Demonstration of a hybrid (mesophile – thermophile) “side-stream” MBR solution to reuse waste water in chemical industry

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LAYMAN’S REPORT
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Summary of project scope and objective

In a lot of industrial processes, process/flue gasses have to be treated before they can be discharged to the atmosphere. The goal of this treatment is to remove the hazardous gasses, fine particles and aerosols from the flue gas stream. These process/flue gasses often originate from thermal (high temperature) processes, such as drying, incineration, burning, and cracking. A significant amount of process/flue gas treatment techniques (e.g. scrubbers, wet electrostatic filters, wet dust filters) are so called wet cleaning techniques, which bring the gases, aerosols and particles to the water phase. The waste water originating from the wet process/flue gas cleaning is therefore polluted with dissolved and suspended components and has significantly elevated temperatures.

Norit Activated Carbon (NAC) owns and operates an activated carbon production plant in Glasgow (Scotland). In this plant different grades of wood and olive cores are chemically activated in ovens, using phosphoric acid. The drying and especially the oven processes produce polluted process gasses that are transferred to the water phase by washing them out in venture and plate scrubbers. Majority of the pollutants that are transferred to the water phase are organic carbons, of which a significant part can be considered recalcitrant (hydrocarbon cracking products). The concentration of these pollutants is expressed as Chemical Oxygen Demand (COD), which represents the amount of oxygen required to oxidize the organic carbons. The washing water is heated by the hot process/flue gasses and exits the scrubbers with temperatures of 50 - 55 degC. Over time the Glasgow plant produces different types of activated carbon based on different feedstocks. I.e. every few weeks, feedstock is changed between WOOD and olive stones (ELCD). This leads to strong variations in wastewater constitution, strongly influencing the traditional biological treatability.

In this project NAC will demonstrate the application of a hybrid Membrane BioReactor (MBR), i.e. an aerobic bioreactor with “side stream” membranes, to improve its environmental performance by significantly reducing its waste water discharge volume and pollutant load and maximize the reuse of treated waste water. The hybrid MBR design enables both mesophile (20-40 degC) and thermophile (>40 degC) operation, which provides optimum flexibility to the biological process.
Purpose of this project is to demonstrate the effectiveness and efficiency of the hybrid MBR, with main focus on thermophile operation, with the following main objectives:

- High COD removal (>90%) and high TSS removal (>94%), making effluent suitable for reuse and consequently reducing waste water discharge volume
- Maximum reuse of effluent as process water (>80%)
- Minimum (almost zero) sludge production
- Reduced energy consumption compared to mesophile “side stream” MBR systems
- Reduction of chemical usage for sludge processing and/or pH correction in case of direct discharge to sewer

**Process Description**

**Main MBR components**
The hybrid MBR installation consists of the following main components:
- Aerobic Bioreactor
- “Side stream” ultrafiltration (UF) membrane units
- Pre-cooling (for mesophile operation only) and downstream cooling.

In the aerobic bioreactor, the COD is converted to water and carbon dioxide by the activated sludge (microbiology). The activated sludge is fully maintained in the system through the utilization of the UF membranes instead of a secondary clarification (as done in traditional activated sludge plants). This results in a longer Sludge Retention Time (SRT) and a higher activated sludge concentration (Mixed Liquor Suspended Solids = MLSS). In combination with a higher process temperature this offers the advantage of minimal sludge production (sludge growth and die-off are in balance, the microbiology “consumes” itself) and stable effluent quality even with varying wastewater constituents and loads.

**Aerobic Bioreactor → COD Removal**

\[ C_x H_y O_z + O_2 + \text{nutrients} \rightarrow CO_2 + H_2O + \text{biomass} \]

**UF Membranes → Absolute removal of solids**

Separation filtrate from activated sludge

- 8 mm tubular PVDF membranes
- Mean pore size 30 nm

The membranes used are cross-flow tubular membranes that are situated outside the bioreactor (side stream). The membrane tissue of most submerged membranes cannot withstand the higher process temperatures that occur when operating under thermophile conditions and will wear out very fast. Also fouling and scaling control is easier when using side stream membranes. Cooling down of the
UF permeate, that will be reused as process water, is required to realize/enforce condensation of the pollutants in the flue gasses and therefore support a high efficiency flue gas cleaning.

**Cross-flow UF system based on 8 inch tubular membrane modules**

The cross-flow mode is used most generally for industrial wastewater treatment applications. The main characteristic of cross-flow is that a part of the feed is withdrawn as permeate, while the other part is forced to flow along the membrane surface. The pressure pump pressurizes the feed, while the circulation pump recirculates the concentrate; part of the concentrate is purged to the bioreactor. The advantage is a better control of the cake layer build-up resulting in a long time constant flux without any cleaning. Typically, a system consists of several modules in-series (one street) and several streets in-parallel. Norit Cross-Flow MBR systems are available as standardised, modular skids. The modules are placed horizontally resulting in very reliable and compact installations.

The heart of the cross-flow membrane installations is the 8 inch GPR module with tubular membranes with an inner diameter of 8 mm. Norit X-Flow has developed especially for the Norit Cross-Flow MBR application high flux membranes with excellent anti-fouling behavior. Together with an optimal CIP procedure the Norit CrossFlow MBR process is an efficient solution for industrial wastewater treatment.

**Process summary**

Below figure shows the process flow diagram of the hybrid MBR with “side-stream” Ultrafiltration membranes. Hot COD-rich wastewater from the AC plant is collected and sent to an aerobic bioreactor via a plate exchanger for pre-cooling. Depending on the operation of the bioreactor, the plate exchanger is either fully utilized (mesophile operation, 20-40 degC) or partially / not utilized (thermophile operation, >45 degC). Pre-cooling is required, especially for mesophile operation, to handle heat accumulation in the bioreactor as a result of the exothermic biological process and energy input from the cross-flow UF system.
Pre-cooled influent from the plate exchanger is sent to the aerobic bioreactor. In the bioreactor the COD waste is converted into water and carbon dioxide by the activated sludge. Oxygen to the activated biomass is provided by means of air blowers. Biomass circulation pumps in combination with jet aerators are applied for mixing the air into the activated sludge. Facilities have been provided for dosing urea (N-Nutrient) to the bioreactor if required. Since sufficient P-Nutrient is present in the MBR influent (PO$_4^{3-}$), no P-Nutrient dosing facility is required. Based on the MBR pilot study, no pH-correction of the low pH influent will be required. However, NaOH dosing is provided for potential pH correction of the bioreactor.

The biologically treated water is pumped into a single-stage ultra-filtration (UF) system, consisting of four units of six membrane modules each. During cross-flow operation, part of the biomass feed flow is discharged as (clean, solids free) permeate, while the majority of the biomass feed flow is circulated back to the bioreactor. This will limit fouling of the membranes during operation and minimize cleaning frequency.

**Aerobic bioreactor with 3 blowers**

**2 membrane units (containerized)**
UF permeate is sent to an after-cooler (cooling tower) and collected in a treated water tank. From this tank UF permeate is pumped to the existing river water main in the AC plant with a frequency-controlled pump. For controlling potential accumulation of salts and hydrocarbons in the bioreactor (due to the recycle), a bleed facility is provided to discharge a limited (clean) UF permeate flow to the sewer.

Since sludge growth during the four months of pilot trials proved to be negligible, a final decision on surplus sludge treatment was postponed to the mesophile operating phase of the full-scale project. During this period, sludge growth was higher than during the pilot trials, but still very limited. Consequently the decision was made not to install a permanent sludge treatment but to have an intermittent discharge of sludge to the sewer.

Results
Introduction
Throughout the total project period, the MBR plant has suffered operational drawback, which has strongly restricted overall utilization and affected the results of the MBR plant. The main problems can be categorized as follows:

Insufficient and unstable influent flow:
Design of the MBR plant was based on continuous influent availability, except for a limited shut-down period during the Christmas period. In practice however, the MBR plant suffered multiple periods of limited or disrupted influent flow, varying from a couple of days to several weeks.

Insufficient COD load:
Influent COD concentrations for both Wood and ELCD turned out to be far less than anticipated during the design stage. In combination with insufficient and unstable influent flow (item above), COD load for the biomass has been (far) below design level. Consequently, adaptation and growth of the activated sludge have been restricted. Although this situation has lasted the total project period, no significant negative impact on COD conversion has been observed. Fortunately also the membranes hardly suffered from this phenomenon. Although membrane fouling is a common phenomenon in MBR plants suffering too low COD loads (causing unstable sludge floc formation and consequently declining membrane filtration characteristics), membrane cleaning has only been required every now and then.

Rotating equipment failure:
On several occasions, the bioreactor circulation pumps and membrane system pumps have suffered mechanical seal failures. These problems not only caused multiple turn-down and shut-down periods, but also took a lot of effort and time for investigation and corrective actions. The mechanical seal problems have most probably been caused by wrong selection of both the type and material of the seals.

Temperature limitations thermophile operation
During the thermophile operation period, unfortunately the maximum achievable temperature in the bioreactor was only 45°C, where temperatures of approx. 55°C were anticipated. As detailed below,
MBR performance during these (pseudo) thermophile conditions deteriorated. Main reason for the maximum temperature limitation is the fact that early 2007 the Scottish Water Protection Agency (SEPA) has reallocated the Norit UK Activated Carbon factory from a category “B” to a category “A” process plant. This involved much greater control of the process, waste disposals and other preventative measures to eliminate or reduce the chance of environmental pollution. One area specifically highlighted was the scrubbing systems and scrubber efficiency. Consequently SEPA has demanded that in no case scrubber operation is allowed above 45°C. As a result the maximum achievable temperature of the scrubber effluent, i.e. MBR influent, is limited to 45°C which makes it impossible to reach the theoretically ideal thermophile operation range of 50-55°C.

Damage oxygen distribution system bioreactor
In March 2008 the central post in the bioreactor broke down as a result of extreme storm conditions on site and sank to the bottom. Unfortunately the pipe has seriously damaged the aeration piping and consequently the oxygen supply to the biomass completely deteriorated. Since overall MBR performance (biology and membranes) seriously declined ever since, the project team has decided early April 2008 to stop MBR operation and to empty the bioreactor (draining the biomass to the sewer) for repair. Restart is anticipated in September 2008.

Summary MBR performance results
A summary of the main MBR performance results throughout the total project period is presented in the following figures:

- Figure 1 : Bioreactor temperature, MLSS (DS) and COD conversion
- Figure 2 : Influent flow (MBR capacity), sludge discharge flow
- Figure 3 : Influent COD
- Figure 4 : UF membrane units fluxes and flows
- Figure 5 : Typical daily operational costs savings MBR
**Figure 1:** Bioreactor temperature, DS and COD-conversion

**Figure 2:** Influent flow (MBR capacity) and sludge discharge flow
Figure 3: Influent COD

Figure 4: UF membrane units fluxes and flows
As visualised in above graphs, during the total project period the following operational phases can be distinguished:

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mesophile-1A</td>
<td>May – Sept’06</td>
<td>5 months Mesophile operation from Start-up till design level of 15 g/l DS in the bioreactor</td>
</tr>
<tr>
<td>2. Mesophile-1B</td>
<td>Oct’06 – Mar’07</td>
<td>6 months Mesophile operation from 15 – 30 g/l DS in the bioreactor</td>
</tr>
<tr>
<td>3. Transition</td>
<td>Apr – Jun’07</td>
<td>3 months Transition from mesophile to thermophile operation with sludge discharge to design level of 15 g/l</td>
</tr>
<tr>
<td>4. Thermophile</td>
<td>Jul – Nov’07</td>
<td>5 months Thermophile operation</td>
</tr>
<tr>
<td>5. Mesophile-2</td>
<td>Dec’07 – Feb’08</td>
<td>3 months Fall back scenario to mesophile operation</td>
</tr>
<tr>
<td>6. MBR-stop</td>
<td>Mar – May’08</td>
<td>3 months Gradual stop of MBR operation due irreversible damage to aeration system</td>
</tr>
</tbody>
</table>

**Mesophile-1A/B operation**

Based on the first period of mesophile operation (May’06 – Mar’07), MBR plant performance has proven to be reliable and robust. Although influent capacity has been insufficient and unstable (33 m³/h avg. vs 65 m³/h design, Figure 2) and COD loads have been less than anticipated
(WOOD: 2276 mg/l avg. vs 3500 mg/l design, ELCD: 4782 mg/l avg. vs 5400 mg/l design, Figure 3), COD removal has been beyond expectation and very stable (avg. 97%, Figure 1).

Although COD loads have been far less than required, MLSS in the bioreactor has increased gradually (3 g/l in June 2006 to 30 g/l in March 2007, Figure 1). However, avg. sludge growth has been far less than anticipated (0,06 DS/kg COD avg. vs 0,15 DS/kg COD design, Figure 1) In-line with the excellent biological performance, also performance of the membranes has been beyond expectations. As from start-pup, the four UF units have been running above design capacity (120-250 l/m2h vs 110 l/m2h design, Figure 4).

**Transition - thermophile operation**
Starting from April 2007 operation has gradually been shifted to thermophile operation. In parallel, MLSS has been reduced to the design level of 15 g/l (Figure 1). During the period Aug – Dec’07, temperature has been 40-45°C. As a result, the installation has been running under (pseudo)thermophile conditions for approximately 5 months.

Unfortunately MBR performance has deteriorated during this period and COD removal dropped to avg. 77%. To recover plant performance, COD load to the bioreactor had to be reduced drastically by reducing the influent capacity far below design capacity (Figure 2). Sludge growth has completely stopped and has even been inclining towards a slightly negative trend. Throughout Mesophile-1A/B, similar performance dips have never been observed.

Despite the decline of biological performance, initially the UF membranes are not negatively affected. Capacities are maintained above design levels (Figure 4). However towards the end of the thermophile period, all 4 units are suffering a distinct decline of flow, indicating membrane fouling due to destabilisation of the activated sludge.

**Fall-back to Mesophile-2 operation**
Due to poor performance at thermophile conditions a fall-back to mesophile operation was required. This fall-back scenario was part of the project plan in case thermophile performance would be less than expected. The return to mesophile operation has effectively been initiated in Dec’07.

During the first months after restoring mesophile temperatures, biological performance has improved to the same level as Mesophile-1A/B. COD removal efficiencies have recovered and stabilised at avg. 97% (Figure 1), MBR capacity has been increased to 30 – 70 m3/h (Figure 2) and MLSS has increased from 15 – 27 g/l, meaning an avg. sludge growth of 0,08 kg DS/kg COD.

**MBR-STOP**
Due to the irreversible damage to the aeration system MBR-operation is stopped. The sludge is gradually discharged to the sewer system to have maximum dilution of solids.
A summary of the main results during both mesophile and thermophile operation are presented in below table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Design</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mesophile</td>
</tr>
<tr>
<td>MLSS Bioreactor</td>
<td>g/l</td>
<td>15</td>
<td>3 → 30 optimum</td>
</tr>
<tr>
<td>pH Bioreactor</td>
<td></td>
<td>6 – 8,5</td>
<td>6,5 – 8,5</td>
</tr>
<tr>
<td>Influent flow</td>
<td>m3/h (% of design)</td>
<td>WOOD: 70</td>
<td>Avg: 40 (62%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ELCD: 50</td>
<td>Avg: 65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg overall: 33 (51%)</td>
<td></td>
</tr>
<tr>
<td>Influent COD</td>
<td>mg/l (% of design)</td>
<td>WOOD: 3500</td>
<td>WOOD: 2276 (65%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ELCD: 5400</td>
<td>ELCD: 4782 (89%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg: 4000</td>
<td>Avg: 3110 (78%)</td>
</tr>
<tr>
<td>COD load</td>
<td>kg COD / kg DS.day (% of design)</td>
<td>WOOD: 0,15 – 0,25</td>
<td>WOOD: 0,09 (45%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ELCD: 0,2 – 0,3</td>
<td>ELCD: 0,14 (56%)</td>
</tr>
<tr>
<td>COD removal</td>
<td>% (% of design)</td>
<td>&gt;90</td>
<td>93 - 99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg: 97 (108%)</td>
<td>Avg: 77 (86%)</td>
</tr>
<tr>
<td>Reuse water</td>
<td>% (% of design)</td>
<td>&gt;80</td>
<td>100 (125%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg: 97 (108%)</td>
<td>Avg: 77 (86%)</td>
</tr>
<tr>
<td>Sludge yield</td>
<td>kg DS / kg COD (% of design)</td>
<td>0,15</td>
<td>0,07 (47%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg: 40 (62%)</td>
<td></td>
</tr>
<tr>
<td>UF unit flux</td>
<td>1/m2.h (% of design)</td>
<td>110</td>
<td>120-300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(120-273%)</td>
</tr>
<tr>
<td>CIP cleaning UF</td>
<td>frequency per UF unit</td>
<td>1 CIP per 2-3 months</td>
<td>1 CIP per 4-6 months</td>
</tr>
</tbody>
</table>

**Operational costs**
Operational cost balance after installation of the MBR plant is mainly determined by the following factors:
- Additional costs MBR power consumption
- Cost savings reduced river water intake and effluent disposal
- Cost savings reduced NaOH consumption for neutralizing low pH waste water

**Power consumption:**
Power consumption per m3 treated water strongly depends on capacity of the MBR plant. This is mainly caused by the fact that the air blowers, which are the major energy consumers, are always running to provide oxygen to the biology, even when no influent is provided. Since utilization of the MBR plant has been limited (influent flow has only been 50% of design), not only the power costs per m3 treated water have been relatively high, also the effluent disposal costs have been relatively high.
Sludge disposal:
Because no permanent sludge treatment facility has been installed, the minimum volumes of surplus
sludge have directly been discharged to the sewer (diluted). Consequently the MBR sludge disposal
costs are included in the overall effluent disposal costs of NUK.

NaOH consumption:
Since pH of the MBR influent is low (pH 3 – 5) due to the Norit UK chemical activation process
with phosphoric acid, this waste water required neutralization with NaOH prior to discharge to the
sewer before installation of the MBR. In the MBR however, the acidic organic carbons are
converted by the activated sludge, resulting in a neutral pH in the bioreactor. This strongly reduces
the operational costs for NaOH. This phenomenon has already been noticed during the four months
pilot trails, during which no NaOH dosing had been required for pH correction of the bioreactor.

Unfortunately the specific NaOH consumption data for MBR operation is not available (part of
existing Norit UK NaOH system which does not allows specific MBR consumption monitoring).
However, based on historical Norit UK NaOH consumption data, the available MBR pilot data and
the utilization data of the MBR plant, the estimated reduction in NaOH consumption related to the
MBR plant has been at least 2 tons/day.

Overall operational cost savings MBR:
Based on Figure 5, the following can be concluded:
• Average cost saving is approx. £250 per day, i.e. £90,000 per year.
  Virtual cost saving incl. estimated NaOH saving is approx. £450 per day (£149,000 per year).
• In case utilization of the MBR plant could be optimized, average cost savings can be increased
to £500 per day, i.e. £165,000 per year.
  Taking into account the higher virtual cost saving for NaOH in case utilization of the MBR
  plant is increased, average cost savings can even be increased to £900 per day, i.e. £300,000 per
  year.

Environmental impact of the project
During a two years project period, the plant was initially operated under mesophile conditions,
showing excellent performance, and was gradually shifted to thermophile operation. Unfortunately,
the influent temperature to the MBR was less than expected and could not be further increased,
resulting in pseudo-thermophile conditions in the bioreactor. Under these conditions thermophile
operation proved to be not feasible, i.e. performance of the MBR declined and results were below
expectations. Inevitably mesophile operation was reinstated towards the end of the project.

Although thermophile operation proved to be not feasible under the given influent temperature
constraints, mesophile operation has proven to be beyond expectation, achieving excellent COD
removal and absolute solids removal. Since utilization of the MBR plant has been limited, this has
enabled absolute reuse of the treated water.
Overall, we achieved the following main results:

**Mesophile operation**
- COD removal: 97% avg. (design 90%)
- Solids removal: ~100% (design 94%)
- Avg. MBR capacity: 40 m³/h (design 65 m³/h average)
- Reuse of effluent: 100% (due to limited plant capacity, i.e. utilisation) (design 80%)
- Sludge yield: 0.07 kg DS / kg COD (design 0.15 kg DS / kg COD)
- UF membrane flux: 120-250 lmh (design 110 lmh)
- UF CIP frequency: 1x per 4-6 months (1x per 2-3 months)

**Thermophile operation**
- COD removal: 77% avg. (design 90%)
- Solids removal: ~100% (design 94%)
- Avg. MBR capacity: 20 m³/h (design 65 m³/h average)
- Reuse of effluent: 100% (due to limited plant capacity, i.e. utilisation) (design 80%)
- Sludge yield: nil, slightly negative (design 0.15 kg DS / kg COD)
- UF membrane flux: 50-175 lmh (design 110 lmh)
- UF CIP frequency: 1x per month (1x per 2-3 months)

**Transferability of project results**
Given the characteristics of the application demonstrated in this project, project results are considered transferable to similar applications (that is treatment of effluent from flue-gas and offgas stripping) as well as the following industries:

- brewery industry
- maltery industry
- dairy industry

Within this project a selection of companies within these industries has already been informed on the project, project results and potential of the technology for them. Continuous effort will be made to inform more companies within these three industries.