NEW TRENDS IN TREATMENT OF REJECT WATER FROM DEWATERING OF SLUDGE

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Summary

Due to the considerable nitrogen load of up to 25% reject water from dewatering of sludge could impose on the wastewater treatment process. Various research works into finding innovative ways that takes advantage of the high temperature and ammonium rich composition of reject water, has gained prominence in the wastewater industry over the last two decades. This has lead to significant advances in process methods that have evolved over the years for reject water treatment. In this regard this thesis aims to make a concise up to date compilation of the various treatment methods from literature and to provide it as reference text for reject water treatment technology. Secondly evaluate the applicability of the treatment method on reject water treatment process for the Helsingborg and Malmö Wastewater Treatment Plants (WWTPs).

The conventional process of nitrification/denitrification and ammonia stripping were the earliest methods for sludge liquor treatment for ammonium removal. The conventional process was carried out in different treatment reactors or by expanding the biological zone, which has turned out to be very expensive. The traditional process involves the conversion of ammonium in sludge liquor by nitrifying bacteria *Nitrosomonas* and *Nitrobacter* to nitrate before heterotrophic bacteria denitrify nitrate to nitrogen gas. While, that of ammonia stripping occurs when by increasing the pH of sludge liquor free ammonia occurs thus allowing it to be removed by air or steam. Currently new heights have been attained through the nitritation/denitritation step and emerging partial nitritation/Anammox process. These and other methods can be categorised into three groups namely biological, physical and chemicals processes.

However, progress at phosphorus removal has largely remained at the experimental stage, in spite of its considerable composition in reject water. Some of the reasons that have contributed to the current situation are the complexity and cost in operating chemical precipitation of phosphorus plants at full-scale level. These are due to the clogging of pipes that can lead to breakdowns and the cost involved in dewatering and drying of the precipitate. More so chemicals needed for precipitation are sometimes expensive. However, operation of bio-p plants does present major hurdles in sludge liquor, which warrant critical attention.

But there are a number of methods for treating phosphorus in reject water namely: magnesium-ammonium-phosphorus (MAP) or struvite precipitation, hydroxyapatite (HAP) precipitation and natural aging of phosphorus in a thermostatic room. The precipitation of phosphorus in both MAP and HAP requires addition of alkaline to a pH value of 8 to 9.5 coupled with the right ratio for magnesium in MAP and calcium in HAP respectively. Crystallization of HAP is performed with seed crystals and at best with magnesia clinker, zirconium hydroxide, pumice and sand. MAP precipitation is performed with best results at Mg(OH)₂ concentration of 400 mg/l. In both cases the solubility product of MAP and HAP needs to be exceeded.

The biological process of nitritation/denitritation can be performed in a number of reactor configurations. This happens when *Nitrobacters* are suppressed at high temperatures so that nitrification stops at nitrite. These are the pH control, no pH control or full nitritation/denitritation in a sequencing batch reactor (SBR) and the Single reactor High activity Ammonia Removal over Nitrite (SHARON®) process performed at temperatures of 30-40 °C. These processes save about 25% of oxygen and 40% external carbon source
requirement. Removal efficiencies of over 90% in the SHARON® and pH control SBR process have been reported, while that of the no pH control SBR process reaches efficiency of about 60%. The SHARON® operates in a continuous stirred reactor tank (CSRT) without sludge retention requiring pH control, addition of alkaline and dosing of external carbon source for the elimination of ammonium. The cyclic operation of the sludge retention SBR allows for a period of filling/aeration, sedimentation and withdrawal for nitrogen removal.

Emergence of the partial nitritation/Anammox process for nitrogen elimination presents a significant step as sludge liquor treatment technology. The completely autotrophic process where ammonium is oxidised by nitrite under oxygen limitation has great potential in saving cost. What is crucial though is maintaining the ratio of 1:1.3 for nitrite and ammonium in the partial nitritation step before a subsequent Anammox reaction performed by the recently identified planctomycetes bacteria. Growth of the Anammox bacteria is slow therefore a longer start up time is needed.

Comparison of the various treatment processes shows that the partial nitritation/Anammox process is the most cost effective method. This is due to the huge savings of up to 40% on oxygen requirement and the complete absence of the need of an external carbon source. But this has only been achieved on pilot scale plants with very high nitrogen elimination rates 8.9 kg N/m³ d⁻¹ in a gas lift reactor. Therefore none pH control nitritation process in an SBR currently operated at full-scale level at Hamburg’s Wastewater Treatment Plant, at a cost of 0.3 euro kg/N is the way to go. Denitrification in this type of process takes place in the anoxic zone of the biological process. There are 14 wastewater treatment plants all located in Europe currently treating reject water.

Evaluation of treatment options for Helsingborg WWTP based on reject water composition, space, COD, energy, number of reactor, reactor operation, oxygen, alkalinity, precipitant, plant configuration and present operating capacity concluded that the current recycling of reject water without pre-treatment should proceed. However, should the plant require reject water treatment technology if for instance the design capacity of the plant is reached. Then a SHARON® or a no pH control SBR process is recommended. The operation of the SBR at the Sjölunda WWTP in Malmö that is currently achieving only 6% nitrate in the effluent is typical of treatment in an SBR, therefore its operation should continue. But factors such as temperature, sludge age and volume and alkalinity dosage needs further investigation.
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Thank you
1.0 Background

1.1 Introduction
Reject water resulting from sludge dewatering or digester supernatant has become a very important process within wastewater treatment over the last 2 decades. Recycled water from dewatering of sludge (see Fig. 1) can contribute up to 30% mainly ammonium nitrogen to the influent of the WWTP (Wett et al., 1998). This is because the anaerobic digester sludge is dewatered to reduce its huge volume as well as condition it for safe disposal. The result of the dewatering process is reject water also called sludge liquor, return liquor, sludge centrate liquor or digester supernatant. Effluent water from sludge digestion/dewatering process can contain up to more than 1000 mg/L ammonium nitrogen, of high temperatures as well as considerable concentrations of phosphate and chemical oxygen demand (COD) (Arnold et al., 2000).

Recycling of reject water to the influent of WWTP can significantly increase the load on the plant and may cause occasional overloading in situations where the plant is operating at design loading level (Arnold et al., 2000). This has consequences for the efficient performance of the total nitrogen removal processes or may result in increases in cost for a further provision of nitrification/denitrification systems to treat reject water (Siegrist, 1996). However, return liquor treatment may be beneficial when the processed nitrogen in the form of ammonium sulphate precipitated from the ammonia stripping process is used as fertilizer or as an industrial chemical (Thorndahl 1993). Moreover the chemical composition of sludge liquor favours the formation of the mineral magnesium-ammonium-phosphate (MAP) or struvite, which can also be used as fertilizer (Momberg and Oellermann, 1992). Wett and Alex (2003) found that separate reject water treatment for nitrogen results in higher process stability on the main biological stage. Lastly the high temperatures and ammonium concentrations could be harnessed to aid the growth of bacteria in the activated sludge stream during winter.

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**Fig. 1** A model WWTP showing rejects water return flow in thick line with a treatment reactor. (van Dongen et al., 2001)
In order to meet stringent demands by environmental authorities for total nitrogen removal, separate treatment of this high temperature and high strength flow could considerably reduce the total nitrogen concentration in the final effluent (van Kempen et al., 2001). Reducing the total nitrogen content in the effluent of WWTPs has stimulated research towards new strategies for upgrading existing plants (Hellinga et al., 1998) with new innovations in reject water treatment methods playing a significant part. The discovery of nitrification/denitrification via nitrite as a cheaper means of nitrogen removal than nitrate, since the latter requires 60% amount of carbon and lesser energy for aeration (Abeling and Seyfried, 1992) galvanised more research into finding a sustainable nitritation route for nitrogen elimination. One such process that achieves nitrogen removal via nitrite is the SHARON® process (Hellinga et al., 1998) and more, which are discussed in later chapters.

On phosphorus removal from reject water, the focus in the seventies concentrated on the chemical crystallisation of hydroxyapatite (HAP) (Momberg and Oellerman, 1992). But this has progressed over the years to include research into the removal and recovery of MAP through the addition of metal salts and or high pH level (Pitman, 1999). In general three categories of processes namely biological, chemical and physical describes the removal of nutrients from reject water.

The aim of this thesis therefore is to find a descriptive list of the methods for reject water treatments and search in detail for full-scale operation reports. This includes processes for reject water treatment by physical, chemical and biological methods. Thus make a concise up to date compilation of the various treatment methods from literature and to provide it as reference text for reject water treatment technology.

1.2 Sludge liquor characteristics
The characteristics of sludge liquor are different to the influent to the WWTP in terms of its concentration and composition (Arnold et al., 2000). This stems from the fact that the sludge dewatering or digestion method gives different total nitrogen concentration in returned liquors (Thorndahl, 1993). According to Pitman 1999 the differences arise from the type of machine used, alkaline doses and the dewatering properties of the sludge in question. However, nitrogen in reject water is mainly present as ammonium; since it is not removed in digestion process and therefore sludge digestion generally produce an ammonium-rich effluent (Strous et al., 1997). The high ammonium content of reject water is due to the incorporation of the reminder of the non-oxidized nitrogen from the biological stage into the excess sludge. Then during anaerobic sludge digestion and dewatering process ammonium nitrogen is released in to sludge liquor (Siegrist, 1996).

Pitman et al., (1991) found sludge liquor can also contain considerable quantities of phosphorus in solution and fine colloidal suspension. Phosphorus concentration although considerable is most significant in bio-p plants where the nutrient is accumulated in the sludge. Characteristics of sludge liquor from Hamburg’s Combined Waste Water Treatment Plant according to Laurich and Gunner (2003) and Frederikshavn Sewage-Treatment works (Thorndahl, 1993) composed of total nitrogen, NH₄-N, Total P, COD, Suspended Solids (SS) and bicarbonate. Characteristics of sludge liquor in sludge the digestion effluent from the Rotterdam’s treatment plant showed high elevations of nitrogen that could potentially over load the biological stage (Hellinga et al., 1998).
Table 1 Typical sludge liquor composition

<table>
<thead>
<tr>
<th>Reagent</th>
<th>Range</th>
<th>Unit</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_tot</td>
<td>&lt;800</td>
<td>mg/l</td>
<td>Mossakowska et al., (1997)</td>
</tr>
</tbody>
</table>

Typical reject water composition and concentration ranges are found in Table 1. pH values of sludge liquor are normally slightly alkaline and have a wide variability depending on whether alkaline is added to aid the dewatering process or not. Temperature ranges for sludge liquor is also high due to the application of very high temperatures during the anaerobic digestion process. In sludge liquor COD removal rate at this stage of the treatment process is limited due to the relative low fraction of biodegradable substances. Additionally carbon to nitrogen ratio is mostly less than 1, which warrants the need of an external carbon source to eliminate nitrogen.

1.3 Objectives

The objectives of this thesis are as follows:
- To find all methods used for the treatment of reject-water from dewatering of sludge
- Give a description of the various treatment processes for reject water
- Make a comparison of the reject water treatment processes
- Evaluate the methods and find an optimum reject water treatment process for the Helsingborg and Malmö WWTP

1.4 Aim

The aim of this thesis work is to try to identify all the methods that have evolved over the years at treating reject water from dewatering sludge. From the introductory part of this thesis based on referenced literature, studies on sludge liquor treatment have been done independent of the wastewater treatment plant as a whole. It has specifically looked at nitrogen or phosphorus removal based on particular systems depending on the type of study, without looking at its’ effect on a year round operation of the plant. Such as treatment by biological, physical, chemical methods and the type of reactor configuration that achieves nutrient removal. This thesis attempts to bring all the treatment methods in a single source and with a descriptive list of the treatment processes provide easy reference for adaptation of the technology.

More so, find what factors have stimulated the continued interest at improving the technology of reject water treatment. Trace how the discoveries of new processes in the biological cycle from different parts of Europe; deammonification in Switzerland, Holland, Germany and Sweden, oxygen-limited autotrophic nitrification-denitrification (OLAND) in Belgium and complete autotrophic nitrogen removal over nitrite (CANON) process in Holland are shaping
advanced research in sludge liquor treatment and management. Lastly evaluate the applicability of these processes at treating sludge liquor from 2 WWTPs in Sweden.

1.5 Methodology
The approach to this study is to do a desktop study of the various reject water treatment processes. Provide a list of the treatment methodologies from laboratory, pilot and full-scale operation plants. Describe the treatment processes of reject water from physical, biological and chemical point of view. Do a comparison of the treatment process and find out any savings on energy, cost of treatment, demands on space and efficiency of the treatment process. Each of the treatment methods is then evaluated on the Helsingborg WWTP, which as yet has no reject water treatment plant to evolve an optimum reject water treatment facility. The Malmö WWTP currently operating an SBR reactor will also be evaluated for possible upgrading. It will take into consideration the unique characteristics of the wastewater processes, layout and design of the plant.
2.0 Reject water treatment

2.1 Traditional
Historically sludge thickening and dewatering liquors have been recycled directly to inlet of the biological stage without any pre-treatment (Janus et al., 1997; Pitman, 1999; Teichgräber and Stein, 1994). From the eighties when increased efforts were devoted to reject water treatment, it was ostensibly at nutrient removal with the application of conventional biological nitrification/denitrification and steam stripping processes (Teichgräber and Stein, 1994). The Water group firm in Denmark in the late eighties began operating two full-scale ammonia-stripping plants with remarkable success for total nitrogen removal, Frederikshavn in Denmark and Eslöv in Sweden (Thorndahl, 1993). The treatment method was found to be cheaper per kg of nitrogen removed compared to the nitrification/denitrification process coupled with the fact that the precipitation of ammonium sulphate from the process serves as an excellent fertilizer.

\[ \text{NH}_4^+ + \text{OH} \leftrightarrow \text{NH}_3 \uparrow + \text{H}_2\text{O} \]  

In the biological process micro organisms identified to be autotrophic in nature carry out the nitrification process. Species belonging to the genera *Nitrosomonas* and *Nitrobacter* are responsible for most naturally occurring nitrification. With adequate supply of dissolved oxygen (DO) and no inhibition *nitrosomonas* oxidise ammonium to nitrite and *nitrobacters* oxidise nitrite to nitrate (Anthonisen et al., 1976). See equation 2 for the complete nitrification reaction. Later new species have been described as important for aerobic ammonium oxidation with the Nitroso-species (*Nitrosomonas, Nitrosococcus, and Nitrosospira* etc) as principal members (Wyffels et al., 2004). However, a varied mix of facultative bacteria oxidize nitrate to nitrogen gas in the denitrification process with the aid a carbon source (see eq. 3). But COD removal rate is limited due to the relative low fraction of biodegradable substances in reject water or the COD: N ratio for denitrification is unfavourable (Arnold et al., 2000, Fux et al., 2003, Siegrist, 1996).

Nitrification reaction

\[ \text{Nitritation} \quad \text{NH}_4^+ + 1.5\text{O}_2 \rightarrow \text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O} \]  

\[ \text{Nitratation} \quad \text{NO}_2^- + 0.5\text{O}_2 \rightarrow \text{NO}_3^- \]  

Denitrification reaction

\[ \text{Denitritation} \quad 2\text{NO}_3^- + 10\text{H}^+ + 10\text{e}^- \rightarrow 2\text{OH}^- + 4\text{H}_2\text{O} + \text{N}_2 \]  

\[ \text{Denitratation} \quad 2\text{NO}_2^- + 6\text{H}^+ + 6\text{e}^- \rightarrow 2\text{OH}^- + 2\text{H}_2\text{O} + \text{N}_2 \]  

Studies on phosphorus removal from sludge liquor has been performed mostly on experimental basis through the hydroxyapatite (HAP) or magnesium-ammonium-phosphate (MAP) precipitation at high pH caused by addition of alkaline or CO\(_2\) degassing after acidification on a laboratory scale (Momberg and Oellermann, 1992). Others such as Pitman et al., (1991) suggests improved sludge handling techniques during the anaerobic digestion and dewatering stages to minimize the release of phosphorus to the sludge liquor. This is done by aeration and the addition of lime. Sludge liquor from bio-p plant has specific concentration that is suitable for MAP precipitation due to high phosphorus accumulation in the sludge.
2.2 Current trends in sludge liquor treatment

Sludge liquor is normally treated for nitrogen and phosphorus due their ability to over load the biological treatment process of the WWTP. In recent years studies have been focused on finding new methods that affect nitrification, thus DO, sludge handling, pH, ammonium, temperature and inhibition to improve reject water treatment. This is to achieve nitrification/denitrification with nitrite as intermediate (Abeling and Seyfried, 1992). This forms part of the various research work in wastewater treatment seeking inexpensive technology to meet nitrogen and phosphorus removal.

Nitrogen removal in reject water has seen more advances in process technology development and implementation at full-scale levels compared to phosphorus. Studies have shown that at any given temperature pH and sludge age are the critical parameters for partial nitrification, when oxygen supply is not limiting (Pollice et al., 2002). However pH control, ammonium concentration and temperature are also important to keep a stable nitritation process (Abeling and Seyfried, 1992).

\[
\text{Nitritation} \quad \text{NH}_4^+ + 1.5\text{O}_2 \rightarrow \text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O}
\]

\[
\text{Denitrification} \quad 2\text{NO}_2^- + 6\text{H}^+ + 6\text{e}^- \rightarrow 2\text{OH}^- + 2\text{H}_2\text{O} + \text{N}_2 \quad (4)
\]

At full-scale level the Sequencing Batch Reactor (SBR) has proven adequate at achieving stable nitritation. The partial nitrification process shown in eq. 4 gives a 25 and 40% reduction in oxygen demand and carbon source requirement respectively. These undoubtedly are huge savings on the operations of the plant. The SBR operates by filling/aeration, sedimentation and withdrawal. In reactors where settling sludge does not produce enough carbon (see Table 1) or biodegradation is low a carbon source can be added to aid the denitrification process as operated at the WWTP in Bern Switzerland (Fux et al., 2003). Two types of operation of SBR are currently in practise. Ammonium removal with pH controlled nitritation in the SBR with a subsequent denitrification in the anoxic zone of the biological process (Mossakowska et al., 1997, Wett et al., 1998, Arnold et al., 2000). The other has nitritation taking place in the SBR without pH control with denitrification taking place in the anoxic zone of the activated sludge process (Laurich and Gunner, 2003). In a parallel system from Rosen et al., (1998) complete nitrification/denitrification was achieved in the SBR with the aid of about 30% raw wastewater diverted from the influent to serve as a carbon source.

Another biological process that is able to achieve nitritation is the SHARON® process, which according to Gronmtij Water & Reststoffen (2004) has moved beyond the development stage. Four full-scale SHARON® systems have been constructed at large wastewater treatment plants in Rotterdam, Utrecht, Zwolle and Beverwijk (all in the Netherlands). SHARON®s for Groningen (the Netherlands) and New York City (USA) are currently in the design phase. The Utrecht plant has been in operation since 1997. While the Rotterdam, Dokhaven plant has been in operation since 1999. The Zwolle plant and Beverwijk plant were commissioned in 2003. Treatment methodologies for reject water are quiet many from biological, physical, chemical point of view and/or a combination of the three processes. In Fig. 2, shows the process routes at which ammonium could be removed from sludge liquor.
Although phosphorus composition in reject water can be in considerable quantities research in to its removal has been largely focused on removal through precipitation and more recently on its recovery. Experimental work at laboratory scale for chemical precipitation of phosphorus including works by Wu et al., (2001), Çelen and Turker, (2001) have found good estimates for the chemical process. However full-scale implementation of such chemical plants are difficult to come by as this thesis work has uncovered, the reason could be due to the high cost of operating such a process at full-scale level. However studies by Battistoni et al., (2001) have shown that it is possible to operate a full-scale HAP plant without adding alkalinity in Treviso Italy.

2.3 Emerging trends
The Anammox® process discovered in a denitrifying fluidised-bed reactor as a novel process in which ammonium is converted to nitrogen gas under anoxic conditions Mulder et al., (1995), leads the way at the new trends in reject water treatment. In a further study of the biological nature of the Anammox® process (Graaf et al., 1995) in anoxic batch experiments, ammonium and nitrate were converted within 9 days of incubation when seed from the pilot plant was added. However when the seed material was subjected to γ-radiation/sterilization at 121°C or when it was omitted from the incubation no changes in ammonium and nitrate were observed. Similarly addition of various inhibitors resulted in complete inhibition of ammonium oxidation or nitrate reduction; thus confirming the biological nature of the Anammox® process. Recently the species that performs the Anammox® process have being discovered, “Candidatus Brocadia anammoxidans” and “Candidatus Kuenenia stuttgartiensis” from fresh water and one marine species, “Candidatus Scalindua sorokinii” all of the planctomycete Anammox bacteria (Jetten et al., 2003).

In another study of the Anammox® process it was found that it was more likely that ammonium was being oxidised with nitrite as the electron acceptor rather than nitrate (Strous et al., 1997). Nitrite as the electron acceptor supplied together with the sludge digestion effluent was always completely (>99%) converted. Moreover the sludge inoculums match the pH and temperature of the digester effluent of pH 7.7-8.2 and 30°C. It was then concluded

![Diagram of nitrogen removal process](image-url)
based on the Anammox process on the fixed bed reactor that; partial nitrification preceding the Anammox process would require less than half of the oxygen required for nitrification/denitrification process; moreover addition of carbon would not be needed therefore sludge production will be lower. The stoichoimetry of the Anammox® process according to Strous et al., (1998) is represented as

$$\begin{align*}
1\text{NH}_4^+ + 1.32\text{NO}_2^- + 0.066\text{HCO}_3^- + 0.13\text{H}^+ & \rightarrow 1.02\text{N}_2 + 0.26\text{NO}_3^- \\
+ 0.0666\text{CH}_2\text{O}_{0.5} \text{NO}_{0.15} + 2.03\text{H}_2\text{O} & \quad (5)
\end{align*}$$

To ensure a stable nitritation from abundant ammonium effluent, nitrite/ammonium ration should be about 1.3 from eq. (5). The nitrate produced in the reaction is returned to the effluent of the WWTP.

Aerobic deammonification identified (independent of the Anammox) in a leachate treatment plant in Merchemich in Germany by Hippen et al., (1997). Is a process of, firstly nitrification under aerobic conditions but with oxygen limitation before a subsequent ammonium oxidation to nitrogen gas. Helmer and Kunst (1998) described the process as a simultaneous nitrification/denitrification under limited oxygen conditions without addition of any extra carbon source. Denitrification under aerobic conditions has been cited many times in literature and in as far back as that of Krul (1976), and that of Robertson and Kuenen (1984) that proved under laboratory conditions of the ability of denitrifiers to also denitrify in the presence of oxygen.

Deammonification alternatively described as oxygen-limited autotrophic nitrification-denitrification (OLAND) by Kuai and Vestraete (1998), and also as complete autotrophic nitrogen removal over nitrite CANON-process (Sliekers et al., 2002). The OLAND and CANON process, works as described under deammonification but is briefly summarised as follows. It is the process where ammonium-oxidizing organisms co-exist with the organisms performing the Anammox process to eliminate nitrogen. Wyffels et al., (2004), showed that high performance of the OLAND process depends on high sludge ages since the bacteria involved in the process grows relatively slowly. Therefore a medium with high biomass retention that allows growth of the Anammox bacteria is most appropriate, such as a bio film.

The three and same biological processes mentioned above can be operated together with the Anammox process depending on the reactor type, like SBR, fluidised bed reactor (FBR), completely stirred tank reactor (CSTR) or rotating biological contactor (RBC). In operating the FBR sand grains of specific size are used as the carrier material for the micro organism. Sludge liquor is pumped up at a constant flow rate to keep the sand grains suspended in the aqueous phase, thus ensuring good contact between the micro organism and the water. That of the RBC works when wastewater passes through a carrier material, which is attached to a rotating drum or disc on which the micro organism grows. The wastewater passes through a trough in which the bio-rotor is partially immersed and by rotating the drum oxygen is supplied. The reactor type with the biological process described in literature include CANON-SBR Sliekers et al., (2002), SHARON/Anammox CSRT+SBR van Dongen et al., (2001), OLAND-SBR Kuai et al., (1998), deammonification-RBC Seyfried et al., (2001). Nitrogen conversion rates per the biological process and reactor type is found in Slieker et al., (2003).
3.0 Nitrogen removal methods

3.1 Introduction
A number of biological, chemical and physical methods are currently available for treating sludge liquor from dewatering sludge for both total nitrogen and total phosphorus. The treatment of sludge liquor is necessary to reduce the high concentration total nitrogen contributes to the influent of the WWTP (see Table. 1). The nitrogen in sludge liquor could contribute up to 25% of the total nitrogen entering the influent of the WWTP and this could create a substantial load on the biological stage (Thorndahl, 1993). Secondly pre-treatment of reject water is necessary to meet stringent effluent standards set by Environmental Authorities for both nitrogen and phosphorus removal. Janus and van der Roest (1996) evaluated options for separate treatment of sludge liquor for nitrogen removal and found it as an alternative for conventional biological extension of sewage plants with sludge digestion. It concluded that the optimal treatment method is dependant on site-specific factors.

3.2 Biological methods
- Conventional nitrification/denitrification process
  - The airlift reactor process
  - Nitritation/denitritation process
- Sequence Batch Reactor (SBR) process with pH control
  - SBR process with none pH control
  - SBR process with complete nitritation/denitritation
- The Single reactor High activity Ammonia Removal over Nitrite (SHARON®) process
  - Partial nitritation/Anaerobic ammonium oxidation (Anammox®) process
- Oxygen Limited Autotrophic Nitrification Denitrification (OLAND)/Anammox® process
- Completely Autotrophic removal of Nitrogen over Nitrite (CANON)/Anammox® process
- The SHARON®-Anammox® process

3.3 Conventional nitrification/denitrification process
Biological nitrification/denitrification is the most commonly used process for nitrogen removal from wastewater, but it use for sludge liquor treatment is rather limited due the high cost of operation. It requires huge amounts of oxygen, external COD and the need to control pH resulting in the high cost of operation. The nitrification/denitrification processes take place in two separate reactors as a two-stage process in a side stream treatment at the WWTP or can be operated as a one-stage process in an SBR. The first part of the process involves the conversion ammonium to nitrate with the aid of oxygen (see eq. 2). The subsequent denitrification process depends strongly on degradable BOD, which is not easily available in reject water. This process therefore requires additional input for effective functioning of the biological stage; this may require extension of the anoxic zone or addition of an external carbon source (Teichgräber and Stein, 1994). The bacteria performing the nitrification/denitrification reactions are shown in eq. (6).

\[
\text{NH}_4^+ \xrightarrow{\text{nitrosomonas}} \text{NO}_2^- \xrightarrow{\text{nitrobacters}} \text{NO}_3^- \xrightarrow{\text{heterotrophic bacteria}} \text{NO}_2^- \xrightarrow{\text{heterotrophic bacteria}} \text{N}_2 \quad (6)
\]
Micro organism *nitrosomonas* and *nitrobacters* are responsible for the nitrification process while heterotrophic organisms are responsible for denitrification. Oxidation of ammonium to nitrite is accompanied by the release of hydrogen ions (eq. 2), which reduces the pH. If the pH drops below 5.5 the nitrification process will stop completely (Kemira water, 2003) as this inhibits the nitrifying bacteria. Further more during the denitrification process two intermediary compounds are formed nitrous oxide and nitric oxide before the release of nitrogen gas; these entire steps require COD with nitrate as the oxidizing agent (Ruiz et al., 2003). In a pilot study of reject water treatment Teichgräber and Stein, (1994) found through monitoring the process conditions of nitrification and denitrification a nitrate-N was removal rate of 90%.

3.3.1 Airlift reactor

Research with the airlift reactor was made in a pilot-plant to look at optimum reject water treatment options are described by Janus and Roest (1997). It used the airlift reactor for a nitrification/denitrification process for ammonium removal. The airlift reactor is a three phase fluidised bed system in which biological active material is adhered to carrier material. The reactor consists of two concentric tubes. Air is introduced in the bottom of the inner tube (riser) to supply oxygen for biological oxidation. In the riser the three phases (air, water and carrier material) are mixed in an up flow. The down flow takes place in an outer tube. The carrier material is completely in suspension, because its settling velocity is lower than the flow velocity of the water phase. At the top of the reactor the three phases are separated in the settler. Sludge is recycled to an anoxic zone, where methanol is dosed for denitrification.

It was found out during the research period that denitrification in the reactor could not be achieved. Thus if removal of total nitrogen is to be achieved, a separate denitrification reactor is needed. Also in the airlift reactor the biomass concentration could be up to 20 times higher compared to the activated sludge process. With a height of 8 m for the pilot plant the maximum nitrogen load at 90% nitrification was 2.8 kg N/(m$^3$.d).

3.4 Nitritation/denitritation processes

The nitritation/denitritation process of nitrogen removal is currently the major technology in full-scale operation for reject water treatment. Due to the ability to influence the biological process of suppressing the *nitrobacter* oxidising bacteria, so nitrification stops at the nitrite step. The process is done at very high temperatures.

3.4.1 None pH controlled SBR process

A description of the full-scale storage and treatment (SAT)/SBR method, for reject water treatment in Hamburg’s CWWTP is given in detailed by Laurich and Gunner (2003). The basic set-up of the reactor is shown in Fig. 3. In this process the SAT or SBR was a preferred option at the plant to manage the 25% additional nitrogen load reject water puts on the biological stage. The objective was to increase the purification rate and ensure optimal economic efficiency. When the process was tested at the Hamburgs-Köhlbrandhöft WWTP the pH value was maintained at a level guaranteeing optimum nitrification results. In that case up to 50% of the ammonium load supply can be oxidized before the pH value deteriorates owing to the fully utilized acid capacity, which limits further nitrification. The nitrification reaction produces 2 moles of hydrogen ion for every mole of ammonium oxidised. At the same time the high hydrogen ion concentration reduces the pH, which hampers the bacteria performing the nitrification reaction.
To monitor the elimination of ammonium and production of nitrate online measurements of the nitrification process is needed. The store and treat process (see Fig. 4) operates on the same basis as the SBR with only nitritation in a single reactor. The difference is in the name and the fact that it is also used for quantity management. The store and treat process was effective at the plant due to the increased ammonium concentration and temperature of the sludge liquor, which permit a high growth rate of nitrifying bacteria. At the beginning of a cycle, the basin is almost empty with activated sludge retained from the last cycle left inside. This retained sludge makes up of approximately 10-20% of storage capacity. At the onset of storage the sludge liquor influent mixes with the activated sludge and nitrification starts with aeration. This stage is termed impounding operation.

When the basin is filled to capacity, treatment can be continued in continuous operation until the basin is emptied. The continuous flow of sludge liquor influent pushes back the treated basin content, which is then evacuated at the overflow. In this phase activated sludge is also discharged continuously as part of the overflow. The sludge liquor is allowed to settle before
basin emptying starts, to ensure that the activated sludge sinks to the bottom so that activated sludge for the next cycle can be retained in the system.

While the basin is fully emptied aeration can be reduced to the level necessary to keep nitrifiers active. The successful operation of SAT with high process performance shown in Fig. 5 has been achieved at an operational cost of 0.30 Euro kg/N (Laurich and Gunner, 2003).

3.4.2 pH controlled SBR process

The SBR can also be operated with pH control ostensibly to increase the pH during nitritation when hydrogen ions are produced. The description of the process is according to Wett et al (1998) from the operation of WWTP Strass, which serves up 200,000 PE. Arnold et al., (2000), Mossakowska et al., (1997) also describes operation of SBRs reactors with pH control. At the WWTP Strass SBR-strategy seemed an appropriate operational scheme, as time control was simpler and more flexible than volume- or flow control respectively. Defined amounts of primary sludge were added to serve as a carbon source through a pump piped to the SBR. A 50m³ storage tank equalized the reject-water flow whilst the chamber filter press churned out between 4 to 6 times per day an equivalent of 28m³ of reject water. In order to increase dewater ability the sludge is conditioned by lime, which causes the high alkalinity of the reject-water with pH of 11.9 to 12.8. Choosing a flow rate that is below the nitrification capacity of the system and aerating the reactor the high pH is managed. The toxic ammonia concentrations of the reject-water require a reliable control of the SBR-influent and the low hydraulic load enables such a control.

There were two possibilities that controlled the interactions between influent and process behaviour:

a) The process runs at highest rate and the influent is controlled by the process capacity (constant process at controlled flow rates).

b) The influent is set on a fixed rate below the process capacity and the process itself is controlled (constant flow at a controlled process).
The time control schedules were operated 3 cycles per day (Fig. 6). The total cycling time was 8 hours. The operation is divided into four phases: 320 minutes of aeration, 30 minutes of stirring, 100 minutes settling, and 30 minutes drawing off. This does not include the fact that the reactor is not aerated during the whole aeration phase. The programmed time frame just determines the periods when aeration is possible and provides a maximum ratio of aerobic to anoxic conditions of exactly 2 to 1. The actual operation of the aerator is exclusively based on the pH-online measurement.

Fig. 6 Scheme of pH control operation (Wett et al., 1998)

The pH-control process shown in Fig. 6 had a 2-setpoint switch, programmed to control the aerator. During the aeration phase reject-water is pumped at a fixed flow rate from the storage tank into the aerated reactor. Due to nitrification the pH-value decreases despite the alkalinity, which comes from the reject-water until the lowest set point of pH=7.2 are reached. Then the aeration is switched off. Under anoxic condition the denitrification process starts. Denitrification and continued reject-water flow recovers alkalinity. When the next set point of pH=7.6 is reached, then aeration starts again. This control mechanism proceeds to the end of the aeration phase. If the storage tank becomes empty during the aeration phase, then short aerated intervals will alternate with anoxic phases until reject-water is available again or the aeration phase ends (time control).

It was found out during the operation of the plant that substrates and inhibitors limit nitrogen removal. Substrate limitation was due to the high sludge retention time, which in this case was much higher than the necessary (SRT in the full scale experiment was approximately 50 days). Autotrophic biomass is determined by growth and lyses but not by sludge removal, therefore the amount of active biomass is in balance with substrate supply. Inhibition by ammonia was due to the high concentration of about 1 mg/l in the reactor (NH$_4^+$ concentration
of 100 to 150 mg/l at a relatively high pH-value) only 30 % of the nitrite was oxidised to nitrate in average. Hence in this case inhibition is welcome to save energy cost. The process performance of the SBR depends on pH measurements and not on ammonium or nitrate. pH is balanced in the reactor is by altering nitrification and denitrification processes with suitable aeration; first to reduce alkalinity then recover slight alkalinity to a stable pH for the effective operation of the process. Denitrification took place in the pre-denitrification zone of the activated sludge process where there was a ready source of biodegradable organic matter coming from a connecting brewery factory serving as carbon source (Wet et al., 1998).

3.4.3 SHARON® process

The SHARON® process described in detailed by Hellinga et al., (1998) is a novel treatment process developed in the mid 90s. It was the first successful technique at which nitrification/denitrification with nitrite as intermediate under stable process conditions were achieved. The SHARON® (Fig. 7) is a biological nitritation/denitritation process carried out in a continuous flow system in a 2-stage process single reactor.

The process distinguishes itself from other biological reject water treatment methods by the complete absence of sludge retention. The SHARON® process was developed to treat reject water of high ammonium concentration by taking advantage of its specific temperature and composition all in a single reactor. Following is a description of the process. The completely stirred reactor was operated in cycles of 2 hours, 80 minutes aerobic and 40 minutes anoxic. Hydraulic residence time (HRT) was used to control sludge residence time (SRT) since there was no sludge retention, this allowed nitrite oxidisers to be washed out while ammonium oxidisers are retained in the reactor.

Since nitrification involves the production of hydrogen ions, at 50% production these were neutralised by stripping CO₂ formed from the bicarbonate present in the sludge digestion effluent. Alternating nitrification/denitrification further enhanced the control of pH. Methanol as COD source was used for the denitrification process because it 40-50% lower in cost than
NaOH addition. The dependency of nitrification rate on temperature was very high at 30 to 40°C, which was most appropriate considering the temperature of effluent anaerobic digester was also high.

Fig. 8 Wash out of nitrite oxidizers (Grontmij Water & Reststoffen, 2004)

At these very high temperatures NO₂ oxidising bacteria grow slower than ammonium oxidisers, thus preventing nitrite oxidation. So in a system without sludge retention and SRT=HRT it is possible to limit the SRT in a way that ammonium is oxidised rather than nitrite as shown in Fig. 8 (Hellinga et al., 1998). However at a full-scale operation plant in Rotterdam Dokhaven WWTP, nitritation stability was difficult to achieve since the seeding material had an aerobic retention time greater than one day therefore allowing the growth of nitrite oxidisers (van Kempen et al., 2001).

3.4.4 Sequencing Batch Bio film Reactor (SBBR)

A Bio film SBR is operated in the same way as the SBR nitritation only activated sludge process. A bio film bed in the SBBR creates the distinction from SBR at the City of Ingostadt Germany, which was operated a pilot scale. The fixed bed was made of 10 m³ of expanded clay and grain size of 4-8 mm with a total volume of 17 m³ and diameter of 2.2 m. The SBBR-cycle consisted of three phases: filling, mixing and aeration and drawing. The process was equipped with aeration, re-circulation and washing devices and excess biomass was removed from the reactor when it is washed every two days. Nitrification was allowed to occur until ammonia concentration measured in the re-circulation dropped to a certain level. Control of pH during the nitrification phase was done with dosing of NaOH into the re-circulation line with pH between 7.3 and 7.8. An online monitoring system was used to keep track of the parameters ammonia, nitrate, pH, oxygen and temperature (Arnold et al, 2000).
3.5 Partial nitritation/Anammox process

Partial nitrification preceding Anammox seemed an interesting reject water treatment option as found in a laboratory study to be low cost, very efficient and without need for process control (Jetten et al., 2001). The process of partial nitrification/Anammox process was tested on a pilot scale and is described in detail by Fux et al., (2002). For the nitrification aspect two steps are essential. Firstly the nitrite oxidisers must be continuously suppressed, and secondly the nitrite/ammonium ratio produced must be about 1.3 eq. (8). If too much nitrite is produced, additional supernatant can be added directly to the Anammox reactor to satisfy the stoichiometry. Because nitrite can completely inhibit the Anammox® process at concentrations higher than 100 g NO₂⁻/N m⁻³, Strous et al., (1999), suggest ammonium should be added in slight excess with respect to eq. (3).

Fig. 9 Reactor configuration for partial nitritation (left) and anaerobic ammonium oxidation (right) by Fux et al., (2002)

Nitritation was performed in a continuously stirred tank reactor (Fig. 9) without sludge retention inoculated with normal activated sludge. Sludge residence time equals the hydraulic residence time and a reactor volume of 2.5 m³, height 2.5 m, and maximum liquid volume 2.1 m³, (adjustable by a level control). The reactor was inoculated with 1 m³ of activated sludge (approx. 10 kg TSS m⁻³) from the WWTP. At 24.8°C it was possible to compete the nitrite oxidisers so an appropriate nitrite/ammonium mixture for the Anammox® process was reached within one month.

The reactor temperature, the ammonium concentration in the digester effluent and the growth rate of the ammonium oxidisers, determines the volume of the nitritation reactor. No pH adjustments were made in the nitrification reactor. Anaerobic ammonium oxidation takes place in a sequencing batch reactor (total volume 2.5 m³, height 2.5 m, maximum liquid volume 2.1 m³, adjustable by a level control). The Anammox reactor was inoculated with excess sludge (about 1000 g TSS) from the WWTP. The SBR operated by first filling, mixing then settling. Influent to the Anammox is provided from the partial nitrification stage where the remaining ammonium and nitrite produced including the nitritation biomass. The pH in the reactor is controlled at about 7.52 by addition of a 2M HCL solution or CO₂ sparging. Temperature in both reactors is kept constant with the aid of heat exchanges at around 31.1°C. The whole operation cycle is 120 minutes with 90 minutes of reaction time and by the fortieth minute (Fig. 10) all the nitrite was used up, while the ammonium stayed constant for the
remaining period of the cycle. Ammonium removal from the reactors is 92% at 2.4 kg N/(m³.d).

![Concentration profiles of soluble nitrogen compounds and degradation rates in the Anammox reactor](Fux et al., 2002)

### 3.5.1 OLAND/Anammox® process

In two membranes assisted bioreactors (MBR) Wyffels et al., (2004) performed a study on the performance of the Anammox process. In the first stage pre-filtered reject water from dewatering sludge is cooled to room temperature to feed the OLAND process. The OLAND step is the same as the partial nitrification step which precedes the Anammox reaction. Cooling the reject water means that at WWTPs where the pre-sedimentation sludge is added to sludge liquor from the dewatered anaerobic sludge, which reduces the temperature of reject water can be operated with this process.

Reject water from the Deurne-Schijnpoort WWTP in Belgium was used to fill the 1.5 l reactor volume. Effluent was removed the reactor by creating a membrane under pressure with suction pumps. Internal hollow fibre membranes for micro filtration with a pore size of 0.6 µm were used to completely retain the suspended biomass. Complete biomass retention ensures no wash out of nitrifying bacteria into the Anammox stage. Sludge liquor was added to the first MBR after which biomass free intermediary liquor was collected and fed to the second MBR. The first reactor is inoculated with available nitrifying sludge, whereas the second reactor is inoculated with bio film sludge from a RBC showing high autotrophic nitrogen removal capacity.

In the partial nitritation step oxygen supplied was below 0.2 mg DO L⁻¹ resulting in a sustained nitrite accumulation. The pH was controlled at 7.9 by adding a base. The use of a membrane ensured longer SRT therefore higher loading rates. Total HRT in both reactors was approximately two and half days. During the Anammox process nitrite is completely removed whereas ammonium is oxidised to about 82%.
3.5.2 CANON/Anammox® process

Slieker et al., (2003) carried out a study to evaluate the process performance of the CANON-Anammox process in the elimination of nitrogen with the airlift reactor. The experiment was carried out in two phases all in a single reactor. Firstly the airlift reactor was kept anoxic with a seed biomass consisting of anaerobic ammonium-oxidizing bacterial from an existing Anammox SBR. It was kept anoxic to grow and maintain a stable consortium of bacteria capable of Anammox. During this phase biomass trapped from the effluent was returned manually to the reactor.

After the initial period, limited amounts of air were carefully introduced to support activity and growth of aerobic ammonia oxidizers. The biomass with aerobic ammonia-oxidizing bacteria was obtained from an oxygen-limited ammonia-oxidizing SBR. The goal was to achieve simultaneous aerobic/anaerobic ammonia oxidation. At this stage the biomass in the effluent was not returned to the reactor. Due to the possible influence of the biomass on the Anammox process, since any slight accumulation of sludge from the influent reactor could negatively affect the Anammox process. The reason for the negative effect is that, the net production of Anammox cells is low and accumulation of the influent biomass would dilute the Anammox process significantly (van Dongen et al., 2001).

The 1.8 l gas-lift reactor used was supplied with synthetic wastewater with no biomass retention in the reactor. Synthetic wastewater was added at the top of the reactor. Gas was sparged from the bottom of the reactor at a maximum gas flow of 200 ml/ min for fluidisation of the biomass. The compressed air comprised 95% Ar and 5% of CO₂ supplied for sparging and maintaining a constant anoxic pH at 7. When oxygen-limited conditions were needed, Ar CO₂ mixed with air, or solely air was used. Oxygen concentration was controlled by manual variation of the air supplied. Very good nitrogen conversion and elimination rates were obtained using the gas-lift reactor at 8.9 kg N/ (m³.d) for the Anammox process and 1.5 kg N/ (m³.d) for the CANON stage. Limitations found during the study were the oxygen transfer from gas to liquid and the amount of biomass needed. However the CANON-Anammox proved to be suitable for treating reject water with high nitrogen concentration with no carbon addition and limited oxygen supply in a single reactor. It remains to be seen how the gas lift will perform with real wastewaterr, but this could be difficult run on long-term basis due to the slow growth of the bacteria. Moreover when the two processes run in the same reactor maintaining a constant ratio for nitrite to ammonium may present problems.

3.5.3 The SHARON-Anammox process

The SHARON process, which operates by partial nitritation of ammonium under high temperature without sludge retention is used in combination with the Anammox process (van Dongen et al., 2001). SHARON-Anammox processes a CSRT and SBR of a 2-stage reactor configuration. The Anammox process works under oxygen limitation without addition of a carbon source, for ammonium to be oxidized to nitrogen gas with nitrite as electron acceptor. The pilot scale study was influenced by the conclusions of Strous et al., (1997), which investigated digester effluents with the Anammox process. The results showed that compounds in the digester effluent did not negatively affect the Anammox sludge. The pH (7.0-8.5) and temperature (30-37°C) optimum for the process were well within the range of the values expected for digested effluents. The potential process configuration and expected removal efficiency is shown in Fig.11. The combination of the Anammox process and partial nitritation (SHARON) process has been tested on a laboratory scale and found to have 83% ammonium removal efficiency (Jetten et al., 1997). The SHARON reactor is operated without pH control with a total nitrogen load of about 1.2 kg N/ (m³.d) and operated to the nitrite step.
The ammonium present in the digester sludge was converted at 53%, which is consistent with results from Jetten et al. (1999) on the ammonium concentration needed for the Anammox process. This achievement ensured a right ammonium-nitrite mixture suitable for the Anammox stage. The effluent of the SHARON reactor is used an influent for the Anammox sequencing batch reactor.

In the nitrite limited Anammox reactor all nitrite was removed, the surplus ammonium remained. One limitation to the process is the fact that any slight accumulation of sludge from the influent to the Anammox reactor could negatively influence the Anammox process. To prevent the accumulation of sludge in the Anammox reactor the effluent from the SHARON should pass through a filtration mechanism before entering the Anammox reactor. This will prevent any nitrifying bacteria from entering the influent to the Anammox to cause the disruption of the Anammox process.

3.6 Physico-chemical methods

The process for nitrogen elimination by either air or steam stripping in reject water involves both the application of physical and chemical methods. The chemical part allows for the attainment of the right pH before the physical process of stripping the ammonia gas in a stripping tower or column. The combined treatment method is termed physico-chemical process.

3.6.1 Air stripping

Ammonia stripping is a simple adsorption process used to lower the ammonia nitrogen content of a wastewater stream (USEPA, 2000). But since nitrogen in reject water is mainly present as ammonium, the pH has to be raised to convert ammonium to ammonia (Janus and van der Roest, 1997). When the pH is increase by the addition of lime or caustic to between 10.8 and 11.5, the resulting ammonium hydroxide is converted to ammonia gas (USEPA, 2000). At the high pH value the equilibrium reaction (see eq. 1) shifts totally towards ammonia (Thorndahl, 1993) and this is removed by stripping. Sludge flocs and precipitated CaCO$_3$ from the pH increase have to be removed in a pre-sedimentation step (Siegrist, 1996).
The stripping process takes place in a stripping tower, which comes in two types according to the USEPA cross-flow and counter current. In a cross-flow tower, the solvent gas (air) enters along the entire depth of fill and flows through the packing, as the reject water flows downward. A counter current tower draws air through openings at the bottom, as wastewater is pumped to the top of a packed tower. Free ammonia is stripped from falling water droplets into the air stream, and then discharged to the atmosphere or collected.

3.6.2 Steam stripping

Steam stripping follows the above process description for air stripping except in the final discharge of ammonia. In the air stripping process the ammonia rich air is either scrubbed with acid or busted. During steam stripping process aqueous ammonia is produced which can be concentrated by reflux. Complete removal of ammonia is noticed at pH values less than 3.5 during acid scrubbing (eg. sulphuric acid) while at catalytic combustion of temperatures greater 275°C ammonia was also completely removed according to Janus and van der Roest (1997) during a pilot scale air stripping process.

3.6.3 Precipitation of Struvite/MAP

Crystallization as a process for precipitation of chemicals can be categorised into processes, nucleation and growth (Momberg and Oellermann, 1992). Nucleation is the generation of crystals from solution. Growth is the process where by ions are transported to the crystal surface and then oriented into the crystal lattice. But in situations of small concentrations of seed crystals such as in conventional precipitation processes, both nucleation and growth takes place simultaneously, which is referred to as homogeneous crystallization.

The chemical precipitation of Magnesium-ammonium-phosphate (MAP) or struvite is effective for nitrogen removal in reject water. MAP as a basic salt and is soluble in acid solution. But its precipitation is much more efficient with increasing pH. Struvite precipitates (Celen and Tuker, 2001) in the presence of Mg\(^{2+}\), NH\(_4\)^+ (N) and PO\(_4\)^{3-} (P) according to following reaction when the thermodynamic solubility product Ks is exceeded:

\[
\text{Mg}^{2+} + \text{PO}_4^{3-} + \text{NH}_4^+ \rightleftharpoons \text{MgNH}_4\text{PO}_4\cdot6\text{H}_2\text{O} \quad \text{pK}_s = 12.6 \quad (T= 25^\circ\text{C}) \tag{7}
\]

MAP precipitation described by (Siegrist, 1996) proceeds with the removal of SS in the digester supernatant by flocculation with a highly cationic polyelectrolyte. In a pilot study of MAP precipitation phosphoric acid and magnesium oxide were added with an Mg: P: N ratio of 1.3:1:1, to three reactors in series each of volume 0.5m\(^3\). In the first reactor phosphoric acid is added after which the CO\(_2\) produced is stripped. Magnesium oxide is then added to the second reactor to eliminate 70% of ammonium. The pH is adjusted to 9 in the third reactor with NaOH while 85-90% of the ammonium is removed at a hydraulic load of 0.5m\(^3\)h. Excess magnesium is necessary to lower the equilibrium concentration of ammonium, to save NaOH, and to prevent re-circulation of phosphate to the treatment plant by over dosing of phosphoric acid. The MAP slurry is directly dewatered with a decanting centrifuge to 50% dry solids.
4.0 Phosphorus removal processes

4.1 Introduction
Due to high content of phosphorus in sludge liquor, which sometimes can be considerably high than the effluent content. A typical case reported by Momberg and Oellermann, (1992) mentions phosphate influent concentrations of 10 mg P/l were increased to 60 mg P/l due to the release during the anaerobic phase. This brings to the fore the need for careful management of sludge especially for bio-P plants, however phosphorus removal in this chapter is considered strictly based on composition in sludge liquor. In view of this there is the need for treatment of reject water for phosphorus removal. In spite of this need not many systems are currently in operation partly due to the difficulty in combining the low flow of reject water with both nitrogen and phosphorus removal. The removal of phosphorus involves the application of physical and chemical methods described below.

4.2 Physico-chemical processes
- Natural aging of phosphorus
- Crystallization of phosphate- hydroxyapatite (HAP)
- Magnesium-ammonium-phosphate precipitation (MAP)

4.2.1 Natural aging of phosphorus
According to Battistoni et al., 2000 natural aging of phosphorus occurs when anaerobic supernatant is phosphate enriched with Na\textsubscript{3} PO\textsubscript{4} and left in a thermostatic room (25°C). During the study when 5 litres of supernatant enriched with an appropriate amount of phosphorous were put in an open vessel with a good superficial exposition and then left aside a thermostatic room. There was a trend of (Fig. 12) decrement of phosphate and increment of pH. Over a period of 2 to 8 days it was observed that there were 96% reductions in phosphate (Battistoni et al., 2000). This shows that at constant temperature and the right concentrations decrease in phosphate concentrations is possible to be attained as a mechanism of elimination of phosphorus.

![Graph](image)

Fig. 12 Decreasing phosphorus concentration with pH increment (Battistoni et al., 2003).
4.2.2 Crystallization of hydroxyapatite (HAP)

Crystallization of HAP for phosphorus removal from sludge liquor follows the equation below and this relies on the calcium ion concentration (Momberg and Oellermann, 1992). For chemical precipitation of HAP it has been deduced from HAP molecular formula that the Ca: P ratio must be in the range of 2:1 for efficient HAP formation.

\[ 3\text{PO}_4^{3-} + 5\text{Ca}^{2+} + 3\text{OH}^- \rightarrow \text{Ca}_3(\text{PO}_4)_2\text{OH} \]  

(8)

Removal of phosphate in anaerobic supernatant without the addition of chemicals has been carried out in a fluidised bed reactor (FBR) column with quartz sand as seed material for struvite crystallization Battistoni et al., (2000) and is summarised here. Other seed crystals of good HAP precipitation characteristics are magnesia clinker, zirconium hydroxide and pumice. The use of seed crystals allows both to produce pellets and avoid sedimentation or filtration step and to operate at a lower pH. Crystallization of HAP is precipitated when the CO2 is strip with air to increase the pH and the pKs= 57.8 are exceeded. The crystallization technique allows operation in the metastable state and requires a lower pH, thus obtaining phosphorus removal without addition of alkaline. At pH of 8-8.5 is sufficient to obtain a co-precipitation of HAP and MAP (Pitman et al., 1991).

The struvite crystallization process (SCP) plant sketched in Fig. 13 is operating at full-scale level at Treviso in Italy (Battistoni et al., 2001). The plant is constituted of a pre-treatment and two operative sections: a stripping tank and a fluidised bed reactor. The pre-treatment section is composed of an apparatus to remove suspended solids and a reservoir tank to manage the FBR in continuous mode, notwithstanding how the dewatering section runs. A stripper and a connected deareation column compose the stripping section.

![Fig. 13 The full-scale SCP at Treviso in Italy](image)

The anaerobic supernatant after pre-treatment is supplied from the reservoir tank and sent to the stripper, together with the recycle flow rate from FBR. The air flow rate needed for CO2 stripping is pumped from bottom using ceramic aerators, while the effluent exits from the
deareation column together with the recycle flow rate. The system stripper plus the deareation column can work at three different levels (H= 1.7, 2.2, 2.7 m), allowing different hydraulic heads and hydraulic retention times. The reactor is a steel column. At the bottom of the column a steel cylinder filled with gravel with decreasing size distribution to work as a filter, avoiding sand return to the pump and allowing a homogeneous distribution of the stream to the reactor. At the top of the column an expansion tank is provided in order to prevent the loss of sand from the reactor.

### 4.2.3 Precipitation of phosphate

The removal of phosphate was found during a laboratory experiment to depend on the initial phosphate concentration and the chemical dosage in this case MgCl₂ and Mg(OH)₂ added (Wu et al., 2001). The set-up is composed of a column, sampling ports, compressor for aeration and CO₂ stripping. The process depends on a period of aeration and settling, which is consistent with process methods described by Pitman et al., (1991). An air compressor provides the air required for mixing and CO₂ stripping. The time distribution for operating the process was 60 minutes for aeration and another 60 minutes for settling. The reject water used for the experiment came from sludge dewatering facility (both centrifuging and belt-press) at the Mill Creek WWTP. It was found that the higher the dosage and higher initial phosphate concentration, the larger the concentration of insoluble salts. An initial concentration of 400 mg/l Mg(OH)₂ results in faster depletion of phosphate. The important step of aeration provided both adequate mixing and CO₂ stripping, thus reducing alkalinity with a resulting in pH increases which favours nucleation and crystal growth. Through this process a phosphate removal rate of 60% is achieved.
5.0 Comparison of treatment methods

5.1 Introduction
This chapter makes a comparison of the various treatment methods, firstly on the nitrogen removal processes then subsequently for phosphorus removal in sludge liquor. Normally to evaluate the performance of the individual process the following criteria are used: chemical and energy demand, process stability, sludge production, area requirements and production of greenhouse gases. However Table 2 present a more comprehensive list other than the standard indicators listed above, this is to enable a thorough evaluation of the different processes. It looks at different processes for nitrogen removal in sludge liquor. The figures have been compiled from various published works and this may not reflect a more standard dimension, especially for experimental cases performed with synthetic wastewater and reactor size. Secondly no evaluation of area demands is made since sludge liquor flow depends on the quantity of sludge production and the operation of the dewatering systems at the wastewater treatment plant.

5.2 Nitrogen removal methods
In general processes that require the addition of external carbon source generates biological sludge and in quantities higher than those without the need of carbon source. Moreover between the SBR and SHARON reactor the latter demands more space than the former, but this can be argued that the SHARON operates on a continues basis while the SBR does not. The two systems mentions are the once currently in full-scale operation, while the promising Anammox processes have been evaluated on pilot scales. The evaluation of the nitritation/denitritation systems based on the SBR, incorporating operation with and without pH control and complete denitrification in the SBR. The process performance of the SBR to achieve complete nitritation is found in Janicek et al., (2004). The study found that a stable nitritation is reached if O\textsubscript{2} is increased to 1.5-4 mg/l coupled with pH control, at 99% nitritation efficiency without the appearance of nitrate.
Table 2 Comparison of nitrogen removal methods

<table>
<thead>
<tr>
<th>Removal process</th>
<th>Biological</th>
<th>Physical</th>
<th>Chemical</th>
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<tr>
<td>System</td>
<td>Conventional nitrification/denitrification</td>
<td>Nitritation/denitrification</td>
<td>Anammox</td>
</tr>
<tr>
<td></td>
<td>SHARON</td>
<td>pH/no pH control full nitrit/denitrit</td>
<td>Partial nitritation</td>
</tr>
<tr>
<td>Number of reactor</td>
<td>2</td>
<td>1/2</td>
<td>1</td>
</tr>
<tr>
<td>Reactor type</td>
<td>activated sludge</td>
<td>CSTR/SHARON</td>
<td>SBR</td>
</tr>
<tr>
<td>Reactor operation</td>
<td>continues</td>
<td>continues/batch</td>
<td>batch; continues</td>
</tr>
<tr>
<td>Reactor medium</td>
<td>suspended</td>
<td>suspended</td>
<td>suspended</td>
</tr>
<tr>
<td>pH control</td>
<td>yes</td>
<td>yes</td>
<td>yes/no</td>
</tr>
<tr>
<td>Discharge conditions</td>
<td>NO_3^-, N_2O, N_2</td>
<td>N_2, NO</td>
<td>N_2, NO_3^-</td>
</tr>
<tr>
<td>Biomass retention</td>
<td>none</td>
<td>none</td>
<td>yes</td>
</tr>
<tr>
<td>Bacteria</td>
<td>nitrifiers + heterotrophs</td>
<td>Aerobic NH_4^+ oxidizers + various heterotrophs</td>
<td>nitrifiers</td>
</tr>
<tr>
<td>Condition</td>
<td>oxic, anoxic</td>
<td>oxic, anoxic</td>
<td>oxic, anoxic</td>
</tr>
<tr>
<td>Sludge/biomass production (kg d.w./kg N)</td>
<td>1-1.2</td>
<td>0.8-0.9</td>
<td>0.8-0.9</td>
</tr>
</tbody>
</table>
Table 2 Cont

<table>
<thead>
<tr>
<th>Operating temperature</th>
<th>N removal place</th>
<th>COD : N requirements (kg : kg)</th>
<th>O₂ : N requirements (kg : kg)</th>
<th>Energy consumption (kWh/kg N)</th>
<th>Cost euro/kg N</th>
<th>N conversion rate kg N m⁻³ reactor⁻¹ d⁻¹</th>
<th>N removal (%)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>26-30°C nitrification</td>
<td>pre-denitrification</td>
<td>5.5</td>
<td>4.6</td>
<td>2.3</td>
<td>2.5-3.6</td>
<td>0.005-4</td>
<td>&gt;75</td>
<td>Mulder, 2003; Abeling &amp; Seyfried, 1992; Mulder, 2003; Fux et al 2003; van Dongen, 2001</td>
</tr>
<tr>
<td>30-40°C</td>
<td>reactor; pre-denitrification</td>
<td>2-4</td>
<td>3.42</td>
<td>1.7</td>
<td>1.5</td>
<td>1.4/0.3</td>
<td>&gt;75</td>
<td>Johansson et al 1998; Mulder, 2003; Laurich &amp; Gunner, 2003; Fux et al 2003</td>
</tr>
<tr>
<td>32-40°C</td>
<td>reactor</td>
<td>3.7</td>
<td>3.4</td>
<td>2.4</td>
<td>-</td>
<td>-</td>
<td>40 – 60; &gt;90</td>
<td>Johansson et al 1998; Fux et al 2003; Mulder, 2003</td>
</tr>
<tr>
<td>25-30°C</td>
<td>reactor</td>
<td>0</td>
<td>1.71</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>&gt;80</td>
<td>Johansson et al 1998; Fux et al 2003; Mulder, 2003</td>
</tr>
<tr>
<td>20-30°C</td>
<td>reactor</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&gt;80</td>
<td>Johansson et al 1998; Fux et al 2003; Mulder, 2003</td>
</tr>
<tr>
<td>10-22°C</td>
<td>scrupper tower</td>
<td>0</td>
<td>0</td>
<td>8.75</td>
<td>2.64</td>
<td>8.9</td>
<td>&gt;80</td>
<td>Sliekers et al 2003; Wyffels et al. 2003; Siegrist, 1996; Siegrist, 1996</td>
</tr>
<tr>
<td>25°C</td>
<td>settling tank</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>7</td>
<td>1.1</td>
<td>&gt;85</td>
<td>Siegrist, 1996; Janus &amp; Roest, 1997</td>
</tr>
</tbody>
</table>

- figures not available
S- synthetic wastewater
d.w.-dryweight
5.3 Phosphorus removal methods
Although a number of methods mostly through crystallization have been described as being suitable for phosphorus removal in sludge liquor, their application in real world or full-scale systems are difficult to come by. The technologies for both MAP and HAP crystallization are fundamentally the same with only slight differences occurring in the parameters. The only major difference is the reliance on calcium ion concentration for HAP crystallization and magnesium and ammonia concentrations for struvite crystallization. Eventually the products are removed as they are precipitated and these products have the tendency to clog the equipments and may cause temporal breakdown of the systems. In my view this may account for the apparent difficulty in implementation at full-scale level. So in effect qualitative comparison of the systems is difficult to be look at and moreover the technology remains invariably the same. However a plant operating with bio-P removal needs a critical look at sludge handling to minimize the re-circulation of phosphorus through sludge liquor back to the plant.

5.4 Full-scale sludge liquor operating plants
The compilation in Table 3 is as a result of an extensive search of full-scale sludge liquor operating plants reports from literature and internet sources reviewed for this thesis work.

Table 3 List of sludge liquor treatment plants

<table>
<thead>
<tr>
<th>System</th>
<th>SHARON</th>
<th>SBR</th>
<th>HAP</th>
<th>Ammonia stripping</th>
<th>Place</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>pH control</td>
<td>no pH control</td>
<td>full nitrit/denitrit</td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holland</td>
<td>4</td>
<td>no pH control</td>
<td>full nitrit/denitrit</td>
<td></td>
<td>Rotterdam, Utrecht, Zwollle, Beverwijk</td>
</tr>
<tr>
<td>Switzerland</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Bern</td>
</tr>
<tr>
<td>Germany</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Hamburg</td>
</tr>
<tr>
<td>Sweden</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Eslöv, Eslöv, Västerik, Kalmar, Linköping</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Treviso</td>
</tr>
<tr>
<td>Austria</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Strass</td>
</tr>
<tr>
<td>Denmark</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Frederikshavn</td>
</tr>
</tbody>
</table>
6.0 Evaluation of reject water treatment method for a WWTP

6.1 Introduction
Although several advances have been made at improving the technology of sludge liquor treatment, recycling of sludge liquor directly to the influent of WWTP still exist in most plants. The reasons may include inadequacy of space in built up areas where some plants are located, lack of resources for upgrading, high cost of installation and the slow pace of embracing and adaptation of new technologies. This chapter makes an evaluation of treatment methods for reject water at the Helsingborg and Malmö WWTPs. The evaluation of the treatment method is based on:

- Composition of reject water
- Availability of space
- Key process parameters

The evaluation of the Helsingborg WWTP is a desktop approach aimed at process implementation. Since sludge liquor at the plant is currently recycled to the influent, it will take into consideration the unique characteristics of the wastewater processes, layout and design of the plant. The Malmö WWTP currently operates a nitrification only SBR process for nitrogen elimination in reject water. The evaluations aims at process optimisation and cost saving.

6.2 Helsingborg wastewater treatment plant
The port city of Helsingborg is located in the Skane region of Sweden with an estimated population of 110 000 people. The Helsingborg WWTP, which serves both the inhabitants and the industrial entities within the area, began operation in 1974. Initially it was operating a mechanical and biological treatments for BOD removal, until upgrading in the early nineties lead to the inclusion of nitrogen and phosphorus removal (see Fig. 14).

Fig. 14 Schematic layout of the Helsingborg WWTP
The operating parameters of the plant are as follows:

<table>
<thead>
<tr>
<th>Design criteria</th>
<th>Effluent limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium flow</td>
<td>BOD$_7$ &lt;10 mg/l</td>
</tr>
<tr>
<td>BOD$_7$</td>
<td>Nitrogen$_{tot}$ &lt;12 mg/l</td>
</tr>
<tr>
<td>Nitrogen$_{tot}$</td>
<td>Phosphorus$_{tot}$ &lt;0.3 mg/l</td>
</tr>
<tr>
<td>Phosphorus$_{tot}$</td>
<td></td>
</tr>
</tbody>
</table>

The influent entering the plant firstly goes through a mechanical process consisting of bar screens (10 mm), grit chambers, flocculation basins and primary sedimentation. Through the primary sedimentation SS and flocs formed in the flocculation basins are removed. The next stage is the biological treatment, where phosphorus and nitrogen compounds are removed. Nitrogen removal is by a process configuration of anaerobic-anoxic-aeration basins. This allows for pre-denitrification in an activated sludge system of the anoxic zone. This is after ammonium nitrogen is oxidized to nitrate in the aeration basins.

Secondary sedimentation follows as the next stage of the process. At this stage the majority of sludge formed is returned to the anoxic zone while excess sludge is directed to the sludge treatment system. Next in line is a dual media sand filtration for high efficient removal of SS. After which the effluent is discharged into Öresund. The processes described above runs in four parallel lines this allows for comparing tests for process optimisation.

In the last stage of the process the sludge collected from both the pre-sedimentation and sedimentations are thickened by gravity followed by anaerobic digestion. Centrifuges then dewater the supernatant sludge from the anaerobic process, after which sludge liquor is recycled back to the plant and sludge disposed off as a soil conditioner (extracts from Helsingborg WWTP brochure). Removal of phosphorus at the Helsingborg plant since 1990-91 is performed through enhanced biological phosphorus removal (EBPR) process and sometimes on some of the lines ferrous sulphate is added as precipitant for simultaneous precipitation (Tykesson et al., 2004). The layout of the plant is shown in Fig. 18. Specific characteristics of operating the Helsingborg WWTP include an average flow of 55 000 m$^3$/d and highest dry weather flow of 19 000 m$^3$/d (Tykesson et al., 2004). Compared with the designed medium flow at the plant, the current flow is below design capacity. Therefore any anticipated imposition of additional flow would not impose any constraints on the plant. Secondly since recycled flow is normally less than 5% of the influent and in this case 0.02% its impact is insignificant. COD and ammonium load on the plant is averagely 7 390 and 1 100 kg/d respectively which is also below design capacity (Jönsson et al., 1996).

This means that additional load on the plant is effectively contained without affecting process performance. The BOD/N of the influent wastewater is characterised as typical as the 5.5 falls within the typical values of 4-6. Considering the ratio of BOD/N in the wastewater, any additional composition of nitrogen from reject water will not alter the balance to a critical lower level. At this figure a pre-denitrification system is a suitable process for operating the wastewater treatment process. This underscores why there is no pre-treatment of reject water at the plant. At the present wastewater composition and process performance of the plant, there is no need to treat reject water. But options for reject treatment may be considered when the plant starts operating at or nearing design load levels or there is a significant increment in the nitrogen composition so that reject water flows may overload the system. Currently methane gas generated at the plant during the anaerobic stage is flared; this can be utilized in reject water treatment to great advantage.
6.3 Evaluation of treatments methods

The Helsingborg WWTP for this evaluation is assumed to have a typical sludge liquor composition (see Table 1) and have enough space to install any additional facilities including that of a sludge liquor plant. The flow of wastewater to the Helsingborg WWTP varies both in time and in composition, as do most wastewater treatment plants. This is very much evident during the winter and summer seasons when flows to the plant are significantly different, with summer experiencing lower flow of the two major seasons. Flow and load characteristics showing typical variations are found in (Jönsson et al., 1996).

Although the sludge liquor may contain considerable quantities of COD and phosphorus Arnold et al., (2000) it is not being evaluated here. At this stage of the wastewater treatment process COD are less likely to degrade biologically so its removal from reject water is not proposed (Arnold et al., 2000, Fux et al., 2003, Siegrist, 1996). Additionally removal of phosphorus is not proposed since after many studies done experimentally transformations to full-scale plants are not easily available. Precipitation of phosphorus can cause severe scaling and clogging on heat exchanger surfaces and in the pipe networks Momberg and Oellermann (1992), which can affect the efficiency of the plant through frequent breakdowns. The precipitation of phosphorus requires high concentrations of magnesium in addition to ammonium, which is very costly. This makes chemical precipitation of phosphorus at full-scale level expensive and difficult to operate. Moreover the composition of phosphorus can sometimes be low when effluent concentrations to the plant are also low, as assumed for this evaluation.

To help evaluate the system appropriate for nitrogen removal at the plant a score format is used based on Table 2. These include the number of reactors that performs the process, the degree of difficulty in operating the reactor, alkalinity, COD, DO and energy requirements. Operating systems such as equalization tanks are neglected due to intermitted flow of dewatering systems or are considered as standard for all the removal processes unless otherwise stated. Precipitation of mineral requires high doses of chemicals so it is included in the evaluation table. Number of reactors looks at all the tanks that lead to the final elimination of nitrogen including processes in the anoxic zone of the main biological process, complexity of reactors and storage tanks for chemicals as well. Reactor operation emphasises on monitoring apparatus, production of chemical sludge and degree of supervision. Evaluation of alkalinity, COD and DO requirements is drawn from the calculated values obtained in Table 2. DO is based on the specific amounts needed for the elimination of nitrogen, while energy requirements looks generally at the energy consumption (including stirring) that is used based on values in Table 2.

After which elaboration on the adaptation of the system to the general WWTP configuration is discussed. Reasons for the unsuitability of some of the methods specifically for this treatment plant are mentioned. In all cases the start up of the reactor is inoculated with a suitable biomass for the biological processes. For the nitrification/denitrification systems a seed biomass from the activated sludge stage is sufficient. The biomass for Anammox process should come from an oxygen-limited ammonia-oxidizing reactor Strous et al., (1997) or from RBC since growth of biomass results in limited supply of oxygen to the nitrificants (Hippen et al., 1997). This seed biomass will need cultivation in a separate or abandoned reactor before it is used to start the reactor. Excess sludge is also possible at cultivating the Anammox bacteria (Fux et al., 2003). Reactor operation reviewed from literature indicates that it is less difficult to operate a SHARON than an SBR, which is taken into account in Table 4. The continuously flowing SHARON system lessens the burden of vigorous monitoring compared to operating a
batch system. Although the operation of an ammonia stripping plant can be costly it is considered moderate to operate if steam generated at the WWTP is harnessed for stripping the ammonia. Ranking of process performance is from 0 to 10, where 0 is the lowest value in any of the processes and 10 is the highest in terms of complexity or numbers.

Table 4 Evaluation of treatment systems

<table>
<thead>
<tr>
<th>System</th>
<th>No. of reactors</th>
<th>Reactor operation</th>
<th>COD</th>
<th>O₂</th>
<th>Energy</th>
<th>Alkalinity</th>
<th>Precip.</th>
<th>Space Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>recycled directly</td>
<td>0</td>
<td>10/0</td>
<td>10/0</td>
<td>10</td>
<td>10/0</td>
<td>0</td>
<td>10/0</td>
<td>60/20*</td>
</tr>
<tr>
<td>Common nitrit./denitrit.</td>
<td>8</td>
<td>3</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>9</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>SHARON</td>
<td>7</td>
<td>0</td>
<td>8</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>SBR-pH control</td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>4</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>SBR-no pH control</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>SBR-full nitrit./denitrit.</td>
<td>6</td>
<td>4</td>
<td>9</td>
<td>4</td>
<td>7</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Partial nitrit./Anammox</td>
<td>2</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>CANON/Anammox</td>
<td>1</td>
<td>7</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>OLAND/Anammox</td>
<td>3</td>
<td>6</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>NH₃ Stripping</td>
<td>9</td>
<td>8</td>
<td>0</td>
<td>9</td>
<td>10</td>
<td>7</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>MAP</td>
<td>10</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>10</td>
<td>9</td>
</tr>
</tbody>
</table>

Ranking from 0 to 10, (*) plant operating below design capacity

Results from the ranking in Table 3 give a highest point of 80, which is adjudged to be the worst system to treat reject water. A low score of 0 is the most suitable system to treat reject water. However factors such as O₂ need, alkalinity and reactor operation are essential for the elimination of nitrogen in reject water. Therefore a lower limit of 25 is best suited for the plant while an upper limit set at 45 is not suitable as treatment method. Values in between 25 and 45 are taken as good, but other reasons such as site-specific characteristics needs to taken into consideration when making the choice. This may include space demands of the sludge liquor plant, availability of unused tanks and by-products from the main treatment process that can be of use such, as steam or methane gas. In addition technology that has not reached full-scale implementation would need pilot trials at the plant before going into operation.

Recycling of reject water directly to the biological process can create additional load on the plant as Table 4 shows. The evaluation of recycling reject water directly to the influent is based on a plants operating at designed capacity, as is the case in most plants. This would require either of the following; extension of the biological process; additional COD, alkalinity and a lot more difficulty in reactor operation. The method receives a high score of 60 when sludge liquor is recycled directly to the influent so is not suitable to operate at the plant. But if the plant operates lower than designed values that should not present much of a problem. In that case recycling reject water directly is preferred since the point score is then 20, which is the current practise at the Helsingborg WWTP. However if further nitrification capacity at the plant is limiting then recycled water without treatment presents a great threat. From Table 4 treatment processes that are not suitable are MAP and complete nitrification/denitrification except recycling directly when additional loads are not a problem or ammonium stripping if steam or methane gas is generated at the plant.
Conventional nitrification/denitrification
This system pulled the highest score confirming why it is not a popular choice (Siegrist, 2003) when considering a treatment plant for reject water. It requires longer retention time to operate effectively and this increases the cost of installation. Coupled with its high COD, energy, and alkalinity requirement, this system is not considered suitable for operation as reject water treatment among the processes listed in Table 4.

Struvite precipitation
Most of the research done in this area has been at the laboratory level with very good process results. But full-scale implementation have not materialise yet. The installation of storage tanks for the chemicals and amounts required to precipitate MAP makes it an expensive process. Its operation is judged to be complex according to van Kempen et al., (2001). It had a high score from Table 4, rendering it inappropriate as treatment method for the plant. Little wonder the research uncovered no existing full-scale plant.

Ammonia stripping
Operation of ammonia stripping plant is considered to be expensive when the stripping column is operated with air. But this can significantly reduce if steam generated at the plant especially from the anaerobic digester is harvested for ammonia stripping. But steam stripping of ammonia is considered to be more complex to operate than air stripping (van Kempen et al., 2001). In spite of this seemingly advantage of steam stripping, it operation can sometimes be difficulty comparing with other biological processes. With a high point score from Table 4, ammonia stripping with air is not suitable for the Helsingborg WWTP. But steam stripping could be considered as suitable since the gas from the digester is available.

SBR full nitritation/denitritation
This system also obtained a high score although it operates only to nitritation (less aeration) and high nitrogen removal rate of 2.2 kg Nm\(^{-3}\)d\(^{-1}\), due to the need for carbon source to aid the denitritation process. The decision is also influenced by the fact that operation of such a system needs a more thorough monitoring for a batch process. Secondly the Helsingborg plant has a pre-denitrification process, so it does not sound reasonable to be dosing additional carbon in the SBR as at the Bern WWTP (Fux et al., 2003). While easily available and degradable carbon is present in the influent, the NO\(_x\) should be taking to main biological process.

CANON/Anammox process
This system, although for its low score from Table 4 and the highest nitrogen removal rate of 8.9 kg Nm\(^{-3}\)d\(^{-1}\) (Sliekers et al., 2003) from all the nitrogen removal systems including that of the Anammox processes (see Table 3). The start up of the Anammox reactor is long and in gas lift reactor requires extra attention. The need for pH control when the gas supplied contains air increases the cost for operation the system more than the estimation in Table 4. It was based on a process without pH control, where constant level is maintained through the sparging of the system with Ar and CO\(_2\). So the CANON/Anammox process is considered a system of very high potential requiring more trials possibly with the use of ‘real’ wastewater.

The SHARON
The SHARON is a preferred system for sludge liquor treatment at the Helsingborg WWTP over the point score obtained in Table 4. This is in view of the fact its transition from experimental work to full-scale operation has been successful as stated earlier. Secondly the reported advantages during the operation at the various WWTP make a tried and tested
method against the others still running on pilot scale. The advantages include; a low investment costs; low operational costs; no chemical by-products; simple operation and maintenance; easy start-up; insensitive to high influent SS levels; negligible odour emission (van Kempen et al., 2001). A single SHARON rector will be operated as a side stream treatment for sludge liquor at the plant before it’s recycled to the influent to the plant.

Critical parameters to ensure the successful operation of the system are pH, temperature and aeration. By dosing the system with alkalinity and altering the nitrification and denitrification process a stable pH level of 7-8 can be maintained. Savings on the nitrification process at the biological stage will offset the cost of alkalinity used for the system. Temperature ranges of 30-40 °C are needed to wash out the nitrobacters for nitrification to nitrite is attained. At higher temperatures nitrosomonas prove to have significantly higher maximum growth rates than nitrobacter. The nitrite route reduces up to 25% oxygen, 40% methanol requirement and 40% sludge production. A suitable carbon source is needed to for the denitrification process. A HRT = SRT of 3 days is proposed, 2 days for oxic and 1 day for anoxic. Since a higher retention time will ensure the effective wash out of the nitrobacters (see Fig. 10). Also in a single reactor system a higher retention time is better operated than the 1.5 days given in van Kempen et al., (2001).

In the summer when flows are reduced the large volume of the reactor will not be fully utilised. This gives a high installation cost compared to the operation of the reactor. In that case separation of the process in time and space is also feasible. Separate reactors for nitrification and denitrification, in that way during the summer the denitrification reactor can be turned into single system performing both processes.

**SBR-pH control**

This system is especially suited for optimising an existing pre-denitrification WWTP, since the ammonium oxidised to nitrite in the reject water is denitrified in the main biological process. In Table 4 this system obtained a low score justifying it use for reject water treatment. Batch operation time will depend on the volume of the reactor. The volume of the reactor is normally calculated at \( V \geq 2Q_d \) (Laurich and Gunner, 2003). The separation of the batch process in ratio of aeration/filling, settling and withdrawal will depend on the nitrification capacity of sludge liquor and the seed biomass, which is determined experimentally. But normally a time distribution of 70-80% aeration, 10-20% sedimentation and <10% withdrawal respectively has been successfully reported. The O\(_2\) concentration is maintained at 1.5-4 mg/l to achieve a stable nitrite production (Jenicek et al., 2004). This is complemented by pH control with alkalinity. The process can be controlled by pH or time.

**SBR none pH control**

This process is operated as stated above except in this case no control of pH is needed. Therefore with this system there is savings on alkalinity, which is substantial. However this affects the nitrification capacity of the system to about 60% as reported by Jenicek et al., (2004) and Laurich (2004). Measuring facilities for temperature, pH, and O\(_2\) is needed to monitor the process, while O\(_2\) control is also very important. As described by Laurich (2004) the reactor can be operated in a continuous or batch format from the Hamburg’s WWTP at a cost of 0.3 euro kg/N.
Anammox

The Anammox process, which can be preceded by any of the partial nitritation step described, previously is lumped together. Since the biological removal process remains the same but only performed from different reactors. Such as the SHARON/Anammox process this is the same as partial nitritation/Anammox process since the nitritation was performed in a CSRT without sludge retention and CANON/Anammox process on a bio film. The choice of a 2-stage reactor type will depend on installation and estimated operational cost. But since the Anammox bacteria grow slowly a bio film reactor is preferred. The operation of this system depends on good supply of the planctomycetes bacteria, which prolongs the start up of the reactor. Therefore start up of the reactor could begin in the summer period to cultivate the Anammox bacteria and operated during the winter. The reject water reactor plant could be operated seasonally, thus grow the Anammox every summer and operate during winter. In that case sludge liquor in the summer would be returned to the influent of the plant.

The huge savings on aeration and carbon source makes it feasible to operate at the Helsingborg WWTP. This is because the amount of oxygen supplied can be kept under 1 mg O\(_2\)/l while the oxidation of ammonium with nitrite neglects the need for a carbon source. However studies show that limited O\(_2\) supplies (0.3 mg/l) improves the efficiency of the Anammox process as against the complete absence of aeration like the name denotes (Szatkowska, 2004). The treated water will then returned to the effluent of the plant.

Recycling of reject water to the influent of the Helsingborg WWTP can continue since the plant has adequate capacity to contain the increased load from sludge liquor. This stems from the typical ratio of 5.5 BOD/N in the influent including sludge liquor gives. This could also be the reason why at present there is no treatment of reject water or the cost of installation. But should the need be for sludge liquor treatment especially when design capacity is being neared. A SHARON with its simplicity of operation or SBR without pH control due to the low cost of operation as well as the scored obtained in Table 4 are good candidates.

6.4 Sjöllunda wastewater treatment plant

The Sjöllunda wastewater treatment plant was taken into operation in 1963 for biological treatment of wastewater from the city of Malmö. At that time it was only treating sewage from half of the city. But currently it is covering the whole of Malmö and some other outlining towns and many industries. Treated wastewater from the plant is then discharged to the Öresund. A schematic model of the plant is shown in Fig. 15.
The plant is designed for 550,000 population equivalents with the following parameters.

<table>
<thead>
<tr>
<th>Design criteria</th>
<th>Effluent limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium flow</td>
<td>BOD$_7$ $&lt;$15 mg/l</td>
</tr>
<tr>
<td>BOD$_7$</td>
<td>Nitrogen$_{tot}$ $&lt;$12 mg/l</td>
</tr>
<tr>
<td></td>
<td>Phosphorus$_{tot}$ $&lt;$0.5 mg/l</td>
</tr>
</tbody>
</table>

The plant is composed of three stages of primary, secondary and tertiary treatment of the incoming wastewater. The primary stage includes screening, grit removal, pre-aeration and primary clarification. Phosphorus is removed in the pre-aeration basin with the addition of ferrous sulphate. The secondary stage involves a high loaded activated sludge process for removal of BOD and suspended solids. A trickling filter follows for nitrification, after which the nitrogen is removed through a moving-bed biological reactor process with the addition of an external carbon source. The tertiary step is used for SS removal through chemical coagulation, flocculation and flotation. Aluminum sulphate is added to the effluent from the trickling filters. The sludge that is removed is treated by thickening, digestion and dewatering. The supernatant from the dewatering process is treated in an SBR-process designed for nitrification, in order to decrease the ammonia load and minimise the use of external carbon source. The dewatered sludge is utilised for soil improvement. Sludge stabilisation through digestion produces methane gas, which is recovered in gas motor plant for electric energy and heat. The energy in the effluent wastewater is utilised in a heat pump plant for heat delivery to the district heating system in Malmö (extracts from brochure of Sjölunda WWTP, 2001).

### 6.5 The SBR process

At Sjölunda the SBR is used to treat sludge liquor (Table 5) from the dewatered sludge. The plant is operated for nitrification and has a volume of 1,920 m$^3$. Two basins of 154 m$^3$ at the inlet and 323 m$^3$ at the outlet are used to equalise the flow respectively. The outlet flows continuously to the influent to the pre-precipitation zone. The nitrate from the reactor is re-circulated to the influent of the activated sludge basin and is removed in the non-aerated inlet section of the basin. Two storage tanks for NaOH are provided to adjust the pH value. Operation of the SBR is carried out in 4 cycles per day; at 6 hours per cycle of 310 minutes for aeration within that time is 200 minutes of filling. Sedimentation last for 25 minutes and the final 25 minutes is withdrawal.

Currently the SBR is operating with some limitations since the designed process of nitrification to nitrate is not fully attained. This is in spite of the control of pH in the reactor that cost about 1M K a month for alkalinity and 500,000 K on aeration. Effluent from the SBR shows a rather high level of nitrite than nitrate when measurements were taken. The NO$_2$ concentration was within 700-800 mg/l while that of NO$_3$ was from the range of 50-100 mg/l (Dimitrova, 2004).

The question now is how to maintain an efficient nitrification in the SBR or investigate the nitrification process so that the reactor operates as designed. The main biological process is limited by further nitrification because of the fixed capacity of the trickling filter. Thus ammonium elimination in the SBR is inevitable in order to lessen the constraints on the biological process. The wide variability of alkalinity values needs to be addressed as the following data indicates. Data received from the plant on 5th November 2004 gave alkalinity values of between 4000-4500 mg HCO$_3$/l while on the 26th of the same month alkalinity was...
stable around 1000 mg/l. Reasons for this phenomena could be in how much CO₂ is being stripped in the digester and consistency of the polymer concentration added during the dewatering stage.

Secondly the time and day in which the measurements are taken as well as the general performance of the centrifuge machine is necessary also to understand how these factors are related to each other. The possible optimisation strategies are discussed below. But firstly the composition of sludge liquor should firmly be established, which is the processed water between the centrifuge machine and the first equalisation basin. Composition of sludge liquor should compose of the parameters in Table 5. This would erase any doubt about alkalinity concentration of sludge liquor as been affected by dosing of NaOH in the SBR. Alkalinity values of the sludge liquor measured are however within typical ranges but the range showned are too wide. Therefore critical attention should be paid to how the experiments are handled to erase any doubts the results.

### Table 5 Sludge liquor composition from Sjölunda WWTP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-Kj</td>
<td>700-1000</td>
<td>mg/l</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>700-900</td>
<td>mg/l</td>
</tr>
<tr>
<td>P_tot*</td>
<td>27</td>
<td>mg/l</td>
</tr>
<tr>
<td>SS</td>
<td>200-300</td>
<td>mg/l</td>
</tr>
<tr>
<td>COD*</td>
<td>690</td>
<td>mg/l</td>
</tr>
<tr>
<td>Temperature</td>
<td>30-32</td>
<td>°C</td>
</tr>
<tr>
<td>pH</td>
<td>6.5-7.2</td>
<td></td>
</tr>
<tr>
<td>Alkalinity</td>
<td>16-74</td>
<td>mmol/l</td>
</tr>
</tbody>
</table>

(Source Dimitrova, 2004)
* Thorndahl, (1991)

### 6.5.1 Optimisation strategies

To improve the operation of the reject water treatment reactor, a number of interventions are suggested as follows. Firstly the reason why complete nitrification is not achieved has to be investigated especially nitrification rates for ammonification, nitritation and nitratation. Secondly try to optimise the current nitritation process. This does not preclude the fact that in all cases a thorough experimental study needs to be carried to test the performance of the strategy.

The lack of nitrification could be due to high temperatures that favour the suppressing of nitrobacters therefore nitrite accumulation. From Fig 8 at HRT less than one day and at very high temperatures nitrobacters are completely washed out. This is also affected by oxygen supplied but different values are reported in literature. Ruiz et al., (2002) reports that at DO concentrations of over 1.7 mg/l complete nitrification to nitrate is achieved, which is at variance to a decreasing trend of nitrification rate with increase in DO supplied reported by Mossakowska et al., (1997). However one can conclude based on experiments carried out by Pollice et al., (2001) which investigated the effect of alternating aeration on partial nitrification at different sludge ages. That nitrate accumulation on the experiments never exceeded 8% of total nitrogen for wastewater of C/N ratio of 5-8.2. This compares favourably to the 6% nitrate composition from the effluent SBR when nitrate of 50-100 mg/l and nitrite 700-800 mg/l were measured. Considering sludge liquor from Sjölunda as typical then it is no
surprise that nitrite accumulates more than nitrate. However the performance of the reactor during the winter season would be worthy to note since sludge liquor temperatures reduce slightly. Nitrification rates were higher during the summer than in winter at the following rates 23 g NH$_4$-N/kg MLVSS h and 45 g NH$_4$-N/kg MLVSS h respectively. Sludge age just as high temperatures and pH control, are critical parameters for operational performance for reject water treatment. Therefore by increasing sludge age it is possible to achieve nitrification as found by Pollice at al., (2002). The volume of sludge in the reactor needs further analysis to assess the effect of increase volume on process performance for nitrification. It is also possible to achieve nitrification when the HRT is increased coupled with aeration so as to allow the growth of nitrobacters.

Current operation of the SBR should continue since levels of nitrite accumulation can be described as typical. Standardisation of alkalinity measurement is suggested as well as sludge liquor composition. Increase sludge age, HRT and lower the temperature in the reactor to influence the behaviour of the nitrifiers to assess if nitrification is possible. Lastly monitoring the nitrification reaction on that of ammonification, nitritation and nitratation is also suggested.
7.0 Conclusion

Reject water poses a great challenge to the efficient performance of the wastewater treatment process due to its ability to increase mainly the nitrogen load of the plant. This has the tendency to overload the treatment process with a return flow of just about 2% contributed to the influent. Due to stringent effluents demands as well as protection of the environment from nutrient impacts, treatment of reject water is inevitable since reject water treatment is able to reduce effluent limits by up to 25%.

The treatment process for both nitrogen and phosphorus are categorised into 3 processes of biological, chemical and physical methods. Nitrogen treatment methods for the 3 categories are biological: conventional nitrification/denitrification by suspension or airlift reactor operation, nitritation/denitritation and partial nitritation/Anammox process in different reactor configuration. Physical methods include ammonia stripping and that of chemical methods involve MAP precipitation. Removal of phosphorus is performed through MAP/HAP precipitation method, which has largely remained at the laboratory level.

In spite of the advantages of treating reject water, most plants recycled sludge liquor directly to the influent. Only few wastewater treatment plants are currently treating sludge liquor for nutrients. The Netherlands is treating sludge with the SHARON in 4 WWTPs, Sweden 4 SBRs of different configurations, Switzerland 1 SBR, Italy 1 struvite plant and one ammonia stripping plant each in Sweden and Denmark. Reasons such as inadequacy of space in built up areas where plants are located, lack of resources for upgrading, high cost of installation and slow pace of embracing and adaptation of new technologies could be attributed to the current situation. Aside the reasons and the fact that all the sludge liquor plants in sites in Europe, it would be interesting to know what is happening in other parts of the world.

The notable and most effective method to date that has been successful in treating reject water at full-scale level is the different configuration of the nitritation/denitrification process. The different methods are the SHARON process without sludge retention and the SBR process of pH control or without pH control with sludge retention. The achievement over the years has come about due to the ability to influence the biological process of suppressing the nitrobacter oxidising bacteria, so nitrification stops at the nitrite step. The process is done at very high temperatures together with aerating.

The Anammox process presents new trends at reject water treatment, since it is completely autotrophic and requires half the oxygen needed in the nitritation process. However optimisation of start up time, getting right the process for nitrite and ammonium ratio and operation of the reactor during the summer periods are critical areas which need to be addressed.

Recycling of reject water to the influent of the Helsingborg WWTP can continue since the plant has adequate capacity to contain the increased load from sludge liquor. This could also be the reason why at present there is no treatment of reject water. But should the need be, a SHARON or SBR without pH control are good candidates.

Current operation of the SBR at the Sjölunda WWTP should continue since levels of nitrite accumulation can be described as typical, although the original design was to achieve nitrification. Standardisation of alkalinity measurement is suggested as well as sludge liquor composition. Increase sludge age,
HRT and lower the temperature in the reactor to influence the behaviour of the nitrifiers to assess if nitrification is possible.

Lastly monitoring the nitrification reaction on that of ammonification, nitritation and nitratation is also needed to understand why the original concept is not being reached. This should include analysis of the influence of pH or the alkalinity requirement for the nitritation process since the current nitrite accumulation is based on alkalinity requirements for nitrification.
References


Helsingborg wastewater treatment plant, brochure (obtained October, 2004).


http://www.lwr.kth.se/forskningsprojekt/Polishproject/JPS3s65.pdf (November 2004)


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