-by generators, automatically controlled by-passes, alarms etc. All such equipment should be activated during the maintenance period.

- The cleaning, painting and maintenance where necessary of buildings; pipelines and other structures.

The programme should be co-ordinated with the operating programme as it may well be found that there are times during the year when the demand for the product water falls and operation of the plant can be halted for a period of time.

Each item of equipment, each building etc. should be numbered with the same number appearing on a 'Job card' on which the date of attendance of the preventative maintenance personnel should be recorded. This will enable a maintenance record to be kept of the entire plant.

The programme should include for an annual report on the overall wear and depreciation of the plants' equipment. In addition, the programme should be reviewed at least once a year and updated if necessary.

The reader is referred to the United States EPA. Publication 430/9-74-004, "Maintenance Management

Systems for Municipal Wastewater Facilities'' for a discussion on the variety of methods by which a preventative maintenance programme can be implemented.

2.1.2 **Breakdown maintenance programmes**

The breakdown maintenance programme generally has two aims:

- To ensure that steps will be taken immediately to rectify equipment breakdowns or failures.
- To ensure that the steps taken to rectify breakdowns are not only quick but are also cost effective.

To this end a 'breakdown maintenance programme' should be drawn up with the overall aim of enabling rapid contact to be made between the operator who locates the breakdown and the person (or people) responsible for the repairs.

In addition, the programme should contain channels by which the plant superintendent is immediately informed (a) of the breakdown, (b) of the process consequences and (c) whether spare parts are required.

The range of responsibilities of maintenance personnel should be carefully delineated prior to plant 'start-up' in order that the responsibility of rectifying equipment failures falls under the jurisdiction of one person only. Such a person should not be able to relieve himself of the responsibility should he delegate the work to someone else.

Such breakdown maintenance programmes should be prepared in advance and should be available to each section operator or engineer.

This programme which is aimed at reducing the effect of equipment failure should comprise an extensive record section, as efficient logging of breakdown statistics will inform management as to the sufficiency of the preventative maintenance programme.

This records section should take the form of a table with the following columns:

Equipment description and number

Year of manufacture

Year of installation

Running time

Previous breakdowns (in last 2 — 3 years)

Nature of present breakdown (mechanical, electrical etc)

Reason for breakdown (design inadequacy, operational error, poor maintenance, unknown etc.)

Repairing body (from reclamation plant or from external firm)

Spare parts used

Date and time of reported failure

Date and time of commencement of repair work

Date and time of equipment recommissioning

As an addendum to the above table, comments should be recorded as to whether the breakdown brought the plant to a standstill and if not what sections did it affect. This will enable advance planning to be made into the rerouting of various flows in order to maintain the plant operational *should* various items of equipment fail.

2.2 SPARE PARTS POLICY AND LEVELS OF STORAGE

These aspects are an important part of the overall maintenance programme for a biological and advanced treatment plant.

In deciding upon a spare parts policy and the levels of storage required the following points should be considered:

- The spare parts policy should be such that a supply of spare parts will be ensured with as little time delay and cost as possible.
- The distance of the plant from a source of spare part supply should be considered in relation to the administrative difficulties in direct purchasing (particularly in the case of Statutory Bodies, Municipalities etc.) when deciding upon which spare parts should be stored on-site.
- The on-site level of storage should be such that the operation of the plant is not jeopardized.
- The level of on-site storage should be determined for each item of equipment, based on the frequency with which the equipment has to be replaced and on the influence such an item of equipment has on the overall plant operational efficiency. Duplicates of breakdown parts should be obtained (within reason).
- Once the initial levels of on-site storage have been set, the eventual levels will be determined after a number of years of operation. The spare parts flow should be evaluated at least once a year.
- With respect to the fourth item, the maintenance programmes should make some provision for the devaluation, on a 'time between requirement' basis, of the necessity of maintaining certain items in the store.

It is preferable for the store to be adjacent to the repair workshops. The store should be supervised by a suitable storeman, either full time or part time, but full time supervision is preferred in order to avoid maintenance personnel accumulating spares of their own in order to avoid the time delays in withdrawing spares as and when required. The accumulation of 'private stores' is particularly wasteful and creates spares inventory assessment problems.

Experience has shown that the storage area or volume actually designed for should be some 30% greater than that considered necessary at the initial stages of the operation of the plant.

The maintenance staff should all be equipped with sets of tools of sufficient range to enable routine work to be handled. More exotic tools should be housed under lock in the workshop.

The range of tools required for the intended degree of maintenance should be established through consultation between the process engineer, the maintenance engineers and the equipment manufacturers. There is merit in including for exotic tools in the equipment tender, to be supplied by the equipment manufacturer.

2.3 MATERIALS OF CONSTRUCTION AND ANTI-CORROSION COATINGS

The design of the various unit processes and interconnecting channels and/or pipework should take into account the materials of construction and anti-corrosion coatings required to prevent corrosion, not only from the environment but also from the wastewater, treated effluent and chemical flows.

As there are considerable ranges of materials of construction and protective coatings it is common for specialist corrosion engineers to be consulted in instances where either the environment or the wastewater flow or both are particularly corrosive.

In general however, the nature of wastewater allows materials such as mild steel, cast iron and occasionally stainless steel to be used. In the case of the mild steel and cast irons there are proven painting schedules available that are sufficient for corrosion protection of these materials.

In excessively corrosive environments, such as at the coast, there is great benefit from a maintenance point of view in installing bolts of stainless steel (type 316 or 316L) manufacture in equipment prone to regular maintenance and of using protective tape systems for all exposed metal pipework.

Anti-corrosion maintenance generally falls under the preventative maintenance programme. The measurement of corrosion rates is usually accomplished by installing 'corrosion spools' both in the liquor flows and exposed to the elements. Such spools consist of preweighed specimens of not only the material of construction selected but others reported to be more and less resistant than that selected to the expected corrosive conditions. As part of the preventative maintenance programme these spools are taken out of service, cleaned, dismantled and the specimens weighed, thereby enabling the corrosion rates, in terms of say mm/m^2 per annum to be ascertained.

A further important aspect of the anti-corrosion programme is that should corrosion be detected it should not be covered with a coat of paint before the cause has been determined. It may well be found that the replacement of, for example, a copper washer with a steel one would eliminate corrosion at a bolt hole which otherwise may well have progressed to such an extent that the bolt was not able to serve the function it was intended for.

2.4 OILS AND LUBRICANTS

A lubrication schedule for all items of equipment should form a part of the preventative maintenance programme. In drawing up such a programme cognisance should be taken of the following:

- The programme should be initially based on the programmes submitted by the various equipment manufacturers. Time and experience will tell if these programmes were optimistic or pessimistic and the plant lubrication programme should then be changed accordingly.
- Only lubricants recommended by the equipment manufacturers should be used. Overseas lubricant standards should be matched to local lubricants by either the equipment manufacturer or by the local oil companies themselves.
- All lubricant transfer lines, be they of copper or high density plastic manufacture, should be cleaned out and reprimed, thereby obviating blockages in the all important lubrication system.

The storage of lubricants on site should be carefully considered as it does create a fire hazard and can take up a large area. It is also generally cheaper to have the oil and lubricants delivered, say at monthly intervals, rather than to allow for extensive on-site storage facilities.

2.5 THE ORGANIZATION OF MAINTENANCE SERVICES

Plant maintenance can be carried out in two ways: by the plant's maintenance staff or by external private engineering concerns.

The decision as to which method will be adopted at a particular installation depends upon whether or not the controlling authority has qualified maintenance engineers and technicians available who are fully conversant with the range of equipment to be installed.

In instances where qualified personnel are available but who are not fully familiar with the equipment it is common for either private concerns to be engaged for the initial running in periods, during which time the client's personnel work closely with the 'outside' personnel and thereby learn the necessary expertise, or the equipment manufacturers are paid to run courses at their factories for the personnel prior to plant start-up.

However, even if the client's personnel become fully familiar with the equipment it may still be prudent to employ private concerns particularly in the following instances:

- *Rare and sophisticated services:*

  It is recommended that access to external specialists be maintained at all times in order that unusual breakdown situations may be rectified as quickly as possible.

- *Sophisticated services which are often required:*

  It is usually cheaper to have access to private concerns for sophisticated equipment maintenance rather than invest sums of money in training personnel for such eventualities.

- *Simple maintenance services which are regularly required:*

  These services will generally be carried out by plant personnel, however in certain instances such as sickness, holidays or large scale breakdowns the services of the private concerns should be used.

The external private concerns should be carefully selected and once selected their personnel should be briefed on all safety and security regulations pertaining to the plant prior to commencement of their commission.

CHAPTER 3

PLANT OPERATIONS ADMINISTRATION

3.1 PERSONNEL REQUIREMENTS

A biological and advanced treatment plant is a complex mechanical and chemical installation using sophisticated equipment and electronic instrumentation, and as such the personnel requirements differ from those of conventional water or wastewater treatment plants.

Most biological and advanced treatment plants require the services of a superintendent, a chemist, laboratory technicians, operators and maintenance personnel for mechanical, electrical and instrumentation equipment.

Some plants also include a bacteriologist amongst their personnel but this is not typical as in most cases all bacteriological assays are carried out at a central specialized laboratory.

In proposing personnel requirements for the production of a potable quality effluent, it has been assumed that the plant would operate for 24 h a day, thereby requiring three shifts of personnel. In addition it has been assumed that all bacteriological assays would be carried out at a central laboratory.

Personnel requirements for a 100 Mℓ/d biological and advanced treatment plant *could* therefore be as indicated in Figure 4.2.

In addition to the requirements set out in Figure 4.2 there must be standby personnel to cater for sick-leave, normal leave and the usual requirement of 6 shifts per person per week.

The plant will require close surveillance during the first few months but will then settle down to a lower level. It would be politic to take on a minimum of new staff in order to avoid embarassment later.

3.2 PERSONNEL TRAINING

Operating and maintenance personnel training should include, but not necessarily be limited to, the following:

- A general description of the plants and their various components together with expected effluent quality and final destination of the product water. Clearly marked drawings would be a great asset.
- The personnel must be motivated for their work and the consequences of bad operating and maintenance work should be discussed.
- An in-depth study course on all operating, maintenance and safety regulations pertaining to each section of the plant. The courses should stress the importance of prompt, clear reporting no matter how insignificant the subject may appear to be.
- A study of the plans of the various units, detailing the functions of the various items of equipment. A tour to see similar equipment in operation would be of great benefit.
- It should be stressed that on no account must operating or maintenance personnel carry out improvements to items of equipment or to methods of operation without obtaining permission to do so. However, the personnel should be encouraged to suggest improvements to their foremen or others.
- The trainees should work for a period of time with experienced personnel prior to their being 'on their own'.
- The trainees should be regularly submitted to tests, both practical and written.
- As equipment is installed at the plant so the key operating and maintenance personnel should be brought on-site.
- Operating personnel should be encouraged to better their overall qualifications by studying and to this end they should have ready access to a library, in which books, manuals and periodicals would be located.

3.3 WORKING CONDITIONS

The working conditions of the operating and maintenance personnel should be carefully evaluated at the design stage and aspects such as human comfort, safety and health should be considered.

Human comfort

Human comfort includes items such as adequate lighting, ventilation, noise levels, seating and occasionally ablution and toilet facilities within the operating area.

Safety

Safety is of the utmost importance to the uninterrupted operation of the treatment plants.

The process designer in South Africa should ensure that his design complies with the requirements of the Factories, Machinery and Building Works Act and Regulations (Act no. 22 of 1941).

It is usual for a safety officer to be appointed and

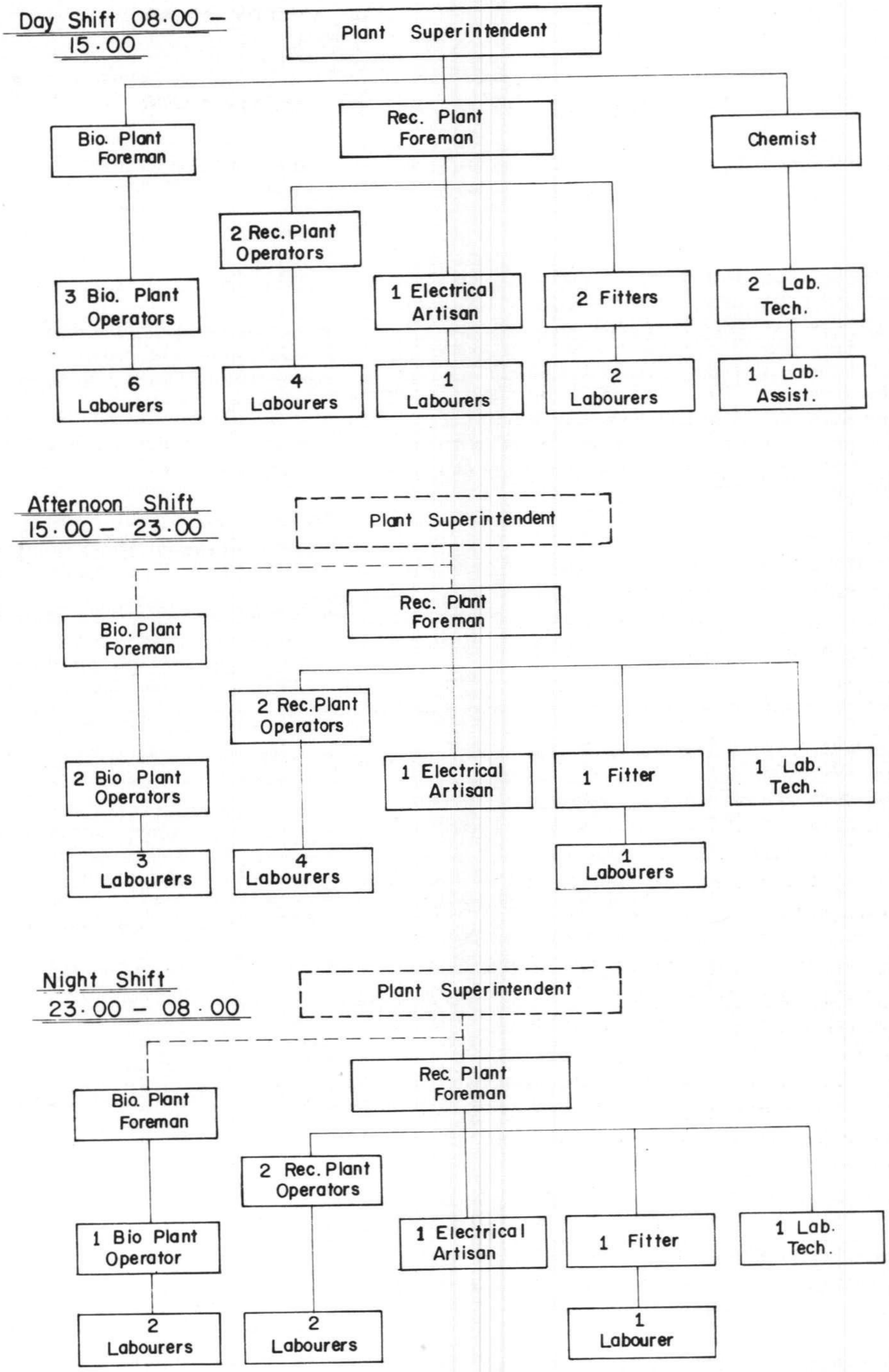


FIGURE 4.2: Proposed personnel requirements for a 100 Mℓ/d biological and advanced treatment plant

whose duties would comprise ensuring compliance with the operational aspects of the abovementioned regulations as well as training newly appointed personnel in their requirements.

Table 4.2 lists some general safety considerations relating to a biological and advanced treatment plant.[1]

Health

Health aspects include items such as the laundry of plant issued clothing, provision of drinking water points, positioning of first aid stations, annual medical checks and medical aid schemes.

TABLE 4.2 GENERAL SAFETY CONSIDERATIONS[1]

- Never start a positive displacement pump against a closed valve.
- **CAUTION**: When applying protective coatings in a clarifier or any other tank or pit, whether enclosed or open topped, use protective equipment to prevent skin burns from vapors from asphaltic or bitumastic coatings. This may involve the use of protective clothing as well as protective creams to be applied to exposed skin areas. An air supply must be used when painting inside closed vessels or in an open deep tank. Many paint fumes are heavier than air; therefore, ventilation must be from the bottom upward.

  Check with your paint supplier for any hazards involved in using his products.
- Never attempt to do a job unless you have sufficient help, the proper tools, and necessary safety equipment.
- Never use fingers to remove a manhole cover or heavy grate. Use the proper tools.
- "Lift with your legs, not your back" to prevent back strains.
- Use ladders of any kind with caution. Be certain that portable ladders are positioned so they will not slip or twist. Whenever possible, tie the top of a ladder used to enter below-grade structures. Do not use metal ladders near electrical boards or appliances.
- Never enter a manhole, pit, sump, or below-grade enclosed area when by yourself.
- Always test manholes, pits, sumps and below-grade enclosed areas for explosive atmosphere, oxygen deficiency, and hydrogen sulphide. Before entering, thoroughly ventilate with forced air blower.
- Wear or use safety devices such as safety harnesses, gas detectors and rubber gloves to prevent infections and injuries.
- Never use a tool or piece of equipment unless you are thoroughly familiar with its use or operation and know its limitations.
- Before starting a job, be certain that work area is of adequate size. If not, make allowances for this. Keep all working surfaces free of material that may cause surface to be slippery.
- See to it that all guardrails and chains are properly installed and maintained.
- Provide and maintain guards on all chains, sprockets, gears, shafts and other similar moving pieces of equipment that are normally accessible.
- Before working on mechanical or electrical equipment, properly turn off and/or tag breakers to prevent the accidental starting or the equipment while you are working on it. Wear rubber gloves and boots whenever you may contact "live" electrical circuits.
- Never enter a launder, channel, conduit, or other slippery area when by yourself.
- Never enter a chlorine atmosphere by yourself and without proper protective equipment.
- Inspect all chlorine connectors and lines before using. Discard any of these that appear defective.
- Keep all chlorine containers secured to prevent falling or rolling. Use only approved methods of moving and lifting containers.
- Maintain a good housekeeping programme. This is a proven method of preventing many accidents.

REFERENCES

1. Operation and Maintenance Manual for the Water Reclamation Plant at Palo Alto, California. Prepared by Jenks and Harrison, Palo Alto, December (1977).
2. Counts C.A. Development of a Water Treatment Plant Operational Manual. Clemson, South Carolina. Special Problem Environmental Systems Engineering, Clemson University, (1972).
3. Hart O.O. Operational Guidelines. Chapter 13 of the 'Manual for Water Renovation and Reclamation'. CSIR Technical Guide K42, Pretoria (1978).

PART V
COST ESTIMATION IN WATER RECLAMATION

CONTENTS

PRINCIPLES OF COST ESTIMATION IN WATER RECLAMATION

Cost estimation for either budgetary or process optimization purposes plays an important role in the planning and implementation of a water reclamation scheme.

The cost estimate should only be attempted once a detailed process flow sheet and material balance of the entire biological treatment and advanced treatment plant has been drawn up and the individual units correctly sized for the intended duty. The flow sheet, materials balance and unit sizing should preferably be based on laboratory or pilot plant scale experiments, with the interpretation of the results obtained therefrom being carried out by specialists who are fully aware of scale up procedures and factors, particularly when sludge treatment options are considered.[1]

In the absence of test work, unit sizing may be carried out by referring to similar plants already in operation.

1.1 ORIGINS OF COST DATA

The cost data required for estimating the cost of each of the individual unit operations, and hence the entire plant may, in the case of mechanical and electrical items, be obtained from the equipment suppliers and/or from recently let contracts of a similar nature. Similarly the costings for the civil work would be based on recently contracted (or tendered) concrete, steel, pipework, etc. prices.

Cost estimating may also be carried out by the factoring[2] or other methods,[3] but as uncertainties in cost estimation result in reduced accuracy in process optimization, it is essential that any approximations in cost data by correlations or factored estimates be based on the best available information.

1.2 COST FIGURE INDEXING

The effect of inflation within a country is that the prices of most commodities rise with time, giving rise to 'price escalation'. It is therefore imperative that all cost data relating to the plant be indexed in the sense that the date at which the data was obtained — the 'base date' — be clearly identified.

This base date will enable the effect of escalation on the overall cost estimate to be evaluated over the construction period of the plant through the judicious use of relevant escalation formulae and associated indices.

As the cost data will also consider the location of the plant, i.e. distance from and ease of accessibility from the point of manufacture, it is important that this item also be clearly identified.

1.3 ESCALATION ESTIMATION

The major cost components of any plant are clearly labour and materials, and as these items are affected by escalation, indicies and formulae have been developed whereby the escalation value may be estimated or calculated. Indices must be increased in those applications where sales tax apply.

Equipment escalation

The effect of escalation on local material and equipment costs may be calculated through the use of the following formula:

$$F = (1 - x)\left(A\frac{L}{L_o} + A_1\frac{L_1}{L_{10}} + \dots + B\frac{M}{M_o} + B_1\frac{M_1}{M_{10}} + \dots - 1\right)$$

where

F = escalation factor

x = fixed price portion of the total cost (usually 0,10 — 0,15)

A = proportion of the total cost representing labour

B = proportion of the total cost representing material

$A + A_1 + \dots + B + B_1 + \dots = 1$

L_o = Labour indices relative to A, ----- at the base date

L = Corresponding labour indices as finally adjusted and published n months prior to delivery of equipment, or in the case of erection, prior to the date of measurement.

M_o = Material indices relative to B ----- at the base date

M = Corresponding material indices as finally adjusted and published n months prior to delivery of equipment

Civil work escalation

The effect of escalation on the civil work required within the biological and advanced treatment plant may be calculated using an equation similar to that for the equipment but one that includes for plant and machinery, such that:

$$F = (1 - x)\left(A\frac{L}{L_o} + B\frac{M}{M_o} + C\frac{P}{P_o} - 1\right)$$

where $A + B + C = 1$

C = proportion of the total civil costs representing plant and machinery

P_o = Plant index relative to C at the base date.

P = corresponding plant index as published in month of measurement for payment.

Index source

The indices required for substitution in the above formulae may, in the case of local material etc., be found in the relevant publication, as itemised below:

Index	Source	Table
Labour (actual labour cost — all hourly paid employees)	SEIFSA*	C3
Labour (all hourly paid field force)	SEIFSA or SADS**	C3A 3 (all items)
Steel — all types	SEIFSA	E
Stainless steel	SEIFSA	Q
Mechanical Engineering material	SADS	G
Electrical Engineering material	SADS	G
Construction machinery	SADS	2.2
Building and construction material	SADS	2.1

* Steel and Engineering Industries Federation of South Africa

**South African Department of Statistics

Imported equipment

Items of equipment will invariably have to be imported for certain sections of the plant. Escalation in such instances is difficult to assess as it depends not only upon the rate of inflation in the country of origin but also upon fluctuations in the rate of exchange between the countries concerned.

Although the escalation formulae will not be greatly different from that presented above, the indices will be as they will relate to the particular country concerned.

Both the escalation formula and the indices may be ascertained from the relevant embassy, publication or equipment supplier.

1.4 COST FORECASTING

While the present day cost of a plant may be readily ascertained once the base date and correct table of indecies have been identified, the same is not true for predicting future plant costs.

However, by studying the movements of a particular index over say the past 5 years, trends do appear. The escalation of the index may vary linearly or exponentially and by plotting the data on a semi-log graph one may extrapolate to a 'future index'.

In addition, a monthly plot of the index's value may indicate that increases take place at regular intervals and that the increase is also regular. For example, the index for "Steel All Types" (SEIFSA table E) has increased at a rate of approximately 16% p.a. over the past 5 years and the increases take place in January and July of each year, with the January increase being greater than that of July.

The labour indices also follow similar trends but they are however more dependent upon factors such as politics and the economic condition (boom, recession, tax concessions etc.) and as such can at times be unpredictable.

It is imperative that when such a method is used for forecasting the base date at which the prices were obtained be clearly identified. A change in base date can result in a change in the relative proportions between labour and material. For example, with rates of increase in labour cost of 20% p.a. and in materials of 10% p.a., an item of equipment costing 100 units at a base date and made up as follows:

fixed = 10
labour = 50
material = 40

would for a base date 3 years later cost 149.6 units, made up as follows:

fixed = 10 i.e. 6,7%
labour = $50 \times (1,2)^3 = 86,4$ 57,8%
material = $40 \times (1,1)^3 = 53,2$ 35,5%

1.5 ESTIMATION OF THE COSTS OF RECLAIMED WATER

The cost of reclaimed water involves the estimation of the annual operation costs, which include the following:

capital amortization (or interest and redemption charges)
personnel costs
maintenance costs
electricity costs
chemical costs

Personnel requirements are briefly discussed in Part IV, section 3.1 while maintenance costs should be based on experiences at similar plants and with similar equipment as well as on equipment manufacturer's advice.

The plant availability (i.e. the plant running time per annum) should be taken into account when assessing the maintenance, electricity, chemical and overall costs.

REFERENCES

1. Purchas D.B. Solid-Liquid Separation Equipment Scale Up. Upland Press, Croydon, England.
2. Anderson D. and Marks R.H. The Economic Implications of Water Reuse. *Chemsa, September,* **149**, (1977).
3. Guthrie K.M. Capital Cost Estimating. *Chemical Engineering, March,* **114** (1969).

PART VI
WATER RECLAMATION IN SOUTHERN AFRICA

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CHAPTER 1

THE NEED FOR WATER RECLAMATION IN SOUTHERN AFRICA

South Africa is a relatively arid country with an average annual rainfall of only 483 mm, compared to 735 mm for the USA and to a world average of 860 mm. In addition, the distribution of rainfall is uneven, varying from 50 mm p.a. on the west coast to 2 500 mm p.a. in the mountains of the south western and eastern regions. About a third of the country receives an annual rainfall of less than 300 mm.[1]

Within the framework of present knowledge and expertise, it has been estimated that South Africa's total water credit — i.e. distributable water supplies — is 33 000 million m^3 per year.[2] Demand is rising rapidly and projections indicate that by the year 2 000 the demand will be 30 000 million m^3 per year — only 3 000 million m^3 less than the total quantity of water potentially available.[3]

Measures could be applied, however, to reduce water demand and the following figures are based upon estimates by the Commission of Enquiry into Water Matters.[4]

Savings through improved utilization of irrigation water	1 500 million m^3 p.a.
Savings through water reclamation and reuse	7 200 million m^3 p.a.
TOTAL REDUCTION IN DEMAND	8 700 million m^3 p.a.

It is important to note that the estimated 7 200 million m^3 p.a. which can be saved by reuse, constitutes almost 22% of the country's distributable water supplies. It is evident, therefore, that reuse is destined to play a key role in the South African water economy in the near future.

Part VI therefore highlights instances where water reclamation and reuse are either at the research stage or have been implemented in full scale practice in Southern Africa.

CHAPTER 2

WATER RECLAMATION SCHEMES FOR POTABLE REUSE

2.1 RESEARCH AND DEMONSTRATION PLANTS

2.1.1 The Stander Plant, Pretoria

The reader is referred to the 'Manual for Water Renovation and Reclamation' for discussions on, and details of, the 4,5 Mℓ/d Stander Plant. Figure 6.1 shows the flow diagram of the plant when biological filter effluent was treated and Figure 6.2 the flow diagram when activated sludge plant effluent was treated.[5]

Ferric chloride has subsequently been used as the primary coagulant in lieu of lime and Figure 6.3 shows the flow diagram of the Stander Plant when using the iron salt as the primary coagulant on the activated sludge plant effluent.[6]

2.1.2 The Cape Flats Plant, Cape Town

The 4,5 Mℓ/d Cape Flats plant, situated near Muizenberg, is being constructed in two stages. The first stage, commissioned in August 1978, draws its influent from a nearby oxidation pond and consists essentially of lime treatment, recarbonation and disinfection.

The second stage, soon to be completed, will add further unit operations to the process flow-path and by so doing enable a water of potable quality to be produced.

The influent to the 'complete' plant will be drawn from the new 200 Mℓ/d Cape Flats Sewage Works which incorporates the biological removal of both nitrogen and phosphorus.

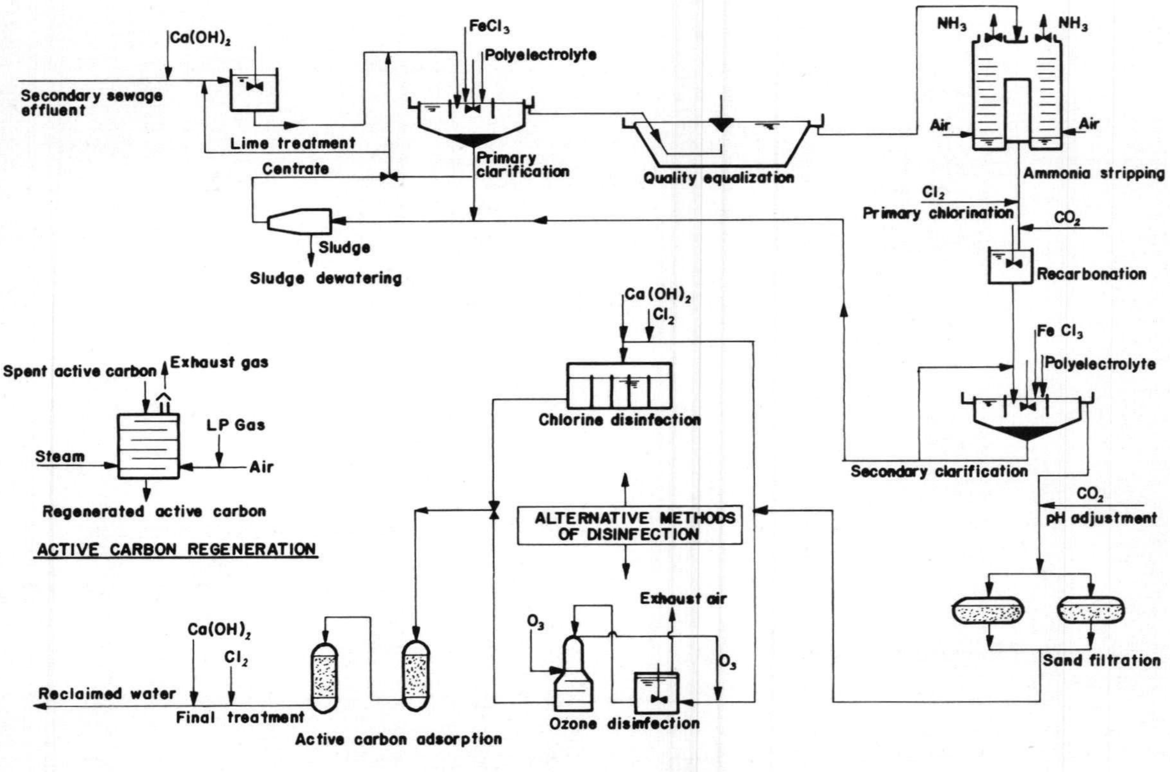


FIGURE 6.1: Flow diagram of the Stander Plant when treating biological filter effluent

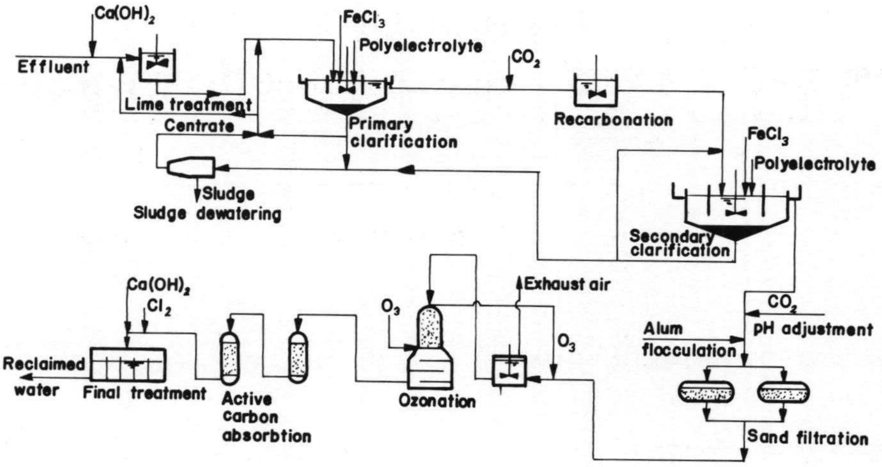


FIGURE 6.2: Flow diagram of the Stander Plant when treating activated sludge plant effluent[5]

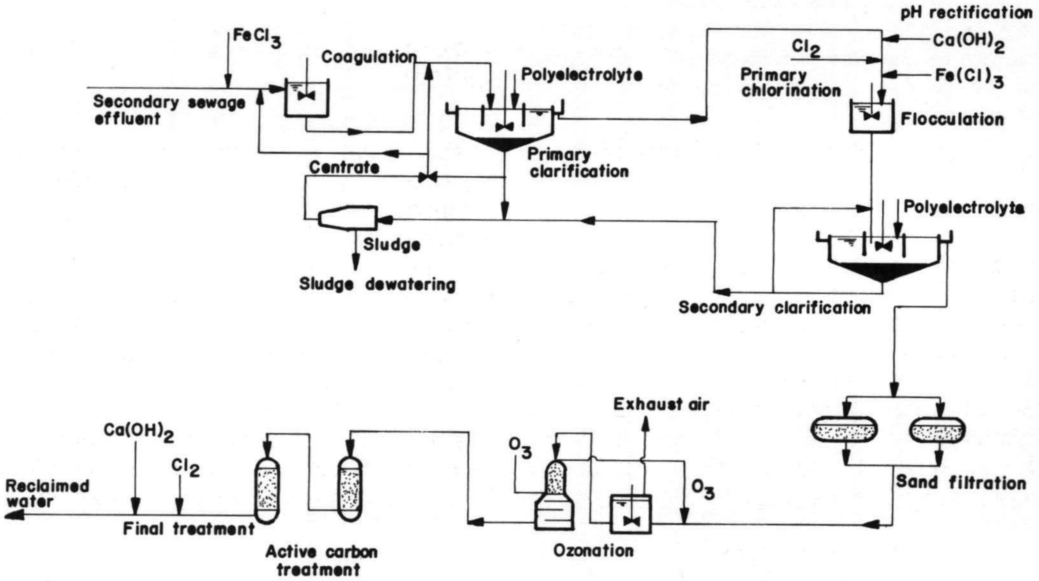


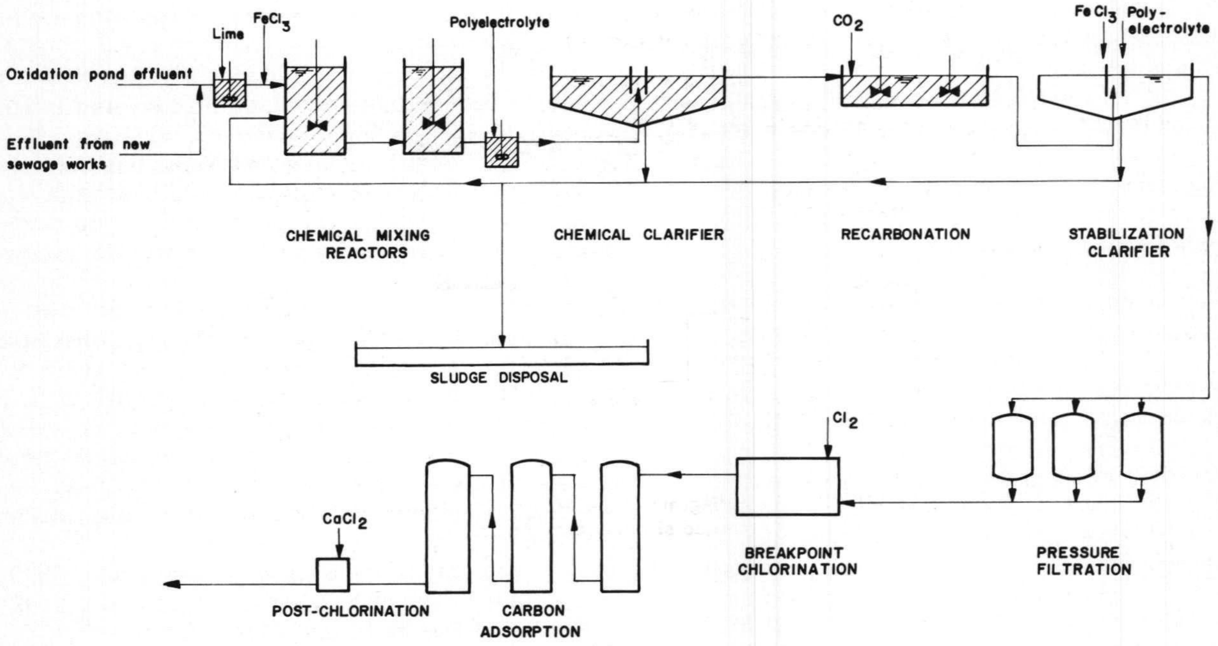
FIGURE 6.3: Flow diagram of the Stander Plant when using ferric chloride as primary coagulant[6]

Figure 6.4 shows the flow diagram of the plant with those units forming the first stage being clearly marked.

2.1.3 Ongoing laboratory and pilot scale research

Laboratory and pilot scale experiments are being conducted into the following as part of an ongoing research programme:

- The role of ozone in water reclamation.
- The positioning of the ozonation, chlorination and activated carbon adsorption stages in relation to each other.
- Biological activity on the activated carbon.
- Performances of various activated carbons.
- Efficacies of various coagulants and floc-aids.



NOTE: UNITS SHOWN SHADED FORM FIRST STAGE

FIGURE 6.4: Flow diagram of the Cape Flats Water Reclamation Plant, Cape Town

2.2 FULL SCALE OPERATIONAL PLANTS

2.2.1 The Windhoek Plant, Namibia/S.W.A.

The reader is referred to the literature for the history of, and reasons for, the Windhoek Plant,[7,8,9] but suffice it to say at this stage that the original plant was commissioned in 1969 and was designed for the reclamation of effluent derived from maturation ponds which served as polishing units for secondary effluent discharged from a biological filtration plant. The reclaimed water was then blended with fresh water supplies and distributed within the city. Figure 6.5 shows the unit operations employed at that stage, indicating that use was made of algae separation by flotation, foam fractionation, chemical clarification, sand filtration, activated carbon adsorption and breakpoint chlorination.[8]

From a technological point of view the performance of this advanced treatment plant was highly satisfactory, but the final quality and cost depended on the quality of the maturation pond effluent which served as water intake to the plant.

The increasing overload on the municipal sewage treatment plant resulted in the effluent from the maturation ponds regularly being of such poor quality that the advanced treatment plant was only operated intermit-

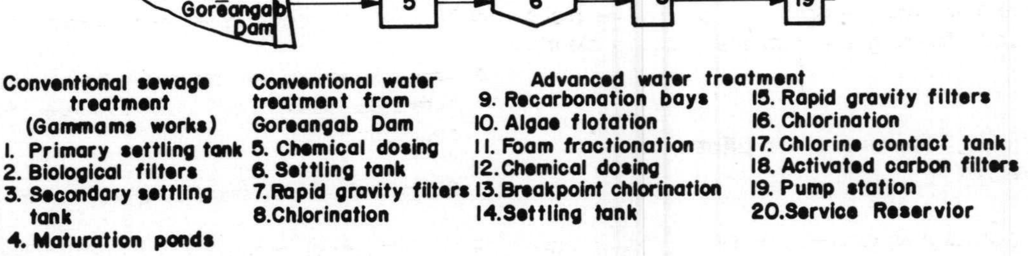


FIGURE 6.5: Flow diagram of original Windhoek reclamation scheme[8]

tently. Indeed the annual period of operation in 1973 was only 70 days as opposed to eight months during initial commissioning.[10]

The advanced treatment plant was therefore modified in 1975 with the modifications comprising:

- High lime treatment in a solids contact clarifier.
- Ammonia stripping tower.
- Conversion of the algae flotation and foam fractionation tanks into recarbonation reactor units.
- Modification of a secondary clarifier to serve as a stabilization and pre-chlorination contacting unit.
- Provision of secondary recarbonation facilities.

Additional activated carbon adsorption columns were commissioned in 1977 followed by the installation of a carbon regeneration furnace in 1978.

Figure 6.6 shows the flow diagram of the 'modified' advanced treatment plant and Table 6.1 summarizes the physico-chemical parameters for the 1977/78 period.[10]

The provision of ammonia stripping facilities extended the utilization period of the advanced treatment plant to between 9 and 10 months per annum.[10]

The cost of the reclaimed water has been shown to be highly dependent upon the chlorine requirements for residual ammonia oxidation and was approximately 29c/kℓ in 1978[10] as compared to some 23c for further supply sources.[11]

While the advanced treatment plant was being modified, alternative designs were being considered for the extensions to the sewage treatment plant. It was finally decided in 1977 that in order to obviate the need for ammonia stripping at the advanced treatment plant, the extensions to the sewage works would take the form of an activated sludge plant designed for the biological removal of both N and P (refer to Part II, Chapter 10 for further discussion).

The extensions were commissioned in 1979 and the effluent now discharged to the advanced treatment plant consistently contains less than 0,5 mg/ℓ of ammonia (as N) and 5 mg/ℓ of nitrate (as N).

TABLE 6.1 WINDHOEK PLANT — AVERAGE ANALYSES[10]

Parameter		Influent[1]	Lime clarifier effluent[3]	Stripper effluent[6]	Cl_2 contact tank effluent[12]	Carbon Column effluent[13]
Ammonia (as N)	mg/ℓ	3,2	2,9	2,4	0,1	0,1
Organic nitrogen	mg/ℓ	6,9	5,2	4,8	0,9	0,6
Nitrite (as N)	mg/ℓ	1,4	—	—	—	—
Nitrate (as N)	mg/ℓ	9,7	—	—	10,1	9,7
COD	mg/ℓ	48,1	27,9	—	21,5	11,6
Total dissolved solids	mg/ℓ	705,0	634,0	647,0	650,0	646,0
pH		7,8	11,1	11,0	7,4	7,3
Chloride (as Cl)	mg/ℓ	118,0	121,0	—	—	162,0
Total phosphorus (as P)	mg/ℓ	9,8	0,3	—	0,3	0,3
Calcium (as Ca)	mg/ℓ	50,4	42,8	42,4	46,0	49,2
Magnesium (as Mg)	mg/ℓ	12,9	2,7	—	2,9	3,4
Sulphate (as SO_4)	mg/ℓ	123,0	141,0	—	—	139,0

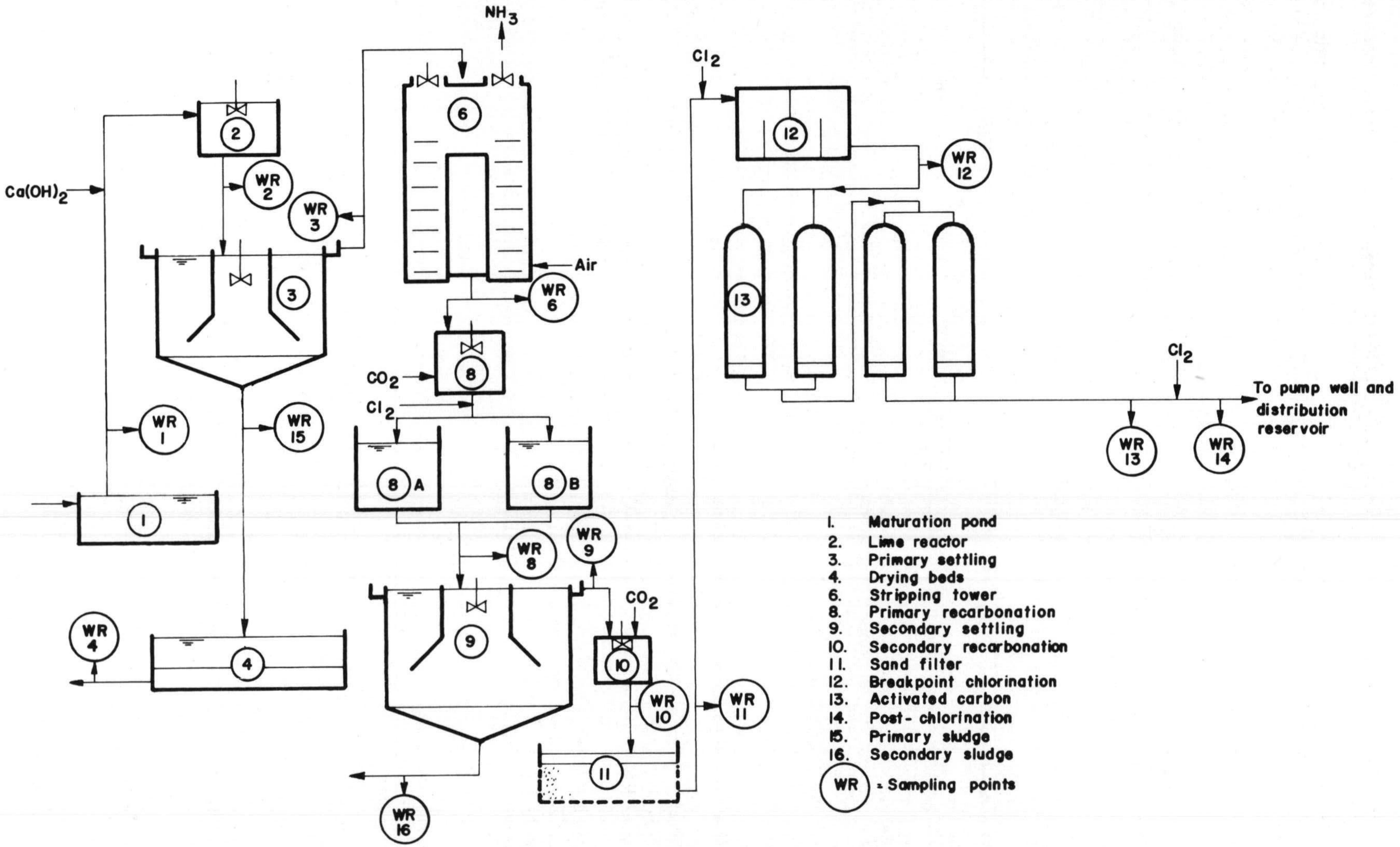


FIGURE 6.6: Flow diagram of modified Windhoek water reclamation plant[10]

CHAPTER 3

WATER RECLAMATION FOR INDUSTRIAL REUSE

This chapter is concerned only with the existing pilot and fullscale plants that produce reclaimed water suitable for industrial reuse.

3.1 RESEARCH AND DEMONSTRATION PLANTS

3.1.1 The Athlone Plant, Cape Town

The 0,3 Mℓ/d Athlone plant was commissioned in 1976 with the aim of reclaiming a water suitable for reuse by selected industries, such as textiles. The influent to the plant is of a poor quality; emanating from an overloaded biological filtration plant that receives a raw sewage with a high industrial effluent content.

Figure 6.7 shows the flow diagram of the plant and Table 6.2 shows typical influent/effluent qualities.[12]

3.1.2 The modified 'LFB' plant, Pretoria

The modified LFB plant is essentially a modification of the high lime (L), dissolved air flotation (F) and biological treatment (B) combination previously reported on.[13]

Figure 6.8 shows the flow diagram of the 60 m^3/d modified LFB pilot plant installed at Pretoria and Table 6.3 shows typical performance results taken over a 16 week period.[12]

Perhaps the most significant aspects of this plant are that ferric chloride is used as the primary coagulant in lieu of lime and that nitrogen removal is achieved through biological nitrification/denitrification, using an internal carbon source.

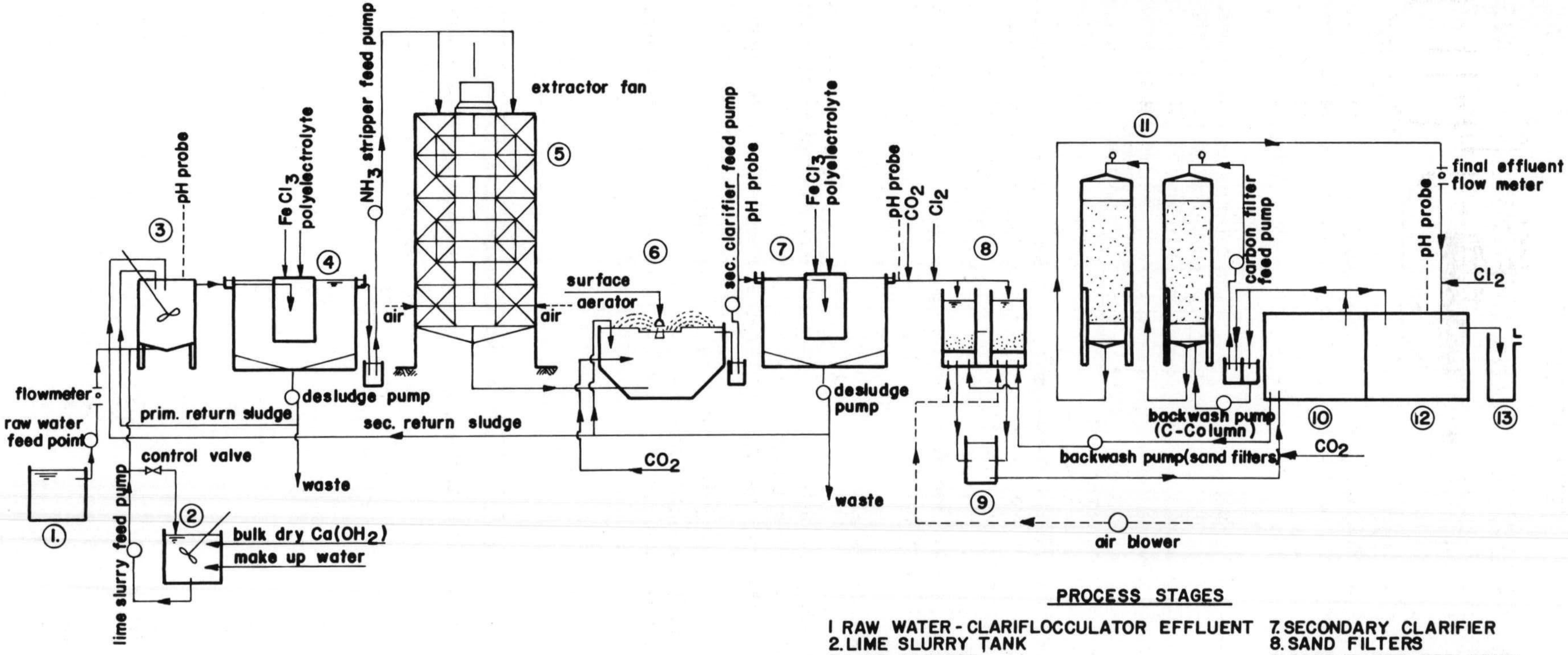
Preliminary studies into the anaerobic digestion of the iron rich sludges indicate little release of phosphorus into the supernatant.

The advantages of this process configuration may be listed as:

- A short interruption in chemical addition will not adversely affect the performance of the plant or its ability to remove phosphorus.
- The removal of much of the colloidal matter in the first stage of the process will result in a low COD in the treated effluent.
- The addition of ferric chloride and lime will remove heavy metals that may be toxic in nature.
- Anaerobic digestion of the organic load removed in the chemical clarifier would enable energy recovery to be practised.
- The high quality of treated effluent renders it suitable for reuse.

TABLE 6.2 ATHLONE RECLAMATION PLANT — AVERAGE ANALYSES[12]

		Influent	Primary Clarifier Effluent	Ammonia Stripper Effluent	Secondary Clarifier Effluent	Sand Filter Effluent	Final Water
Ammonia as N	mg/ℓ	36,2	33,3	17,3	0,2	0,2	0,2
Organic Nitrogen	mg/ℓ	9,5	4,3	4,2	3,0	2,0	0,6
Nitrite as N	mg/ℓ	0,2	0,6	2,3	0,2	—	0,03
Nitrate as N	mg/ℓ	0,8	1,2	2,6	22,6	—	23,1
COD	mg/ℓ	220	91		65	52	22
Dissolved Solids	mg/ℓ	785	—	—	—	—	800
pH		—	—	—	—	7,2	6,8
Chloride as Cl	mg/ℓ	—	—	—	—	—	233
Total phosphorus as P	mg/ℓ	10,2	0,8	—	0,85	0,7	0,8
Calcium as Ca	mg/ℓ	37	35	—	57	67	63
Magnesium as Mg	mg/ℓ	15	4	—	4	4	4
Iron as Fe	mg/ℓ	1,1	1,8	—	1,3	0,2	0,3
Manganese as Mn	mg/ℓ	0,14	0,04	—	0,04	0,03	0,02
Sulphate as SO_4	mg/ℓ	99	—	—	—	—	84
Colour (Hazen)		205	68	—	58	50	9
Turbidity, JTU		—	—	—	—	1,2	1,0



PROCESS STAGES

1. RAW WATER - CLARIFLOCCULATOR EFFLUENT
2. LIME SLURRY TANK
3. LIME REACTOR
4. PRIMARY CLARIFIER
5. AMMONIA STRIPPER
6. AERATION TANK
7. SECONDARY CLARIFIER
8. SAND FILTERS
9. SAND FILTER EFFLUENT
10. CHLORINE CONTACT TANK
11. CARBON FILTERS
12. FINAL EFFLUENT TANK
13. FINAL EFFLUENT SAMPLE MODULE

FIGURE 6.7: Flow diagram of the Athlone water reclamation plant[12]

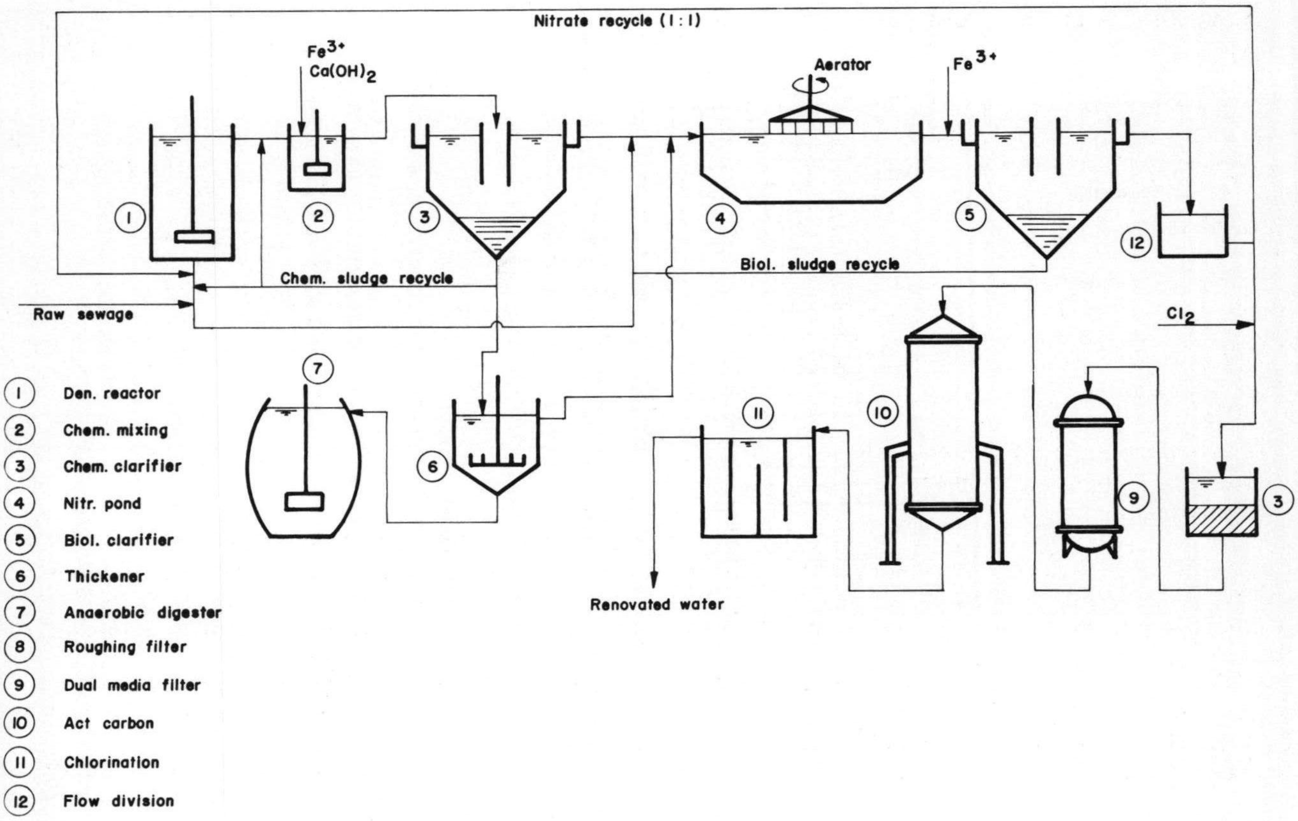


FIGURE 6.8: Flow diagram of the modified LFB pilot plant[12]

TABLE 6.3 MODIFIED LFB PLANT — AVERAGE ANALYSES[12]

Parameter	Raw screened sewage	Chemical clarifier effluent	Biological clarifier effluent	Final effluent
Turbidity (JTU)	8	—	—	<0,6
Colour (Hazen)	120	—	—	8
pH	7,3	—	—	7,8
Electrical Conductivity (mS/m)	69	—	—	67
Sodium (mg/ℓ)	45	—	—	40
Potassium (mg/ℓ)	12	—	—	10
Calcium (mg/ℓ)	38	—	—	55
Magnesium (mg/ℓ)	20	—	—	22
Total Kjeldahl Nitrogen (mg/ℓ)	28	12,9	—	<0,5
Ammonia Nitrogen (mg/ℓ)	18	9,6	0,2	<0,2
Nitrate + Nitrite (mg/ℓ)	< 0,1	0,6	11,8	11,0
Total Phosphorus (mg/ℓ)	6,0	—	—	<0,2
Ortho Phosphorus (mg/ℓ)	4,1	0,3	0,13	<0,2
Total COD (mg/ℓ)	350	—	—	< 10
Soluble COD (mg/ℓ)	112	41	26	—
Total Alkalinity (mg/ℓ)	220	—	—	102
Chloride, as Cl (mg/ℓ)	50	—	—	100
Sulphate (mg/ℓ)	70	—	—	35

However the process does have disadvantages namely:

- The low rate of recycle from the final effluent to the denitrification reactor will result in the effluent nitrate concentration being far in excess of 10 mg/ℓ (as NO_3-N) when the influent nitrogen concentration is high (e.g. 60 mg/ℓ as N).
- The saving in power costs of some 0,2c/m^3 (in 1979) when the primary sludge is anaerobically digested, is off-set by the chemical costs of some 1,8c/m^3. Aerobic digestion of the primary sludge will result in there being no saving in power costs.
- The mass of sludge to be disposed of is significantly increased over that of an extended aeration activated sludge system.
- Chemical costs could be significantly higher than in the case of chemical addition to conventional activated sludge processes to obtain phosphorus removal.

3.2 REUSE OF TERTIARY EFFLUENTS FOR COOLING

Some 67% of the total water demand by industry, the mining industry excluded, is required for cooling purposes.[14] The largest consumers of water for cooling purposes are power stations where cooling water contributes 90 — 95% of their total water intake.

TABLE 6.4 USE OF TERTIARY EFFLUENTS IN POWER STATIONS[15]

	Capacity MW	Reclaimed sewage effluent m^3/d
Cape Town (Athlone)	180	10 000
Bloemfontein	102,5	7 500
Johannesburg (Orlando)	300	58 000
Johannesburg (Kelvin)	600	
Pretoria West	180	27 300 (including ash handling)
Pretoria Rooiwal	300	18 200

The scarcity of fresh water supplies in areas of South Africa has prompted the use of tertiary effluents in power stations and Table 6.4 indicates the extent to which such effluents are used.[15]

Figure 6.9 indicates a schematic layout of the Rooiwal power station cooling water supply scheme in Pretoria.[15]

Purified sewage effluent is also used in other industries. For example the Dunswart Iron and Steel Ltd. factory at Benoni utilizes some 1 700 to 1 800 kℓ/day of purified sewage effluent mainly for cooling of the continuous casting plant, and partly for washing.

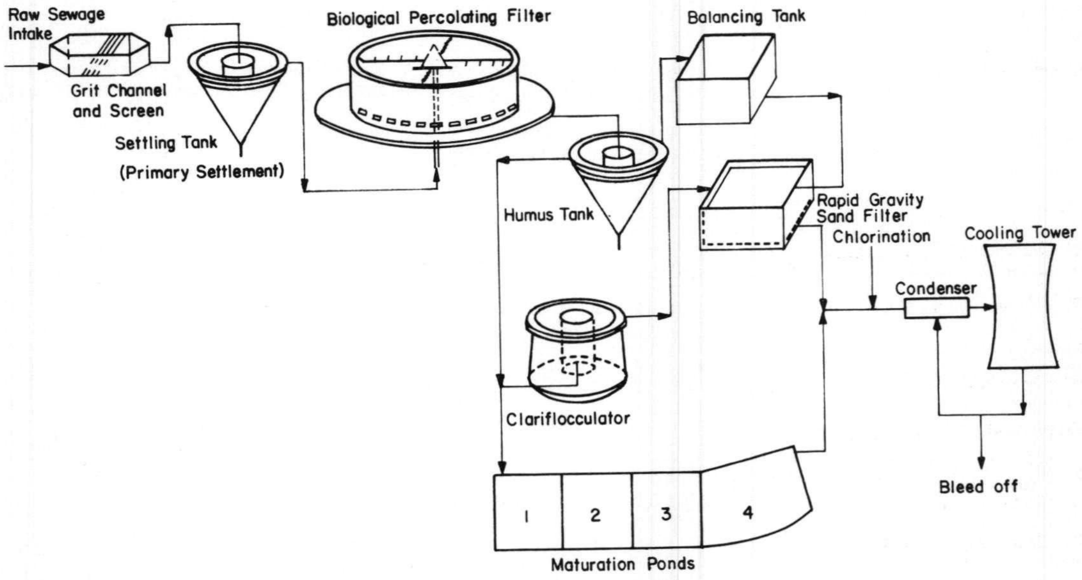


FIGURE 6.9: Reuse of sewage effluent as cooling water for power generation at Rooiwal, Pretoria[15]

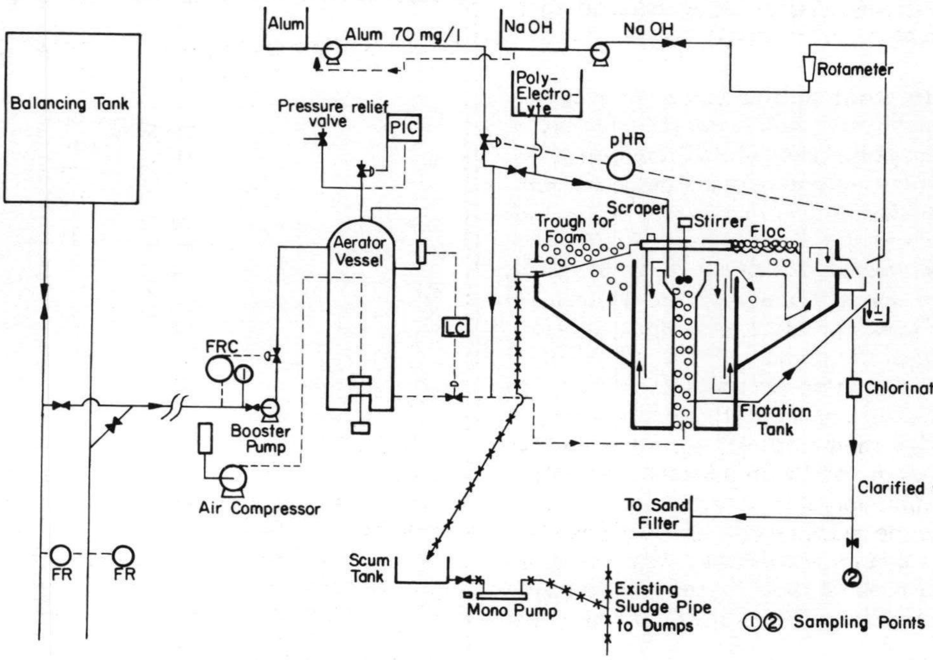


FIGURE 6.10: Flow diagram of the SAPPI plant[15.16]

TABLE 6.5 TYPICAL RESULTS OBTAINED FROM THE SAPPI PLANT[15.16]

	Springs purified sewage	Reclaimed water Initial period July '70 — Feb. '71	 After alterations March '71 onwards
pH	7,2	7,0	6,7
Conductivity, mS/m 20°C	1 100	1 300	1 200
Colour (Hazen units)	40	23	10
Suspended solids	25	14	nil — 1
COD	75	40	
Total hardness (as $CaCO_3$)	240	240	
Total alkalinity (as $CaCO_3$)	210	150	
Bicarbonate alkalinity (as $CaCO_3$)	210	150	
Total phosphate (as P)	2,6 — 6,7	0,6 — 1,2	
Detergents	1,0 — 1,5	0,7 — 0,9	
Sulphates (as SO_4)	150 — 200	220 — 270	185 — 235
Fe	0,26	0,06	
Mn	0,55	0,50	
Co	0,34	0,34	
Ni	0,27	0,26	
Cu	0,45	0,025	
Cr	0,02	nil	
Brightness* (average) of test sheets % Elrepho	76,9	84,2 — 84,5	

*Brightness of test sheets for comparison:	82,4 with Rand Water Board water 85,6 with distilled water		
Throughflow (average):	25 000 m³/day		
Chemical dosage during initial period:		$Al_2(SO_4)_3.14H_2O$ NaOH Cl_2	130 — 140 mg/ℓ 20 mg/ℓ nil
Chemical dosage after alterations:		$Al_2(SO_4)_3.14H_2O$ NaOH Polyelectrolyte Cl_2	70 — 75 mg/ℓ nil to 10 mg/ℓ 1,2 — 1,7 mg/ℓ 3 mg/ℓ

3.3 WATER RECLAMATION FOR REUSE IN THE PAPER INDUSTRY

3.3.1 The SAPPI plant, Springs

The ENSTRA Mill of South African Pulp and Paper Industries Ltd. (SAPPI), situated near the city of Springs in Transvaal, South Africa, uses secondary sewage effluent as the major part of its water supply.[15.16] The present rate of water usage is made up of 16 000 m^3/d fresh water (Rand Water Board) and of 25 000 m^3/d purified sewage effluent from the McComb works of the Springs Municipality.

As the residual organic matter and heavy metal contents of the secondary sewage effluent are not compatible with the production of a high quality paper, this effluent is further upgraded by an advanced treatment plant that was commissioned in July 1970.

The design of the reclamation plant was based on investigations carried out by SAPPI and the National Institute of Water Research and makes use of alum coagulation, dissolved air flotation, chlorination and sand filtration.

Figure 6.10 shows the flow diagram of the SAPPI plant[16] and Table 6.5 summarizes typical results obtained.[15.16]

3.3.2 The Mondi plant, Durban

The Mondi paper mill, consisting of a groundwood pump mill and three paper machines for the production of approximately 750 ton/d of newsprint and fine paper grades was designed to use up to 12 Mℓ/d of treated sewage effluent from the nearby Durban southern sewage works as process water.[17]

The advanced treatment plant required for upgrading the quality of the secondary effluent to that compatible with the production of newsprint and fine paper was designed on the basis of results obtained from a pilot plant study and was commissioned in October 1972.

TABLE 6.6 AVERAGE RESULTS OBTAINED FROM THE MONDI PLANT DURING 1976[17]

	Before Treatment at Mondi Waterworks	After Treatment as supplied to the mill
	Average	Average
pH	7,1	7,0
Turbidity, Jackson units	3,4	0,6
Colour, Hazen units	57	7
Temperature, °C	24,2	
Chlorine, as Cl_2	0	0,2
Total dissolved solids	443	549
Suspended solids	15	0
Chemical oxygen demand	88	43
Oxygen absorbed	8,7	2,6
Phosphates, as PO_4	6,3	0,6
Detergents, as Manoxol	0,3	0,1
Oil, soap and grease	50	13
Total hardness, as $CaCO_3$	66	104
Total alkalinity, as $CaCO_3$	104	74
Free saline ammonia, as N	1,7	0,6
Nitrite, as N	0,4	0,3
Nitrate as N	4,4	6,5
Chlorides, as Cl	107	111
Sulphates, as SO_4	63	152
Iron, as Fe	0,36	0,08
Manganese, as Mn	0	0
Aluminium, as Al	0,12	0,24
Sodium, as Na	110	137

The plant consists of chemical coagulation with aluminium sulphate, activated silica and polyelectrolyte, followed by clarification, foam fractionation, sand filtration and activated carbon adsorption. Figure 6.11 shows the flow diagram of the plant and Table 6.6 indicates the quality of effluent produced during 1976.[17]

The mill has also instituted a mill effluent and solids recovery scheme whereby, after a degree of treatment, both are reused.[17]

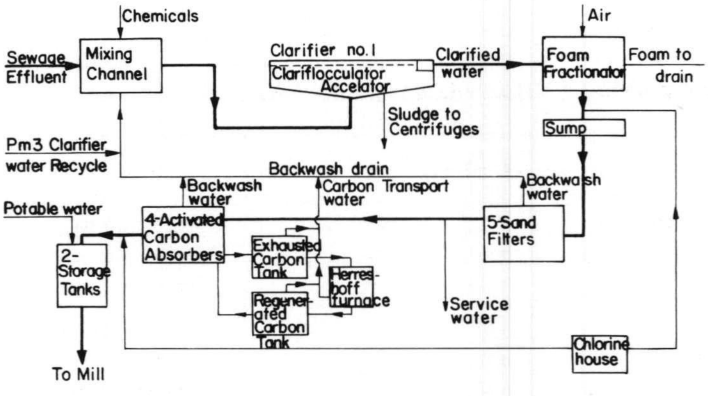


FIGURE 6.11: Flow diagram of the Mondi reclamation plant[17]

3.3.3 **S.A. Board Mills, Bellville**

The S.A. Board Mills in Bellville produce lined grey backed or manila backed board, either coated or uncoated, at a rate of 71 ton/d. Fibrous raw material consists of bleached pulp, mechanical pulp and various grades of waste paper, with the latter constituting some 85% of the total fibrous raw material intake.

The total water intake to the mill is approximately 1,5 Mℓ/d of which a secondary effluent, produced by an activated sludge plant followed by sandfiltration and chlorination at the Bellville sewage works, constitutes some 67%; the balance being made up with potable water.

TABLE 6.7 PERFORMANCE OF ADVANCED TREATMENT PLANT AT SASOL[18]

	Influent (mg/ℓ)	Effluent (mg/ℓ)
Suspended solids	100	—
COD	4 000	50
BOD	3 000	10
SO_4^{2-}	150	—
Cl^-	50	10
F^-	100	20

3.4 WATER RECLAMATION FOR REUSE IN THE CHEMICAL INDUSTRY

The liquor discharged from the coal gasification section of the SASOL 'petrol from coal' plant at Secunda is treated to such a standard that the reclaimed water is used for cooling purposes within the plant.

Figure 6.12 shows a flow diagram of the biological and advanced treatment plants and Table 6.7 shows the performance of the advanced treatment section.[18]

3.5 WATER RECLAMATION FOR PUBLIC AREA IRRIGATION — THE THORNGROVE PLANT, BULAWAYO, ZIMBABWE

The Thorngrove plant, situated near the centre of the City of Bulawayo in Zimbabwe, receives predominantly domestic sewage and through two-stage biological filtration produces a good quality secondary effluent.

A portion of this effluent is further treated by means of chemical flocculation, clarification, sand filtration and chlorination prior to being pumped away for irrigating public open spaces, parks and playing grounds.

All sludges generated at this plant are discharged into a main outfall sewer that feeds the larger Aiselby works, situated on the outskirts of the city, and which also receives most of the city's industrial discharges.

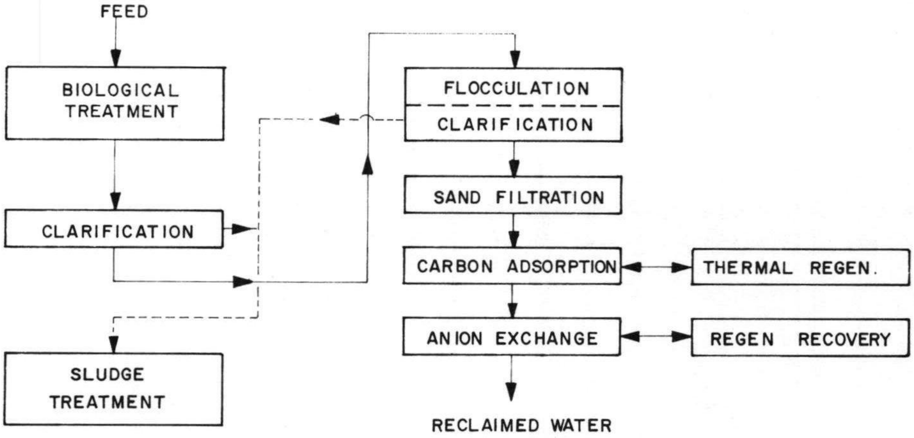


FIGURE 6.12: Flow diagram of Sasol reclamation scheme

REFERENCES

1. Kriel J.P. Planning and Progress in the Development of the Water Resources of South Africa, with Special Reference to South Western Cape. Congress of the South African Assoc. for the Advancement of Science, Stellenbosch, June (1978).
2. Kriel J.P. Resources of Southern Africa Today and Tomorrow — Interaction in Water Resources Development. Conference of Assoc. Scientific and Tech. Societies, Johannesburg, September (1975).
3. Van der Merwe W. A Prognosis of Water Reuse in the Republic of South Africa. Paper presented at Symposium on Recycling Wastewater for Agricultural and Industrial Uses, Tel Aviv, Israel, November (1975).
4. Republic of South Africa. Report of the Commission of Enquiry into Water Matters, R.P. 34/1970, (1970).
5. Van Blerk S.H.V., Prinsloo J. and Van Leeuwen J. Comparative Reclamation of Potable Water from Biofilter and Activated Sludge Effluents at the Stander Water Reclamation Plant. *Prog. Wat. Tech.* **10** (1/2) 81 (1978).
6. Van Leeuwen J. and Prinsloo J. Ozonation at the Stander Water Reclamation Plant. *Water S.A.* **6** (2) 96 (1980).
7. Stander G.J., Van Vuuren L.R.J. and Dalton G.L. Current Status of Research on Wastewater Reclamation in South Africa. *Wat. Polln. Cont.,* **70** (2) 213 (1971).
8. Clayton A.J. and Pybus P.J. Windhoek Reclaiming Sewage for Drinking Water. *Civil Engineering — ASCE* September, 103, (1972).
9. Stander G.J. Reuse of Wastewater for Industrial and Household Purposes. Paper presented at IWSA Conference, New York, September (1972).
10. Van Vuuren L.R.J., Clayton A.J. and Van der Post D.C. Current Status of Water Reclamation at Windhoek. WPCF 51st Annual Conf. Anaheim 1—6 October, 1978.
11. Clayton A.J. Private Communication, 1979.
12. Van Vuuren L.R.J. and Taljard M.P. The Reclamation of Industrial/Domestic Wastewaters. Paper presented at Water Reuse Symposium, Washington, March (1979).
13. Van Vuuren L.R.J. and Wiechers S.G. Nitrification and Denitrification of Lime Treated Wastewaters. *Prog. Wat. Tech.* **10** (1/2) 185 (1978).
14. Hart O.O. and Van Vuuren L.R.J. Water Reuse in South Africa. Chapter 13 of 'Water Renovation and Reuse'. Edited by Shuval H.I. and published by Academic Press Inc., London (1977).
15. Funke J.W. and Van Vuuren L.R.J. Water Conservation, Reuse of Effluent and Prevention of Pollution in South African Industry. Group discussion on Water Reuse. Organized by the Iranian Ministry of Power and Energy, Teheran, November (1977).
16. Van Vuuren L.R.J., Funke J.W. and Smith L. The Full-scale Refinement of Purified Sewage for Unrestricted Industrial Use in the Manufacture of Fully Bleached Kraft-Pulp and Fine Paper. Paper presented at the 6th Int. Assoc. Wat. Polln. Res. Conference, Jerusalem, June (1972).
17. Giampietri A., Funke J.W. and Voysey J.A. The Reclamation of Process Water from Sewage Effluent and the Reuse of Mill Effluents and Solids at Mondi Paper Company, Durban, South Africa. *Prog. Wat. Tech.* **10** (1/2) 113 (1978).
18. Rolke D.E. Effluent Treatment with Particular Reference to Reuse of Water. *Chemsa,* September, 142 (1979).