DEPARTMENT OF WATER AFFAIRS & FORESTRY

CODE OF PRACTICE: VOLUME 4

BIOLOGICAL TREATMENT
ACTIVATED SLUDGE PROCESSES

GENERAL GUIDELINES

(July 2008)

CONTENTS

TERMS FREQUENTLY USED

General

Activated Sludge (AS): Active mass of microbial floc that is formed when microorganisms grow under aerobic conditions inside a basin filled with wastewater that is agitated with air.

Aerobic: Condition/environment where adequate free oxygen is available for aerobic microorganisms to grow – the electron acceptor is molecular oxygen (O_2) and latter is reduced to water (H_2O).

Anaerobic: Condition/environment lacking oxygen where only anaerobic microorganisms can grow – no O_2, NO_2^- or NO_3^- is present and the organism generates its own electron acceptor internally.

Anoxic: Condition where free oxygen is lacking, but oxygen in the form of NO_2^- or NO_3^- is available - microorganisms use NO_2^- or NO_3^- as electron acceptor and both are reduced to nitrogen gas (N_2) and water.

Biological Filter: Biological process whereby sewage is distributed over and slowly trickles through a bed containing media that houses microorganisms. Latter oxidise the biodegradable matter contained in sewage aerobically.

BNR: Biological nutrient removal. Denotes activated sludge plants that incorporate biological nitrogen (N) and phosphate (P) –removal.

DWAF: Department of Water Affairs and Forestry.

ML: Mixed liquor = mixture of the activated sludge (microbial flocs) and wastewater in the aeration basin.

MLSS: Mixed liquor suspended solids = solids concentration (=biomass) expressed as mg/l that is suspended in the liquor taken from the activated sludge basin.

PE: Population Equivalent. This term is used to express the total flow and load discharged into a sewage works in terms of population, e.g. number of users.

Primary: Generally the first stage of a treatment process.

Pond System: System of dams that are designed to receive and treat wastewater, utilising mainly natural resources, e.g. solar energy, algae and a variety of microorganisms, to physically and biologically remove solids, organic matter, nutrients and reduce pathogens. Often called lagoons, e.g. USA.

Retention Period: Average time that liquids or solids are retained in a containment structure.

Septic Tank: Tank that collects and contains sewage for a specific period.

Secondary: Treatment process that follows the primary treatment stage.

Tertiary: All treatment processes that follow a secondary treatment stage.

Chemical

BOD: Biodegradable Oxygen Demand = measurement of oxygen utilized by microorganisms during oxidation of organic material contained in wastewater.

BOD_5: Oxygen utilized within 5 days (BOD_5) of microbial activity. This duration was selected to minimize the effect of nitrification.

COD: Chemical Oxygen Demand = measurement of the amount of oxidisable organic matter, *viz* the amount of oxygen required to convert all organic carbon constituents to CO_2 and H_2O.

DO: Dissolved Oxygen = measurement of the dissolved oxygen available in a water body.

DOL: Daily Organic Load = people served times BOD or COD discharged per person per day.

Flow

ADWF: Average Dry Weather Flow = average total quantity of sewage received per day divided by 24 hours.

PDWF: Peak Dry Weather Flow = maximum flow during peak hours. Generally assumed (if not specifically measured) as twice the ADWF.

AWWF: Average Wet Weather Flow = average flow during the rainy season, which includes rain- and groundwater infiltration into the sewer. Generally assumed (if not specifically measured) as three times ADWF.

1. INTRODUCTION

In the Water Resources Management Act, 2004 (Act No. 24 of 2004), there are conditions laid down to ensure that proper wastewater treatment is provided and to facilitate good operation of different sewage treatment systems and their methods of disposal. The Act's main objectives are to use and protect one of our most valuable natural resources, namely water, and to encourage reuse of the treated effluent.

The need to protect our environment and especially the ever-dwindling potable water resources has resulted in an increased demand raised on effluent quality of a wastewater before being finally discharged. Especially the excessive enrichment of a water body by plant nutrients such as phosphates and nitrates results in eutrophication, which is an undesirable proliferation of organisms and plants in the receiving water body. This again results in increased water purification costs, aesthetic problems, loss of a balanced aquatic ecosystem, loss of livestock and possibly sub-lethal effects on humans. Activated sludge processes lend itself well for treatment of domestic sewage as well as organically laden industrial effluents to produce a final effluent of exceptionally high standard, typically as would be required to conform to the Special Standard for effluent treatment (Water Resources Management Act, 2004).

The construction, operation and disposal of effluent using an activated sludge (AS) treatment system is subject to a wastewater discharge permit from the Department of Water Affairs and Forestry (DWAF).

Activated sludge processes rely on microorganisms that grow as submerged cultures in a volume of water (effluent), typically in the form of small flocs suspended in the effluent that is being treated. It therefore falls into the category of submerged-growth biological treatment processes. A substantial level of sophistication and mechanization is employed in activated sludge treatment processes and plants based on this technology are generally classified as first-world, advanced treatment plants. It is therefore advisable that activated sludge (AS) technology is only considered for towns or centres where good mechanical back-up and process expertise is readily available, e.g. for industries and expansions close to Windhoek and Walvis Bay.

This manual addresses treatment of wastewater by means of AS systems. It includes basic information to understand the processes employed and strives to present information that may be helpful to the following users:

- Persons performing compliance inspections, sampling and writing or assessing technical reports on which permit conditions are based;
- Engineers and Consultants not specialised in wastewater treatment as background information only;
- AS plant operators;
- Owners of AS plants;
- Scientists who become involved in AS technology for the first time.

Activated sludge processes are fairly complex and numerous computer models have been developed to assist designers in providing the most optimal solution for their clients. Therefore, only a specialist in this field should design new plants.

2. BACKGROUND INFORMATION

Some background information on sewage characterisation needs to be given before the principles of AS can be further elucidated.

2.1 DOMESTIC SEWAGE CHARACTERISATION

Domestic sewage is a diluted suspension of human discharges in water. The polluting material is mainly of an organic nature (organic carbon) and ammonia nitrogen (main constituent of urine). Organic material consists of a soluble and insoluble portion, each again with a biologically degradable and undegradable fraction.

The strength of sewage is indirectly obtained by determining chemically the amount of oxygen required to fully oxidize organic and inorganic matter to carbon dioxide and water. The load placed on a treatment plant varies substantially throughout a typical day and week and, to design a new plant, a wastewater expert should rather be consulted to determine the flow and make-up of sewage for each particular set-up.

2.1.1 FLOWRATES

The amount of sewage generated is classified in terms of different flows that can reach a treatment plant and is expressed as:

- AVERAGE DRY WEATHER FLOW (ADWF). The average dry weather flow is the average total quantity of sewage received per day divided by 24 hours and must be averaged over 12 months. For example, average sewage received over the last year was 10 m^3 a day:

  ADWF = 10 000 ℓ/d ÷ 24 h = 417 ℓ/h; Design for ADWF = 420 ℓ/h

- PEAK DRY WEATHER FLOW (PDWF). Peak dry weather flows are maximum discharge figures into a plant (or septic tank) during a specific day when it is not raining. It is usually assumed that this figure is double the ADWF. From above example:

  PDWF = 840 ℓ/h

- AVERAGE WET WEATHER FLOW (AWWF). The wet weather flows are maximum flow rates recorded during the rainy season and include infiltrated (rain) water into the sewer. It is usually estimated to be three times the average dry weather flow. From above example:

  AWWF = 1 260 ℓ/h

Please note, care must be taken in the design and lay-out of a town to prevent stormwater from being collected and directed into the sewage reticulation network. This specifically applies to stormwater run-off on individual premises, roads, parking areas and sports fields. Reason being, that stormwater, if discharged into a treatment plant, places a high instantaneous hydraulic load on the plant (for which treatment plants are not designed) and will result in washout of micro-organisms especially in submerged-growth systems such as activated sludge plants.

2.1.2 LOAD (SEWAGE STRENGTH)

The strength of sewage arriving at treatment works varies considerably, depending largely upon the domestic living standards of the contributing population. Main constituents taken into consideration to characterise sewage include:

- Oxidisable organic material, or substrate e.g. COD or BOD;
- Nutrients, mainly N and P;
- Solids concentration.

The loading of a treatment plant is the quantity of polluted water (flow and organic matter) that will flow into the system per day and determines the size of the system. The following are the most common parameters used to measure organic matter:

- Chemical Oxygen Demand (COD)

  The COD test measures the amount of oxygen required to chemically oxidise organic compounds in the wastewater to carbon dioxide and water. Pond system designs are based on the daily COD load that is discharged into the ponds. It is therefore important to obtain a fairly accurate figure for design purposes. The test itself takes about 4 hours.

- Five-day Biochemical Oxygen Demand (BOD_5)

  The BOD test measures the quantity of biologically degradable organic matter in a wastewater in terms of the amount of oxygen required by microorganisms to oxidise it to carbon dioxide and water. The test is usually conducted over a period of five days and therefore called BOD_5.

In domestic sewages there is a fairly constant COD/BOD_5 ratio of about 2:1. This does not apply to industrial effluents (see Section 2.3). As a general approximation, it may be assumed that the organic load discharged by humans is approximately 100 g COD per person per day.

A wastewater expert should be consulted to determine the make-up, volume and strength of sewage for each particular set-up. COD and BOD tests are complex and should be undertaken by an approved and recognised (in the wastewater treatment field) analytical laboratory only.

2.2 ESTIMATING ORGANIC LOAD

The daily organic load, either expressed as COD or BOD, is used as the main design parameter for sizing pond systems. This figure can be estimated from the number of people that discharge wastewater into the pond system but may vary depending on the diet and social structure of the population served. For design purposes the load estimation criteria as given in Table 1 can be used.

TABLE 1. Load Estimation Criteria (Voysey 1988) per Capita

Type of Area Serviced	Hydraulic load* l/p/d	Organic load (g BOD/p/d)	Organic load (g COD/p/d)
Affluent residential area, fully sewered	135-200	54-60	115-130
Residential area with denser housing > 20 houses/ha, fully sewered.	80-150	50-56	105-120
Conservancy tank, contents carted to ponds, with bathrooms, basins and kitchen sinks connected.	80-150	45-54	96-115
Conservancy tanks (or septic tanks) with no bathwater, basins and kitchen sinks connected.	50-60	35-40	75-85
Townships with water supply standpipes and externally collected wastewater.	50-60	35-45	75-96
Load for night-soil pond system.	---	36	76

* p denotes person (= per Capita)

Average concentration of the BOD of raw municipal sewage discharged into a treatment plant system can be calculated using the above Table as follows:

$$P_o = (b/q).10^3$$

Where: P_o = BOD concentration in the influent to the pond (mg/l)
b = BOD contribution per person per day (g BOD/p/d)
q = Effluent discharged per person per day (l/p/d)

2.3 INDUSTRIAL WASTEWATERS

There is no "typical" composition for wastewaters discharged by different industries. The COD of an industrial effluent can be as low as 100 mg/l, or even as high as 350 000 mg/l (e.g. synthetic petroleum industry). Also, when comparing wastewaters discharged by similar industries but in different plants, large discrepancies in constituents have been found to exist. The reason being, that even a small change in water management policy by the individual plant operators can result in totally different concentrations and volumes of final effluent being produced. For design and evaluation purposes each industrial plant must therefore be treated as unique and a full assessment of each effluent stream must be undertaken. Table 2 shows relationships between COD and BOD values that can be expected in the inflow and final effluent after activated sludge treatment, for different industrial wastewaters. However, it needs to be stressed that these are indications only and each effluent needs to be analysed to determine its true composition.

TABLE 2. COD and BOD relationships for different Industrial Effluents (Eckenfelder, 1996)

	Influent		Effluent	
Wastewater	**BOD (mg/L)**	**COD (mg/L)**	**BOD (mg/L)**	**COD (mg/L)**
Pharmaceutical	3,290	5,780	23	561
Cellulose	1,250	3,455	58	1,015
Tannery	1,160	4,360	54	561
Alkyl Benzene Sulfonate	1,070	4,560	68	510
Polyester Fibres	208	559	4	71
Protein Process	3,178	5,355	5	245
Tobacco	2,420	4,270	139	546
Paper Mill	380	686	7	75
Vegetable Oil	3,474	6,302	76	332
Vegetable Tannery	2,396	11,663	92	1,578
Hardboard	3,725	5,827	58	643
Saline Organic Chemical	3,171	8,597	82	3,311
Coal Liquid	2,070	3,160	12	378
Textile Dye	393	951	20	261
Kraft Paper Mill	308	1,153	7	575

Many industrial wastewaters, although high in organic matter, are nutrient deficient and nitrogen and/or phosphorus must be added in the biological treatment process to ensure proper microbial growth. Also, heavy metals or other organic and inorganic toxins contained in the effluent inhibit microbial growth and must be removed first, before subjecting the effluent to a biological process.

3. ACTIVATED SLUDGE PROCESSES

3.1 BACKGROUND

Strictly speaking, the activated sludge process only includes one specific treatment step/process reactor in an overall activated sludge treatment plant, *viz* the aerobic treatment step. In the activated sludge process microorganisms are mixed under aerobic conditions with the wastewater where they use (feed on) the organic material and other nutrients to grow. The microorganisms, in the presence of oxygen, convert the biodegradable organics into carbon dioxide, water, more cell material and other inert products. Sufficient oxygen must be available in the wastewater to maintain aerobic conditions and, as the organisms grow, they lump together (flocculate) to form an active mass of microbial floc, which is called "activated sludge". This mixture of microbial flocs and wastewater is called the "mixed liquor" and the biological matter (flocs) suspended in the mixed liquor is called "mixed liquor suspended solids".

The following sections will give more background information on the biological processes involved in a typical activated sludge treatment plant as used for municipal applications and the most important aspects that play a role in this technology will be discussed.

3.1.1 Organic material removal

The incoming wastewater contains organic matter, which is removed by various different groups of microorganisms dictated by the environmental conditions prevailing. In generalized terms, the equation for microbial growth (in the presence of microorganisms) can be written as:

Carbon source + Energy + H^+-acceptor + Nutrients → Microorganisms + By/end-products

The main biochemical reactions taking place during organic material removal contained in sewage are shown below.

- Anaerobic digestion:

  This process takes place strictly with the exclusion of molecular oxygen, i.e. no dissolved oxygen may be present! Two major groups of bacteria are responsible for stabilising the organic matter: One group is responsible for the hydrolysis of the solids with major end products being soluble, short chain fatty acids and stable, insoluble residue, similar to humus. The other group is responsible for the conversion of the fatty acids formed, to methane gas and carbon dioxide. The process is controlled by the methane-forming bacteria, which are very pH and temperature sensitive. If the pH drops to below 6,0 methane formation ceases and the digestion process comes to a standstill.

  Anaerobic digestion typically prevails in the first treatment step of a biological treatment plant, e.g. anaerobic sludge beds of a pond system, septic tanks, primary clarifiers, humus tanks and anaerobic digesters.

- Aerobic carbonaceous material breakdown (eg carbohydrates, glucose):

  $$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \text{ (+ energy)}$$

This process needs molecular oxygen, e.g. dissolved oxygen obtained from the air that is introduced into the wastewater during aeration. The energy that has been liberated is used for bacterial growth to form new cells.

- Protein breakdown:

  Protein → amino acids → ammonia → nitrite → nitrate

- Ammonia removal/nitrification:

  $NH_4^+ + 1\,½O_2 \rightarrow NO_2^- + H_2O + 2H^+$

  $NO_2^- + ½O_2 \rightarrow NO_3^-$

  The above reactions take place with the aid of autotrophic bacteria, called nitrifiers, in two sequential steps: Ammonia is converted to nitrite by *Nitrosomonas* while *Nitrobacter* then converts the nitrite to nitrate, and both reactions need oxygen to take place.

- Denitrification (Anoxic Process):

  In the absence of molecular (dissolved) oxygen the nitrate ion that is formed in the above reaction, is converted to nitrogen gas by microorganisms undergoing anaerobic respiration. This process takes place when aerobic microorganisms are introduced to an anaerobic effluent to obtain to an anoxic environment, typically by recycling activated sludge back to a section of the anaerobic reactor. The microorganisms then convert the nitrates (and nitrites) to nitrogen yet do not allow sulphates to be converted to sulphides. This process is used for nitrogen-removal in biological reactors.

3.1.2 Process application

A complete activated sludge treatment plant as employed for domestic sewage treatment consists, as a minimum, of the following main treatment processes:

- Inlet works. Screens and sand/grid traps are provided to remove large, foreign objects such as plastic bags and stones from the incoming sewage;
- Primary treatment. This is an anaerobic or anoxic stage, which can consist of a septic tank, anaerobic pond or primary clarifier;
- Activated sludge treatment. This is an aerobic stage, where air is artificially introduced to the wastewater by mechanical means. Carbonaceous material removal and nitrification takes place in one reactor;
- Settling tank for secondary clarification, which is used to separate and remove the microbial mass from the wastewater to obtain a clear effluent. A part of the concentrated slurry of microorganisms is continuously recycled from the settler underflow to the aerated tank;
- Disinfection, whereby chlorine in various forms (gas, liquid, pills) is used primarily as disinfectant throughout Namibia.
- Sludge treatment. Sludge from the clarifiers and thickener (if installed) is further digested in a digester and/or discarded into sludge drying beds. Advanced sludge treatment systems such as belt-presses are also often installed in large plants.

Figure 1 shows schematically the basic activated sludge process employed in organic material removal treatment plants.

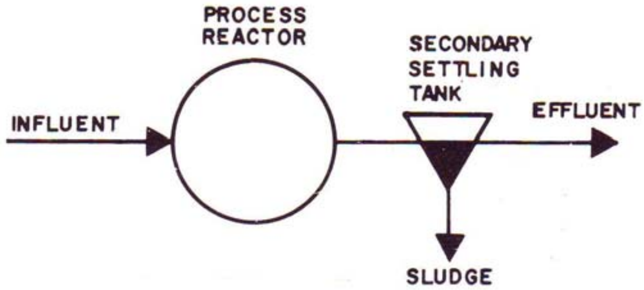


Figure 1. **Basic "once-through" activated sludge process** (Ekama *et.al*., 1984)

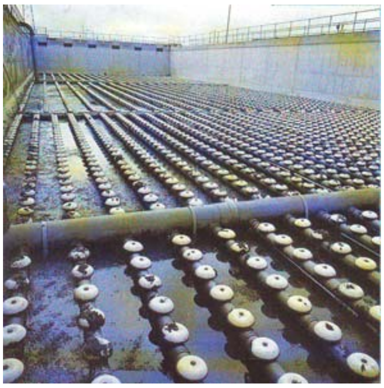
Additional process steps such as anoxic and anaerobic treatment with recycle flows are often included to achieve additional biological nutrient removal such as phosphate- (P) and nitrogen- (N) removal. A plant incorporating the latter will be called an "activated sludge plant with biological N- and P-removal". This aspect will be further discussed in Section 4.

3.1.3 Aeration

Aeration is the most crucial aspect when operating activated sludge treatment plants. Factors affecting the quantity and transfer efficiency of the air supply system include bubble size, temperature of the water, water depth, biomass concentration and mixing intensity. Two major groups of aeration systems are used, *viz* diffused aeration and mechanical aeration with different types of equipment available for each group:

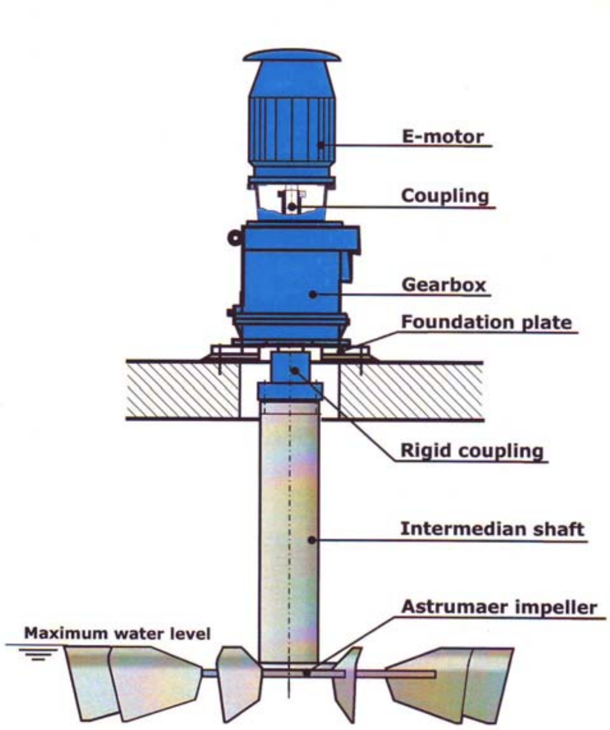
- Diffused aeration. Air is introduced into the water at the bottom of the activated sludge basin through air nozzles or porous diffusers. The air is released as small bubbles that rise to the surface, resulting in oxygen transfer and mixing of the biomass. Figure 2a) shows some diffused aeration equipment commonly employed, e.g. tube diffusers (Figure 2 a2) are employed by Nakar's effluent treatment plant .
- Mechanical aeration. They consist of submerged or partially submerged impellers that are attached to motors mounted on floats or fixed structures. Water is sucked in from the bottom of the activated sludge tank and sprayed over the surface, thereby entrapping air. Figure 2b) shows typical mechanical aeration devices, e.g. as employed by the Walvis Bay Municipality in their Pasveer Ditch. Aeration brushes are employed by the sewage treatment works in Arandis.

Table 3 gives a summary of main characteristics of the different aeration systems commonly employed in activated sludge treatment systems.



a1) Dome diffusers (Porvair™) a2) Membrane tube diffusers (Raubioxon™)

a) Diffused Aeration Systems



b1) Floating aerator (Aire-O_2 Triton®) b2) Vertical shaft surface aerator (Astrumaer™)

b) Mechanical Aerators

Figure 2. Typical aeration equipment employed in activated sludge treatment plants

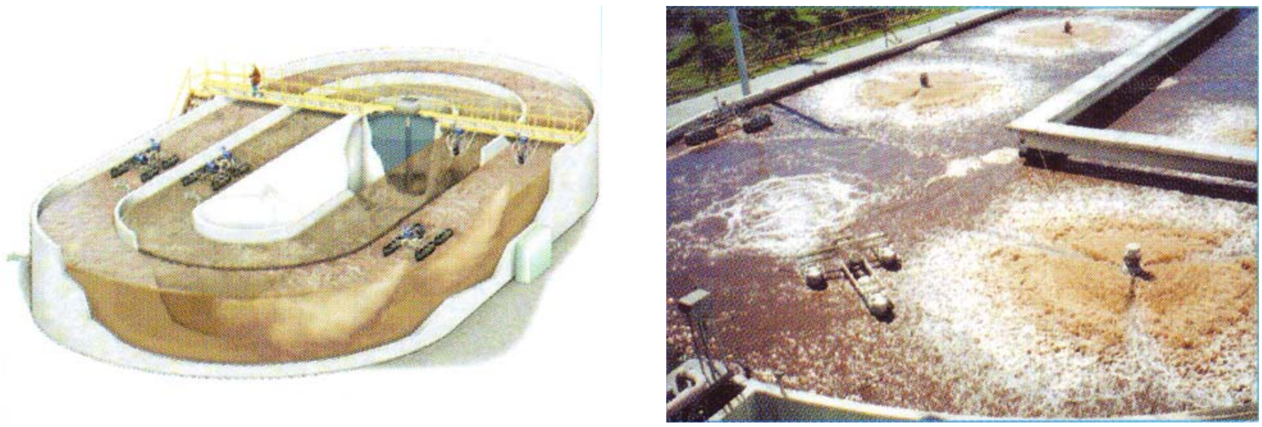
TABLE 3. Characteristics of Typical Aeration Devices (Quasim, 1984)

Aeration System	Description	Advantages	Disadvantages	Transfer Efficiency, (Percent)	Transfer Rate (Standard $kgO_2/kW\text{-}h$)[a]
Fine bubble	Porous plates, tube, or domes made of nitrile rubber or ceramic media such as bonded grains of fused crystal-line aluminium oxide, vitreous-silicate-bonded grains, or resin-bonded grains of pure silica.	Good mixing, varying air flow provides good operational flexibility, and good oxygen transfer.	High initial and maintenance costs, air filter needed.	10 –30	1.2 – 2.0
Medium bubble	Made of a perforated stainless steel tube and coated with spiral winding of saran cord, or covering with woven fabric sock or sleeve to form a tube 7.5 cm diameter and 61 cm long.	Good mixing, lower maint. cost as wrappers or sock could be changed, used to produce spiral flow.	High initial cost, air filter may be needed.	6 –15	1.0 – 1.6
Coarse bubble	Various nozzles or orifices with check-valve feature; sparger air escapes from perephery of a flexible disc that may lift over its seat under air pressure; slot orifice injector.	Nonclogging; low maintenance; air filter not needed, used to produce spiral flow.	High initial cost; low oxygen transfer, high power cost.	4 –8	0.6 – 1.2
Tubular system	The air flows upward through a tortuous pathway within a tube. Mixing and oxygen transfer is accomplished because the tube aerator acts as air-lift pump.	Low initial cost, low maintenance, high transfer efficiency.	Low mixing.	7 - 10	1.2 – 1.6
Jet	Compressed air and liquid are mixed and discharged horizontally. The rising plume of fine bubbles produces mixing and oxygen transfer.	Moderate costs, suited for deep tanks, high transfer efficiency.	Requires blower and pumping equipment, nozzle clogging.	10 - 25	1.2 – 2.4
Radial flow, low-speed 20 – 60 rpm	Low speed, use large diameter impeller, floating or fixed base (bridge or platform), use gear reducer.	Flexibility in tank shape and size, good mixing.	Initial cost high, icing in cold climate, gear reducer may cause maintenance problem.	-	1.2 –2.4
Axial flow high-speed 300 – 1200 rpm	High speed, use smaller diameter propeller, and floating structure.	Low initial cost, can be adjusted to varying water level, flexible operation.	Icing in cold climate, poor accessibility for maintenance, mixing inadequate.	-	1.2 – 2.4
Brush rotor	Used to provide aeration and circulation. Consists of a cylinder or drum with bristles of steel protruding from its perimeter into wastewater.	Provide aeration and circulation, used in oxidation ditch, moderate initial cost, good maintenance accessibility.	Tank geometry is limited, low efficiency	-	1.2 – 2.4
Submerged turbine	Provide violent agitation, compressed air may be introduced beneath the impeller by open pipe or a diffuser ring located beneath the impeller. Require fixed-bridge.	Good mixing, high capacity input per unit volume, suitable for deep tank, operational flexibility, no icing or splash.	Require both gear reducer and blower, high total power requirement, high initial cost.	-	1.0 – 1.5

3.2 APPLICATION

Activated sludge processes are generally employed only in larger centres in Namibia, mainly because it constitutes advanced treatment technology, often includes sophisticated mechanical equipment and requires some degree of skilled operators and specialised supervision. Municipalities that employ activated sludge treatment processes to treat their sewage include Windhoek (2 plants), Walvis Bay, Arandis, and will also shortly include Lüderitz (Nov. 2007). Furthermore, there are several industries that produce comparatively small volumes of organically laden effluent and have installed plants based on activated sludge technology, eg Meatco, Swakara, Rössing etc.

The activated sludge treatment technologies currently employed at municipalities in Namibia include aerated tanks and Pasveer Ditches. Figure 3 shows these different systems. Whereas the layout of the two systems may seem very different, they use exactly the same biological principles and different zones (anoxic and aerobic) are created within the structures with recycling streams to obtain biological N- and P-removal as well.



a) Pasveer Ditch (Tri-Oval™ System) **b) Aerated Tank – combined systems (ACT®)**

Figure 3. Activated sludge technologies employed in Namibia (Walvis Bay Municipality)

4. ACTIVATED SLUDGE SYSTEM DESIGN

Before considering providing a new treatment system, suitability of the general set-up and area intended for such a system should be thoroughly assessed. Fairly accurate figures for the design loading (volume and COD/BOD) should then be established and general climatic conditions of the area intended should be obtained before any design can be considered. For the latter, future needs should also be taken into account, eg. population growth, influx etc.

The processes employed in activated sludge plants are fairly complex and only an overview of typical considerations for the design of an activated sludge plant will be given in the following section. It should definitely not be seen as a designer's manual for submerged growth systems. Numerous computer programs have been developed in different parts of the world to design and simulate activated sludge plants. For Southern African conditions, we would recommend *Activated Sludge System Simulation Programs* Version 1.0 as first published in 1991 [Dold et. al., 1991] and its successive versions published by the Water Research Commission.

4.1 BASIC CONSIDERATIONS

Activated sludge plants constitute advanced treatment technology and careful consideration should be given as to the suitability of a community to operate and maintain such a plant. The following basic considerations need to be taken into account:

- If a biological N- and P-removal process is required, an AS treatment plant should be installed. For example, if the final effluent will be discharged into an environmentally sensitive receiving body such as a running river or dam, it needs to conform to the Special Standard (Water Resources Management Act, 2004) and therefore activated sludge treatment would be highly recommended.
- If the final water will be reused for irrigation, e.g. gardening or (limited) agricultural purposes, it can/should contain nutrients and a simpler and cheaper treatment option such as pond systems or trickling filter systems can be installed.
- AS plants are capital intensive and not cheap to run but suitable for industries and large-scale consumers that have skilled operators available.
- Extensive mechanical equipment and also often substantial instrumentation is built into activated sludge plants and the necessary technical resources, support services and qualified personnel should be readily available to run such a plant.
- The final water, before being discharged, shall be disinfected and shall contain no typical (*feacal*) *coli* per 100 ml.

4.2 SITE SELECTION

If anaerobic ponds will be employed as primary (anaerobic) treatment stage they may not be built closer than 500 m from the nearest residential area, but ideally, this distance should be increased to 1,0 km. If a septic tank or primary clarifier is employed as primary treatment process this distance may be reduced to 250 m.

4.3 INFORMATION REQUIRED FOR DESIGN

The following minimum, reliable design information must be available for designing submerged-growth systems:

- Sewage volume discharged (ADWF and WWF – Section 2.2.1);
- Sewage strength (organic load – COD/BOD – Section 2.2.2);
- Climatic conditions (mainly temperature and rainfall).

4.4 TREATMENT PROCESSES

The AS process comprises the flow regime in the reactor(s), the number, sizes and configuration of the reactors, recycle flows and external factors affecting the selection and growth of the microorganisms that define the process.

4.4.1 Main Controlling Parameters in AS Tanks.

Besides providing sufficient oxygen (air) for the microorganisms the basic activated sludge process is controlled by only two parameters, *viz* hydraulic retention time and sludge age. These forms the basis for activated sludge treatment and therefore need to be well understood:

- Hydraulic retention time. This is the volume of the process (tank) divided by the average inflow over a given time:

$$R_h = \frac{V_p}{Q}$$

where:

R_h = Average nominal hydraulic retention time (d)
V_p = Volume of the reactor/tank (m^3)
Q = Daily average inflow (m^3/d)

- Sludge age. This is an average time that the microbial culture remains inside the process tank before it is discarded:

$$R_s = \frac{\text{Mass of sludge in tank}}{\text{Mass of sludge wasted per day}}$$

where:

R_s = Sludge age (d)

Whereas sludge can and often is abstracted/wasted from the underflow of the secondary settler, better process control is achieved if sludge is directly abstracted from the reactor. By abstracting the sludge directly from the reactor, the wasted liquor and reactor liquor concentrations are the same. Thus, if a sludge age of, say 10 days is required, one tenth of the volume of the reactor must be wasted per day, which can be achieved by a constant draw-off flow rate.

Optimum performance of an activated sludge systems can be achieved only when the sludge age is maintained at its optimum/design value. Below this value, a system can experience low dissolved oxygen filamentous bulking, poor ammonia removal and nitrate breakthrough, dispersed growth of biomass and an overloaded thickening facility (if provided). Above the optimum/design sludge age, a system may show a low food-to-microorganisms ratio (F:M) that leads to filamentous bulking and foaming, increased oxygen demand and increased clarifier loading.

4.4.2 Carbonaceous Material Removal and Nitrification

Two major groups of microorganisms are employed in activated sludge processes, the first for carbonaceous material removal and the second for nitrification:

- Aerobic carbonaceous material removal is achieved by heterotrophic microorganisms and forms the basis of the activated sludge process. Theoretically, only short sludge ages of 1 to 3 days are required to obtain 75 to 90% BOD removal. Nitrification should be absent. A completely mixed single, aerated reactor with hydraulic control and sludge recycle, as shown in Figure 4 can be used for this application.

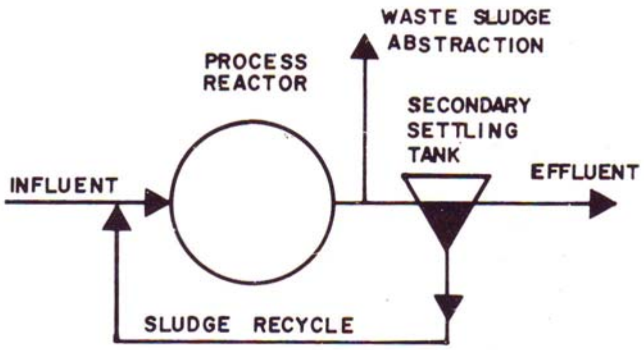


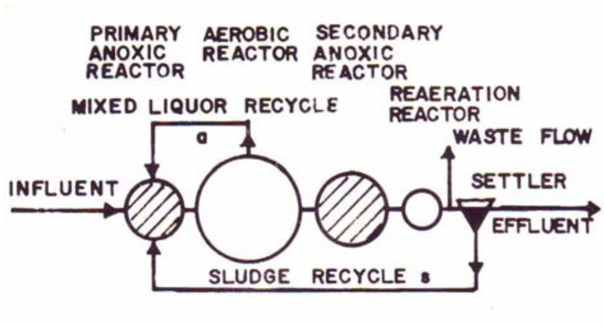
Figure 4. Schematics of a basic activated sludge treatment plant with hydraulic control of sludge age and sludge recycle (Ekama et. al., 1984)

- Nitrification is the second most important process that needs to take place in an activated sludge plant. Two specific autotrophic bacteria, *Nitrosomonas* and *Nitrobacter*, effect nitrification, during which ammonia nitrogen is converted to nitrites and nitrates. They are commonly called the “nitrifiers”. Much longer sludge ages, typically 5 to 8 times more than for carbonaceous material removal, are required for proper nitrification to take place. Typically, 90 to 95% conversion of ammonia nitrogen into nitrate and nitrite is achieved in the AS process. With nitrification, the oxygen demand increases considerably, as much as 40% more of what is required for carbonaceous material oxidation only (Ekama et.al., 1984).

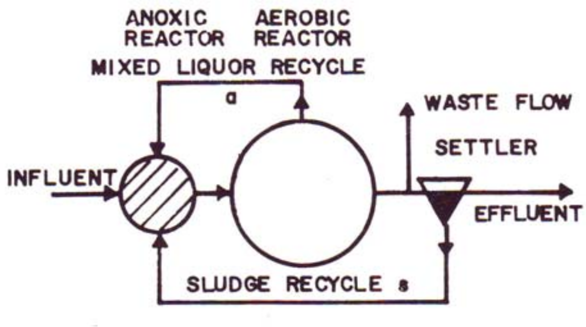
Where nitrification is obligatory (to achieve the required environmental discharge parameters), AS plants are usually designed to house carbonaceous material removers and nitrifiers in one basin. This, however, results in the nitrification step dictating the size of the activated sludge basin and typical design sludge ages are 10 to 15 days. Smaller basins can be used if carbonaceous removal and nitrification is undertaken in separate reactors/basins.

4.4.3 Biological Nutrient Removal (BNR)

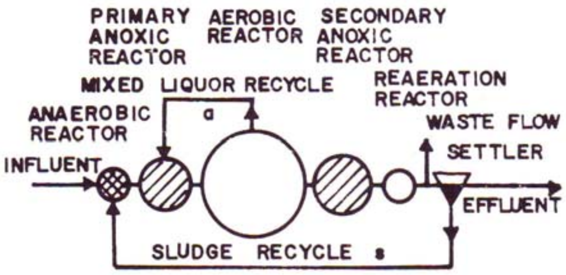
Where a final effluent must be produced that meets the Special Standard, activated sludge plants that incorporate biological nutrient removal (BNR) are provided. BNR plants are also called excess phosphate removal plants and utilise biological processes to reduce/remove the ortho-phosphate and nitrate/nitrite (denitrification) contents in the final effluent. Denitrification takes place when nitrate-rich water is treated in an unaerated zone, latter thus becoming anoxic, in the presence of microorganisms. Phosphorus removal is achieved biologically when a zone is created where influent wastewater is received but no oxygen or nitrate is present, typically via the recycle of mixed liquor. Figure 5 shows how different reactor configurations have been employed in activated sludge systems to achieve biological nutrient removal and the names under which each system has become known.



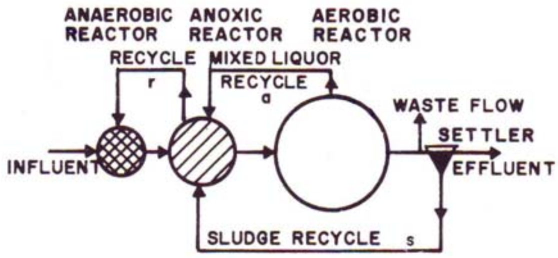
a) Bardenpho process for biological nitrogen removal



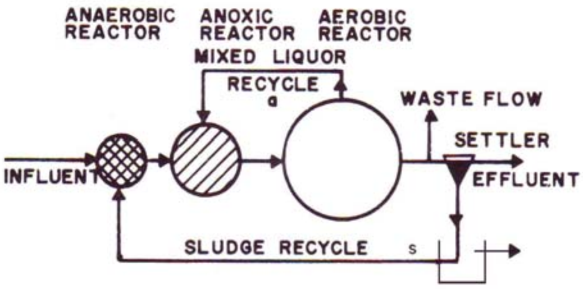
b) Modified Ludzack-Ettinger process for biological nitrogen removal



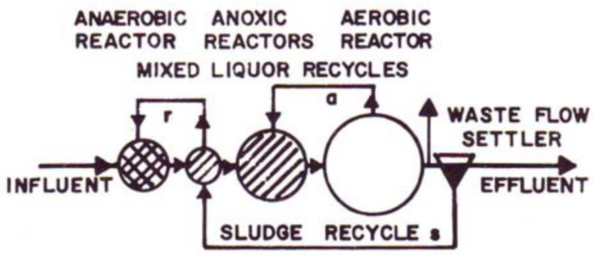
c) Modified Bardenpho process for biological nitrogen and phosphorus removal



d) UCT process for biological nitrogen and phosphorus removal



e) 3-Stage Phoredox process for biological nitrogen and phosphorus removal



f) Modified UCT process for biological nitrogen and phosphorus removal

Figure 5. **Schematics of different activated sludge treatment systems that were developed for biological nutrient removal**

Of all of the BNR systems depicted in Figure 5, the best know activated sludge system is the UCT process (Figure 5 d), which includes biological N- and P-removal. The process typically consists of an anaerobic reactor such as a primary settling tank, followed by an anoxic and aerobic reactor and subsequent biomass removal in a secondary settling tank. The settling tank underflow and a portion of the mixed liquor is recycled back to the anoxic reactor. Latter is usually incorporated as the first section of the aerated tank. An additional mixed liquor recycle is maintained from the anoxic to the anaerobic reactor. The nitrate recycled to the anoxic reactor can be controlled by adjusting the mixed liquor recycle such that the nitrate concentration in the outflow of the anoxic reactor remains approximately zero. Consequently, the mixed liquor recycle from the anoxic to the anaerobic reactor will contain very little or no nitrate and anaerobic conditions in the anaerobic reactor will be optimal. Phosphate removal is achieved via excess phosphorus associated with the sludge (underflow from the settler), but latter must be maintained in an aerobic condition. If the sludge turns anaerobic, excess phosphorus captured by the microorganisms will be released again into solution and can not be removed by the activated sludge system. If problems are experienced with biologically removing phosphates, this can also be accomplished with chemical addition to precipitate residual phosphorus not removed by the biological nutrient removal process. Ferric chloride is generally used for chemical precipitation of phosphates. This would increase operational costs due to increased chemical costs.

4.5 PRACTICAL CONSIDERATIONS

The different conditions required in the activated sludge process for BNR are usually incorporated into one biological reactor consisting of different zones. Each has a specific function to perform and the design of each zone must provide the optimum condition for the performance of these functions.

4.5.1 Anaerobic Zone

The retention time of the influent sewage in this zone plus the development of authentic anaerobic conditions are of extreme importance. Conditions which are likely to affect either, such as return flows with high dissolved oxygen or nitrate concentrations, must be avoided. To ensure an adequate retention time and no dilution of the readily biodegrable COD concentration in this zone, provision should be made to divert peak storm flows past this zone directly into the aeration zone.

Enclosure of this zone to exclude atmospheric oxygen is not necessary provided excessive surface turbulence as a result of mixing does not occur. To limit turbulence, the power imparted to the liquid by the mixers should be kept to a minimum. It has been found that an energy input of about 4 W/m^3 provides adequate mixing without causing excessive turbulence. Actual power requirements for mixing will depend on the shape and size of the reactor and the type of mixer installed. Mixer manufacturers should be consulted regarding the most suitable configuration. Where feasible, the use of the kinetic energy in the influent flow or recycle streams to achieve hydraulic mixing in both the anoxic and/or anaerobic zone should be considered.

The concentration of readily biodegradable COD in the anaerobic zone should be as high as possible to promote biological phosphorus removal. This can best be achieved in a plug flow reactor or in a series of small completely mixed reactors rather than in a single large completely mixed reactor. Baffles between the zones should be designed to prevent back-mixing but need not be completely watertight.

4.5.2 Anoxic Zone

The introduction of extraneous dissolved oxygen into these zones must be prevented. The size of the primary anoxic zone must be based on denitrification rates determined by experiment using the sewage to be treated. The second anoxic zone is not always needed. It is most effective when treating high strength sewage particulary when the sewage has a high biodegradable solids content. Under these conditions particulate organic matter is absorbed onto the sludge and is carried through to the second anoxic zone on the sludge. Metabolism of the absorbed particulate COD in the second anoxic zone enables higher denitrification rates to be achieved.

With low strength sewages, for example settled sewages, and with sewages containing a large proportion of soluble and colloidal biodegradable matter which are readily removed in the primary anoxic zone, there is likely to be deficiency of organic matter in the second anoxic zone and only minimal quantities of nitrate may be removed.

4.5.3 Aerobic Zone

The main aerobic zone must be sized for complete nitrification at the minimum sewage temperature, at the selected residual dissolved oxygen concentration and sludge age. The choice of aeration system and the measurement and control of dissolved oxygen levels has been discussed in Section 4.5.1.

The final aerobic zone is required:

- To boost the dissolved oxygen concentration in the mixed liquor before it enters the clarifiers; and
- To polish the final effluent by removal of additional phosphorus and the oxidation of residual ammonia.

Excess aeration in this zone must be avoided as it will result in the conversion of organically bound nitrogen to nitrate and the slow aerobic release of phosphorus.

4.5.4 Economics

The main objective of wastewater treatment is to produce an effluent meeting the required standard at the lowest possible cost. To accomplish this the trade-offs between the cost components of the various wastewater treatment processes must be determined in order to establish the optimum scheme. For example, when comparing the cost of biological filtration with chemical phosphorus removal and the cost of biological. Phosphorus removal in the activated sludge process, the major trade-off is cost of chemicals as opposed to the cost of electricity. Thus for an existing biological filter plant where little additional capital expenditure need be incurred, the most cost effective solution is probably chemical precipitation of phosphorus. The alternative is some modification of the activated sludge process which will incur additional capital expenditure and will involve the use of electricity.

4.6 TREATMENT PLANT PERFORMANCE EMPLOYING BNR ACTIVATED SLUDGE

A properly designed and well-managed sewage treatment plant that employs grid removal, primary (anaerobic) treatment, activated sludge with BNR, settling and disinfection will produce a high quality effluent that conforms to the Special Standard and can even be discharged into flowing rivers. Typical effluent qualities that can be obtained at the different stages of treatment in a treatment plant employing trickling filter technology are shown in Table 4.

Table 2: Typical effluent quality parameters at different stages of treatment in an activated sludge plant

	BOD (mg/ℓ)	COD (mg/ℓ)	TKN (mg/ℓ)	NH_3-N (mg/ℓ)	NO_2/NO_3 (mg/ℓ)	Ortho-P (mg P/ℓ)	Alkalinity (mg/ℓ)
Raw Sewage	300	600	45	30	-	6	220
After Primary Treatment	150	300	45	4	-	20	220
After Activated Sludge	8	120	25	0,5	2	0,2	50
After Secondary Settler*	5	60	15	0,5	2	0,2	50

Please note: The final water, before being discharged, shall be disinfected and shall contain no typical (*feacal*) *coli* per 100 ml.

5. PERIPHERALS/ASSOCIATED ITEMS TO BE PROVIDED

Consideration should be given to the following items that form part of the overall treatment plant to ensure that the system can be easily maintained and be kept in a properly functioning condition:

5.1 SCREENS AND GRIT CHANNELS

Bar screens and detritus channels, correctly sized and designed, should be installed in front of the primary treatment reactor. The screens must be cleaned daily and utmost care should be exercised that no rags, plastic bags or other large objects are discharged into the process downstream. Screenings should be discarded to the municipal dumping site or buried underneath a layer of soil not less than 800 mm deep at a site specifically set aside for this purpose.

5.2 MEASURING DEVICES

As a minimum, a V-Notch weir to measure flow at the inlet to a plant must be provided. If possible, mechanical or electronic flow measurement with the possibility to continuously log this, should be provided. Flow discharge data is useful for load calculations and to indicate when a system needs extending.

5.3 DISINFECTION

Only if the final water conforms to the General Standard as per the Water Resources Management Act, 2004 (Act No. 24 of 2004), is it allowed to be discharged into the environment. Since water is a scarce commodity in Namibia, reuse thereof is strongly encouraged. A reuse permit obtainable from DWAF is required for this purpose.

Before discharge, the final effluent must be disinfected, even if it does not come in direct contact with humans. For proper disinfection, chlorine or any other recognised disinfection method may be applied. Chlorine comes commercially in various forms:

- As a gas (but liquefied under pressure) in steel cylinders;
- In liquid form (containers) as sodium hypochlorite;
- In solid form, commonly distributed as chlorine pills or granules (e.g. HTH).

If chlorine is used, this chemical must be added to the final effluent and be allowed to react for at least 20 minutes to kill potentially harmful microorganisms. This is done in a chlorination tank, properly designed to ensure the chlorine is spread evenly throughout the complete volume of water. Sufficient chlorine must be added to obtain and maintain a free chlorine residual above 0,3 mg Cl_2/ℓ, measured 20 minutes after application and at peak flows.

5.4 FENCING

The treatment plant must be completely fenced in to prevent people and animals entering the area and ample signage must be provided to warn and keep people out of this area. As a minimum, a "jakkalsproef" fence at least 1,8 m high with double-gate to allow access for trucks must be provided. The gate must be kept properly locked.

No animals or people are allowed to swim in any of the process treatment units!

5.5 FINAL DISCHARGE

Final effluent from an AS treatment plant can be discharged, after disinfection, into a dry riverbed or sub-surface percolation system. It is encouraged to reuse the final effluent from AS plants for gardening and/or limited agricultural application, provided final water quality conforms to the General Standard. However, a permit from DWAF is required to reuse such water.

6. OPERATION AND MAINTENANCE

Regular maintenance should be carried out to maintain a high standard of effluent, to avoid nuisance problems and to avoid a rapid physical decline of the infrastructure.

One highly-skilled plant manager is required for routine operation and maintenance of an AS plant. This person must be assisted at least by one trained plant operator and one assistant (plant operator) per shift. Regular cleaning, periodic sampling and checking certain items should be attended to conscientiously. It is also important to check the inflow to the plant and reassess the number of users (population growth) once a year to ensure that the system does not become overloaded. These points will be further highlighted in this section.

Where a new biological treatment plant with a capacity of 1 000 kl/d or larger is constructed, the owner must include for a one-year operation and maintenance period during which the wastewater treatment contractor must provide an operator full-time on site to train the owner's personnel to properly operate and maintain this plant.

The following should be included in the operation and maintenance routine (as a minimum):

6.1 DAILY INSPECTION

The following maintenance functions are required:

- Clean the screens and detritus channels. Discard to municipal waste site or bury all screenings, detritus and extraneous material in prepared pits;
- Record the inflow once a day if a flowmeter has been installed;
- Check if all motors and pumps are running – repair immediately if broken;
- Check aeration equipment and test DO in the aeration basin. DO concentration should be close to 2 mg/l (between 1,5 and 3 mg/l);
- Look out for any leakages – fix pipes etc immediately;
- Keep the area inside the fence and up to 1 m outside of the fence free from any vegetation;
- Check that all overflows are clear;
- Check fence and repair immediately if damaged;
- Check disinfection system;
  - Check that disinfection system is properly functioning;
  - Check that disinfection chemicals are sufficient;
  - Check dosing rates are sufficient for proper disinfection;
- Check other mechanical items employed are functioning, e.g. pumps.

6.2 PERIODIC/INFREQUENT INSPECTION

A wastewater treatment specialist or consultant needs to be employed to visit the sewage treatment plant and especially to assess the activated sludge system at least twice per year to carry out certain inspections and tests and to advise the owner of changes in the operation or additional, periodic maintenance to be undertaken. This will include (as a minimum):

- Check, assess and report on the performance of the operator(s);
- Check, assess and report on the general condition of the site (e.g. neat and tidy, fence and gate properly maintained, etc.;
- Note and raise any concern regarding possible leaks or situation that may lead to contamination of the groundwater or endanger human and/or animals;
- Check flow meter readings (check condition of flow meter);
- Check DO in aerobic reactor;
- Collect a set of composite samples of the inflow and final effluent (minimum requirement) – also refer to Section 7 below. Ideally, each unit process should be sampled and analysed to assess its operation and to build up a database;
- Observations of smell and colour should be noted. This can serve as check for possible overloading of plant or malfunctioning;
- Measurements of pH and DO to confirm the observations indicated by smell and colour;
- Check, assess and report on dosing rates, condition of dosing equipment, performance etc of the disinfection system;
- Check, assess and report on all other mechanical equipment installed;
- Compile a report of all findings. This report should be made available on request to DWAF;

7. SAMPLING AND ANALYSES

DWAF will specify the required frequency of sampling in the permit conditions. Where no frequency is specified, samples must be taken once every six months and analysed for the tests required by DWAF. These analyses must be undertaken by an approved, recognised laboratory for wastewater analyses.

The load of the wastewater entering the treatment plant during a normal day varies significantly, both with regards to volume and organic load, depending on the domestic activities at that time. Therefore a composite sample over 24 hours of the inflow should ideally be taken. This is not a simple process and should rather be left to be undertaken by an expert in the wastewater treatment field. However, grab samples can be used as an indication.

Grab samples at the final outflow of the plant will give a good indication of the overall performance achieved by the plant. The following procedure describes how to take grab samples and store them for analyses by a suitable laboratory:

- Collect samples at the inlet (as inflow) or outlet (as outflow) of a specific unit process;
- Put on surgical gloves;
- Take a sealed, clean 2 ℓ plastic bottle, fill and rinse three times with the wastewater that is to be sampled;
- If microbial indicators need to be established, sterilised glass bottles should be used (obtainable from the lab that will later do these analyses);
- Fill sampling bottle completely and seal (put on cap) while still under water/while bottle overflows;
- Marc or label each bottle immediately. The labels on the bottles should clearly indicate the name of the plant, owner, exact sampling point/place, date, time and the parameters that should be analysed for;
- Store sample bottles at or below 4°C and deliver them to the laboratory to be analysed. This can be achieved by storing the sample bottles in a refrigerator and transporting them inside a cooler bag/box with ice cubes;
- Samples must reach the laboratory within 24 hours, otherwise the bottles must be preserved with sulphuric acid (H_2SO_4) or nitric acid (HNO_3) and be kept at cool temperatures;
- If microbial indicators need to be established, the samples must reach the lab within 24 hours.

REFERENCES

DWA. 1998. Code of Practice: *Biological Filtration.* The General Guidelines for Operation Technical Reports, Permits and Sampling. Windhoek. December 1998.

Eckenfelder, W.W. 1980. *Principles of Water Quality Management.* Boston: CBI.

Eckenfelder, W.W. and Musterman, J.L. 1996. *Activated Sludge Treatment of Industrial Wastewater*. Lancaster: Technomic Publishing Co. Inc.

Ekama, G.A., Marais, G.V.R. and Siebritz, I.P. 1984. Theory Design and Operation of Nutrient Removal Activated Sludge Processes. Pretoria: Water Research Commission.

Grady, L.C.P. and Lim, H.C. 1980. *Biological Wastewater Treatment.* Theory and Applications. New York: Marcel Dekker.

Quasim, S.R. 1983. *Wastewater Treatment Plants: Planning, Design and Operation.* New York: Holt, Rinehart and Winston.

Water Resources Management Act. 2004. Act No 24 of 2004: Government Gazette of the Republic of Namibia, No 3357 of 23 December 2004.