SBR-TECHNOLOGY - USE AND POTENTIAL APPLICATIONS FOR TREATMENT OF COLD WASTEWATER

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June 2009
Ölmanäs SBR plant in Kungsbacka, SWEDEN
In warm memory of our daughter Johanna
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ABSTRACT
Biological nutrient removal is used as an indicator of SBR performance at nine different SBR plants operated for a long period at low water temperatures (5 – 10°C). Typically needed aerated SRT (Solids Residence Time) for complete nitrification is found to be in the range of 6 –10 days. Biological phosphorus removal has been found to take place at 5°C.

The specific nitrification and denitrification rates (g N/kg VSS/h) have been found to be substantially higher than those found in design recommendations. At temperatures <10°C the nitrification rates have been found up to 4 g N\textsubscript{ox}/kg VSS/h.

It has also been possible to establish a relation between the COD/N ratio and the nitrification rate, showing that the rate increases to high rates when the ratio decreases.

Enhanced biological phosphorus removal has been demonstrated at two different plants even at low water temperatures 5 – 7°C.

Efficient biological nitrogen removal and phosphorus removal has been demonstrated at both low water temperatures and in presence of very high Chromium concentrations in inlet water, up to 20 mg Cr/l.

The plants operated with a short fill time in comparison with the total cycle time for the SBR process have all demonstrated good sludge settling properties, suggesting that the SBR process may incorporate a good sludge selection performance.

Once a flexible operation strategy has been installed (in most cases through PLC systems) it has been possible to meet load variations to maintain good treatment results. This has been found to be true for most of the plants included in the thesis.

Finally, a modified way to assess the energy efficiency for the system is analysed and suggested. Instead of using the traditional ratio kWh/kg BOD\textsubscript{removed} the use of kWh/kg OCP\textsubscript{removed} as a basis for energy efficiency is used as a far more relevant efficiency measurement.

Keywords: Intermittent operation, Water temperature, nitrogen, phosphorus, SBR, reaction rates
SAMMANFATTNING

Biologisk närsaltreduktion vid låga vattentemperaturer har använts som indikator vid fullskalunder sökningar av funktionen SBR (Sequencing Batch Reactors). Sammanlagt nio anläggningar i olika storlek ingår. Framförallt har anläggningarnas kvävereducerande förmåga undersömts. En typisk nödvändig luftad slamålder för att uppnå komplett nitrifikation har varierat inom 6 till 10 dygn då temperaturen varit 5 – 10 °C.

Resultaten visar också att så länge inte de grundläggande driftsvillkoren överskrids är nitrifikationshastigheten proportionell mot kvävebelastningen. Väsentligt högre nitrifikationshastigheter än de vanliga angivna i dimensioneringsdokument har kunnat konstateras, upp till 4 g Nox/kg VSS/h vid temperaturer < 10 °C.


Biologisk fosforreduktion har visat sig vid åtminstone två av anläggningarna och kunnat drivas stabilt vid temperaturer ner till 5 °C. Biologisk kvävereduktion och samtidig hög fosforreduktion har kunnat konstateras vara stabil vid låga vattentemperaturer och samtidigt hög halt krom i inkommande vatten, upp till 20 mg Cr/l. Efter acklimatisering har nitrifikationsbakterierna inte visat någon hämning relaterad till närvaron av krom i vatten eller slam.

En adekvat automatiserad drift med hjälp av moderna PLC system möjliggör en flexibel drift av SBR-anläggningarna. Detta ger goda möjligheter att behandla varierande belastningar med goda reningsresultat.

Slutligen används en modifierad modell för bedömning av energieffektiviteten, genom att nytta relationen kWh/kg OCP_reduced (Oxygen Consumption Potential) istället för den traditionella modellen med relationen kWh/kg BOD_reduced.
ACKNOWLEDGEMENTS

Why does an old man write a thesis, and why bother your environment and friends with lengthy discussions and questions? In my case three different reasons are apparent; they can be labelled as two mortal sins and one virtue.

The first reason is vanity. It would be hypocritical to deny that a strong driving force for writing is to demonstrate – at least to yourself – that you are able to produce the work.

The second reason is anger. When I started to focus on Sequencing Batch Reactor technology some twenty years ago I encountered some astonishing attitudes in the Swedish water industry: arrogance, scornful comments and most of all a lack of curiosity and perspective on the international development of intermittent biological systems.

The third reason is, by necessity, curiosity. I discovered that by going beyond my day to day work as a consultant doors of new knowledge would be opened to me. It also means that I have taken an interesting intellectual journey along both well-known and to some extent new paths relating to SBR technology.

This work would not have been made possible without tremendous support from a number of people and organisations.

First of all I direct my thanks to my wife Monica, who has had to withstand a more than usually self-obsessed husband for some years. My thanks go also to my daughter Lovisa who has encouraged her father to carry on.

My tutor professor, Elzbieta Plaza at KTH, deserves huge thanks for her guidance, her patience and the very constructive critical comments and advice on improvements to both the thesis and the technical papers I have produced. Her consistent skill in guiding me to write scientific papers and not “consultancy reports” has been of great value.

My co-tutor, Professor Bengt Hultman, has given helpful input on which scientific papers to study, and he has also been most encouraging in his support and criticism of the additional papers included in my work.

This thesis would not have been possible without the number of skilled, patient and observant site engineers and operators at different plants who have all contributed substantially in at least three ways: through understanding and developing SBR operations at their plants; giving of their time to answer my questions and providing ingenious answers; and providing all the necessary data on the very varied operating conditions at the different plants. Great thanks to all of you - please find your names in the various papers appended in the last section of the thesis.

I have also plagued a number of good friends and colleges with discussions and comments on parts of the thesis.

Professor Emeritus Klas Cedervall has taken time to read the thesis and given constructive and encouraging comments.

Rolf Bergström discussed with me and offered advice on my work until he passed away early in 2008. His unique knowledge of the Swedish water market was invaluable and his encouragement gave me the strength to continue the work.
Professor Emeritus Jan Rennerfelt has given encouraging comments and also given of his time in reading the draft versions of the thesis.

My friend Dr Johan Lundborg has been a valuable partner in discussion throughout the work by providing input from other fields of the scientific world.

For linguistic support and correction I express my gratitude to my college Guy Taylor for reading and correcting my English in the attached papers.

For the final linguistic examination and correction of the entire thesis I express my gratitude to Nicola Krikorian.

For the formatting of the document associate professor Erik Levlin has been of invaluable assistance, thank you!

I would also like to express my gratitude to my employer, SWECO Environment for supporting my work by allowing me leave time and financial support in order to participate in international conferences related to the thesis.

Last, but not least, great thanks to the J. Gust. Richert Foundation for financial support of the work. This support has enabled me to participate in international conferences, presenting papers included in the thesis and the time for writing and to complete this thesis.

Stig Morling
Falun and Stockholm, June 2009
### ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross section of the reactor area</td>
</tr>
<tr>
<td>A2/O system</td>
<td>Anaerobic/Anoxic/Oxic activated sludge plant system</td>
</tr>
<tr>
<td>Anamnox</td>
<td>Anaerobic Ammonium Oxidation</td>
</tr>
<tr>
<td>AOB</td>
<td>Ammonia-Oxidizing Bacteria</td>
</tr>
<tr>
<td>ATV</td>
<td>(German guidelines for design of municipal wastewater treatment plants)</td>
</tr>
<tr>
<td>b</td>
<td>Coefficient for solids decay due to oxidation (used in CIT reports)</td>
</tr>
<tr>
<td>bA</td>
<td>Decay rate of nitrifiers, in 1/d</td>
</tr>
<tr>
<td>Bio-denitro</td>
<td>Intermittently operated low load biological treatment system</td>
</tr>
<tr>
<td>BOD</td>
<td>Biochemical Oxygen Demand, general term, not specifying the time for analysis</td>
</tr>
<tr>
<td>BOD$_5$</td>
<td>Biochemical Oxygen Demand over five days, used in most countries as a definition of organic pollution, and used for both the definition of pe – see below - and in virtually all process calculations</td>
</tr>
<tr>
<td>BOD$_7$</td>
<td>Biochemical Oxygen Demand over seven days, used in Nordic countries as a replacement of BOD$_5$</td>
</tr>
<tr>
<td>CASS</td>
<td>Cyclic Activated Sludge System</td>
</tr>
<tr>
<td>CFSTR</td>
<td>Continuous Flow, Stirred Tank Reactor</td>
</tr>
<tr>
<td>Ce</td>
<td>Substrate concentration in effluent wastewater, g/m$^3$</td>
</tr>
<tr>
<td>CF</td>
<td>Readily biodegradable organic substrates by time, g/m$^3$</td>
</tr>
<tr>
<td>Ci</td>
<td>Substrate concentration in raw wastewater, g/m$^3$</td>
</tr>
<tr>
<td>Cox</td>
<td>Oxidised substrate, in days.</td>
</tr>
<tr>
<td>Cr</td>
<td>Substrate concentration in the SBR unit during Fill, g/m$^3$</td>
</tr>
<tr>
<td>Cr</td>
<td>Chromium</td>
</tr>
<tr>
<td>Csf</td>
<td>Concentration of waste in the SBR tank at end of Fill</td>
</tr>
<tr>
<td>CIT</td>
<td>Chalmers Institute of Technology</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand, based on dichromate oxidation</td>
</tr>
<tr>
<td>d</td>
<td>Specific BOD content in the sludge leaving the plant (used in CIT reports)</td>
</tr>
<tr>
<td>DEAMOX</td>
<td>Denitrifying Ammonium Oxidation</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved Oxygen</td>
</tr>
<tr>
<td>DPB</td>
<td>Denitrifying Phosphorus removal Bacteria</td>
</tr>
<tr>
<td>E$_{actual}$</td>
<td>Energy actually used in aeration, in kWh/d</td>
</tr>
<tr>
<td>EBPR</td>
<td>Enhanced Biological Phosphorus Removal</td>
</tr>
<tr>
<td>EEC</td>
<td>European Economic Community</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>f</td>
<td>Ratio between the tank volume before Fill ($V_0$) and the reactor volume after end of Fill ($V$), m$^3$/m$^3$</td>
</tr>
<tr>
<td>f$_N$</td>
<td>Fraction of nitrifying bacteria in the reactor, in g COD</td>
</tr>
<tr>
<td>f$_r$</td>
<td>Average fraction of the total cycle time under aeration in all tanks, in hours/day</td>
</tr>
<tr>
<td>F/M ratio</td>
<td>Relation between Food (normally expressed as kg BOD$_5$/d) and total amount of active biomass in the aeration reactor (normally expressed as kg MLSS, or kg MLVSS)</td>
</tr>
<tr>
<td>F/M$_{volatile}$</td>
<td>kg BOD$_5$/kg MLVSS/d</td>
</tr>
<tr>
<td>F/M$_{total}$</td>
<td>kg BOD$_5$/kg MLSS/d</td>
</tr>
<tr>
<td>h$_A$</td>
<td>Total time inside the cycle used for aerobic reactions, in hours/day</td>
</tr>
<tr>
<td>h$_E$</td>
<td>Total time inside the cycle used for anoxic and aerobic reactions, in hours/day</td>
</tr>
<tr>
<td>h$_C$</td>
<td>Total cycle time, in hours/day</td>
</tr>
<tr>
<td>h$_s$</td>
<td>Time dedicated for settling in an SBR unit, in hours/day</td>
</tr>
<tr>
<td>H$_{max}$</td>
<td>Maximum water depth in the SBR tank</td>
</tr>
<tr>
<td>H$_{act}$</td>
<td>Actual (mean) water depth in the SBR tank during aeration</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>HRT</td>
<td>(mean) Hydraulic Retention Time, in hours</td>
</tr>
<tr>
<td>HRT&lt;sub&gt;min&lt;/sub&gt;</td>
<td>Minimum Hydraulic Retention Time, in hours or minutes</td>
</tr>
<tr>
<td>ICEAS</td>
<td>Intermittent Cycle Extended Aeration System</td>
</tr>
<tr>
<td>InNitri</td>
<td>Patented nitrification model treating a side stream, rich in ammonia for nitrification</td>
</tr>
<tr>
<td>K&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Half saturation coefficient, mg/l</td>
</tr>
<tr>
<td>K&lt;sub&gt;1&lt;/sub&gt;</td>
<td>First order reaction rate coefficient, l/mg/d</td>
</tr>
<tr>
<td>MLSS</td>
<td>Mixed Liquor Suspended Solids</td>
</tr>
<tr>
<td>MLVSS</td>
<td>Mixed Liquor Volatile Suspended Solids</td>
</tr>
<tr>
<td>MX&lt;sub&gt;n&lt;/sub&gt;,&lt;sub&gt;A&lt;/sub&gt;</td>
<td>Mass of nitrifying bacteria in the reactor, in g COD</td>
</tr>
<tr>
<td>n&lt;sub&gt;cycle&lt;/sub&gt;</td>
<td>Number of cycles/d used in the SBR process</td>
</tr>
<tr>
<td>N&lt;sub&gt;ox,1&lt;/sub&gt;</td>
<td>Oxygen consumption due to nitrification of ammonia N, in kg O&lt;sub&gt;2&lt;/sub&gt;/d</td>
</tr>
<tr>
<td>N&lt;sub&gt;ox,2&lt;/sub&gt;</td>
<td>Oxygen consumption in the receiving water body due to algae growth and decay caused by nitrogen; in kg O&lt;sub&gt;2&lt;/sub&gt;/d</td>
</tr>
<tr>
<td>NOB</td>
<td>Nitrite-Oxidizing Bacteria</td>
</tr>
<tr>
<td>OUR</td>
<td>Oxygen Uptake Rate</td>
</tr>
<tr>
<td>OCP</td>
<td>Oxygen Consumption Potential</td>
</tr>
<tr>
<td>PAB</td>
<td>Phosphate-accumulating bacteria</td>
</tr>
<tr>
<td>pe</td>
<td>Person equivalent, normally defined as 1 pe = 60 g BOD&lt;sub&gt;5&lt;/sub&gt;/d</td>
</tr>
<tr>
<td>PHA</td>
<td>Polyhydroxyalkanoates</td>
</tr>
<tr>
<td>PHB</td>
<td>Polyhydroxibutyrate</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Control</td>
</tr>
<tr>
<td>P&lt;sub&gt;ox,1&lt;/sub&gt;</td>
<td>Oxygen consumption in the receiving water body due to algae growth and decay caused by phosphorus; in kg O&lt;sub&gt;2&lt;/sub&gt;/d</td>
</tr>
<tr>
<td>Pow&lt;sub&gt;installed&lt;/sub&gt;</td>
<td>Installed power for the blower device in operation, in kW</td>
</tr>
<tr>
<td>PRP</td>
<td>Residual Phosphate uptake Potential</td>
</tr>
<tr>
<td>Q</td>
<td>Inlet flow, in m&lt;sup&gt;3&lt;/sup&gt;/d, or m&lt;sup&gt;3&lt;/sup&gt;/h</td>
</tr>
<tr>
<td>Q + Q&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Flow from reactor to clarifier, in m&lt;sup&gt;3&lt;/sup&gt;/d</td>
</tr>
<tr>
<td>Q - q&lt;sub&gt;w&lt;/sub&gt;</td>
<td>Discharge flow, in m&lt;sup&gt;3&lt;/sup&gt;/d</td>
</tr>
<tr>
<td>Q&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Flow from clarifier to reactor, in m&lt;sup&gt;3&lt;/sup&gt;/d</td>
</tr>
<tr>
<td>q&lt;sub&gt;w&lt;/sub&gt;</td>
<td>Waste activated sludge flow, in m&lt;sup&gt;3&lt;/sup&gt;/d</td>
</tr>
<tr>
<td>Ro</td>
<td>Organic conversion rate</td>
</tr>
<tr>
<td>R&lt;sub&gt;g&lt;/sub&gt;</td>
<td>Microbiological growth rate</td>
</tr>
<tr>
<td>R&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Regression Coefficient Factor</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>S</td>
<td>Substrate concentration in mg/l</td>
</tr>
<tr>
<td>SBR</td>
<td>Sequencing Batch Reactor</td>
</tr>
<tr>
<td>SBBR</td>
<td>Sequencing Batch Biofilm Reactor</td>
</tr>
<tr>
<td>SHARON</td>
<td>Single reactor system for High activity Ammonia Removal Over Nitrate</td>
</tr>
<tr>
<td>SNV</td>
<td>Statens Natuurwûrdsverk (National Swedish Environmental Protection Agency)</td>
</tr>
<tr>
<td>SOR</td>
<td>Standard Oxygen Requirements, in kg O&lt;sub&gt;2&lt;/sub&gt;/d</td>
</tr>
<tr>
<td>SQI</td>
<td>Sludge Quality Index, in l/g</td>
</tr>
<tr>
<td>SRT</td>
<td>Solids Retention Time, normally given in days, often presented with the symbol θ</td>
</tr>
<tr>
<td>SS</td>
<td>Suspended Solids, normally in g/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>SV</td>
<td>Sludge Volume in ml/l</td>
</tr>
<tr>
<td>SVI</td>
<td>Sludge Volume Index, in l/g</td>
</tr>
<tr>
<td>SWOT</td>
<td>Strength, Weaknesses, Opportunities and Threats</td>
</tr>
<tr>
<td>T</td>
<td>Temperature in °C</td>
</tr>
<tr>
<td>TKN</td>
<td>Total Kjeldahl Nitrogen</td>
</tr>
<tr>
<td>TSB</td>
<td>Trypticase Soy Broth</td>
</tr>
<tr>
<td>UASB</td>
<td>Upflow Anaerobic Sludge Blanket</td>
</tr>
</tbody>
</table>
SBR-technology - use and potential applications for treatment of cold wastewater

UCT = University Cape Town, in this context used for a process concept developed at the university to enhance biological nutrient removal

US EPA = United States Environmental Protection Agency

\( \mu \) = Growth rate of bacteria, in g VSS/d

\( \mu_{\text{max}} \) = Maximum growth rate on non-substrate limited growth rate of bacteria, in g VSS/d

\( V \) = Reactor volume, in m³

\( V_T \) = maximum liquid volume in all SBR tanks, in m³

VSS = Volatile Suspended Solids, normally in g/m³

\( X'_{b} \) = Concentration of organisms in the tank before Fill, at fully mixed conditions, in mg MLVSS/l

WWTP = Wastewater Treatment Plant

\( X'_{b} \) = Concentration of organisms in the tank before Fill, at fully mixed conditions, in mg MLVSS/l

\( X_e \) = Suspended solids concentration in effluent wastewater, g/m³

\( X_i \) = Suspended solids concentration in raw wastewater, g/m³

\( X_{\text{max}} \) = Maximum MLVSS concentration for all reactors at the end of Fill (understood as a totally and uniform mixed situation).

\( X_r \) = Mixed Liquor Suspended Solids concentration in return activated sludge flow, g/m³

\( X_v \) = Mixed Liquor Suspended Solids concentration in the reactor, g/m³

\( X_w \) = Suspended solids concentration in waste activated sludge flow, g/m³

\( Y \) = Sludge yield, in kg SS/kg Substrate removed (often expressed as BOD₅)

\( Y_A \) = Yield of nitrifying bacteria, in g COD produced/g N nitrified

\( Y_H \) = Yield of heterotrophic bacteria, in g COD produced/g N nitrified

\( \upsilon(C_i) \) = Microbiological growth rate as function of \( C_i \), in h⁻¹

\( Z \) = Longitude distance of the reactor from the inlet

\( Z \) = Section in the reactor where the substrate level is determined

\( \Phi N_{\text{nitr}} \) = Nitrified nitrogen mass per day, in g N/d
LIST OF PAPERS

1. Papers appended as a part of the thesis
This thesis is inter alia based on the following appended papers. The references to them in the text are given in Latin numbers.


2. Other papers not appended in the thesis but relating to the subject


1 INTRODUCTION

The development of the Sequencing Batch Reactor (SBR) technology mirrors in many respects a unique situation. The original activated sludge system was based on a fill and draw mode, later on coined SBR. The technology was more or less omitted for nearly five decades. Now on the other hand a wide acceptance of the technology has emerged as one of the “state-of-the-art” activated sludge systems. The versatility embedded in the very simple basic concept has paved the way for the SBR technique into a variety of applications. Its suitability to convert bench scale and pilot scale operation into full-scale applications is one reason why the technique has achieved a respected and popular position within wastewater processes today.

As the SBR technology has “old roots” it is relevant to give a short outline of the technique. The early development of wastewater treatment began in the late 19th century, and the research and application during those years took place to a large extent in Britain, Germany and the US. This development was related to the obvious need to safeguard health in urban areas. A later, but today more apparent motive, was the environmental protection of the water bodies surrounding us.

However, along with the development of the modern wastewater management systems we see today, has grown a profound criticism of them, implying that the whole concept is basically wrong and is a misuse of water as a limited resource. This perspective is often seen under the banner of “Sustainable Solutions”.

In the following some main guidelines related to “sustainability” may have special relevance to wastewater treatment, and will to a certain extent also act as points of reference when analysing the specific subject of the thesis - SBR performance:

- knowledge within water science and especially biological treatment is normally insufficient to fully understand and cover the complex problems arising from them – nevertheless we must work, using the knowledge we have to our best ability for the time being;
- the contribution from natural scientists and engineers to the concept of sustainability tends to be to focus on “quantifying” the problems. It will thus be essential to find ways to “measure” the points related to sustainability. This in turn limits us to analysing environmental, technical and economical sustainability. Only to a lesser extent can the “soft parameters” related to social sustainability be addressed;
- there must be an understanding that sustainability is time-related. No system will be sustainable “for ever”. We must even acknowledge that sometimes our conclusions have been based on insufficient (or false) conditions;
- the demand on cost efficiency, measured by various tools such as cost benefit analysis, environmental impact assessment and so forth, will always be an important factor when defining a sustainable project;
- the demand for good and efficient environmental protection is normally a fundamental prerequisite when it comes to a wastewater treatment plant – thus this demand is not expressed as part of the sustainability.

When creating a wastewater treatment management system a number of classic criteria are used in order to find a “sustainable” solution to the problem. Many of the criteria are by convention used for key decisions on investments but, as will be seen, some are “unique” to wastewater treatment:

- the necessity for establishing and maintaining safe sanitation;
- the environmental protection of the receiving water bodies;
- the prevention of unwanted water being distributed to the treatment facility (normally storm water);
the protection of the plant from unwanted or toxic pollution;

the demand for an economically feasible solution;

the operation of the plant over a stipulated period of time;

the plant configuration has to be as flexible as possible in order to meet future modifications.

However, these criteria may not be sufficient for a comprehensive decision on a forthcoming treatment facility. From environmental, technical as well as social aspects some additional criteria may need to be included:

social and political acceptance is imperative in calculating the value of the investment;

the use of consumables, such as chemicals, should be kept as low as possible;

energy use should be minimized;

“natural” processes should be used as far as possible;

the area for the plant should be well-defined, as competing activities and “safety distances” between the plant and housing areas will place restrictions on land use;

last, but not least, any plant performance has to be dependent on accurate and skilled operation and maintenance; otherwise the “sustainability” will not happen.

What have these considerations to do with the specific question of Sequencing Batch Reactor (SBR) technology? From a purely technical/feasible point of view it may be easiest to answer the question by stating that the technique represents the oldest working model of an activated sludge system. Thus, in our limited time perspective of about one hundred years, the SBR system has proved to be “sustainable”. More precisely, the experiments, case studies and plant operation investigations in this thesis will help define the criteria for wastewater treatment selection.

Some of these criteria have been discussed by Rosén & Morling (1998) that deals with the question of upgrading existing plants, and does not focus specifically on the SBR (Paper I). On the other hand it outlines a number of considerations of a technical nature that can be addressed and accepted as key issues. In many ways the thesis may be seen as a further and more detailed outline of the criteria given above. Some of the statements in the thesis are highlighted as they represent essential aspects in any planning of a treatment facility.

The actual overall lifetime for the combined system of sewers, pumping stations and the treatment plant can often exceed one hundred years. This must not overshadow the fact that the different technical parts have varying lifetime expectancies. Another aspect in this context is the “environmental lifetime” of a project. This “lifetime” may be explained as follows. Whenever a permit is given by the authorities for a treatment facility (often expressed as a permit to discharge a given amount of wastewater and complying with defined effluent standards) a certain time frame is stipulated. In the Scandinavian countries this time frame has generally been set at ten years. On the other hand it may be concluded that the actual major changes in revision of effluent standards have taken about fifteen years. Some examples may be given from Sweden:

- during the 1950s the effluent standards focused on BOD removal;
- in the late 1960s it was apparent that phosphorus played a major role as a water pollutant agent, especially due to “secondary oxygen consumption”. From 1969 a large number of plants were built mainly based on advanced chemical phosphorus removal throughout the country;
- in the mid-1980s an “explosion” of algae growth in bodies of water off the Swedish west coast made nitrogen removal a major issue especially related to the discharges from the coastal plants in mid- and southern Sweden. This in turn changed the effluent standards to include limitations on nitrogen. At the same time
more stringent standards were implemented on both total phosphorus and BOD. These levels have been further refined and are now to a large extent in compliance with an EU directive (Council directive EEC 91/271) except that, from a geographical point of view, the discharges from plants in northern Sweden have no limitations on nitrogen removal. As an example a comparison between the currently exercised EU directive and adopted effluent standards for a major Swedish plant is given below (Table 1);

- the current discussion on discharge quality is focused on specific pollutants, such as not easily degradable organic pollutants, for example the residuals of pharmaceutics. The discussion has not yet resulted in a revision of the effluent standards.

**Table 1 Effluent standards according to EU directive EEC 91/271 and adopted standards for the Stockholm water plants (values in mg/l)**

<table>
<thead>
<tr>
<th>Pollution variable</th>
<th>EEC 91/271</th>
<th>Stockholm Water Company standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>&lt; 25</td>
<td>&lt; 8</td>
</tr>
<tr>
<td>COD</td>
<td>&lt; 125</td>
<td>(&lt; 70)</td>
</tr>
<tr>
<td>SS</td>
<td>&lt; 35</td>
<td>n.a.</td>
</tr>
<tr>
<td>Total N</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Total P</td>
<td>&lt; 1</td>
<td>&lt; 0.3</td>
</tr>
</tbody>
</table>

It is fruitful to compare the concept “sustainability” with what may be called the environmental lifetime of a Wastewater Treatment Plant (WWTP). In most cases this lifetime is found to be between 10 and 20 years for a specific process and plant configuration.

Another aspect regarding “sustainable” wastewater treatment may be labelled “Mental depreciation” and it’s opposite, “Mental upgrade”. This focuses on the recognition of the role played by the operators of a plant in both the planning of the plant and in its day-to-day running and the appreciation and respect that they are due. The question was addressed at a seminar on sustainable science, February 2007, at the Royal Institute of Technology, Stockholm (Professor Hans Liljenström 2007, oral communication):

The matter of “sustainability” is a question of mental adaptation and relationship to the physical world. This point highlights the fact that plant performance is dependant on accurate and skilled operation and maintenance; otherwise the “sustaina-ility” will not take place. The role played by operators in plant performance is too often overlooked.

Most of research on the SBR system has been focused on laboratory scale operation, either in a bench scale (a few litres size) or pilot plant studies (10 – 50 litre reactors). It may be seen as a paradox that a very simple process configuration – based on a fill, react and draw mode – is found feasible for application on diversified treatment objectives. During the last three decades the SBR system has been used as an efficient activated sludge model for “classic” demands, such as treating municipal wastewater and organic industrial wastewater. Thanks to imaginative and skilled developers various “upgrades” of the technique have emerged. Good examples of such upgrades are for instance the incorporation of attached growth carriers into the batch operation, the development of Anammox operation using the SBR technology and the development of SBR in combination with so called “Bio Membranes”. In addition to these technical diversifications another proof of the “SBR sustainability” is the diversified use for treating complex wastewater: landfill leachates, wastewater from coke plant, focusing on the elimination of cyanides, phenols and other nitrogen compounds (Papadimitriou et al 2006), and high strength wastewater from tanneries and so forth.

Many wastewater treatment processes, mainly biological used for nutrient removal, are temperature dependent. Accordingly treatment efficiency with SBR technology is influenced by wastewater temperature. At the same time a growing number of plants are located in areas where low wastewater temperature is an important factor for at least four months a year, in some cases water temperature is even below 10°C for most of the time. Moreover, more stringent effluent requirements are expected to be implemented
in future, as the negative influence of nutrients become more apparent.

2 Objectives

The main objective of this thesis is to analyse and evaluate the performance of SBR technology operated under cold wastewater conditions.

Especially the main goal is to investigate:
- nitrogen removal;
- phosphorus removal;
- sludge quality aspects;
- SBR cycle composition and operation strategy;
- energy efficiency.

The findings will be used to further develop SBR technology for more efficient wastewater treatment, by usage of appropriate operation strategies.

In the following, “low temperature wastewater” is defined as water entering the treatment plant at temperatures between 3–10°C. SBR operations have been studied and reported extensively on wastewater temperature in ranges between 12–25°C, however, few systematic studies have been conducted on treatment on cold wastewater.

Today a number of full-scale SBR plants are in operation in the Scandinavian countries and an additional number in central Europe under climatic conditions similar to those in Scandinavia.

In this context it has been important to use a variety of plants; both with respect to size, formal performance demands (stipulated effluent standards) and the actual loading situations. In all cases it has been essential to relate the studies to the prevailing water temperatures.

The focus on process performance is related to the dominant pollution factors, such as the presence of nitrogen, total phosphorus, to a certain extent to COD, and in one case also to the presence of high chromium content in the incoming wastewater. As biological nutrient (nitrogen and phosphorus) removal is held to be especially temperature dependant and sensitive it has been deemed relevant to focus on the conversion and removal of these nutrients.

Thus, it is seen as two important objectives to study full-scale SBR plants that have been in operation for some years; and to derive some conclusions and experience from their performance, especially on biological nitrogen and to some extent on biological phosphorus removal.

The third objective is to analyse the sludge quality aspects, as the operation mode may influence on the settling properties of the sludge. In this context the way to avoid filamentous growth of the activated sludge is of central importance.

A fourth objective with the full-scale investigations has been to study specific operation modes, and from the results draw conclusions on further development of the SBR technology. In this respect the conducted experiments and test operations contribute to further improvement of operation strategy, design considerations and also to identify the limitations of the process.

A fifth objective in the thesis is to address and identify possible improvements of the energy use. A relevant question to be addressed is energy efficiency within wastewater treatment. The SBR system is not excluded from critical questions on how electric energy is used for the purification.

In general terms, a limited nitrification capacity - or even its total fadeout at low temperatures - has determined the following hypothesis for the study:
- a correctly sized (designed) and operated activated sludge plant – in this thesis limited to an SBR system - will perform nitrification and denitrification even at very low wastewater temperatures, without presenting an “unfeasible” option for the biological treatment of organic wastewater.

An effect of the thesis has been the contribution toward plant operation strategies for SBR systems. These developments have been found necessary in order to meet the (normally) stringent effluent standards even in very unfavourable loading conditions.
This, in turn, leads to the following statement that may be seen as a side hypothesis regarding the operation of SBR plants:

- it is very important that the system is designed with an inbuilt capacity for operational flexibility: to allow for alterations in the operation mode when ever deemed appropriate.

Some more specific aims within the study are presented in the papers found in the next chapter of this thesis (Table 2):

3 DEVELOPMENT OF SBR TECHNOLOGY

SBR technology is the “mother” of all activated sludge systems. The initial experiments on suspended growth biological treatment of wastewater began in Manchester, UK in the 1910s. Reports on the

bench-scale tests were presented that soon after encouraged the full-scale development of the “Fill and Draw” system (Arden & Lockett 1915). This was the original name of SBR. It is interesting to observe that one of the initial objectives for biological treatment of wastewater included the conversion of ammonia nitrogen into nitrates (Arden 1917). Later on, when the SBR was “reborn” one of its proven merits was its nitrification capacity. Another early observation on treatment efficiency that was much discussed, was that the time needed to obtain a given treatment result was substantially shorter in a “Fill-and-Draw” system than in a continuously working activated sludge system (Arden 1917, O’Shaughnessy 1923). For a number of reasons the SBR technique was abandoned in

<table>
<thead>
<tr>
<th>Paper No</th>
<th>Title</th>
<th>Specific objectives</th>
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<tr>
<td>IV</td>
<td>Morling, S. (2009) Nitrogen removal efficiency, heavy metals and complex organic compounds in leachate treatment using SBR technology. Submitted for publication in Journal of Hazardous Materials</td>
<td>Presents test operations of leachate treatment with SBR technology at different reactor sizes, evaluates the test results for guidance of future full-scale operation and focuses on heavy metals and complex compounds capture in the biological sludge.</td>
</tr>
<tr>
<td>VI</td>
<td>Morling, S. (2009) Plant performance of an Sequencing Batch Reactor in Poland, operated with high Chromium load, reaching advanced nutrient removal. Water, Practice &amp;Technology, Number.WPT_4#1_014.</td>
<td>Analysis and evaluation of a long term performance of an SBR plant at full load or even overloaded with respect to important parameters especially nitrogen and phosphorus, showing temperature dependence and Cr removal capacity.</td>
</tr>
<tr>
<td>VIII</td>
<td>Morling, S. (2008) Nitrogen removal efficiency and nitrification rates at the Sequencing Batch Reactor in Nowy Targ, Poland. VATTEN 2. pp 121- 128.</td>
<td>Analysis and evaluation of the nitrogen removal capacity at the SBR plant in Nowy Targ under full load conditions and low water temperatures. Presents the background, early and recent technical development of the SBR technology as well as analysing further options and addressed criticism against the technology.</td>
</tr>
</tbody>
</table>
favour of continuous activated sludge during the 1920s. The main reason for this shift can be summarised as follows: the lack of efficient equipment and of an automation system at that time (Barth 1981). A more comprehensive description of the background to this development is found in (Paper IX).

The intermittent operation of activated sludge systems became popular in the 1950s when the oxidation ditch was introduced in the Netherlands (Pasveer 1959). Work on the oxidation ditch played a crucial role in activated sludge development, and may be seen as the forerunner of a number of activated sludge plant systems, especially those aimed at biological nutrient removal. The “original” oxidation ditch systems were built as a one-reactor system, in this respect identical to a true SBR system. Thus it was very similar to the original SBR model. This is the reason why the findings and technical development of the oxidation ditch should be seen as an important contribution toward the “rebirth” of the modern SBR system as it took place in the late 1960s and 1970s. The term “Sequencing Batch Reactor” was coined in the early 1970s, when the definitions of the phases of the process were also given (Irvine 1970). To facilitate an understanding of the process the different phases in a SBR cycle the modes are defined in Table 3. The SBR operation mode is often presented as a “cycle” (Figure 1). The cycle composition is taken from one of the plants included in this thesis, the Nowy Targ plant in Southern Poland.

Since the development period in the 1970s and 1980s SBR technology has become acknowledged as a viable and competitive treatment option for advanced biological nutrient removal, as well as for highly concentrated wastewater. The development may be defined in a number of ways. This will explain how the SBR has grown from being a typical small and simple treatment model with limited options. Six different perspectives of the technical development are identified and commented.

- Development of reactor size

The first SBR units were all built as rather small units, normally serving a population for less than 2,000 person equivalents (pe), when used for municipal wastewater. In industrial applications the typical daily flow ranged from 50-500 m³/d according to early reference lists from the different suppliers. Thus it is not astonishing that the conviction that “SBR is suited only for small installa-

<table>
<thead>
<tr>
<th>Table 3 Explanation of the different operational phases in the SBR cycle</th>
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<tbody>
<tr>
<td><strong>Fill + Mix</strong></td>
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<tr>
<td><strong>Fill + React</strong></td>
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<tr>
<td><strong>React</strong></td>
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<tr>
<td><strong>Settle</strong></td>
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<tr>
<td><strong>Draw</strong></td>
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<tr>
<td><strong>Idle</strong></td>
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<tr>
<td><strong>Sludge withdrawal</strong></td>
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</table>
“rebirth” was widespread for a considerable time. However, the development of any technology is strongly influenced by upsizing. By the mid 1980s plants serving between 50,000 and 100,000 pe were being built and in operation. Today plants with a capacity exceeding 1,000,000 pe, and a daily design flow of more than 200,000 m³ are in operation. A survey of SBR plants in Germany showed that plants sized for more than 100,000 pe had been installed in the 1990s (Teichgräber et al 2001).

- Development of process flexibility
The development from small SBR plants to large installations puts heavy demands on the designer and operator in terms of improved theoretical and practical knowledge of the process that is needed. In the first place it is not feasible or even practical to use a two reactor system when the plant capacity is large. From a process point of view the plant becomes very sensitive to peak loads and the possibility are of any alteration of the process cycle becomes limited. The use of upstream equalization when operating a two reactor system provides an improved process control, as the fill time may be kept very short in comparison with the total cycle time. This in turn means that the SBR unit may be operated with an initial “sludge selector” that is found to be very beneficial with respect to sludge quality, especially as a tool to combat bulking sludge. Even more this means also that the SBR system can be operated as a “plug flow” reactor rather than a total mix system. These two concepts are fundamental when characterizing continuous flow activated sludge systems (Paper IX). The improved understanding of the process performance also results in a better use of the energy input. This is linked to the cyclic operation and the possibilities of controlling the changes in the process variables throughout the cycle. An important feature in this context is the excellent control possibilities of the oxygen supply.

- Development of equipment
As important as a process understanding for the up size of any plant is the development of adequate and efficient equipment devices used for the technology. In the case of the SBR the most pronounced difficulty has been to arrange safe and efficient decant devices. The fundamental requirement for decanting is that it takes place without any unwanted loss of suspended solids. Going from small to large sized systems means also that the decanter size will increase substantially. In addition to the decanter have requirements for the aeration system have been found important for the successful process performance of the process. In the first place the aeration must be designed for oxygen addition during only a fraction of the 24 hours a day. The time dedicated for aeration in a SBR unit may range from 6 to 15 hours a day; the time is related to the specific application.

- The automation adjustments needed for the SBR systems
One of the early shortcomings of SBR technology was the lack of reliable and simple on-line probes and developed automation systems. Through the use of modern PLC systems and the development of more reliable on-line meters to ascertain the amount of free oxygen in the water, level control devices and suspended solids meters the situation has changed for the system. Today all plants normally include at least these probes.

- Diversification of applications for different types of wastewater
The original SBR system (in 1914) was tested on municipal wastewater. Even when the “rebirth” with the oxidation ditch came in the 1950s the early applications were mainly aimed for municipal wastewater, even if the report from one of the first oxidation ditches in Voorschoten also treated industrial wastewater (Pasveer 1959). With the advent of the modern SBR in the 1970s new applications were soon found, for example in the treatment of industrial wastewater and leachate treatment (Kulpa et al 1982). The treatment pattern with intermittent charging of the reactor fit well with some industrial activities where batch mode operation is part of the normal process. Thus, the SBR was soon used for various food industry
applications, sometimes in conjunction with municipal wastewater (Irvine et al. 1987). Further step in the diversification occurred when side stream treatment at municipal plants was found to be feasible. This is especially true when anaerobic digestion of the sludge takes place, resulting in ammonia-rich reject water. In Sweden alone at least 18 plants have been built for reject water treatment based on the SBR system. The diversification of SBR applications will most likely continue to grow in the future, mainly because of the flexibility inherent in the operation mode and the relatively simple equipment needed.

- Integration of the SBR system into other technical treatment models

Another important development of the SBR system is the clear tendency to integrate the basic intermittent operation based on “Fill and Draw” into other systems to achieve an even better performance. Some of these integrations or adjustments of the technology are presented below (Paper IX).

a. The use of SBR technology to facilitate the Anammox process

The Anammox bacteria options were identified of the for nitrogen removal in the 1990s. Since then a large number of experiments and investigations on the Anammox process have been conducted (Dapena-Mora et al. 2004a, 2004b, Gaul et al. 2006, Pambrun et al. 2006, Strous et al. 1998). Only one of these studies was carried out on a full-scale operation of nitrogen-rich wastewater (Gaul et al. 2006). The four other investigations were all based on bench-scale studies.

b. The combination of the SBR operation mode with attached growth systems, often labeled SBBR (Sequencing Batch Biofilm Reactor)

One such example has been presented in a technical scale (Arnz et al. 2001).

c. The use of SBR technology to promote granular activated sludge system

This approach is deemed as very interesting, as SBR technology allows for operation modes focusing on “sludge selection”. A number of recent studies have been presented, all using SBR technology to develop the granular activated sludge model (Carucci et al. 2008, Dulekgurgen et al. 2008, Figueroa et al. 2008, Ivanov et al. 2008, Kishida 2008, Liu et al. 2008, McSwain Sturm & Irvine 2008, Wichern et al. 2008).

Finally, the combination of the SBR with an advanced separation technique such as the Membrane Bio Reactors is seen as an interesting field of improved efficiency of wastewater treatment.

All these aspects of SBR development are more comprehensively presented in Paper IX. An overview of a modern SBR facility in operation is shown (Nynäshamn wastewater treatment plant, south of Stockholm, Figure 2).

“Every purpose is established by counsel: and with good advice make war.”

Proverbs 20.18

4 MATERIAL AND METHODS

4.1 Research strategies

4.1.1 Establishment of test plants for research and experimental sampling programs

From 26 wastewater treatment plants (WWTP) designed by the author, and based on SBR technology, nine plants have been selected for the study (Table 4). Five of them (Dokkas, Bösarp, Tjustvik, Nowy Targ and Nynäshamn) have served as full-scale test facilities with the special objective of studying different processes to improve SBR performance knowledge. Planning and supervision of these tests have been done by the author. Moreover laboratory tests have been planned and performed to study the performance of different specialised processes within SBR technology. Such studies have included nitrification inhibition, oxygen uptake rate and sludge quality.
Tests have been performed at most of the plants over a period of at least 6 months; among the chosen plants in this thesis all but two (Norsa and Chon Buri) are operated at significantly low water temperatures during the winter and early spring seasons. The plants are shown with some typical design data and remarks on any specific investigations (Table 4). The specific conditions for the different plants are of course reflected in their design, the mode of operation and their performance.

4.1.2 Evaluation and comparisons of process performance of full-scale SBR plants

The plants have been objectively researched and their performances have been observed over several years. Full-scale experiments have been conducted, planned and performed, including planning for sampling, tests, analysis and evaluation of the results. The selection of the plants for the investigations has been based on a number of criteria:

- they have all have been in operation for some time;
- they treat cold wastewater, at least in the winter and spring seasons;
- they represent a variation in configurations and treatment objectives.
Chon Buri wastewater treatment plant in Bangkok has been chosen as a reference plant. The reason is that the plant operates with very dilute and warm wastewater, and is the only one that operates at loads substantially below the design load. In addition to these conditions it represents a very large plant with intermittent operation. All plants in the study with the exception of Chon Buri have been designed by the author of this thesis; the work has included the process configuration; sizing and detailed outlines for these plants (Table 4). Design data for the plants from the planning stage have been elaborated, and later on used for corrections and alterations for selected plant configurations. The chosen process equipment and on-line control devices are in all cases, well-known makes available on the commercial market. It should be stressed that most of the on line control units are similar to those found in a laboratory test, with one important difference: they all serve in a much more demanding environment than in a laboratory. Evaluation and integration of the results from the tests have been used in at least two ways; to add to existing knowledge of the operating conditions of an SBR plant under low temperature, and to make it possible to adjust the operation at specific plants.

Table 4 Performed experimental work

<table>
<thead>
<tr>
<th>Name of plant</th>
<th>Capacity</th>
<th>Reactor configuration</th>
<th>Start of operation</th>
<th>Reference</th>
<th>Specific investigations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plants used for experimental tests</strong></td>
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<tr>
<td><strong>Municipal plants</strong></td>
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<td></td>
</tr>
<tr>
<td>1. Dokkas, Sweden</td>
<td>100 m³/d</td>
<td>1 * 27 m³</td>
<td>1989</td>
<td>Paper II</td>
<td>Trial operation for 18 months, focused on biological phosphorus removal.</td>
</tr>
<tr>
<td>2. Tjustvik, Sweden</td>
<td>8,000 m³/d</td>
<td>2 * 3,338 m³</td>
<td>1997</td>
<td>Paper III and Paper VII</td>
<td>Full-scale test operations on the use of septic sludge as a carbon source; investigations on microbiological communities in the process.</td>
</tr>
<tr>
<td>3. Nowy Targ, Poland</td>
<td>21,000 m³/d</td>
<td>3 * 7,600 m³</td>
<td>1994</td>
<td>Paper VI and Paper VIII</td>
<td>Full-scale investigations of the effect of heavy chromium load from tanneries; investigations on nitrification rates related to temperature variations and behaviour of phosphorus removal.</td>
</tr>
<tr>
<td>4. Nynäshamn, Sweden</td>
<td>8,500 m³/d</td>
<td>4 * 1,100 m³</td>
<td>2002</td>
<td>Paper VII</td>
<td>Full-scale performance test of the plant especially with respect to short cycle times and low COD/Nitrogen ratios.</td>
</tr>
<tr>
<td><strong>Leachate treatment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>5. Bösarp, Varberg, Sweden</td>
<td>20 m³/d</td>
<td>1 * 70 m³</td>
<td>1988</td>
<td>Paper IV</td>
<td>Test plant for SBR technology used for leachate in Sweden.</td>
</tr>
<tr>
<td><strong>Plants used with long term operation experience</strong></td>
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<tr>
<td><strong>Municipal plants</strong></td>
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</tr>
<tr>
<td>6. Holbaek, Denmark</td>
<td>15,000 m³/d</td>
<td>4 * 3,000 m³</td>
<td>1991</td>
<td>Paper VII</td>
<td>Operation with biological nitrogen and phosphorus removal, adjustments on process for strict nitrogen discharge.</td>
</tr>
<tr>
<td>7. Ölanäs, Sweden</td>
<td>8,000 m³/d</td>
<td>2 * 3,000 m³</td>
<td>1994</td>
<td>Paper VII</td>
<td>Evaluation of the impact of a upstream equalization basin, sharp temperature drop in winter and of biological nitrogen and phosphorus removal.</td>
</tr>
<tr>
<td><strong>Leachate treatment</strong></td>
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<td></td>
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</tr>
<tr>
<td>8. Norsa, Köping, Sweden</td>
<td>150 m³/d</td>
<td>1 * 300</td>
<td>2001</td>
<td>Paper IV</td>
<td>Operation of a SBR unit at controlled temperature, with addition of a small amount of municipal wastewater.</td>
</tr>
<tr>
<td>9. Isätra, Sala, Sweden</td>
<td>100 m³/d</td>
<td>1 * 300 m³</td>
<td>1999</td>
<td>Paper IV</td>
<td>Operation of a SBR unit with leachate treatment at low winter temperature, constructed wetland used as polishing step.</td>
</tr>
<tr>
<td><strong>Reference plant</strong></td>
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<tr>
<td>10. Chon Buri, Bangkok, Thailand</td>
<td>200,000 m³/d</td>
<td>24 * 4,500 m³</td>
<td>1999</td>
<td></td>
<td>Large plant, operated at high water temperature and under low load conditions.</td>
</tr>
</tbody>
</table>
Additional sources used for evaluation are annual environmental reports from the plants that are regulated by the laws in Denmark and Sweden.

The findings from the different plants have been compared with scientific papers focusing on SBR performance and theory.

4.1.3 Literature studies regarding SBR technology and development

An important part of the work in this thesis has been to address scientific reports, papers and presentations from other scientists. This material serves as a point of comparison and references to other similar plants and also to the relevant development of the SBR technology (Paper IX).

In addition to the experimental work performed research results from pilot plants and bench-scale development are presented in research papers, used to illustrate some aspects of SBR performance and capabilities. Furthermore full-scale investigations, experiments and observations from other SBR facilities are used to add further perspective to the observations and the hypothesis.

4.2 Description of the plants and experimental activities

In the following a short technical description is given of each one of the plants used for the studies and included in the thesis (Table 4).

4.2.1 Dokkas SBR plant (test plant facility)

The objective was to operate a test plant facility, based on the SBR process and to evaluate the possibility of operating enhanced biological phosphorus removal at very low water temperatures. A full presentation of the results is found in Paper II of the thesis.

The test period lasted for 18 months covering both winter and summer conditions at the plant.

The SBR configuration of the plant was arranged by converting the aeration basin in a small “compact” plant built with a direct activated sludge plant followed by a chemical post precipitation. After conversion of the plant into the test facility the process chain for the plant was as follows (Figure 3):

- an inlet pumping station;
- a mechanical screen;
- a combined sand trap and pump sump for the SBR unit line. The wastewater was pumped from the upper part of the sand trap, allowing a separation of the sand in this stage;
- the SBR unit;
- discharge directly to the receiving water body.

The “excess” wastewater amounts entering the plant were directed to the post precipitation stage, a part of the non-converted plant. Arrangements were made to isolate the chemical sludge from the excess biological sludge. Accordingly they ensured that no surplus reject water from the chemical storage tank could reach the biological treatment part.

Typical operation cycles for the SBR facility are shown in Table 5.

Figure 3 Simplified flow sheet for the Dokkas SBR test plant
4.2.2 Tjustvik SBR plant

This plant was a major extension of an old plant. Only parts of the original plant were retained when the SBR basins were built. Different conditions at the plant made it necessary to conduct full-scale performance tests and operation adjustments. These tests lasted for six months (planned and directed by the author). The operation data, results and other conditions regarding the plant is found in Paper III. In 2005 an additional test was initiated focusing on the sludge quality in the SBR reactors at the plant. This test period lasted another 6 months.

The process chain for the integrated SBR plant is as follows (Figure 4):

- pre-treatment facilities containing two units of fine grade screens, two parallel sand traps and a Parshall flume;
- the main biological treatment containing a distribution chamber followed by the two SBR basins. The installation allows for simultaneous precipitation;
- the post treatment contains chemical precipitation followed by two parallel sedimentation tanks.

The special operation conditions at the plant include the reception of a large quantity of septic sludge from the south eastern archipelago of greater Stockholm. The addition was initially beneficial for improved treatment results (Paper III). However, an overloading of the plant has caused performance problems in recent years. A special condition affecting this plant has been the decision taken by the Värmdö community to close most of the neighbouring treatment plants and direct the wastewater to a large regional treatment facility. This decision has influenced the operation in a “non-technical” way. This matter is further discussed in the following section. Operational data and other conditions regarding the plant have been presented (Paper III).

4.2.3 Nowy Targ SBR plant

The Nowy Targ plant was built as an entirely new facility and taken into operation in 1994. This plant belongs to the most investigated SBR plant in the world. Studies regarding the Nowy Targ WWTP performance have been

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**Table 5 SBR Cycle composition at the Dokkas SBR test plant throughout the operation period**

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Fill 3 h</th>
<th>Anoxic fill 48 min</th>
<th>Aerobic fill 12 min</th>
<th>React 45 min</th>
<th>Sludge wasting during react &lt; 0.5 h</th>
<th>Mixing 15 min</th>
<th>Settling 1 h</th>
<th>Decant + idle 1 h</th>
<th>Total cycle time:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Short cycle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 h</td>
</tr>
<tr>
<td><strong>Long cycle</strong></td>
<td>Fill 3 h</td>
<td>Anoxic react 31 min</td>
<td>Aerobic react 10 min</td>
<td>Settling 1h 29 min</td>
<td>Decant 20 min</td>
<td>Total cycle time:</td>
<td>10 h</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ratio fill to total cycle: 0.25:1 to 0.5:1
Ratio fill to total + react: 0.75:1

Fe salt dose 1

Fe salt dose 2

Pumping Station for septic sludge

Grit Chambers

Fine Grade Screen

SBR 2 units

Precipitation and sedimentation

**Figure 4 Simplified flow sheet at the Tjustvik SBR plant**
presented earlier (Banas et al 1999, Finnell 1998, Hultman et al 1999, Johansson & Salberg 1996, Kabacinski et al 1998, Mikosz et al 2001, Sharif 1998). The plant was designed to receive both municipal and some industrial loadings from a dairy and a limited number of tanneries. The actual loading from the tanneries is far beyond the design level (Papers VI and VIII). The process chain for the integrated SBR plant is as follows (Figure 5):

- pre-treatment facilities containing a screw pumping station, two units of fine grade screens and two parallel sand and grease traps;
- the main biological treatment containing a distribution chamber followed by the three SBR basins. The installation allows for simultaneous precipitation;
- the treated water is passed into an equalization tank. Flow measurement takes place at the outlet from the equalization basin by a Thomson overflow weir.

The operational data and other conditions regarding the plant are found in Papers VI and VIII. Typical operation cycle for the SBR facility is shown in Table 7.

### 4.2.4 Nynäshamn SBR plant

The SBR facility was included as a result of two major shortcomings within the community’s wastewater management: the limited performance by an earlier process configuration, especially with respect to nitrogen removal, and the need to improve substantially the septic sludge handling. All existing parts in the old plant were retained when the SBR basins were built. The plant was built in 2001-2002 and was taken into operation in 2003.

---

**Table 6 SBR Cycle composition at the Tjustvik WWTP**

<table>
<thead>
<tr>
<th>Initial cycle composition</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill 3 h</td>
<td>React 45 min</td>
<td>Mixing 15 min</td>
<td>Settling 1 h</td>
<td>Decant + idle 1 h</td>
</tr>
<tr>
<td>Anox fill 48 min</td>
<td>Aerobic fill 2h 12</td>
<td>Sludge wasting</td>
<td>Total cycle time:</td>
<td>6 h</td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>during react &lt; 0.5 h</td>
<td>6 h</td>
<td></td>
</tr>
<tr>
<td>Adjusted cycle composition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fill 3.5 h</td>
<td>Anoxic react/Aerobic react 125 min</td>
<td>Settling 60 min</td>
<td>Decant 60 min</td>
<td></td>
</tr>
<tr>
<td>Anox 48 -159 min</td>
<td>Aerobic 51 – 132 min</td>
<td>Sludge wasting 35 min</td>
<td>Total cycle time: 7 h</td>
<td></td>
</tr>
</tbody>
</table>

**Table 7 SBR Cycle composition at the Nowy Targ SBR plant, initial and adjusted cycles**

<table>
<thead>
<tr>
<th>Initial operation cycle</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill 2h</td>
<td>React 45 min</td>
<td>Mixing 15 min</td>
<td>Settling 1 h</td>
<td>Decant + idle 1 h</td>
</tr>
<tr>
<td>Anox fill 48 min</td>
<td>Aerobic fill 2h 12</td>
<td>Sludge wasting</td>
<td>Total cycle time:</td>
<td>6 h</td>
</tr>
<tr>
<td>Industrial wastewater</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted operation cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fill 1h 50 min</td>
<td>Aerobic react 2 h</td>
<td>Settling 1 h</td>
<td>Decant &lt; 30 min</td>
<td></td>
</tr>
<tr>
<td>Anoxic fill 1 – 1.5 h;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerobic fill 0.5 – 1.5 h</td>
<td>Sludge wasting during react &lt; 0.5 h</td>
<td>Total cycle time: 5.5 h</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ratio fill to total cycle: 0.36:1
Ratio fill to fill + react: 0.5:1
operation in 2003. In 2004 a full-scale experimental study was conducted and performed (Berg & Biderheim 2004). The process chain for the integrated SBR plant is as follows (Figure 6):

- pre-treatment facilities containing two units of fine grade screens and two parallel sand traps;
- a pre-precipitation and primary sedimentation stage;
- the main biological treatment containing a pumping station followed by four SBR basins. The units also receive septic sludge from the area south of Stockholm;
- post-treatment contains chemical precipitation followed by flocculation and two parallel sedimentation tanks;
- finally the water is pumped to the wetland facility and discharged into the Baltic Sea.

The operation data and other conditions regarding the plant have been presented (Paper VII). Typical operation cycle for the SBR facility is shown in Table 8.

### 4.2.5 Bösarp SBR plant for leachate treatment (test plant facility)

The test facility for a leachate-based SBR process was built and operated with the objective of establishing design data for a forthcoming full-scale plant. Planning of the experiments started in winter 1988, and the first test period started in April 1988 using a 500 l reactor and lasted for 14 months. In September the experiments were extended, and an existing lagoon of 70 m³ was converted into an SBR reactor. Testing and trial operation of this unit lasted for 10 months. The test operation revealed a number of findings (Paper IV, Morling et al 1989). These findings are further discussed in the following chapter and compared with the results from the other two leachate treatment plants presented in this thesis. A very simple process chain was used (Figure 7).

The plant was operated at quite different cycle times, adjusted to the water temperature (Paper IV). A typical operation cycle is presented in Table 9.

### 4.2.6 Holbaek SBR plant

The plant was built in 1990-1991 was and extended by a fourth SBR unit of 3,000 m³ in 2003. The process chain for the integrated SBR plant is as follows (Figure 8):

- pre-treatment facilities containing two
Units of fine grade screens, two parallel aerated sand traps and a pumping station feeding the main treatment plant;

- an equalization basin (old sedimentation tank), combined with a second pumping station feeding the SBR units;
- the main biological treatment contains four SBR units of 3,000 $m^3$ and two units each of 1,465 $m^3$. The installation allows for simultaneous precipitation; normally ferric chloride is used; however other liquid precipitating agents have also been used;
- the biologically treated water is directed to a second equalization basin (an old sedimentation tank) and further passed through two sand filter units prior to discharge into the recipient;
- one of the small SBR units has been used to treat leachate water transported to the plant by trucks.

Follow up of the plant performance has been done by collecting performance analytical data, on-line process data, such as SS-concentration in the reactors, the changes of cycle times and the nutrient removal improvements. Three different operation periods have been used for the evaluation: early operation in 1990s, comprehensive data from 1996, when a more stringent effluent standard was applied, and finally for year 2006, when the plant had been extended by one reactor. Compilation and synthesis of the data have been done, including the first year’s operation of the plant (Paper VII, Morling & Nyhuis 1996). Typical operation cycles for the SBR facility are shown in Table 10.
4.2.7 Ölmanäs SBR plant

The plant was the first full-scale SBR facility in Sweden and was a major extension of an old plant. Most of the old plant was retained when the SBR basins were built, but some of the volumes are used in another way today. A performance study was conducted, including full-scale tests with Enhanced Biological Phosphorus Removal (EBPR). A subsequent performance control was made in 2006, when the plant operated at design load conditions during summer time. The process chain for the integrated plant is as follows (Figure 9):

- untreated wastewater is pumped into the pre-treatment facilities containing fine grade screen and an aerated sand trap;
- an equalization basin (old aeration tank), combined with a second pumping station feeding the SBR units;
- the main biological treatment contains two SBR units of 3,000 m³. The installation allows for simultaneous precipitation, normally ferric chloride is used but also other liquid precipitating agents have been used;
- biologically treated water is directed to a polishing step, where the flocculation and final sedimentation tanks are used. The treated water is passed to the receiving water body.

Plant operation performance and evaluation of low water temperature conditions are presented (Paper VII, Morling & Nyberg 1996). Typical operation cycle for the SBR facility is shown in Table 11.

4.2.8 Norsa SBR plant for leachate treatment

The Norsa plant is located some 150 km west of Stockholm and treats leachate from a sanitary landfill. The landfill has been in operation for almost 40 years, and the leachate composition is typical of water from a landfill in the “anaerobic stage” (Papers IV and V). The plant is located within the premises of the municipal wastewater treatment plant. An unused sludge thickener had adequate volume to suit an SBR unit. The

![Simplified flow sheet of the Ölmanäs SBR plant](image)

![Simplified flow sheet of the Ölmanäs SBR plant](image)

**Table 10 SBR Cycle composition at the Holback SBR plant, during 1993 and 2006**

<table>
<thead>
<tr>
<th>Event</th>
<th>Anoxic fill</th>
<th>Aerobic react</th>
<th>Settling</th>
<th>Decant</th>
<th>Total cycle time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anoxic fill 1 h 40 min</td>
<td>31 min</td>
<td>10 min</td>
<td>29 min</td>
<td>1 h 20 min</td>
<td></td>
</tr>
<tr>
<td>Aerobic fill 1 h 21 min</td>
<td>35 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ratio fill to total cycle: 0.33:1 – 0.5:1
Ratio fill to fill + react: 0.7:1 – 1:1

**Table 11 SBR Cycle composition at the Ölmanäs WWTP**

<table>
<thead>
<tr>
<th>Event</th>
<th>Anoxic fill 80 min</th>
<th>Aerobic react 30 min</th>
<th>Settling &lt;60 min</th>
<th>Decant &lt;70 min</th>
<th>Total cycle time</th>
</tr>
</thead>
<tbody>
<tr>
<td>At high flow: intermittent aerated fill starts after 80 min fill time. Runs for about 70 min totally</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 h</td>
</tr>
<tr>
<td>Sludge wasting up to 100 m³/d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ratio fill to total cycle: 0.4:1 – 0.5:1
Ratio fill to total fill + react: 0.7:1 – 1:1
plant treats leachate, ranging from 50 to 150 m$^3$/d. The plant was put into operation in 2001. During the five first years of operation preliminary consent permits were valid. The authorities also demanded the operator to conduct an extended full-scale process control during this period. The control program along with specific studies were conducted and followed up (Paper IV).

The process chain for the integrated SBR plant is as follows (Figure 10) and a typical operation cycle is shown in Figure 11:

- leachate is collected in a 3,000 m$^3$ equalization basin and pumped to the treatment plant;
- leachate passes through a heat exchanger in order to keep the water temperature at 15°C;
- a small feed of settled municipal wastewater is added to provide necessary phosphorus amounts for the process, and to a minor extent also organic carbon;
- the main biological treatment contains an SBR unit of 300 m$^3$. The installation allows for the addition of methanol as a carbon source and foaming control agent;
- biologically treated water is directed to a polishing step built as two slow speed sand filters;
- treated leachate is discharged to the recipient.

Plant operation has been presented (Paper IV).

![Figure 10 Flow sheet for the Norsa leachate treatment plant](image)

4.2.9 Isätra SBR plant for leachate treatment

The plant is located at a sanitary landfill some 130 km north west of Stockholm. The landfill was put into operation in 1973, and is characterized as a landfill in the methanogenic stage. The SBR facility was implemented as the older treatment facility based on wetlands was found insufficient. The plant was operated with preliminary consent permits for a number of years. Thus it was important to follow the operation closely. A comprehensive control and follow up program was conducted and elaborated (Paper IV). The upgraded plant has been in operation since 2000 and treats about 80
m³/d of leachate and compost water. The process chain for the integrated SBR plant is as follows (Figure 12):

- Leachate is collected from the sanitary landfill and the compost plant, collected in an equalization basin and further pumped into the main biological treatment;
- The main biological treatment contains an SBR unit of 300 m³. The installation allows for the addition of methanol as a carbon source and phosphoric acid;
- Biologically treated water is directed to a constructed wetland;
- Treated water is directed into the municipal sewer system.

An operation cycle is presented (Table 12).

### 4.2.10 Chon Buri CASS plant

To bring a wider perspective to the comparison of energy efficiency a plant with very different operating conditions is included in the picture. The main reason for this is to analyse the efficiency when a plant is operated with very dilute wastewater, and thus substantially below its design loads. This plant is the only one in the thesis that was not designed by the author. All data – including design figures and performance results – are used in the following for comparison purposes, as the plant is operated under low load conditions and water temperatures consistently higher than 20°C.

The Chon Buri WWTP in Bangkok, Thailand is a major plant built as a CASS (Cyclic Activated Sludge System) facility. Although not a true SBR the plant incorporates most of the features of a batch mode operation. In the following a brief presentation is given of this WWTP. The plant is sized to treat 200 000 m³/d under dry weather conditions. The design organic load is BOD₅ load of 30 tons/d. The process chain for the plant is as follows (Figure 13):

- Pre-treatment facilities containing, coarse grade screens, two units of vortex sand traps and fine grade sieving screens;
- The main biological treatment containing a separate pumping station for each one of the four main CASS systems, located on top of each other. Each CASS system has six reactors;
- Treated water is passed into the receiving water body installation. Flow measurement takes place at the outlet from the equalization basin by a overflow weir.

A typical operation cycle for the Chon Buri plant is shown in Table 13.
4.3 Sampling and analysis arrangements

All sampling of influent and effluent at the full-scale WWTPs has been performed with automatic samplers and was always based on flow proportional 24-hour sampling, save for one case. The samples are kept in a refrigerator at 4°C during the sampling day. The sole exception is the Nowy Targ plant that uses time proportional 24-hour sampling.

The large number of data gathered from the plants in the study allowed for a statistical analysis of the results.

For all internal sampling taken at various phases during the operation cycle, grab sampling has been used by convention.

The typical on-line instrumentation of the SBR units included in the thesis contains the following meters:

- a level control device – often based on a piezo-resistive meter;
- an oxygen meter, normally combined with a temperature meter;
- a suspended solids meter;
- pH is controlled at the influent at a few plants, for instance in Nowy Targ.

Sampling frequency on influent and effluent followed the stipulated environmental control stated by the authorities. Internal sampling varies from plant to plant. More intense sampling periods have been performed during experimental studies. For the small facility presented on leachate treatment in Varberg (Paper IV) grab sampling was performed. Collected samples have been analysed according to different national standards. These are by large in accordance with the European Union Standards (EN). As an example the Swedish Standards (SS) are presented:

- BOD, SS-EN 872, including nitrification inhibitor, accuracy in a single analysis result +/- 30%;
- COD SS 28142, accuracy in a single analysis result +/- 17%;
- total P SS 028127-2, accuracy in a single analysis result +/- 10%;
- total Nitrogen SS-EN ISO 13395, accuracy in a single analysis result +/- 20%;
- NH₄-N SS-EN ISO 11732, accuracy in a single analysis result +/- 10%.

Although the COD analysis is questioned today (the use of mercury in the analysis is deemed as an environmental hazard) COD has been used along with the BOD figures when the different plants are discussed. In recent years the Sludge Quality Index (SQI) has been used as an alternative to the more conventional Sludge Volume Index (SVI) (Equation 1, Table 14).
Flow control at an SBR plant is possible as long as the reactor is equipped with an online level meter. By measuring the different levels before and after decant, and multiplying the measured value with the reactor area, the treated volume can be determined accurately. This way of flow control is used at least to check the continuous on-line flow meters installed at the plants.

4.4 Analysis of nitrogen removal

4.4.1 Practical conditions at the plants

Small and medium-sized plants normally do not have an on-line ammonia meter or nitrate meters. The current investment level for on-line nitrogen meters in conjunction with the need for maintenance and calibration of these meters has played a decisive role in the automation and control level of many plants.

When using the measurement data from the different plants, and especially addressing the question of performance at low water temperatures, some definitions and conditions have been used:

- the loading is expressed as total nitrogen;
- the specific nitrification rate is defined as g NH$_4$-N$_{eq}$/kg VSS/h during aeration time in the reactor;
- the F/M values are defined as kg BOD$_5$/kg MLVSS/d, and also distinguished between “total F/M value and an “aerated” F/M value. In the latter case only the aerated time is taken into account.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Equation</th>
<th>Legend for the used symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQI</td>
<td>$\text{SQI} = \frac{200 + \text{SV}/3}{\text{MLSS}} \times 1000$;</td>
<td>$\text{SQI} = \text{Sludge Quality Index in ml/g}$</td>
</tr>
<tr>
<td>SV</td>
<td>= sludge volume in ml/l, as measured in the traditional way in a settling bucket.</td>
<td>$\text{SV} = \text{sludge volume in ml/l}$</td>
</tr>
<tr>
<td>MLSS</td>
<td>= Mixed Liquor Suspended Solids in the reactor, under fully mixed conditions.</td>
<td>$\text{MLSS} = \text{Mixed Liquor Suspended Solids in the reactor}$</td>
</tr>
</tbody>
</table>

Table 14 Equation defining the Sludge Quality Index (SQI)

The (mean) Solids Retention Time (SRT) is expressed both as total SRT and aerated SRT. The latter is defined as the SRT related to the aerated time in the reactor per day.

4.4.2 Overall nitrogen removal balance

For the different SBR plants analysed in this thesis the nitrogen removal efficiency is used as a major indicator of low temperature performance. The results from the plants are calculated by using material balances over the reactor (Figure 14). When addressing the results and using the figures to make mass balances and to calculate the nitrogen removal efficiency some assumptions have been made. In accordance with the model measurements and estimates have been made (Figure 14).

Nitrogen in inlet of untreated wastewater

Total nitrogen is normally analysed (in mg/l); Organic nitrogen is seldom analysed, but assumed in the following to be about 30% of total nitrogen, unless specific data are available. NH$_4$-N is accordingly seldom analysed, but assumed in the following to be about 70% of total nitrogen, unless specific data are available. It is assumed that no oxidised nitrogen is present in the raw wastewater. Whenever found at any of the plants included in this thesis the level of NO$_x$-N is insignificant and does not contribute to the balance in any decisive way.

Nitrogen in Waste Activated Sludge (WAS)

The nitrogen content in the WAS is seldom measured; thus a number of assumptions are
made in order to quantify the nitrogen removal by sludge withdrawal:

- two ways to define the nitrogen content in the sludge are used: either a weight fraction of the sludge is used (Eckenfelder 1989), or a ratio on BOD\text{removed} \text{ to } N\text{removed} by sludge. When using the weight fraction model 8% of the waste activated sludge is assumed to be nitrogen. When the second model is used the removed nitrogen is 5% of the BOD removed. These two models are to a certain extent simplifications of the real performance, as the nitrogen content in the sludge will vary with the SRT and the degree of aerobic sludge stabilization;

- it is assumed that the nitrogen in the sludge is mainly found as organic nitrogen;

- inorganic nitrogen found as NH\textsubscript{4}-N and NO\textsubscript{3}-N is insignificant although both fractions are found in the water transporting the WAS.

**Nitrogen in discharge to water**

Total nitrogen is normally analysed (in mg/l). Organic nitrogen is seldom analysed separately. The organic fraction in the discharge normally is defined as inert organic nitrogen, either impossible to transfer biologically, or as an end product of the biological treatment itself. Often this N-fraction is assumed to be about 1mg/l in the discharge, as long as the inlet concentration is less than about 50 mg/l of total nitrogen. When substantially higher inlet concentrations of nitrogen are found (as in the case of Nowy Targ) the organic nitrogen part in the discharge is estimated at 2 – 3 mg N/l. NH\textsubscript{4}-N is not always analysed separately in the discharge water, but at some plants where the ammonia content is a consent parameter recorded figures are found. Whenever found in the reports the analysis results are used in the balances. NO\textsubscript{3}-N is normally not analysed separately, but at some plants where a more thorough control is performed oxidised nitrogen is included in the analysis programme (Equation 4, Table 15).

**Nitrogen in air discharge**

The nitrogen discharge into air is often assumed to be found as N\textsubscript{2} but very seldom measured. However the SBR system, as with other activated sludge systems, will accordingly discharge certain amounts of N\textsubscript{2}O into the air (Park \textit{et al} 2001). This matter is seen as a “contribution” to the greenhouse effect, but the matter has no direct impact on the removal of nitrogen from wastewater. Thus, this matter is not further addressed in this thesis. The following balance has been used for calculating the denitrified amounts of nitrogen from the reactors (Equation 5, Table 15).

### 4.4.3 Calculations on specific nitrification and denitrification rates

One central part of the work is to estimate nitrogen removal efficiency, expressed as nitrification rate and denitrification rate, and especially to relate these rates to the water temperature. The following definitions are used in order to define the specific rates:

Estimations of the nitrification capacity expressed as g NH\textsubscript{4}N\textsubscript{ox}/kg VSS/h for the different plants are done in the following way. The amounts of nitrogen that are actually oxidised are determined by the following conditions:

- inlet amounts of total nitrogen are normally well defined by sampling and analysis. When a primary sedimentation is located upstream of the SBR facility a certain reduction of organic nitrogen takes place. However, among the plants studied, only the Nynäshamn facility has a primary sedimentation stage. In turn this plant also includes anaerobic digestion that hydrolys a substantial amount of the organic nitrogen into ammonia nitrogen. Thus, in the Nynäshamn case it is assumed that the nitrogen load into the SBR unit is the same as the load at the inlet to the plant;

- assimilated nitrogen in the biological process is assumed to be 5% (by weight) of the removed amounts of BOD;

- the nitrogen balance is then made up by deducting the discharge of non-oxidised
nitrogen in the effluent from the inlet amounts.

As a conservative model the nitrification is deemed to occur only during the aeration phases, when the aeration devices are in operating mode. However, it is very likely that the nitrification takes place also during the phases labelled “anoxic react” or even “anoxic fill”. The amount of MLSS is determined as the concentration under completely mixed conditions at low level in the reactor, multiplied by the reactor volume at the beginning of fill (or end of decant).

The ratio is expressed as g N<sub>ox</sub>/kg MLVSS/h. The reason for using the volatile part in the expression is based on the fact that the inorganic part does not participate in the biological activity. This fact becomes even more apparent as simultaneous precipitation is used at some of the plants (for instance in Holbaek, Olmanäs and Tjustvik). From this perspective the Nowy Targ plant is a specific case, as substantial amounts of chromium are loading the plant, and are further assimilated and or precipitated into the sludge mass (Paper VI).

The calculated nitrification rate is related to water temperature whenever the necessary data are available. Equations defining the nitrification rates and denitrification rates are presented (Equations 6 and 7, Table 16).

### 4.5 Analysis of oxygen demand and energy efficiency

Another aspect of the evaluation the SBR technology performance is the use of energy and to what extent the efficient use of the system may be “acceptable”. The main energy consumer at most activated sludge plant is the aeration system. The plants presented in the thesis are operated using different aeration devices, but all are based on bottom aeration. When oxygen requirements are calculated, the analysis has followed the same model as used for design purposes (Eckenfelder 1989). The equations used for the oxygen supply needs are the following (Equation 8, Table 17; Equation 9, Table 18):

<table>
<thead>
<tr>
<th>Table 15 Equations used for nitrogen balances over the SBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process mode</td>
</tr>
<tr>
<td>Nitrate Nitrogen discharge to water</td>
</tr>
<tr>
<td>Nitrogen discharge to air</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Legend for the used symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO&lt;sub&gt;x&lt;/sub&gt;-N&lt;sub&gt;discharge&lt;/sub&gt;</td>
</tr>
<tr>
<td>Total N&lt;sub&gt;discharge&lt;/sub&gt;</td>
</tr>
<tr>
<td>Total N&lt;sub&gt;inlet&lt;/sub&gt;</td>
</tr>
<tr>
<td>Org N&lt;sub&gt;discharge&lt;/sub&gt;</td>
</tr>
<tr>
<td>Org N&lt;sub&gt;sludge&lt;/sub&gt;</td>
</tr>
<tr>
<td>NH&lt;sub&gt;4&lt;/sub&gt;-N&lt;sub&gt;discharge&lt;/sub&gt;</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt; O</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 16 Equations to determine nitrification and denitrification rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process mode</td>
</tr>
<tr>
<td>Nitrification rate</td>
</tr>
<tr>
<td>Denitrification rate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Legend for the used symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR</td>
</tr>
<tr>
<td>N&lt;sub&gt;ox&lt;/sub&gt;</td>
</tr>
<tr>
<td>V&lt;sub&gt;reactor&lt;/sub&gt;</td>
</tr>
<tr>
<td>No</td>
</tr>
<tr>
<td>h&lt;sub&gt;aer&lt;/sub&gt;</td>
</tr>
<tr>
<td>h&lt;sub&gt;anaer&lt;/sub&gt;</td>
</tr>
</tbody>
</table>
The oxygen demand is calculated in two stages; at the first stage the oxygen requirement in wastewater is defined (Equation 8, Table 18). In the second stage the oxygen requirements in tap water are calculated under standardised conditions (Equation 9, Table 18). The aeration system is normally designed for performance tests on tap water. In order to transfer the oxygen need into SOR (Standard Oxygen Requirements) in tap water the conditions are defined by the following: the water temperature must be 20°C and no free oxygen can be in the water at the start of the test run. The conditions are “normalised” at sea level. The test procedures are defined by Standard Methods and ATV (the German Design Manual). The SOR value must however be related to different operational temperatures (Equation 9, Table 18).

An almost classic question with respect to the numeric value of “α”, is how the value varies both according to the type of aeration device and when during the aeration time “α” is defined.

If not specified some simplified
assumptions are made. For rubber membrane aeration system an “α”–value of 0.6 is used. For jet aeration systems, (installed in the Nynäshamn, Isätra and Norsa SBR plants) the chosen value is 0.7.

This calculation model has been used when the different plant performance figures are analysed with respect to energy consumption efficiency. The energy use is normally split between the blowers and the mixers. By applying the different operation modes – divided into aeration and mixing – the different plants are calculated with respect to energy use. It should be observed that in some cases the aeration time varies according to the variation in loading. This matter is accordingly highlighted when presenting the results.

When the F/M ratio is used as a comparison variable the ratio is based on the following relationship: kg BOD₅/kg MLVSS/d. As the BOD values in Swedish plants are based on the BOD₇, and all process calculations are based on BOD₅ the ratio BOD₇:BOD₅ = 1.15:1 is used and the F/M ratio is thus recalculated for all results from the Swedish plants.

The Solids Retention Time (SRT) is a central design and control variable for any activated sludge system. A mass balance defines the SRT. In the case of an SBR facility the definition is quite simple, the symbols used in this case are explained by the figure. (Equation 10, Figure 15).

A frequently addressed issue regarding SBR technology and its feasibility is energy consumption. In chapter 5 some of the plants included in this thesis are compared with respect to the energy they utilise. In order to give fairly comparable figures the total (electric) energy provided per day to the process is given, as well as specific power consumption, ex-pressed as kWh/kg BOD_removed and kWh/kg N_removed. A third way, not frequently used, is to express the energy efficiency related to the so-called OCP (Oxygen Consumption Potential, Equation 11, Table 20). The power actually used for aeration is calculated (Equation 12, Table 19). The OCP equation was initially suggested by Professor Halvard Ødegaard at Trondheim Technical University (personal communication) and has been used to express environmental efficiency when comparing different treatment options.

In this context the influence of phosphorus will be ignored as the removal of phosphorus is performed to a large extent by chemical precipitation, and thus it has been difficult to assess its biological removal accurately. As only one plant has operated with a distinct EBPR performance it is not relevant to include the phosphorus influence at this stage. Nevertheless biological phosphorus removal is an issue of efficient energy use in the activated sludge system. By including the efficiency of phosphorus removal, an “energy efficiency index” can be established for future assessment.

4.8 Discussion of the chosen methods

The method chosen to address and scrutinise plant performance and try and provide answers on relevant issues may be questioned as it is linked to certain risks. In order to address related questions the method is discussed by using a so-called SWOT analysis. This model is more widespread among economists, but may be a fruitful way to further assess the selected method. The expression SWOT stands for Strengths; Weaknesses; Opportunities and Threats.

The obvious **Strength**, by using long-term experiences and performance figures from plants in operation, is the abundance of data that is available from every plant covering

---

Figure 15 Mass balance model for suspended solids over a SBR unit

\[
\text{SRT} = \frac{V_o \times SS_o}{Q_3 \times SS_3 + q_2 \times SS_2}; \quad \text{Equation 10}
\]
several years’ operation. Another strength linked to the long-term operation is that the variations throughout a year are included in the results, for instance low water temperature in winter and spring time. A third potential advantage of the method occurs if the plant has been continuously operated by the same staff, with improved skills through close attention to the operation. This matter will be addressed for some of the plants. A fourth potential strength is at hand if the same (accredited) laboratory has been performing the analysis over a long period. This means in turn that the statistical method may be used with a high level of credibility, even if some values may differ substantially. As an example the performance data from Nowy Targ is used, (Paper VI). Another advantage of using operational data from plants in operation is that the classic shortcomings of laboratory bench-scale tests are avoided. Typical problems with a small-scale test facility, such as an increased influence of the reactor walls in a one to three litre jar test facility and temperature correction needs, are avoided. Weaknesses are related to some “risks” linked to a lack of scientific accuracy that may be found at a normal treatment plant. As stated, the internal process control is based on two major sources: grab sampling and on-line measurements. It is imperative that the grab sampling is performed with due skill, following three conditions for sampling: “Where”, “When” and “How”. If the internal sampling is not based on a well thought-out programme including all these aspects misleading false information may be derived. This problem is overcome by accurate training of staff responsible for sampling and control of the on-line instruments. In all plants included by experiments and studies these matters have been addressed at the commissioning period of the plant, or at the commencement of the experiments. With respect to the control of on-line instruments the regular cleaning is enforced by regular calibrations.

The conclusions derived from the measurements and calculations points of consideration. To give an example: a number of “qualified assumptions” must be done when a calculation of oxygen requirements for an activated sludge system is done. This is regardless of whatever mathematical model is used. When the calculations are done the different assumed factors such as $a'$ (specific oxygen utilisation for BOD oxidation) $b'$ (endogenous oxygen rate) are presented;

When the results from sampling and data from on-line meters are used it is important that a large a number of observations are available. This in turn provides good possibilities to examine the derived results. The use of statistical analysis is one useful way to address the results. Another way is to compare different pollution parameters. Some classic examples may be used: the ratio COD: BOD in influent and effluent water sampling; the ratio BOD: suspended solids in the effluent water sampling; the question of whether a nitrification inhibitor has been used in the BOD analysis on effluent water.

The Opportunities are related to the operation conditions, and most specifically to the chance that the plant is operated by a skilled and dedicated staff. As will be shown and discussed in the section on results, some plants have very skilled and ingenious operators. By closely observing the performance and changes in the process behaviour they sometimes find good ways to improve the treatment results substantially. In this perspective the SBR system offers unique possibilities, pointed out by scientists (Alleman 1978, Irvine 1983).

The Threats are accordingly related to “social” and “man/machine” related issues. The “mental depreciation” at a wastewater treatment plant is seen as a part of Threats (Paper I). This is most simply explained as ignorance or neglect on the part of the operators and/or owners of the plant with respect to the operational requirements. An example of such a situation will be discussed in the following section. This will inevitably lead to a situation where the presented operation data and performance figures will be of limited value.
5 RESULTS AND DISCUSSION

5.1 General

As already indicated in the selection of the plants included in the study two main categories with respect to the origin of the wastewater may be distinguished:

- municipal wastewater, with or without the influence of various industrial wastewaters, are discussed in all seven plants (Dokkas, Tjustvik, Nowy Targ, Nynäshamn, Holbaek, Ölmans and Chon Buri);
- leachate from sanitary landfills. The results from three plants (Bösarp, Norsa and Isätra) are discussed.

The main hypothesis in this thesis is that SBR technology may be used in a competitive manner with other biological treatment systems also when treating cold wastewater. A useful way of looking at this is to analyse the efficiency of biological nutrient removal at the low water temperature conditions occurring at the different plants. In this respect both nitrogen removal and biological phosphorus removal are analysed and discussed. The fundamental fact is that nitrogen removal is related both to water temperature and to the (mean) Solids Retention Time (SRT). This in turn makes it both logical and important to analyse the sludge quality. The main aspects are the settling characteristics, the variation of the volatile fraction in the sludge as a function of the water temperature, and the limitations on process performance due to the tendencies of bulking sludge.

Another important factor in SBR operation is how the cycle is used to meet the stipulated treatment results. All the plants included in the study have profited from the inbuilt flexibility of the batch mode to alter both the cycle length and the cycle composition to meet variations in load and wastewater temperature, as well as to handle more stringent effluent demands. This matter is described and discussed.

5.2 Prevailing water temperature

For all the plants in the study, with one exception (Chon Buri in Bangkok), climatic conditions with varying water temperatures throughout the year have the greatest effect on operation. The most apparent example is represented by the Dokkas SBR test plant, where the water temperature varies from 3 - 10°C over the course of one year (Paper II). Annual temperature variations at the plants are illustrated with example from four municipal plants: Nowy Targ, Holbaek, Ölmans and Nynäshamn (Figures 16 through 19). Temperature variations are also presented for all plants (Table 20 and Table 21). At Chon Buri plant is the temperature consistently higher than 20°C.

The water temperature at the plants shows the classic seasonal variation in North European municipal treatment plants, reaching low points during early the spring months, when the effect of melting snow is important. The low temperature reaches 5 – 6°C, while the maximum temperature is 18°C.

The temperature pattern shown for the leachate SBR plants needs some comments:

- Norsa SBR plant for leachate treatment operates with a heat exchanger, keeping the water temperature at 15°C throughout the year, apart from the summer months, when the temperature reaches 20°C (Paper IV);
- the two SBR plants in Isätra and Bösarp have a typical temperature variation for leachate emanating from landfills in Sweden. The winter temperature comes down to 0°C while the peak temperature in late summer is well above 20°C.
**SBR-technology - use and potential applications for treatment of cold wastewater**

**Figure 16** Temperature variations in incoming wastewater to Nowy Targ SBR plant, monthly mean values during 2005

**Figure 17** Temperature variations in incoming wastewater to Holbaek SBR plant, 24 observations during 2006

**Figure 18** Temperature variations in incoming wastewater to Ölmanäs SBR plant, 26 observations during 2005

**Figure 19** Temperature variations in incoming wastewater to Nynäshamn WWTP, 24 observations from end of 2006 through 2007

<table>
<thead>
<tr>
<th><strong>Table 20</strong></th>
<th>Water temperature variations at leachate SBR plants included in the thesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>Bösarp</td>
</tr>
<tr>
<td>Max temp. °C</td>
<td>21</td>
</tr>
<tr>
<td>Duration of temp. &gt; 15 °C</td>
<td>June - Sept</td>
</tr>
<tr>
<td>Duration of temp. &lt; 10 °C</td>
<td>Oct- April</td>
</tr>
<tr>
<td>Min temp. °C</td>
<td>&gt; 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Table 21</strong></th>
<th>Water temperature variations at the municipal WWTPs included in the thesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>Dokkas</td>
</tr>
<tr>
<td>Max temp. °C</td>
<td>10</td>
</tr>
<tr>
<td>Duration of temp. &gt; 15 °C</td>
<td>None</td>
</tr>
<tr>
<td>Duration of temp. &lt; 10 °C</td>
<td>Jan - Dec</td>
</tr>
<tr>
<td>Min temp. °C</td>
<td>3</td>
</tr>
</tbody>
</table>
5.3 The cycle composition – SBR operation strategy

By convention the operation cycle composition is one of the key factors in an SBR system. In this respect it is important to distinguish between the cycle compositions found in bench-scale tests and small pilot plant operations on one hand, and on the other the cycles used in full-scale treatment facilities. In order to illustrate this statement two different cycle compositions are shown; (Table 22).

Table 22 Comparison of two different operation cycle models, Bösarp leachate treatment test facility and Nowy Targ full-scale plant (all times in h)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Bösarp</th>
<th>Nowy Targ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor volume</td>
<td>0.500 m³</td>
<td>7,600 m³</td>
</tr>
<tr>
<td>Fill</td>
<td>0.17</td>
<td>1.5</td>
</tr>
<tr>
<td>Fill + react (aerobic)</td>
<td>0.5</td>
<td>n.a.</td>
</tr>
<tr>
<td>Idle</td>
<td>1.8</td>
<td>n.a.</td>
</tr>
<tr>
<td>Mix</td>
<td>2</td>
<td>n.a.</td>
</tr>
<tr>
<td>React 1 (aerobic)</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>React 2 (anoxic)</td>
<td>6</td>
<td>n.a.</td>
</tr>
<tr>
<td>Settle</td>
<td>1.75</td>
<td>1</td>
</tr>
<tr>
<td>Decant/Idle</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>Total time</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td>Ratio fill/total cycle</td>
<td>0.17/24</td>
<td>2/6</td>
</tr>
</tbody>
</table>

While the test plant operation at Bösarp used typically a Fill period of ten minutes in a total cycle length of 24 hours (Table 23), the Nowy Targ plant (a three reactor SBR facility) used two hours for Fill – out of a total cycle length of six hours. This difference in cycle composition between a test facility on one side, and any full-scale treatment facility is typical and to a certain extent necessary due to practical reasons. Early laboratory tests with SBR techniques indicated that the “extreme” low ratio Fill time/total cycle time would strongly improve the sludge quality (Schroeder 1975, Chiesa & Irvine 1979). Most laboratory tests on various SBR process applications have used a similar model for filling (Marsili Libelli et al 2001). In establishing a model simulation for SBR processes they used a six-litre bench-scale reactor working with a six hour total cycle: of which the Fill time was an increment of the total time. The work was done with synthetic wastewater. A “semi-full” scale SBBR (Sequencing Batch Biofilm Reactor) was used to establish an enhanced phosphorus removal used a similar model of filling versus the total cycle time (Arnz et al 2001). The total reactor volume was 17 m³, and the operated cycle was 520 minutes, whereof the Fill time was 20 minutes and the react time (mixing and mixing +aerate) was 480 minutes. A SBR bench-scale reactor was used to test the performance on filamentous sludge (Dagot et al 2001). The following cycle model was used: total cycle time was 24 hours, of which one hour was filling and mixing, twenty hours aeration, two hours for settling and one hour for decant and sludge wasting.

The arrangements in a laboratory test would favour an operation mode with an incremental filling time due to practical reasons, as shown in the different studies above: a continuous filling over an extended time would need a very small-sized feeding arrangement. Other practical arrangements, such as controlling the parts of the cycle, are to a certain extent related to working hours, and so forth. However, taking into account laboratory results (Hoepker & Schroeder 1979), there may be a systematic problem inherent when using laboratory tests to predict a full-scale SBR design and operation:

- technical arrangements needed for a laboratory facility differ substantially from the needs for a full-scale facility;
- inlet flow variations to a full-scale SBR facility will limit the possibilities of operating within a very short fill time;
- as a consequence, and taking into account the rather unique situation in a bench-scale operation, it is advisable not to extrapolate the results from a small-scale test into a full-scale facility “blindfold”. In this context, when considering SBR technology it is especially important to address the filling time as a part of the total cycle time.

Different models have been employed to make the Fill/total cycle time ratio as low as possible in full-scale applications:

- use of upstream equalisation basins, allowing for a shortened filling time. The Ölmanäs plant is an example of this model (Paper VII);
• use of more parallel SBR units. In the case of Holbaek the equally sized reactors number four and in Nowy Targ the number of reactors is three (Paper VI and Paper VIII). As seen in the Fill/total cycle time ratio in Nowy Targ was 1:3, to be compared with the test operation in Börsarp; where the ratio was 0.17/24 (Table 23, Paper IV).

Even so, the possibility of operating a full-scale SBR plant using a very short fill time is limited. The operational mode in Holbaek with four large and two smaller reactors would allow a Fill/total cycle time ratio of 1:5.

Another aspect of the possible cycle options is demonstrated whenever the number of reactors at a plant is more than two. As found at most of the plants studied an increased number of SBR units will allow for a substantially shorter total cycle time, compared with a two-reactor facility (Papers II through VIII). This statement is most clearly illustrated in the case of Nynäshamn SBR plant where four reactors are operated with a total cycle time of about 2.4 hours (Paper VII). This in turn means that the ratio Fill/total cycle time is 0.35/1. The theoretically possible ratio for a four-reactor system would be 0.25/1 if no equalisation were used. This in turn calls for a “modified” approach to the issue. It would be more adequate to use a ratio based on Fill time versus Fill time + total react times, rather than the total cycle time. Using the latter would allow for a comparison with the conventional activated sludge systems, labelled as either totally mixed or plug flow systems. The SBR system has often been characterised as either an ideal totally mixed system – when the Fill sequences are followed directly by Settle – or as a more or less ideal plug flow system. Comparisons, however, are always delicate when such different treatment modes as a batch system and a continuous flow system are addressed.

A simple question arises: what would be the ratio Fill/Fill + total react time necessary to characterise the system as either being totally mixed or a plug flow system? Looking at the different phases of the total cycle the following may be stated: as long as the plant is operated during the different Fill time sub-phases – with the exception of a static Fill time - the operation mode is typically a total mix situation. As soon as the Fill time is terminated and the React phases continue the reactor is operated as an ideal plug flow system, where the length of the React time “indirectly” defines the plug flow “degree”.

Now even more complexity with respect to an “SBR plug flow system” may be addressed: at many SBR operation plants with a long React phase it is observed that the readily available substrate and ammonia is consumed by heterothrophs and autotrophs well before the ending of the React time (Figure 20). The rapid increase in the free oxygen level at the end of the React phase indicates that the need for oxygen is limited at this stage of the cycle. The finalising time of the aerated React may resemble most of all a sludge re-aeration basin in a continuous flow system.

### Table 23 Comparison of the SBR cycles at five full-scale plants included in the thesis

<table>
<thead>
<tr>
<th>Phase</th>
<th>Nowy Targ</th>
<th>Holbaek</th>
<th>Ölmanäs</th>
<th>Tjustvik</th>
<th>Nynäshamn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill 1</td>
<td>Anoxic 1 h 30 min/30 min</td>
<td>Aerobic 81 min</td>
<td>Anox &lt; 80 min</td>
<td>Aerobic 51 – 132 min</td>
<td>Anox 5 – 20 min</td>
</tr>
<tr>
<td>Fill 2</td>
<td>Aerobic 30 min/1 h 30 min</td>
<td>Anox 19 min</td>
<td>Aerobic &lt; 100 min</td>
<td>Aerobic/anox 125 min</td>
<td>Aerobic/anox 54 min</td>
</tr>
<tr>
<td>React</td>
<td>Aerobic 2 h</td>
<td>Aerobic/anox 41 min</td>
<td>Aerobic 30 min</td>
<td>Aerobic/anox 125 min</td>
<td>Aerobic/anox 54 min</td>
</tr>
<tr>
<td>Settle</td>
<td>1 h</td>
<td>89 min</td>
<td>&lt; 60 min</td>
<td>&lt; 60 min</td>
<td>35 min</td>
</tr>
<tr>
<td>Decant/Idle</td>
<td>&lt; 1 h</td>
<td>20 min</td>
<td>&lt; 100 min</td>
<td>&lt; 60 min</td>
<td>35 min</td>
</tr>
<tr>
<td>Total cycle time</td>
<td>5 h 30 min</td>
<td>4 h 10 min</td>
<td>&lt; 100 min</td>
<td>7 h</td>
<td>&lt; 35 min</td>
</tr>
<tr>
<td>Sludge waste</td>
<td>0.045 – 0.27</td>
<td>0.032 – 0.10</td>
<td>0.032 – 0.05</td>
<td>0.04 – 0.05</td>
<td>0.1 – 0.26</td>
</tr>
<tr>
<td>F/M value</td>
<td>kg BOD/kg VSS</td>
<td>kg BOD/kg VSS</td>
<td>kg BOD/kg VSS</td>
<td>kg BOD/kg VSS</td>
<td>kg BOD/kg VSS</td>
</tr>
</tbody>
</table>
A comparison of the cycle compositions at some plants presented, with special attention given to the ratio Fill time/total cycle time and Fill time/ (total Fill time+ total react time), illustrates the variety (Table 24). The Dokkas plant is not included in the following comparison, as the aim in that case was not to operate with nitrogen removal (Paper II).

Another aspect of the SBR operation with respect to the cycle “strategy” and its flexibility is described as follows. Traditionally the total cycle length for a single reactor has been set at an even fraction of 24 hours – for instance 3 hours (equal to 8 cycles per day); or a rather typical length of 4.8 hours (equal to 5 cycles per day). Initially the different plants presented in the papers followed this pattern: for instance the cycle time in Nowy Targ was set at 6 hours (equal to 4 cycles per day). A consequence of this model is that a specific reactor will start its cycle at a constant time each day, for instance at 09.00 hours. This in turn may be advantageous for the practical operation of the plant: the operator will “know” exactly when a specific phase will enter into operation at any of the reactors. At Nowy Targ, however, this matter became an evident problem with respect to performance. As described, the plant successively received an increasing load over several years (Papers VI and VIII). In 1997 the loading had reached levels that principally exceeded some of the design levels. A specialised study on adjusting the cycle length based on a computerized model was performed and presented (Mikosz et al 2001). The final recommendation was to change the cycle to 8 hours, thus limiting the hydraulic capacity of the plant. The proposed change included a substantial extension of the aerated React phase. This scheme was however never implemented, owing to different reasons that resulted in a modification of the cycle length to 5.5 hours in each reactor. This in turn means that “an overall cycle” for the entire plant was implemented: The start of the filling hour now changes from day to day. By adopting this cycle length the “total” time needed for a single reactor to “come back” to the original starting hour for a given cycle is 11 days. This means that the “daily peak loading hour” is received every third day in the same reactor, and not in the same one every day. In the case of Nowy Targ it was possible to take advantage of the PLC system and alter the cycle length and cycle composition in accordance with process needs.

5.4 Sludge quality aspects

5.4.1 Sludge volume index and sludge quality index; influence on sludge separation performance and influence of SRT

The second decisive factor for the good performance of any activated sludge system is the character of the sludge, not only with respect to the obvious (mean) Solids Retention Time, in the following labelled SRT, but also the microbiological composition of the sludge. An often used relation between the SRT needed for full nitrification, including safety factors and the water temperature is shown (Figure 21, Kos et al 2000). This figure illustrates both the “conventional” aerobic SRT needed for complete nitrification, and the same values for a process using a sludge re-aeration model. The difference as presented may be attributed to a “better control” of the unstable situation when a separate sludge re-aeration is included in the continuous flow. This matter has also some relevance when looking at the SBR process.
Considerable attention has been given to the fact that different operation modes will enhance or decrease the possibility of operating an activated sludge plant with good stability. Especially important from the sludge quality perspective is the risk of creating bulking sludge, caused by filamentous growth. The matter was an early concern for the systematic studies in SBR performance (Schroeder 1975, Irvine & Richter 1979). Some bench-scale studies showed very critical and “narrow paths” to establish good sludge quality characteristics. The obvious “problem” with transferring results from bench-scale studies on SBR performance to full-scale situations is discussed in the following chapter on SBR cycle composition and possible models to master the problem with bulking sludge. On the other hand it has been advocated that the SBR cyclic operation mode be run from “feast” to “famine” as a decisive factor in keeping the sludge properties within a desired range (Irvine 1983). When addressing the sludge quality the so-called SVI value (in ml/g) has been a widespread model for estimating the sludge quality. Reports are given on SBR plants operated with severe problems with very high SVI values, (Teichgräber et al 2001). The following SVI ranges have been used to define the properties (German design manual ATV 2000, Table 24).

<table>
<thead>
<tr>
<th>Treatment target</th>
<th>SVI (l/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial/commercial wastewater influence</td>
<td></td>
</tr>
<tr>
<td>Favourable</td>
<td>100 – 150</td>
</tr>
<tr>
<td>Unfavourable</td>
<td>120 - 180</td>
</tr>
<tr>
<td>Nitrification and denitrification</td>
<td>100 – 150</td>
</tr>
<tr>
<td>Sludge stabilization</td>
<td>75 - 120</td>
</tr>
</tbody>
</table>

However the sludge quality problem is not limited to the matter of filamentous growth. A summary of typical sludge quality problems, related to origin and process consequences is shown (Table 25, and Andersson 2006).

An excess of filamentous growth in the SBR process seems to occur rather seldom (Irvine 1983). Only a few occasions of filament dominance in the process have been reported during about ten years’ operation of SBR plants in Sweden. A recent study was performed in 2005-2006 at the Tjustvik SBR plant outside Stockholm, focusing on microbiological behaviour (Andersson 2006). The in situ study could identify filament dominance on one occasion (February 2006), but this did not affect the performance. No
excessive sludge discharge was reported. A similar experience was reported from the Ölmanäs SBR plant (Paper VIII). During more than twelve years of operation excessive filaments, causing high SVI value (around 300 ml/g) was observed on one single occasion. The problem was resolved by a decrease in the decanting velocity. The stable sludge blanket level was about one metre below the low water level in the reactor (personal communication with the plant staff). The situation in the Ölmanäs plant with very stable sludge characteristics was confirmed from the Nowy Targ SBR plant operation. The amounts of the MLVSS (Mixed Liquor Volatile Suspended Solids) are taken from the actual measurements of the MLSS concentration in the reactor. As the MLVSS fraction of the total MLSS varies with water temperature the following assumption is made when no specific measurements on MLVSS are done (Figure 22):

- Winter conditions 0.82:1;
- Spring and fall conditions 0.78:1;
- Summer conditions 0.75:1.

Sludge quality index (SQI) for the three SBR units in operation during nine months in 2005, with the monthly average figures are presented (Figure 23). By comparing the ratio between SVI and SQI for these observations the following variation in the ratios is found (Table 26).

Another way to illustrate the sludge quality “stability” in the three reactors is to analyse the SQI variation over a two-month period; where an “extreme” SQI value has occurred. This “extreme” value occurred once during the period and, according to the regular plant
control; the value has not persisted (Figure 24).

On the other hand the formation of pinpoint sludge in the SBR process has been observed, and resulted in excessive sludge discharges. However, it should be emphasised that this discharge was also linked to rather poor technical arrangements for the decanting of treated water. The first experiences were noted at a test plant operated in the late 1980s at Lund, in the southern part of Sweden. More recently the SBR plant in Norsa, Köping in central Sweden suffered from very high suspended solids concentrations in the decant water (Paper IV). In both cases the formation of pinpoint sludge seems to be closely linked to an extended SRT, in the vicinity of 50 to 60 days. The Lund test plant operated for a couple of years, and the first clear experiences of pinpoint sludge was related to the fact that no controlled wasting of excess sludge had occurred.

The Norsa plant treats landfill leachate and performs nitrogen removal. During the first years of operation, when the SRT was allowed to exceed 50 days, the suspended solids levels in the discharge averaged 86 mg/l, with a maximum value of 231 mg/l and a minimum value of 17 mg/l observed in 2003. The problem was lessened by controlling the SRT more closely, keeping it in the range of 25 – 30 days. After this modification the following discharge levels were observed (January 2004 to April 2006): the average suspended solids content in the decanted water from the reactor was 18.6 mg/l, maximum value 44 mg/l and min. value 5.6 mg/l.

A third sludge management problem was addressed when the SRT exceeded about 40 days, due to the need for sludge control efficiency. The start-up of the Tjustvik plant seems to have confirmed this observation, as the SRT was allowed to exceed 40 days, followed by a “secondary release” of phosphates from the sludge (Paper III). This matter is likely linked to a very high degree of mineralization of the sludge – thus leaving too little organic matter to keep the phosphorus bound in the sludge flocs. The solution in the Tjustvik case was to take down the SRT to about 20 days. This level has ever since been kept at the plant. The early release of phosphorus has not occurred again; see further presentation in the following chapter on phosphorus removal.

Other problems related to a too high suspended solids concentration in the effluent (> 50 ppm) have mainly been related to poorly built decanter devices. The issue of decanter construction is discussed in the following section.

### 5.4.2 Settling and decanting techniques in an SBR system

The settling and decanting phases of the SBR cycle are by convention critical: settling is defined as an “ideal settling” when no disturbing “activities” take place in the reactor (no influent or effluent flow takes place during settling). Nevertheless, the settling efficiency is related to the sludge quality and water temperature. The Dokkas SBR test facility demonstrated a good example of the temperature impact on settling rate: when the water temperature changed from 10°C to 3–4°C the necessary settling time doubled from one to two hours (Paper II). An analysis of SBR and continuous activated sludge systems settling properties was made by using a “Flexibility Index” on the different processes (Hopkins et al. 2001). A conclusion was that the SBR system has a “bottleneck” in terms of flexibility caused by the settling phase and concluded that very deep SBR basins would limit the flexibility. The authors define the flexibility index “F” as “the maximum deviation of the uncertain parameters from a nominal point that allows feasible operation”. They illustrated the limited F value for the SBR process in relation to settling and tank depth (Figure 25). All the SBR plants in this thesis are designed with a maximum water depth of less than five metres. Another conclusion was that the chosen tank depths should include a favourable flexibility with respect to settling (Hopkins et al. 2000). However, the flexibility index incorporates by convention a number of qualitative factors that may be disputed from quantitative
perspectives. With this in mind it would be advisable to use such an index with some caution, and incorporate whenever possible quantified observations when conclusions are drawn.

Regardless of the technical configuration the decanters have to respond to some criteria, all imperative for the safe and correct operation of any SBR system. The hydraulic capacity must be sufficient to evacuate the maximum “batch” amounts in a sufficiently short time otherwise the decanting time will “occupy” too much of the total cycle time, and thus “steal time” from the other phases in the treatment cycle.

The decanter must be sealed during all cycle phases, with the obvious exception of the decanting period; otherwise an uncontrolled and unwanted discharge of suspended solids will be built into the system. This has been the case with too many reactor systems, and has resulted in difficulties with controlling the sludge content and the necessary SRT in the reactor. This situation was fond in the Dokkas test operation (Paper II). The decanter must be built in such a way that no vertical “surge” flow occurs in the reactor when the decanting starts. Such a vertical flow may cause an evacuation of settled activated sludge.

It is advantageous that the decanting takes place at a level in the reactor at a “maximum” distance from the sludge blanket in order to minimise the risks for the evacuation of settled sludge (Figure 26).

5.5 Nitrogen removal

5.5.1 Nitrification performance at low water temperatures

To analyse and question the main hypothesis for this study – on the low temperature influence of the SBR process – the most obvious way is to look at the nitrification performance at the different plants. In all cases nitrification seem to be more crucially related to temperature than denitrification. All the plants built and operated in Scandinavia and Poland (presented in Papers II through VIII) confirm the fact that the SBR operation is capable of producing consistently good and high total nitrogen removal, even under very different and sometimes challenging conditions. In this perspective it is important to address rapid changes in water temperature. The risk for a wash out of nitrifiers at rapid temperature sinks is obvious and has been underlined (Hwang & Oleszkiewicz 2007). On the other hand as long as the temperature change is slower it seems that the nitrifiers have a capacity to adjust to the changes.

The five plants operated with mainly municipal wastewater, and geared toward nitrification, all treat low temperature wastewater during winter conditions. This statement will be presented and discussed for all the five municipal plants, along with views on the potential “wash out” of nitrifiers. The latter phenomenon is linked to the chosen SRT, the prevailing temperature and the specific nitrification rates. An important observation is the following: at several plants nitrification has been completed, regardless of the prevailing water temperature. A “complete nitrification” is, in the following, defined as a remaining NH$_4$-N concentration of less than 1.0 ppm. This in turn means that the calculated nitrification rate in these cases may not be the actual one, but a “minimum” rate. The plants are generally not operated with the capacity to optimise the combination of supplied oxygen, aeration time and residual NH$_4$-N level. These circumstances mean that aeration goes on
even after complete nitrification is achieved in the reactor. The main reason for this circumstance is a limitation either in the equipment – on-line measurement possibilities - or an insufficient flexibility in the PLC system applied. However, all the plants have some provision in their operation to meet the variations in oxygen requirements under different load conditions.

The biological treatment of leachate using SBR technology may be seen as a rather specific situation, yet still contributing to the overall understanding of the process. This statement is based on the very specific composition of a leachate, (Paper V). Thus the results from the three SBR facilities operated with leachate are discussed as a background to the findings at the municipal plants.

The “over capacity” with respect to nitrification may be illustrated by comparing the discharge NH₄-N level (in mg/l) with the calculated specific nitrification rate (in g NH₄-N/g VSS/h) obtained at Isättra SBR plant for leachate treatment (Figure 28). The aeration time per day (distributed between two cycles) varied between 9 hours 40 minutes to 12 hours during operation time. The leachate temperature varied from a few degrees above 0°C during January through March, to about 18°C in August. The VSS concentration in the reactor was on an average about 4.5 kg VSS/m³ and the flow varied from about 50 to 100 m³/d with a median flow = 86 m³/d. The figure shows that no close relation between the nitrification rate and the seasonal variation is found. The fact that the nitrification rate is modest to low during the second and third quarters of the year would be an indication that the plant is operated below its potential. This fact also explains why the nitrification is maintained under low temperature conditions. A logarithmic relation seems to be the most relevant one. However, during the following years (from 2003 onwards) nitrification was at almost zero from January through March or April. When complete nitrification is established in springtime the time needed seems to be about fourteen days. The established nitrification prevails until mid-November or even until December. The relationship between nitrogen loading and the nitrification rate is presented, regardless of the prevailing water temperature (Figure 27). If the nitrogen load and nitrification rate are compared throughout a year (2002) the picture is more complex (Figure 28). It is not easy to relate the nitrification rate to the nitrogen load. The pattern found in Figure 27 may be seen as an indication that the potential nitrification rate is actually higher than the calculated ones from the operation data. The “best” relation is found to be logarithmic – although the relation is not very strong, the R² value is = 0.5322. It should also be observed that the low water temperature in 2003 did not stop the nitrification in the reactor. During later years the nitrification faded out during the last...
months of the year (November – December). The nitrification rate in this case is substantially lower than the observed rates for the plants treating municipal wastewater. The highest single observed nitrification rate is less than 1.2 g N/kg VSS/h. Additional reporting on the Isätra plant performance has been presented (Johansson Westholm 2003).

The pilot plant operation at the Bösarp landfill site outside Varberg gave other results that revealed the temperature influence on nitrification performance (Paper IV). The leachate composition in this case was quite different compared with the other plants treating leachate Isätra and Norsa (Paper IV). The most important aspect was that the landfill received refuse with a high content of easily degradable organics (BOD₃) in the water (Paper IV, Morling et al 1989). The ratio COD: BOD was less than 1.4:1, while a covered landfill in the methane stage has a ratio COD: BOD of about 10:1. Another important characteristic of the leachate in Bösarp was the high total nitrogen level, compared with the other two landfill leachate water compositions. The average total nitrogen level ranged from about 450 to 500 mg N/l; whereas the Isätra and the Norsa plants treat incoming leachate with 60 – 150 mg total N/l. The nitrogen in the Bösarp case was almost completely hydrolysed into NH₄-N. An interesting observation from the Bösarp tests remains with some relevance to current research on ammonification operations (Chapter 4, Paper IX). Different inorganic nitrogen compounds in the leachate during the initial operations were measured (Paper IV). Although the water temperature was less than 15°C the performance shows clearly that the NO₂ occurrence preceded the oxidation into NO₃.

The aim at the Bösarp plant was not to run

![Graph showing nitrogen load and nitrification rate](image)

**Figure 27** Isätra SBR plant, operation 2003, relation between nitrogen load and nitrification rate (24 observations);

\[ y = 0.9356 \times \ln(x) - 1.496; R^2 = 0.5322 \]

![Graph showing nitrification rate and discharge ammonia nitrogen concentrations](image)

**Figure 28** Nitrification rate and discharge ammonia nitrogen concentrations at Isätra SBR plant for leachate treatment, 2002 operation figures
the plant with a nitrification of the ammonia nitrogen. However, the result indicates the possibility of running the treatment mode in such a way even when the water temperature is rather low.

By using the figures from the last period of test operations in Börsarp, with the 70 m³ reactor, and a daily loading of 14 m³ leachate it is possible to estimate the highest nitrification rates, with water temperature at about 12°C. The rate seems to have been about 2 mg N_ox/kg VSS/h. More remarkable is the finding that it was possible to maintain the nitrification even at very low water temperatures during the winter operation 1988, where a more comprehensive presentation of the results from Börsarp test facility is found (Paper IV, Morling et al 1989). By contrast, the Norsa SBR plant for leachate treatment is operated at a more or less constant water temperature throughout the year of 15°C. Thus the nitrification rates taken from the performance figures may be related to variables other than the temperature. This matter is further discussed in the following section. The plant has been operated with a very stable and “complete” nitrification ever since its third year of operation (Paper IV).

Reverting to the results from municipal WWTPs water temperature variation during the year may be observed along with the loading and the nitrification capacity (Papers II and III; Papers VI and VII). From this perspective the test operations in Dokkas case should be studied. The main objective of the study was to establish biological phosphorus removal at low temperatures and not to establish nitrogen removal, (Paper II). It is striking to find that a partial nitrification has occurred already at very low water temperatures - between 6-8°C. At the same time the (total) SRT was 10 -15 days. On the other hand the “aerated SRT” was about 6 – 8 days. These results may be compared with the findings from the other plants in the study, operated under similar conditions with a “deliberate” nitrification/denitrification operation mode.

The performance data from the Nowy Targ SBR plant demonstrate nitrogen removal at low temperature (Papers VI and VIII). For this plant a number of circumstances should be taken into account: as already shown the water temperature in winter is down to 6°C. In the second place the plant is heavily loaded – beyond its nominal capacity, and thus treats regularly high organic loads along with high nutrient and chromium loads. The following discussion is mainly related to the more recent operation performance figures. The 2005 operation performance provides an opportunity to illustrate both the removal capacity and the temperature influence. An illustration of the discharge levels of total nitrogen during 1st and 3rd quarters of 2005 at the plant is shown (Figure 29). The corresponding removal efficiencies during these two periods are recorded (Table 27). The figure shows that the nitrogen removal is very substantial even under winter conditions, at low water temperature. The incremental improvement during the summer season is less than 8%; however an influence of the water temperature on the nitrogen removal level is clear. In addition to the results presented above it is important to observe that the nitrogen loading during summer was higher than the in the winter 2005, (Paper VI).

<table>
<thead>
<tr>
<th>Period</th>
<th>1st quarter 2005</th>
<th>3rd quarter 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of observations</td>
<td>29</td>
<td>25</td>
</tr>
<tr>
<td>Water temperature, °C</td>
<td>6 – 10</td>
<td>15 -20</td>
</tr>
<tr>
<td>Max. value</td>
<td>91</td>
<td>94</td>
</tr>
<tr>
<td>Mean value</td>
<td>85.9</td>
<td>92.0</td>
</tr>
<tr>
<td>Median value</td>
<td>86.1</td>
<td>92.0</td>
</tr>
</tbody>
</table>

Table 27 Removal efficiencies (%) on nitrogen removal 1st and 3rd quarters 2005 at Nowy Targ WWTP
Temperature effects on the nitrification/denitrification are also found at the Tjustvik plant (Paper III) and Nynäshamn plant; (Paper VII, Berg & Biderheim 2004, Franquiz & Morling 2006). The discharge levels of total nitrogen and ammonia nitrogen from the Tjustvik plant is presented (Figure 30). The 2003 operation at the Tjustvik plant represents probably the “best” overall results over a ten-year period. The plant operates with an addition of septic sludge to the SBR units. However, the addition is concentrated from April to the end of October, due to climatic conditions. The additional load from the septic sludge, expressed as organics or nutrients, is not analysed regularly. Thus the true loading of the SBR plant may be underestimated during the “loading season”.

The load variations may explain the short-time peak discharge levels of nitrogen in August and October 2003, while the peak discharge in March is most likely attributed to the drop in water temperature. The recovery of full nitrification is accordingly swift in August and October. During March however, the nitrification recovery seems to be slower.

For the Nynäshamn case the operating conditions are somewhat different as the plant operation in four stages means that the removal of different pollution variables is optimised in the different stages. The pre-precipitation + primary sedimentation is used for a 45-50% removal of organics, and a 40% removal of phosphorus. The SBR unit is used for the main biological removal of organics (additional 50%; incrementally about 90% removal), and limited to high nitrification and denitrification (summer values up to 80% total nitrogen removal). Also a substantial phosphorus removal takes place in the SBR units, up to an additional 50% of the incoming phosphorus content is retained in the biological sludge. Finally the SBR system receives and treats septic sludge. The post-precipitation is used for a polishing of the
phosphorus and suspended solids. Finally the wetland facility is used for minimizing the discharge levels of nitrogen and phosphorus. These conditions have resulted in unique possibilities for perform the nitrogen removal:

- the SBR facility is operated with a very short cycle time, about 2.4 hours per cycle;
- addition of septic sludge to the SBR basins may be done mainly at night in order to use the reactors as efficiently as possible;
- as for the Tjustvik plant the septic sludge may serve as a carbon source for denitrification.

The Nynäshamn SBR plant was capable of delivering a complete nitrification during the summer and fall periods of 2004 (Berg & Biderheim 2004). However the study does not cover the coldest periods (with respect to water temperature). By studying the results during the spring months of 2004 and 2006, and the last quarter of 2005 (results from the first quarter of 2005 are not available) when the temperature was 10 – 12°C, it is possible to assess the temperature influence on nitrogen removal in the Nynäshamn SBR plant. Mass balances with respect to nitrogen and BOD are presented (Figures 31 through 32). These balances are based on the regular sampling and analysis work performed at the plant.

From these mass balances, and taking into account the rather low temperature, it is possible to conclude that the nitrification capacity is more or less intact, and the limitation in the denitrification may be attributed both to the operation mode – leaving a very short time for anoxic/react phases – and the ratio between BOD$_5$ and total nitrogen in the incoming water.

![Figure 31](image1.png) Nitrogen balances and specific nitrification at the Nynäshamn SBR plant, 1st quarter 2004, 13 observations, water temperature 7 – 10°C

![Figure 32](image2.png) Nitrogen balances and specific nitrification at the Nynäshamn SBR plant, 1st quarter 2006, 12 observations, water temperature 6 – 10°C

![Figure 33](image3.png) Nitrogen balances and specific nitrification at the Nynäshamn SBR plant, 4th quarter 2005, 12 observations, water temperature 10 – 12°C
5.5.2 Solids Retention Time in SBR systems with nitrification

At all the municipal plants a typical and “adequate” total SRT has been established after some time, where the operators’ close attention and ability to observe the process performance has been of importance. It is important to underline that the plants all run with an SRT defined in the “conventional” way, see further the discussion below, of less than about 22 days. The “seasonal correction” due to decreasing and increasing water temperature has been rather modest. Most scientists acknowledge the crucial importance of the need for a sufficient SRT to achieve the desired treatment results, especially with respect to nitrogen removal. A “conservative” suggestion has been made that the “efficient SRT” would always be related to the time used for mixing and aeration only in the reactor (Artan et al 2001). Thus the time for settling, decant and idle would be subtracted from the SRT. The argument for this “conservative” view is that during settling and decanting periods no microbial activity is “supported” by the process operation mode. This may be a very practical viewpoint for designing purposes. However, the observations both at test plants and full-scale operations contradict this view. During settling a substantial denitrification takes place, that to some extent also continues during decant. The indications for this statement are mainly the following:

- during initial settling the reactor has to dissipate a substantial kinetic energy, and goes from an ideal mix situation to settling. During this phase the free oxygen level decreases, and an incremental effect may be found on the nitrogen compounds;
- occurrence of sludge floating up to the surface during settling – most likely caused by nitrogen gas acting as flotation support – and some measurements showing that the NO₃ – N level decreases during Settle! This phenomenon has been reported from large-scale continuously working nitrification/denitrification plants such as the main Stockholm WWTP, where an additional reduction of NO₃ – N occurs in the final settling basins. The early SBR tests in Lund, Sweden also found that the phenomenon occurred during the settling phase. A short presentation of these early tests has been presented (Morling 1989).

As conclusions to the proposed design outlines (Artan et al (2001) the following may be stated: the way to address the “efficient” SRT in the SBR -process by calculating only the different reacting phases times (mixing + aeration times) provides a safety margin. An important capacity in a SBR process is the “simultaneous” performance of nitrification and denitrification. This has been highlighted by researchers (Irvine 1983). This factor would further add to the “safety margin” for the system, when considering the SRT required.

As an alternative “efficient” SRT it would be reasonable to include 50% of the dedicated settling time. This would still include a safe calculation basis. In order to outline a reliable SRT an “efficient” SRT has been suggested (Artan et al 2001, Equation 10, Table 28). A number of observations give clear indications that the microbiological activities continue even during the settling period a modified SRT. This modification takes into account the reaction during part of the settling time (Equation 11).

Most of the plants that have been studies within this thesis operated with rather limited SRTs, as compared with a “needed” SRT. A comparison between the different plants and the actually used total SRT, aerated SRT, “needed SRT”, modified SRT and temperature is presented (Table 29). The “Aerobic SRT” is also shown, taking into account that the aerated time in a single reactor varies from about seven hours per day (in the case of Nynäshamn) to fifteen hours per day (in the case of high loading conditions in Nowy Targ). Comparisons are also made with the “required” aerated SRT and the “efficient” SRT, as suggested (Artan et al 2001).

It is overwhelmingly held that a stable and secure enhanced biological nitrogen removal
requires that a minimum Mean Solids Retention Time is kept, corresponding to the needs at a given temperature. As pointed out by several researchers it is vital to address the “aerated SRT” when calculating nitrification capacity (Irvine 1983, Teichgräber et al 2001). In the following only the aerated SRT is used. The “required” aerated SRT for nitrification includes a safety factor, often chosen as 2.5 * the theoretical SRT (Henze et al 1995). When considering the safety level it is found that the different calculated aerated SRT at the different plants are within the range of a “theoretical” aerated SRT. A comparison is presented between the actual SRTs as found at the different plants with the “needed” aerated SRT, including the safety factor (Figure 34).

5.5.3 Nitrogen loading versus specific nitrification rate

The municipal plants in this study, all but one (the Tjustvik plant), are operated at more or less full nitrification even during low water temperature conditions (i.e. 6–10°C). This fact in turn calls for a further assessment of the performance on nitrification. In this section the specific nitrification velocities are calculated for different situations at the different plants. Special attention is given to the fact that the specific nitrification rate – as shown in the Nynäshamn case – is found to be high even in the lower temperature range. This matter is not new: it has been addressed previously (Choubert et al 2005, Palis & Irvine 1985). The experiments and data from Holbaek, Norsa and Nowy Targ reveal that as long as the basic conditions for nitrification are met (that is sufficient oxygen supply and an SRT long enough to prevent a washout of nitrifiers) the maximum nitrification rate is proportional to volumetric nitrogen loading. This finding is in accordance with other experiments and literature data (Choubert et al 2005, Eckenfelder 1989). The maximum specific nitrification rate found in Nowy Targ is about 4.0 - 4.4 g N ox/g MLVSS/h, even during low temperature conditions (8 – 10°C), and comparable with the assumed maximum value of < 4.4 g N ox/g MLVSS/h. (Choubert et al 2005).

The data from the different plants on actual loading, nitrification and the MLVSS amounts in the SBR units makes it possible to calculate the relation between nitrogen
loading and the nitrification rate. For the two plants operated with leachate – Isätra and Norsa - it is found that the maximum rates seem to be lower than for the plants working with municipal wastewater. However, it must be stressed that the maximum rate may not been revealed in these two cases, as long as they perform a complete nitrification. In Norsa the leachate temperature is kept at a minimum value of about 15°C, by the installation of a heat exchanger and use of energy from the nearby energy production facility. Also in this case it is found that the relation between nitrogen loading and nitrification velocity is proportional – in a logarithm –to a normal relation. In this case however the relation is very strong; the $R^2$ value is 0.985. It seems reasonable to suggest that the maximum rate is not found; not even at the highest calculated nitrification rates is the nitrification complete. The same analysis on nitrification rate has been made for the Nowy Targ plant (Paper VIII). The pattern becomes even more pronounced when studying the 2005 year figures from Nowy Targ. Are similar patterns found at the other plants in this study? The matter is not easily answered due to a basic reason already addressed: as long as the nitrification is complete the potential nitrification rate is probably higher than the one found by analysing the figures. By using the Holbaek SBR plant as an example this matter may be clarified. This plant is operated with very stringent effluent requirements. The plant is only occasionally operated close to the design level. Sampling is performed 24 times a year. By using the results from the 2006 operation nitrification performance over the year is presented, showing the discharge $NH_4$-N levels and total nitrogen levels (Figure 35).

The figure demonstrates that the nitrification is complete over the year. If the nitrification rate is related to the prevailing water temperature during the same year it is not possible to find a relation between water temperature and the actual nitrification rate. The main reason for this situation is most likely that the potential nitrification capacity in the system is not fully used. By studying the nitrification rate versus the nitrogen loading, the relation is accordingly found, (Figure 36). It is clear that the nitrification rate increases with an increase of the nitrogen

![Figure 34 Comparison of different SRT concepts used for SBR](image-url)
load. Another important finding with respect to the nitrification behaviour in an SBR unit is presented that the nitrifying rate in the alternating reactor was proportional to ammonium or nitrite concentration (Dythazak et al 2008). The phenomenon is attributed to the shifting aerobic/anoxic environment that favors selected nitrifiers over more sensitive ones – a selector function is integrated into the cyclic operation.

This situation is also apparent at the Tjustvik plant that is operated at design level with respect to nitrogen loading. Due to the lack of adequate loading control of the plant however, in some cases it has been difficult to accurately quantify the loading. The result is that the addition of septic sludge to the SBR treatment and measuring of the “extra loads” from the septic sludge has not always been carried out (Paper III). By using the operation data from year 2003 at the plant, and using the same relation as above (nitrification rate versus nitrogen load) it is possible to find a pattern (Figure 37). These cases reveal the potential nitrification capacity – provided that the remaining NH₄-N levels are less than 1 ppm.

The SBR plant in Nynäshamn resembles the Tjustvik plant as it has been built for reception and direct treatment of septic sludge during seven to eight months per year. The second main reason for building the Nynäshamn plant was the fact that the wetland facility was not able to meet the consent values for nitrogen removal. The background and more relevant information regarding the plant are found in Paper VII. It is however important to summarize some
major changes with respect to the overall performance of the plant. As the construction of the SBR facility was the only upgrade investment at the plant it is reasonable to conclude that these changes may be attributed to the SBR performance:

- nitrogen removal has, ever since the SBR facility was put into stable operation, been in compliance with the consent levels (annual average less than 7 mg total N/l versus 15 mg/l as consent value);
- the downstream wetland was previously closed for two to four months during the winter, whereas now it is possible to operate the wetland all year round;
- needs for the addition of a chemical precipitation agent have been reduced to about 60%, compared with the earlier operation mode.

The simultaneous nitrification/denitrification is discussed in Paper VIII and IX, as being an important feature for the nitrogen removal in the SBR process. Results from a full-scale test plant operation in Rock Falls, Illinois, operated by Aqua Aerobics Systems Inc, Rockford, Illinois are presented (Figure 10 in Paper VIII). Some aspects of the operational performance with respect to phosphorus removal are discussed in Chapter 4, Paper IX. The pilot plant operation ran in 1986 - 87 demonstrates the operation cycle modes – Filling, Mixing, Aeration and React, as well as the ammonia nitrogen and nitrate nitrogen concentrations versus process time. The key to understanding the simultaneous nitrification/denitrification is to observe the variations of the nitrate nitrogen concentrations versus time: regardless of the ambient conditions in the reactor – aerobic or anoxic - the nitrate nitrogen level is kept below 2 mg N/l.

The nitrification rate at the different plants has been calculated in accordance with the model presented in chapter 4. A comparison on the nitrification rate at low temperatures (normally winter conditions) shows a significant variation in the rate: the lowest rate was found at the Tjustvik plant where the rate was 0.4 – 0.8 g N ox/kg VSS/h at temperatures from 6 to 10°C. The highest rates were found at Nowy Targ and Nynäshamn SBR plants working at similar temperatures, and the rates were found from 0.68 – 4.0 g N ox/kg VSS/h (Nowy Targ) and 2.1 – 3.2 g N ox/kg VSS/h at Nynäshamn plant (Table 30). In the Nowy Targ case the maximum nitrification rate seems to be virtually the same regardless of the prevailing temperature (Table 31). At the two leachate treatment plants the nitrification rate has been within “a more expected range” (Table

### Table 30 Specific Nitrification rates at low temperature at five different SBR plants, winter conditions

<table>
<thead>
<tr>
<th>Plant name</th>
<th>Nowy Targ</th>
<th>Holbaek</th>
<th>Tjustvik</th>
<th>Nynäshamn</th>
<th>Ommanäs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of obs.</td>
<td>29</td>
<td>6</td>
<td>12</td>
<td>13 + 12 +12</td>
<td>21</td>
</tr>
<tr>
<td>N load, kg/d</td>
<td>261 -459</td>
<td>6-10</td>
<td>103 - 149</td>
<td>200 – 210</td>
<td>6 -10</td>
</tr>
<tr>
<td>Water temp. °C</td>
<td>6 -10</td>
<td></td>
<td>6 – 10</td>
<td>6 - 10</td>
<td></td>
</tr>
<tr>
<td>F/M ratio, kg BOD/kg VSS/d</td>
<td>0.05 – 0.22</td>
<td>0.03 – 0.08</td>
<td>0.04 – 0.05</td>
<td>0.121 – 0.142</td>
<td>0.014 – 0.046</td>
</tr>
<tr>
<td>Total SRT per day</td>
<td>&lt; 16</td>
<td>&lt; 20</td>
<td>17 – 20</td>
<td>10 – 15</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Aerated daily SRT</td>
<td>7 – 8</td>
<td>8</td>
<td>9 – 10</td>
<td>4 – 7</td>
<td></td>
</tr>
<tr>
<td>Nitrification rate, g N ox/kg VSS/h</td>
<td>0.68 – 4.0</td>
<td>0.8 – 1.60</td>
<td>0.4 – 0.8</td>
<td>2.1 – 3.2</td>
<td>0.15 – 1.18</td>
</tr>
</tbody>
</table>

### Table 31 Nitrification rates, temperature ranges and regression factors for five different observation periods at four plants

<table>
<thead>
<tr>
<th>Plant and Period</th>
<th>Temperature range, °C</th>
<th>Nitrogen load range, kg N/d</th>
<th>Nitrification rate range, g N ox/kg VSS/h</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isätra leachate SBR, year 2003</td>
<td>0 - 20</td>
<td>6 - 12</td>
<td>0.05 – 1.15</td>
<td>0.5322</td>
</tr>
<tr>
<td>Norsa leachate SBR, year 2004</td>
<td>14 - 22</td>
<td>6 - 14</td>
<td>0.8 – 1.9</td>
<td>0.985</td>
</tr>
<tr>
<td>Holbaek, year 2006</td>
<td>6 - 18</td>
<td>250 - 550</td>
<td>0.8 – 1.8</td>
<td>0.7242</td>
</tr>
<tr>
<td>Tjustvik, 2003</td>
<td>7 - 18</td>
<td>80 - 250</td>
<td>0.75 – 2.1</td>
<td>0.8127</td>
</tr>
<tr>
<td>Nowy Targ municipal/industrial SBR, from Paper VIII</td>
<td>1st quarter 2005</td>
<td>6 - 10</td>
<td>1000 -4600</td>
<td>0.6 – 4.0</td>
</tr>
<tr>
<td></td>
<td>2nd quarter 2005</td>
<td>10 - 18</td>
<td>1000- 5200</td>
<td>0.9 -4.6</td>
</tr>
<tr>
<td></td>
<td>3rd quarter 2005</td>
<td>15 - 20</td>
<td>1000 -3400</td>
<td>0.7 – 3.1</td>
</tr>
</tbody>
</table>
The maximum nitrification rate at the Norsa plant was found in the range 0.8 – 1.9 \text{N}_\text{ox}/\text{kg VSS/h}. The relation between the nitrogen load and the nitrification rate at the Norsa plant shows a very good relation (Figure 38). The results from this plant underline the finding that as long as the nitrification rate is not fully used there is an increase in the velocity proportional to the nitrogen load. However, later observations and calculations identify higher rates, up to 2.2 \text{N}_\text{ox}/\text{kg VSS/h} (Paper IV).

Another important aspect to consider in this context is the ratio \text{COD/N} (or \text{BOD}/\text{N}) and its influence on the nitrification rate. The results from an analysis of the performance data at the Nowy Targ plant are presented (Paper VIII). The first three quarters of 2005, with a significant variation of the \text{COD/N} ratio, all show that the ratio is inversely proportional to the nitrification rate. The pattern has not been found in the other plants, mainly due to the absence of a very low \text{COD/N} ratio.

### 5.5.4 Denitrification at different plants

Denitrification has not been found to be a limiting factor in total nitrogen removal with the exception of observations at the Tjustvik SBR facility before the introduction of septic sludge was introduced. However, the situation at this plant during the first years of operation treating only municipal wastewater reveals a specific circumstance. For typical “day migration” towns and suburban areas the ratio \text{BOD}; total \text{N} (and \text{BOD}; total \text{P}) is often found to be rather low (Paper III). This fact is explained simply by the large number of citizens who work at the neighbouring town or city. In the case of Tjustvik a large number are day migrants to Stockholm. A similar pattern is found at the Ölmans plant on the Swedish west coast, where the day migration is directed toward Gothenburg. The ratio \text{BOD}; total nitrogen for these two plants along with the ratios for Holbaek and Nowy Targ plants are presented (Table 32). The ratio in Tjustvik and Ölmans is lower than what is “normally” assumed. In neither of the cases has the low ratio caused a significant limitation of the denitrification. The efficient use of septic sludge as a carbon source for enhanced denitrification is supported by earlier findings that demonstrated the efficiency in using primary sludge as a carbon source (Abufayed & Schroeder 1986). The limited amounts of organic carbon at these two plants have had a more apparent influence on the EBPR efficiency. At the Nowy Targ plant the cycle time for a “true” denitrification is rather short, and would indicate a very high denitrification rate. The calculated denitrification rates at Nowy Targ, Holbaek, Ölmans and Nynäshamn SBR plants are shown (Table 32).

### Table 32 Ratio \text{BOD}; Total Nitrogen in raw wastewater at two Swedish plants with typical “day migration” social structure compared with Holbaek SBR plant and Nowy Targ SBR plant, first three quarters 2005

<table>
<thead>
<tr>
<th>Year</th>
<th>Tjustvik</th>
<th>Ölmans</th>
<th>Holbaek</th>
<th>Nowy Targ</th>
<th>Nowy Targ</th>
<th>Nowy Targ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max value</td>
<td>4.7</td>
<td>5.3</td>
<td>9.76</td>
<td>9.41</td>
<td>7.5</td>
<td>9.86</td>
</tr>
<tr>
<td>Mean value</td>
<td>2.95</td>
<td>3.99</td>
<td>5.48</td>
<td>4.54</td>
<td>3.8</td>
<td>4.66</td>
</tr>
<tr>
<td>Median value</td>
<td>2.80</td>
<td>3.94</td>
<td>5.0</td>
<td>4.35</td>
<td>3.01</td>
<td>4.07</td>
</tr>
<tr>
<td>Min. value</td>
<td>1.03</td>
<td>2.04</td>
<td>2.62</td>
<td>0.98</td>
<td>0.92</td>
<td>2.25</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.19</td>
<td>0.63</td>
<td>2.17</td>
<td>2.13</td>
<td>1.43</td>
<td>2.03</td>
</tr>
</tbody>
</table>
As discussed above this assumption is deemed to be more realistic than using only the non-aerated React times. Another question to be raised is to what extent even this assumption is too “conservative”. The very complex environment in the reactor most likely promotes a “simultaneous” nitrification/denitrification. This phenomenon seems to occur in most full-scale SBR basins; whereas the same pattern is not found in a bench-scale test operation, (Chapter 3, Paper IX). This matter would explain the very high maximum denitrification rates found in the Nowy Targ plant (Table 33 and Paper VIII). Subsequently, the actual denitrification time in all the studied plants may be longer than the calculated ones, and as a consequence the indicated maximum denitrification rates are too high. For the other plants analysed in the thesis the denitrification rates are more “normal” and comparable with other findings illustrating the Holbaek and Ölanans SBR plants (Figure 39 and Figure 40).

5.6 Phosphorus removal

5.6.1 Influence of water temperature on phosphorus removal

As only two of the plants in this thesis have been operated with a more or less explicit EBPR the following discussion is based on a substantially lower number of observations. The Ölanans plant was operated for a short period in 1994 with EBPR, but without meeting the consent levels (Morling & Nyberg 1996). Therefore the tests were abandoned after a short period of time. On the other hand all the other plants are operated with either a simultaneous precipitation or a pre- or post-precipitation. All these plants meet the consent levels and therefore are not addressed in the following discussion (Table 34).

At this stage it is relevant to refer to the long-term test operation at the Dokkas plant, Gällivare community, where EBPR was achieved and maintained down to about 5°C.

Table 33 Denitrification rates, temperature ranges and regression factors for five different observation periods at four plants

<table>
<thead>
<tr>
<th>Plant and Period</th>
<th>Temperature range, °C</th>
<th>Nitrogen load range, kg N/d</th>
<th>Denitrification rate range, g N/kg VSS/h</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nowy Targ municipal/industrial SBR</td>
<td>6 – 10</td>
<td>1000-4600</td>
<td>0.34 – 9.12</td>
<td>0.9438</td>
</tr>
<tr>
<td>1st quarter 2005, 29 obs.</td>
<td>10 – 18</td>
<td>1000-5200</td>
<td>0.32-14.7</td>
<td>0.9451</td>
</tr>
<tr>
<td>2nd quarter 2005, 30 obs.</td>
<td>15 – 20</td>
<td>1000-3400</td>
<td>0.32 – 7.12</td>
<td>0.6897</td>
</tr>
<tr>
<td>Holbaek, year 2006</td>
<td>6 – 18</td>
<td>250 - 550</td>
<td>0.8 – 1.8</td>
<td>0.9579</td>
</tr>
<tr>
<td>Ölanans, year 2006</td>
<td>6 – 18</td>
<td>40 – 115</td>
<td>0.3 – 1.2</td>
<td>0.6793</td>
</tr>
<tr>
<td>Nynäshamn, year 2004, four quarters, 43 observations</td>
<td>7 - 18</td>
<td>176 - 210</td>
<td>1.47 – 1.95</td>
<td>Mean values</td>
</tr>
</tbody>
</table>
(Paper II). The relationship between water temperature and discharge levels of phosphorus at the Dokkas plant during the test operation is shown; (Figure 6 in Paper II). Below 5 °C it was very difficult to find a reliable low soluble phosphorus level in the discharge water. It should be underlined that the operation was possibly affected by the very primitive decanter facility. The unintended discharge of suspended solids had a substantial effect on the SRT. The suspended solid discharge shortened the SRT by about 5-6 days. On the other hand this limited the plant in establishing nitrification (Paper II). With reference to the bench-scale tests performed focusing on limitations and pathways for EBPR, it is likely that the Dokkas test operation benefited from the limitation in SRT and thus the limited nitrification.

5.6.2 Chromium influence on phosphorus removal

A rather “unique” situation occurred in Nowy Targ soon after the start of the plant in 1995. An “explosion” of tannery activity started and after a few years the discharge of chromium into the sewer system showed to be significant. The establishment of more chromium tanneries has increased during recent years. High chromium content in raw wastewater is normally considered as detrimental to biological treatment performance. The question with respect to nitrification has been addressed above. The consent level on phosphorus discharge is less than 1.0 mg/l for the Nowy Targ case. The first years of operation had no “alarming” levels of chromium in influent wastewater. The phosphorus removal was more than satisfactory during the early operation with low chromium content. The initial operation – for about three years – showed a substantial phosphorus removal that could be attributed only to an EBPR situation. The good removal levels remained throughout the winter season, even when the water temperature was down to 6°C. This situation supports the findings from the Dokkas SBR test facility that EBPR works even at low water temperatures (Paper II).

However, when addressing the operation conditions from 2004 the situation has shifted dramatically. An average chromium concentration in the inlet rose to about 12 mg/l. At the same time the phosphorus inlet level was close to 14 mg/l. Accordingly, the organic load increased and thus a substantial assimilation of phosphorus could be expected, as long as the biological process performed correctly. An overall balance of the phosphorus removal, based on 2004 average figures, is presented (Figure 41). The discussion in Paper VII with respect to an influence of a chemical precipitation induced by Cr³⁺ is seen as important in this context. As seen in the balance, more than half of the removed phosphorus can be attributed to either precipitation by Cr³⁺ or by EBPR.

| Table 34 Summary of phosphorus removal at the different plants in the study, including the operation mode |
|-------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| **Operation mode**            | Dokkas         | Nowy Targ      | Holbaek        | Tjustvik       | Nynäshamn      | Olmanäs        |
| Number of obs.                | 21             | 118            | 26             | 26             | 48             | 26             |
| Water temp. range °C          | 3 - 10         | 6 - 19         |                |                |                |                |
| Typical discharge level, mg P/l | < 1.0         | < 0.6          | < 0.5          | 0.15           | 0.35 / < 0.06  | 0.4            |
| Consent level, mg P/l         | (0.5)²         | < 1.0          | < 1.0          | < 0.3          | < 0.5          | < 0.5          |
| Removal efficiency, %         | 70             | 93 - 97        | 93             | 98             | 99             | 92 - 96        |

1 The values for Nynäshamn plant are given after post precipitation and after wetland
2 The Dokkas consent values were not exercised during the test period
Phosphorus removal was, by and large, very stable throughout 2004 and 2005. The sampling from years 2004 - 2005 and analysis may illustrate this fact. A histogram of the discharge concentrations of total phosphorus from the plant, covering in all more than 200 observations is presented (Figure 42). The plant is operated with no chemical addition for phosphorus removal, yet attains more than 90% removal (Paper VII).

The extreme discharge in phosphorus value observed in June 2005 may be compared with the other discharge parameters and the overall removal levels for the same day (Table 35).

Now the question arises: is the total phosphorus (2.07 mg/l) result correct or not? The other “normal” pollution variables that same day show normal low levels on discharge figures, and the removal efficiency is very high, in accordance with the plant performance by large. As has been mentioned before, the Nowy Targ plant is exposed to very high chromium loads (Paper VI). It is also assumed that Cr^3+ acts as a precipitant for phosphorus. During the observation day, 2nd June 2005, the chromium removal efficiency was found to be lower than normal, as was the phosphorus removal efficiency. These facts may be further indications of the suggested explanation that chromium acts as an efficient precipitant agent for phosphorus. The relation between chromium and phosphorus at the plant has been discussed (Paper VII). The ratio of chromium to phosphorus is essential to address when anticipating a possible precipitation. A frequency curve the molecular ratio (Cr/P)
for two years’ observations (2004 and 2005) at the Nowy Targ plant is illustrated (Figure 43). As shown in the table the ratio of chromium to phosphorus is very close in the crude wastewater. Furthermore, if the discharge chromium and phosphorus levels are compared there are periods with abundance of chromium, more than enough to support a chemical precipitation of phosphorus by chromium.

5.6.3 Phosphorus removal and discharged suspended solid levels

Another way to address the phosphorus removal efficiency is to compare the discharge phosphorus level with the ratio SS/P in the discharge. This is illustrated by using data from two quarters in 2005 at the Nowy Targ plant (Figure 44 and Figure 45).

The relation is found to be very limited – or unreliable – during the first and fourth quarters. On the other hand the relation during the second and third quarters seems to be more apparent. The only very clear difference between these periods (first and last quarters on one hand and the second and third quarters on the other) with respect to parameters is the water temperature.
5.7 Energy efficiency

Based on the outlines in Chapter 4.7 some of the plants investigated in this thesis are compared with respect to the energy they utilise.

In this context the influence of phosphorus will be ignored as its removal is performed to a large extent by chemical precipitation. As only one plant operates with a distinct EBPR performance it is not relevant to include the phosphorus influence at this stage. Nevertheless biological phosphorus removal does impact on efficient energy use in the activated sludge system. By including the efficiency of phosphorus removal, an “energy efficiency index” can be established for future assessment. In the following, the three models employed the energy efficiency will be used in parallel to highlight the accuracy – or lack of it – of the different comparisons.

The calculation is based on the power-consuming units directly linked to the SBR process. This means that only the aeration devices, mixers and waste activated sludge pumps in operation are included in the daily energy consumption. In this context it must be stressed that not all plants have contributed a very detailed presentation of how the main energy consumption units are used during the process at varying load conditions. This in turn leaves the comparisons in the following with a limited accuracy. What may be derived from the comparisons are the levels of specific energy consumption at varying loads, and a critical analysis of how accurate the models may be.

The utilised power for aeration is calculated to be related to the actual water depth. In most cases the blower capacity and energy use is designed for a maximum loading with respect to pollution and at the same time a water pressure equal to the maximum water depth. Piston blowers use energy proportional to the actual water depth to a certain extent, but are affected by system losses. Calculations in the following are based on (Table 19, Equation 11).

Thus three different specific energy consumption models are presented in the following:

- based on the BOD removed only, and expressed as kWh/kg $\text{BOD}_{5\text{rem}}$ removed;
- based on the amount of nitrogen removed, expressed as kWh/kg $\text{N}_{\text{rem}}$ removed;
- based on the modified OCP amounts “removed”, and expressed as kWh/kg $\text{OCP}_{\text{mod,rem}}$ removed.

Some additional remarks regarding the comparisons:

- in all cases the $\text{BOD}_{5\text{rem}}$-removal is expressed as $\text{BOD}_{5\text{load in}}$ – discharge amount of $\text{BOD}_{5}$;
- it should be observed that the Chon Buri plant is a CASS system, but its operation mode is very close to the “true” SBR operation;
- the four plants in the comparison differ in some respects: Three of them use rubber membrane disc aerators (Nowy Targ, Ölmanäs and Chon Buri), while Nynäshamn is operated with a jet aeration system. Thus, at least theoretically, the three first plants should have a better energy use, thanks to the rubber membranes, than the Nynäshamn plant;
- three out of the four plants have separate installations for mixing and aeration: Nowy Targ and Ölmanäs have high speed mixers and bottom aeration; Nynäshamn uses the jet aeration system for mixing + aeration or mixing only by operating blowers and submersible pumps either together or the pumps only. Chon Buri has only aeration devices and no separate mixing;
- all plants have the possibility of conducting aeration according to their actual needs by on-line oxygen probes. Thanks to the separation of mixing and aeration the three “classic” SBR plants utilise an active scheme for energy saving. The Chon Buri plant has installed frequency converters on the blowers to control the amounts of air supplied;
- the different loading and flow conditions favour or limit the possibilities of saving. The Chon Buri plant “suffers” from a specific condition: the raw wastewater is
very dilute, and at the same time the daily flow is about 60 to 65% of the design value. The operating conditions are, in other words, not favourable for efficient energy saving.

The different models used to define energy efficiency are illustrated for Chon Buri, Nowy Targ and Ölmanäs (Figure 46 to Figure 55). The basis for the Chon Buri calculations is based on loading figures, treatment results and energy use in December 2006 (Table 36). For Nynäshamn SBR plant the figures are limited to the winter 2004 mean values. A comparison with respect to the “conventional” definition kWh/kg BOD removed is presented (Table 37).

Now a conclusive question remains: are these different models useful for an assessment of the energy efficiency? The pattern is consistent for the different plants observed. It may be concluded that the use of an energy efficiency index; expressed as kWh/kg OCP\text{mod} removed may be a better indicator than the conventionally used definition kWh/kg BOD\text{removed}. This matter is further underlined by the fact that the BOD analysis is less accurate than the nitrogen analysis.
Figure 49 Nowy Targ SBR plant specific energy use versus removed amounts of modified OCP, 1st quarter 2004 (29 observations); \( y = 1437.7x^{0.8236} \); \( R^2 = 0.8769 \)

Figure 50 Ölmanäs SBR plant specific energy use versus BOD load, 2006 (26 observations); \( y = 237.11x - 0.8257 \); \( R^2 = 0.9582 \)

Figure 51 Ölmanäs SBR plant specific energy use versus nitrogen removal levels, 2006 (26 observations); \( y = 341.31x - 0.8491 \); \( R^2 = 0.9473 \)

Figure 52 Ölmanäs SBR plant, specific energy use, expressed as kWh/OCPmod, 2006 (26 observations); \( y = 189.5x - 0.833 \); \( R^2 = 0.9462 \)

Table 36 Loading figures on the Chon Buri CASS plant, December 2006

<table>
<thead>
<tr>
<th>Nos of observations</th>
<th>Design value</th>
<th>Actual loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>200 000</td>
<td>126 401</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>30 000</td>
<td>3261</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>31.3</td>
</tr>
<tr>
<td></td>
<td>60 000</td>
<td>4 079</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>1 374</td>
<td>945</td>
</tr>
</tbody>
</table>

Table 37 Specific energy use at four different SBR-plants, defined in three different ways

<table>
<thead>
<tr>
<th>Plant name</th>
<th>Operation period</th>
<th>Number of obs</th>
<th>Installed power, aeration + mixing</th>
<th>Used energy, kWh/d</th>
<th>Specific energy use. kWh/kg BODrem.</th>
<th>Specific energy use. kWh/kg Nrem.</th>
<th>Specific energy use. kWh/kg OCPmod, removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nowy Targ</td>
<td>Winter 2004</td>
<td>29</td>
<td>840 + 198</td>
<td>7,530</td>
<td>1.05</td>
<td>5.43</td>
<td>0.31</td>
</tr>
<tr>
<td>Nynäshamn</td>
<td>Winter 2004</td>
<td>12</td>
<td>111 + 140</td>
<td>460</td>
<td>1.21</td>
<td>2.46</td>
<td>0.30</td>
</tr>
<tr>
<td>Ölmanäs</td>
<td>Year 2006</td>
<td>26</td>
<td>75 + 30</td>
<td>528</td>
<td>1.62</td>
<td>10.38</td>
<td>0.46</td>
</tr>
<tr>
<td>Chon Buri</td>
<td>Dec 2006</td>
<td>31</td>
<td>2,200</td>
<td>9,520</td>
<td>3.6</td>
<td>23.74</td>
<td>0.94</td>
</tr>
</tbody>
</table>
GENERAL DISCUSSIONS

6.1 Discussion on the findings and the applicability for cold wastewater

As stated in Chapter 3, the batch model of biological wastewater treatment was the “mother” of the activated sludge model. This fundamental fact must be remembered: SBR technology is an activated sludge operation model. As pointed out by many scientists and engineers: its unconventional mode has been a setback for the technology and many critical arguments have been based on an unwillingness to accept technical novelties. Nevertheless a number of critical points can be taken as honest objections, (Chapter 5, Paper IX). As described, some of the points illustrate a lack of insight into the technology. On the other hand they also reflect some of the key issues with respect to SBR technology.

- Very distinct findings from all the plants reflect the capacity to perform nitrification at low water temperatures – defined as down to 5 – 6°C. The actual aerated SRT (Solids Retention Time) has been found to be in the range of five to ten days, at the different plants.

- By checking the nitrification rate against the nitrogen load it has been demonstrated that as long as the fundamental conditions for nitrification are satisfied – that is sufficiently long SRT and an adequate supply of oxygen – the nitrification rate is found proportional to the load. However this statement takes into consideration the very complex pattern where also the ratio COD/nitrogen evidently plays an important role. This again is not a novelty but revealed in practical operations but found at the Nowy Targ plant during the three first quarters of 2005 (Chapter 5 and Paper VIII).

- The process flexibility – that is the possibility of changing the different phases within the operation cycle and also the cycle length – is found to be a very efficient tool for the operator. This fact may also be expressed as follows: a correctly designed automation system will allow the operator to change the operation strategy. In turn this leaves the operator free to continue a process design at full-scale. The obvious reason for this is that the process takes place in a single reactor, and the variations may be enabled by the appropriate use of the installed computer. This may be seen as a unique feature of the SBR system. By contrast most continuous flow systems for biological nitrogen removal need a number of discrete reactors, with pre-set volumes.

- When interpreting laboratory scale or small pilot scale tests and results it is essential to question to what extent all the findings in the small scale may be utilized in a full-scale system. A clear example in this context is the lack of denitrification in the small sized bench-scale tests (Chapter 3, Paper IX). On the other hand virtually all the large sized plants included in the thesis demonstrate a substantial denitrification capacity. This capacity is evident even if the cycle composition is very similar to ones used in the bench-scale tests.

- The matter of Enhanced Biological Phosphorus Removal (EBPR) has been identified in two plants; in the Dokkas test plant and at Nowy Targ SBR plant. However in the latter case the EBPR is at least supported by a precipitation by Cr³⁺ and thus the “true” EBPR is difficult to quantify with accuracy.

- The energy efficiency is related to a number of circumstances. As illustrated by the “CASS” plant in Bangkok very dilute wastewater will most likely result in poor energy efficiency performance (Chapter 5). The specific energy efficiency is also related to the ratio “actual load/design load”. A plant operated at loads significantly below the design load will normally not be able to “optimize” the energy input. In theory at least the SBR process allows for possible savings in energy at low loading conditions: the
practical arrangements and the degree of instrumentation will limit these savings.

- The SBR system has demonstrated a considerable capacity to adapt to considerable variations in loading conditions.
- It is important to enable the SBR facility to run with a “selector” function. This may be achieved in different ways:
  a. To shorten the Fill time as far as possible;
  b. To include a “Static fill” period at the start of the cycle that allows substrate to accumulate in the tank;
  c. To operate the Fill time with a “step-feed” mode;
  d. To arrange a side-stream reactor for various treatment options of concentrated sludge, as further discussed in Chapter 6.2.2.
  e. The possibility to operate the SBR system by altering the cycle by changing the aerated and anoxic times to allow for an extended settling time. However, in this respect the most vital aspect is to select a decanter that safeguards low suspended solids levels in the discharge during the entire decant period.

Additional practically oriented conditions include the following points.

- The ability to build up controlled stress within the microbiological environment that will encourage the growth of a desired bacteria population. In this context the ratio Fill/Total cycle time is argued to be a decisive factor.
- The needs for an efficient decant system of the treated water. It is important to use as large a decanting capacity as possible for any given plant, as a short decant time leaves more time for the other active phases within the cycle.
- The correct sizing of the process equipment; such as installing an aeration device that allows for a short aeration time in each of the cycles.
- To control the sludge wasting in the process and not to allow too extended SRT.

### 6.2 Options and limitations

The following discussion will focus on some key options and also present some limitations of SBR technology. SBR may be characterized as a rather “contradictory” system. On one side it is a very simple “Fill and Draw” system, and on the other side it allows a very flexible operation mode. These two “extremes” of the system enable quite a vast range of treatment options. Some of the interesting options are discussed in Chapter 6.3 “Future perspectives – relevant research and development points”.

#### 6.2.1 Simple operation mode with special focus on low cost situations

The “initial” SBR mode offered a very simple operation, as used in early research studies, but later on, also for small installations, pointed toward a method that to some extent has been abandoned. The obvious possibility of including very sophisticated operation modes within the basic concept have attracted a lot of interest from both scientist and design engineers. However, the option of using the SBR system as a “simple, and low cost treatment alternative” was pointed out at a conference on “Low cost wastewater treatment” held in 1983 in Clemson, South Carolina (Irvine & Carvajal 1983). The merits of using the batch mode for low cost situations, typically in areas with limited financial resources, are obvious. Such a plant may be built with earthen lagoons, possibly reinforced by riprap as erosion protection, surface aerators, and simple decant devices – either by pumps or by siphon systems (as used for the early Oxidation ditch installations) - and an automation scheme based on for instance a 24-hour cycle and using timers and level probes as the only devices for cycle control. The aeration would be directed to the night hours when the power cost often is lower than in daytime. In order to improve the treatment levels (if needed) the downstream facilities may be based on constructed wetlands or natural pond systems.
6.2.2 Operational modes with special focus on biological phosphorus removal

The interest in enhanced biological phosphorus removal (EBPR) will most likely become even more apparent in the future. An interesting improvement in biological phosphorus removal is the use of a separate hydrolysis reactor. In a study the use of a second batch reactor (a Primary Acid Fermenter) was tested to create a controlled anaerobic environment that enhanced EBPR (Danesh & Oleszkiewicz 1997). The results from the study suggest an improvement in the discharge levels from more than 1.5 ppm to less than 0.5 ppm phosphorus by the use of a separate hydrolysis. Similar results have been obtained by others (Vollertsen et al 2006). An important development in this context will be to integrate this operation into the SBR system by using a side-stream hydrolysis reactor for a portion of activated sludge from the main reactor. (Choi et al 2001). By incorporating such a reactor an even better process control of the SBR could be arranged. At the same time a greater complexity can be brought into the system.

6.3 Future perspectives – relevant research and development points

The current status of SBR R&D (Research and Development) covers a wide range of process applications and focuses on relevant and specific issues. However, some aspects seem to be either underestimated as potential problems – or as fields for improved development. Six different aspects are highlighted in the following:

1. development of the SBR for simple and robust applications, especially for low cost situations and for “developing countries”;  
2. “socio-technical” studies on the relationship of man to machine with special focus on the SBR system;  
3. needs for improved on-line metering and control of the process;  
4. integrating “bio-membranes” into the SBR;  
5. operational modes with special focus on using the SBR in the Anammox process;  
6. development of “granular activated sludge” through the use of SBR technology.

Two of these aspects were parts of the initial developments of modern SBR technology (1 and 2): these two points are by nature of general relevance, and most findings within these areas would be applicable for other systems as well.

6.3.1 Development of the SBR for simple applications

To some extent modern development of the SBR system has included “simplicity” as a paradigm. To a large extent this has been overshadowed by a development where the inbuilt flexibility of the system has encouraged scientists and engineers to include advanced process options. A typical example has been illustrated in this thesis: the use of a PLC system for an advanced operation of the SBR, with rather ambitious treatment objectives. On the other hand it is apparent that there is the potential to create a very simple SBR system. Such a development would however need to be supported by relevant research studies; such as how to find simple and affordable systems, not only with respect to investment but even more important to achieve cost-savings operation modes. Especially in sub-tropical and tropical regions such systems would find a relevant application field.

6.3.2 Studies of the relationship between man and machine focusing on the SBR system

For many engineers working on the implementation of an SBR system a surprising insight is revealed when the plant is put into operation: the operators have little or no understanding of the way to operate the specific batch mode system (Teichgräber et al 2001). To acquire the necessary knowledge to run the plant properly is a complex learning and maturing process. This process may be swift or consume a considerable amount of time for the new
operator. Consequently, it would be relevant to analyse and develop training methods as a “cross-disciplinary” task between the traditional technical community and social science. Such a development would also have relevance to the point above as it is more than likely that introducing the batch mode operation would meet considerable demands for training in a traditionally “non-technical environment”.

6.3.3 Improved control of the process

This point is indeed shared with most other process systems: The success of a process is not only related to the operator’s capacity to operate the plant, but also a future way to improved on-line discharge control and perhaps, most of all, a way to efficiently save energy. The need for a number of reliable on-line meters for “traditional” parameters as oxygen, suspended solids, redox potential, conductivity and so forth are apparent. These meters are of course not limited to the SBR process. However, the demands and options in using the “Feast/Famine” strategy to optimize the process give a pronounced motive to include on-line meters in a modern SBR process. An “intelligent” computerized control program would then become a very efficient tool for the skilled operator. This in turn may lead toward a simplified operation, and thus turn out to be a response to the cited criticism that SBR is a “complicated technology”.

6.3.4 Operation modes with special focus on integrating “bio-membranes” into the SBR

One of the critical points in the current SBR system is the decanter configuration. It may be stated that some of the operation problems related to the SBR may be attributed to a non-functioning decanter. This results in an unintended loss of suspended solids from the reactor, and thus a non-compliance with ruling consent limits. Although the problem normally may be solved by the installation of well-functioning decanters, the upgrade of an SBR by the introduction of a bio-membrane facility that replaces the decanter represents a major possible alternative. A comparison based on a small-scale study demonstrated the advantage of the bio-membrane system (MBR) over a conventional combination of SBR + sand filter (Frederickson 2006). Although the results from the full-scale SBR system are compared with a bench scale MBR system the study does indicate the usefulness of a separation based on a fine grade membrane - in the test a 0.35 μm unit was used. An SBR unit would normally be very simple to upgrade into an SBR bio-membrane facility. Some evident advantages are found with this integration:

- upgrade of an existing SBR facility – or a plant based on classic activated sludge - may be done using the same reactor volumes. Thus there would be no need for an extension of the plant area;
- the SBR cycle would be shortened by at least one hour, as the separate time for settling is omitted;
- it is likely that the problems of bulking sludge will be less troublesome; although the problem should never be underestimated. An “exploding” growth of filaments has been demonstrated at a number of plants, and as a consequence the sludge has virtually flooded out of the plant;
- the typical SS concentration in the reactor may be raised from about 3.5 – 5 kg MLSS/m$^3$ to about 6 – 10 kg/m$^3$. Some suppliers of the bio-membrane advocate substantially higher MLSS concentrations.

When converting an SBR facility into a Membrane reactor it may be “tempting” to treat the reactor as a continuous flow, as some of the problems related to a continuous activated sludge system may be avoided. However in this context it is important to underline the advantages of the SBR system – especially the possibility of shifting the environment from aerobic to anoxic and anaerobic thus placing a “controlled” stress on the micro environment. It is also more than likely that the simultaneous anoxic-aerobic conditions as identified in a conventional SBR system would be even
more apparent when the MLSS concentration is 6 - 10 kg/m³.

6.3.5 **Operational modes with special focus on using the SBR in the Anammox process**

An interesting development of the Anammox process incorporated into the SBR system has been going on for a decade (Chapter 4, Paper IX). As illustrated by some researchers the merits of SBR flexibility may add operational efficiency to the Anammox concept (Gaul et al. 2006). The strong selective forces induced by an “instantaneous fill” on the micro-organism population are possibly a key element in this respect. The approach toward treating high strength side streams at municipal WWTPs will gain more interest, as energy prices increase along with the application of ever more stringent effluent standards. These factors will most likely place the Anammox/SBR combination in an attractive position, especially at mid-sized and large WWTPs. Another field of relevant applications already identified by some scientists is to use the Anammox process for leachate emanating from sanitary landfills, with high strengths of nitrogen (especially ammonia nitrogen) (Chapter 4, Paper IX).

6.3.6 **Development “granular activated sludge” by the use of SBR technology**

A large number of studies have provided knowledge on the use of SBR for promoting granular activated sludge. However most of these studies are based on bench-scale works and it remains to implement the operation mode in a larger scale. The potential is evident, judging from the results of the studies: by controlling the process and sludge quality, extended solids retention times may lead the way toward treating complex organic compounds biologically.

7 **CONCLUSIONS**

A number of conclusions may be derived from the findings. These conclusions may be divided into categories, although the conclusions are all to a larger or lesser extent interrelated. The first category may be labelled “Special conclusions”.

**Special conclusions**

The first conclusion concerns SBR nutrient removal capacity at low water temperatures (range 4 – 10°C), being the main subject for the thesis (Chapter 2). The performance of all the plants in the thesis includes low water temperature (with the exception of the SBR plant working on leachate in Norsa, and the CASS plant in Chon Buri). This conclusion is also a response to the main hypothesis of the thesis, regarding the capabilities to perform nutrient removal at low water temperature:

- in all cases the established nitrogen removal has remained even under low water temperatures;
- the prevailing total SRT has ranged from about 15 to 20 days in all cases when the plants operated at full nitrification capacity;
- a modification of the concept “efficient SRT” is proposed that includes half of the settling time as an active part of the SRT results in a needed total SRT of 8 to 14 days;
- a typical time for “aerated SRT” needed for nitrification at the prevailing temperatures of 6 to 10°C is found to be in the range of 6 – 10 days;
- it is found that as long as a sufficient SRT is maintained and sufficient aeration is supplied the nitrification rate is proportional to the nitrogen load;
- it has also been possible to establish a relation between the COD/N ratio and the nitrification rate, showing that the rate increases when the ratio decreases;
- the process has proven good capacity to adapt to changing conditions both in load-

“All's Well that Ends Well”

*William Shakespeare*
ing and temperature, as long as the changes take place over an extended time;

- of special interest is the finding at the Nowy Targ plant the microbiological capacity to adjust to very high Chromium concentrations. After an acclimatisation the nitrification rate is found to be even higher than expected, 4 mg Nox/kg VSS/h at temperatures < 10°C;

- denitrification has not been a limiting factor for nitrogen removal at any of the plants, unless readily available organic carbon is limited;

- at Dokkas SBR plant it has been possible to establish enhanced biological phosphorus removal (EBRP) at T > 5°C;

- it was shown that EBPR has been established even at low water temperature (6 – 10°C). At the Nowy Targ plant the phosphorus removal is performed both by a chemical precipitation by Cr and an EBPR activity. This capacity has been maintained even at the low water temperature range.

- the “conventional” SBR-design of having a fixed number of cycles per day and per reactor is not always found to be the best operation strategy. By using for instance a 5.5 hour cycle as in Nowy Targ, a peak load occurring every day at the same hour is distributed over an “overall cycle” to all reactors during an extended period of days. Similar modifications of the cycle length were established at most of the plants.

**General conclusions**

Other important conclusions derived from the experiments and comparisons with other findings may be defined as “General conclusions”. They will to a certain extent confirm earlier statements regarding the SBR-technology:

- SBR process has demonstrated a diversified capacity with respect to applications. The studied plants represent a variety of applications with different treatment objectives. These objectives have normally been met with a margin;

- it has been possible to use the SBR-process as an integrated part of different treatment chains, and make optimisations of both the SBR-process itself and the other process parts in the treatment chain;

- the performance at most the plants seems to support the statement that the ratio Fill time/total cycle time should be as low as possible, or in other words the Fill time should be as short as possible. The operation mode with a short fill time may be described as a sludge selector function in the process. This operation model is an important tool to avoid filamentous growth bacteria;

- earlier made statements that simultaneous nitrification/denitrification occurs in the process is a key factor is confirmed at all plants and explains the very good total nitrogen removal;

- process capacity to enhance intracellular storage of organic carbon compounds stimulated by the short fill time is likely to enhance both nitrogen removal and EBRP;

- microbiological communities in SBR systems are well able to adapt to varying conditions: for instance temperature shifts, high concentrations of chromium and variations in loading;

- results found in bench-scale tests have given important answers to specific treatment and performance issues, but using the results to draw overall conclusions on full-scale SBR performance should be done with caution. Such examples are presented from small scale tests on nitrogen removal, showing an increase of nitrate at the end of the cycle. In a full-scale plant this normally does not happen, as long as the organic carbon is available in the reactor - see the conclusion above on simultaneous nitrification/denitrification;

- an earlier suggested oxygen supply strategy for sustained nitrification at a free oxygen level of more than 2 mg O₂/l has been confirmed at least at one plant (Olmanäs) and most likely also at Nowy Targ and
Holbaek, as these plants have been running with substantial organic overloads from time to time and have still maintained good nitrogen removal;

- the statement that the SBR system is especially suited to small sized plants cannot be confirmed - instead the opposite appears to be the result: the large plants in Holbaek and Nowy Targ show both very good and stable results;

- the SBR system is also flexible enough to be either used as the main treatment facility in a treatment chain or to be optimized for specific treatment objectives, as for instance in the case of Nynäshamn.

- a modified way of assessing the energy efficiency for the system is analysed, developed and proposed. Instead of using the traditional ratio kWh/kg BOD$_{removed}$ the use of OCP as a basis for energy efficiency is used. Results demonstrate that this is a viable and useful way to address the energy efficiency. The model shows a high degree of reliability as the R$^2$ levels are found in the vicinity of 0.9.

However, it is important to take into consideration the process configuration when this model is used. If the plant is operated with a chemical precipitation it would be advisable to use a “modified” OCP as a comparison basis, excluding the phosphorus impact. On the other hand, if the plant is operated without chemical precipitation, incorporating the EBPR the “full” OCP would be used. Of course, this model is not confined to the SBR process but may be applied to any biological system using energy for purification.

All these points underline the flexibility and potential capacity of batch mode operations. It is however important to focus on the limitations of the process and its applicability in the forthcoming R&D work. No process option should be seen as a “Jack of all trades”. This would be a very unscientific attitude and is likely to become a burden in the long run for any process solution.
REFERENCES


OTHER REFERENCES
EU directive EEC 91/271.

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