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Operational Optimization of Biofilm Membrane BioReactor (BMBR) for decentralized wastewater treatment

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Abstract

Biofilm Membrane BioReactor (BMBR) is a promising technological combination of moving bed biofilm reactor (MBBR) with membrane bioreactor (MBR) for municipal and industrial wastewater treatment. It has resulted in prominent advantages over conventional methods, including treatment efficiency improvement, reduced footprint, better effluent quality, process intensification etc. However, membrane fouling acts as a huge barrier to extensive use of the technology and the only way that control the membrane fouling must be considered in designing BMBR which is optimization of treatment parameters. However in practical situations, these parameters vary from wastewater plant to plant based on membrane type, biological characters and type of wastewater etc. Therefore, optimizing the treatment parameters are essential to control membrane fouling that considers individual treatment plants rather than generalizing. To achieve this goal, current study was focused on two main sub-tasks: understanding and experimental determination of critical flux and comparison of membrane cleaning conditions. In addition, a problem of foaming in BMBR system has been investigated and inputs for system design optimization provided. The results showed that net flux production efficiency in filtration in the pilot plant increased by 20% after introducing the proposed critical flux determination protocol, which helps to optimize the treatment conditions. Fouling could be controlled by relaxation itself using the protocol under the working flux 24-26LMH in the experimental conditions. With increasing flux level to 28, 30LMH application of backwash is needed for better filtration. When considering the fouling removal using chemicals, application of both 0.1 – 0.5%NaOCl and 5% citric acid gives good results in removing both organic and inorganic foulants from membrane surface. Considering physical cleaning, the highest fouling removability was obtained by the physical treatment combination used with a backwash hammer. However the obtained results show that membrane modules require further construction improvements in order to be used under backwash hammer. Effectiveness and usage of ceramic membranes could be increased if the plastic connectors of the ceramic membrane could be made by a durable material that can endure aggressive conditions. It has been found that unbalance in F/M ratio highly affected foaming behaviour, which resulted in many challenging problems in the handling and filtration process. These challenges include contamination by overflow from the separation tank to the permeate tank, obscure level sensors and restricted visual observations etc. In order to avoid contamination to the permeate tank, the proposal is to fix separation walls between tanks.

Conclusively, increased net flux production efficiency of the current pilot plant can be reached as a collective plan when considering critical flux, better combination of physical and chemical cleaning and mitigating foaming under the current plant operational conditions.

Key Words : Biofilm Membrane BioReactor (BMBR), Moving bed biofilm reactor (MBBR), Membrane bioreactor (MBR), ceramic membrane, membrane fouling, foaming, critical flux, chemical cleaning, physical cleaning

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1 Introduction

New technologies regarding wastewater treatment have in recent years been developed continually and vastly. The moving bed biofilm reactor (MBBR) combined with membrane bioreactor (MBR) is a recent popular solution and alternative to conventional processes. To improve the performance of MBR within pollutant removal and membrane filtration, the Biofilm Membrane Bioreactor (BMBR) systems (figure 1) have been developed over the last years (Leyva-Diaz et al. 2014). In this system the MBBR process is introduced before the MBR filtration to obtain a combined advantage when improving the treatment efficiency. MBBR is one of the promising technologies in advanced wastewater treatment.

Therefore, when compared with the conventional activated sludge process, MBBR can work with high organic loading rates and fluctuations with resulting high quality effluent. MBBR can also be used in combination with conventional activated sludge systems or as a hybrid system. Other advantages include robustness, efficiency and compact size, cost efficiency, flexibility and easy of operation (Difference Between | Descriptive Analysis and Comparisons 2018). However, the poor settle-ability of bio-solids is due to high organic loading (high food to microorganism ratio (F/M) conditions), and is a major challenge in MBBR technology (Kimura et al. 2005).

The Membrane Bioreactor (MBR) technology is a unique treatment process for wastewater that combines the activated sludge biological treatment process with membrane filtration technology (Yang, Syed, and Zhou 2014). This is one of several promising technological innovations in wastewater treatment. This MBR technology is widely accepted as a replacement for conventional biological methods for wastewater treatment due to its high purification performance, low environmental impact, small footprint and high possibility to reuse the treated water (Bottino et al. 2009). Furthermore, MBR can positively affect the solids retention time (SRT), hydraulic retention time (HRT), quality of effluent and amount of sludge production (Duan et al. 2015). However, membrane fouling and high energy requirement acts as main barriers. Membrane fouling limits the membrane's performance over time, resulting either a dramatic drop in the permeate flux under constant pressure conditions or an increment of an observable trans-membrane pressure (TMP) under constant flux conditions over time (Miller et al. 2014).

To mitigate the abovementioned poor settle-ability behaviour in MMBR and membrane fouling behaviour in MBR, the combination of membrane bioreactor and moving bed

biofilm reactor (BMBR) technology has been introduced by Leiknes and Ødegaard (2007). It gives higher volumetric loading and shorter sludge retention time (SRT) compared with other wastewater treatment technologies (Leiknes and Ødegaard 2007). BMBR technology is a novel solution for wastewater treatment and has proven to be increasingly popular in the water and wastewater treatment sectors in recent decades (Jamal Khan et al. 2011).
The overall objective of the membrane treatment process is to increase permeate flux while maintaining effluent water quality and reasonable operational costs. The membrane resistance, the operational driving force per unit membrane area, hydro dynamic conditions at the membrane-liquid interface, membrane fouling and subsequent cleaning of the membrane surface are key elements that influence high volume and high quality permeate flux (Radjenović, Matošić, and Mijatović 2008). The operational parameters such as HRT, SRT and the food micro-organisms ratio (F/M ratio) in the treatment process are important factors for membrane filtration. The HRT, SRT, F/M ratio and reactor MLSS concentrations affect the membrane fouling phenomena, TMP behaviour, hydraulic resistance etc. These situations and features collectively affect the membrane filtration efficiency (volume of permeate flux). Therefore, it is impossible to increase permeate flux volume by considering one/few factors (Yoon, Kim, and Yeom 2004). The optimization of the operational parameters is the only available way to increase permeates flux volume while maintaining reasonable operational cost and effluent water quality. This optimization processes can vary according to type of wastewater, model of treatment plant, membrane characters, objective of the treatment process, etc.
The aim of this study was to optimise the combination BMBR treatment process with ceramic membrane. The experiments were conducted in a pilot scale BMBR system situated at Norwegian University of Life Sciences (Norwegian: Norges miljø- og biovitenskapelige universitet, ***NMBU***). The intention after the completion of the preliminary experiments in the pilot-scale BMBR system is to transfer the system into a wastewater treatment plant in crew ships.

2 Literature review

2.1 Biofilm Membrane BioReactor as evolutionary development of MBBR and MBR technologies

According to several kinds of scientific research, the combine MBBR-MBR technology has shown a high ability to remove impurities in municipal wastewater. The combined technology shows a significant removal efficiency of micro-pollutants in comparison to other types of wastewater treatment technologies (Luo et al. 2015). It also shows efficient membrane performances during treatment, due to considerably lower fouling tendency in the process (Ivanovic and Leiknes 2008). The level of soluble microbial products in the combined MBBR-MBR process is five times less than in conventional the MBR process (Luo et al. 2015), (Bottino et al. 2009).

MBBR process operates similarly to the activated sludge process with the addition of freely moving polyethylene biofilm carrier media inside the biological reactor for biofilm growth (Borkar, Gulhane, and Kotangale 2013). In the process, biomass is growing in the reactor as a suspended flocks and a biofilm. The biofilm grows attached to a floatable small polyethylene element called Carrier (figure 1). It moves freely inside the MBBR chamber as a result of the aeration process in the aerobic reactor, or by a mechanical stirrer in an anaerobic or anoxic reactor. Due to the movement, the carrier acts as a supporting media for the biomass' optimal mobilization inside the reactor. Each carrier provides a surface to grow thousands of heterotopic and autotrophic bacteria that helps the biological process in the MBBR technology. This facilitates in maintaining a high density of bacterial population growth in the MBBR reactor (Borkar, Gulhane, and Kotangale 2013). The high population growth provides an ability to keep a high rate of bio degradation in wastewater with minimum maintenance (International n.d.).

In MBR, the membrane module chamber acts as a secondary clarifier, same as in the conventional activated sludge process. Due to the small pore size in membranes, suspended solids can be retained completely in the separation chamber. This results in blocking the passage of particles from wastewater to effluent (Viana et al. 2005).

Leyva-Diaz and group (2013) has shown the combined MBBR-MBR technology's ability to remove high organic matter in municipal wastewater; they refer to 95.5672% COD removal using the combined treatment technology (Leyva-Díaz et al. 2013). The combined process has shown high irreversible cake forming ability compared to the MBR process, due to high biofilm detachment in the process. However, that cake formation process helps prevent pore blocking (Di Trapani et al. 2014).

Some studies indicate that hybrid MBBR–MBR systems could experience severe membrane fouling due the presence of large amounts of submicron colloidal particles in the reactor. Operating conditions and system configurations are key aspects in the applicability of MBBR-MBR systems in order to avoid higher fouling as an effect of submicron colloidal particles (Sun et al. 2012).

Membrane fouling is one of the most important phenomenon in the design and operation of membrane systems. The fouling process results in reduced membrane permeability due to accumulation of suspended or dissolved substances on its external surface or inside pores (Di Trapani et al. 2014), which reduces the efficiency in membrane filtration. Further fouling in the MBR process is very unpredictable and difficult to control (Le Clech et al. 2003). Because of that majority of membrane filtration optimization process, membrane material production and kinetic modelling research and developments mainly concerned about mitigation of membrane fouling phenomena. This fouling mitigation phenomenon is a complex process.

Membrane foulants such as suspended particulates, colloids and solute in the mixed liquor suspended solids (MLSS) leads to decline of permeate flux, increased TMP and reduced treatment efficiency over time. It also results in significant incensement of hydraulic pressure in the filtration process (Campo et al. 2017).

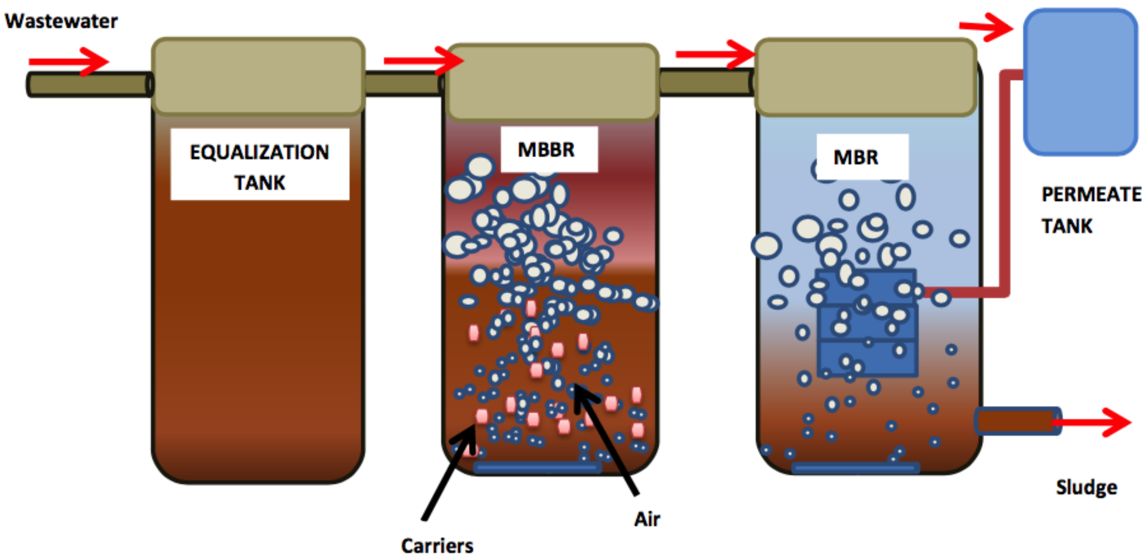

Figure 1: Schematic view of the BMBR plant

Combination of MBBR and MBR is promising technology due to its high advantages over conventional methods. Among many advantages high treatment efficiency improvement, better effluent quality and process intensification are some of them. However, membrane fouling and high energy consumption acts as a huge barrier to extensive use of this technology which reduces the filtration efficiency of the membranes.

2.2 Operation parameters of Biofilm Membrane BioReactor

According to (Judd 2004), the membrane fouling phenomenon can happen due to three factors; membrane characteristics, biomass characteristics and operation conditions, as shown in figure 2.

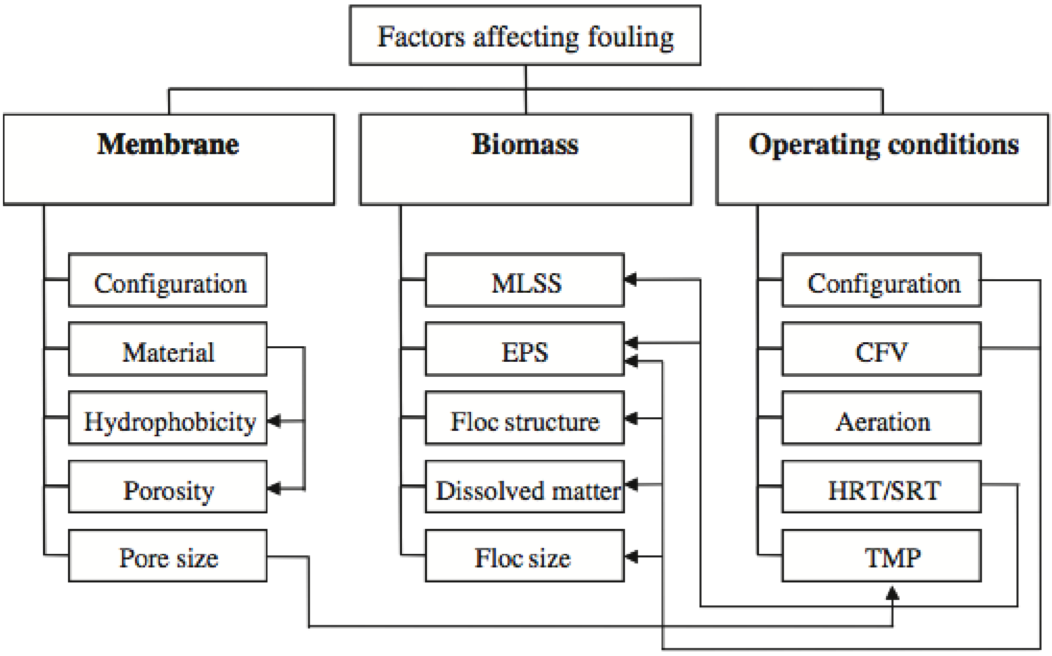

Figure 2: Characteristics affect for membrane fouling in different ways (Judd 2004)

Membrane: Membrane material mainly affects the membrane fouling process. Different types of membrane are available in the market, varying by the material used to produce a range of ceramic membranes, polymeric membranes and composite membranes (Ladewig B, Al-Shaeli 2017).

Ceramic membranes: Ceramic membranes are not widely applied in the wastewater industry in comparison to other types of membranes in use. However, they are getting popular due to lower operational costs, high integrity, suitability for operation at high temperatures and chemical resistance (WEF 2012). Ceramic membranes are artificial membranes made from porous inorganic membrane layers of aluminium oxide, titanium oxide, zirconia oxides or silicon carbide or some glassy materials over a pores support such as alpha alumina. When compared with polymeric membranes, ceramic membranes can be used to separate aggressive media such as acids and where strong solvents are present (Figueiredo et al. 2004). According to Figueiredo et al., the porous layer will have distinct pores ranging from 0.5, 0.1 and even 0.02 microns. Typical pore sizes are a nominal 0.1 micron. The diameter of the tubes varies from 10-180 mm. In some cases the tube diameter will be 6, 9.6, 12, 16, 19 and 25 mm. Ceramic membranes are available in both tubular and multichannel models. There are some flat sheet ceramic membranes, but the majority of ceramic membranes are tubular.

According to the hydrophobicity of membrane materials, ceramic membranes have high hydrophobicity compared to other types of membrane materials. It minimizes the fouling behaviour in the filtration process (Kimura et al. 2005). Polymeric membranes show easy fouling ability due to their low hydrophobicity. Most sections of recent research consider the modification of materials in the membrane and mainly focus on the relationship between membrane fouling and membrane materials. This is due to mitigation of membrane fouling using membrane material modifications being the easiest method to the control fouling phenomenon (Yu et al. 2008). The membrane pore size mainly affects membrane pore blocking according to the particle size distribution in the feed water (Meng et al. 2007).

TMP (Trans membrane pressure): TMP is another factor that affects operational conditions in membrane filtration. The MBR process generally has two types of operating methods; constant TMP filtration and constant permeate flux filtration (Campo et al. 2017). Constant TMP filtration shows permeate flux decline according to the time of filtration. This is to maintain constant TMP. The constant flux filtration process shows incensement of TMP alone with the time of filtration for maintain to constant flux (Mutamim et al. 2013). In the constant permeate flux method, membrane fouling is showed by TMP jump in the filtration process. Finding the critical flux is important in order to operate the plant without TMP jump in the treatment process. Critical flux will be further discussed in chapter 3.

SRT (Solid retention time): SRT mainly correlates with the formation of extracellular polymeric substances (EPS) (Ahmed et al. 2007), (Jiang et al. 2008). A high SRT produces a starving situation in the bioreactor due to reduction of EPS formation (Judd S. J. 2010). However, high SRTs result in high membrane fouling due to the accumulation of high MLSS and high sludge viscosity (Jiang et al. 2008), which results in a reduction of aeration efficiency in the chamber (Van den Broeck et al. 2012). Operating at very low SRT condition increases membrane fouling due to increases in bound and soluble EPS (Meng et al. 2007), (Meng et al. 2009).

HRT (Hydraulic retention time): HRT is another important operational parameter in the membrane filtration process that affects fouling. However, this indirectly influences membrane fouling with other operational and sludge parameters. The low HRT results in the increment of EPS release and forms micro-organisms, helping the overgrowth of filamentous bacteria and the formation of poor flocks in the reactor. Furthermore, decrease of HRT helps to increase MLSS concentration and sludge viscosity in the chamber, mainly affecting the hydrodynamic conditions of MBR system (Deng et al. 2016) (Guo, Ngo, and Li 2012)

Food-micro-organisms (F/M) ratio: In many research findings a correlation can be seen between increasing F/M ratio and fouling increase of MBR filtration (Kimura et al. 2005).

Mixed liquor suspended solid (MLSS): Concentration in the separation chamber accelerates fouling in the membrane. The MLSS contains bacteria flocks, ESP, colloids, micro-solutes and macro-solute (Bottino et al. 2009). Researchers have found a relation between filterability and MLSS concentration. According to (Jinling Wu and Huang 2009), a reduction of filterability occurs when the chamber MLSS concentration goes above 10000mg/l . Also, other findings show an increase in MLSS concentration in the separation chamber, resulting in significant decrease of membrane permeability and increase in the fouling rate in membrane (N. O. Yigit et al. 2008). When the MLSS is low the process will not work efficiently and energy efficiency gets reduced while not treating the influent effectively.

Fouling phenomena can take place in different ways, such as pore narrowing (macromolecule adsorption), pore clogging/plugging, and cake formation (Le Clech et al. 2003). Pore narrowing is due to sticky substances in the solution that deposit or absorb in to the pore wall, in sizes smaller than the membrane pore size. This induces a significant reduction of the cross sectional area available to the filtrate flow. Pore blocking happens due to larger pollutants in the influent deposit or pollutants absorbed in to the pore entrance, which increases resistance against the filtration process. The cake formation happens due to continuous accumulation of bacteria clusters, biopolymers and inorganic matter on the membrane, thus severely increasing filtration resistance in the process (Meng et al. 2007).

Understanding the formation of cake layers is very important to controlling fouling in the membrane filtration process. The cake layer formation is a major process in the fouling phenomenon. It represents more than 80% in the membrane's total resistance. The permeation drag and back transport are main opposite actions that regulate the rate of cake formation. The aeration process is disturbed to make a cake layer in the treatment process. The high aeration rate results in the reduction of cake layer formation on the membrane surface. The cake layer mainly consists of volatile suspended solids (VSS), colloidal particles, solutes and inorganic matters.

The VSS is a major contributor to producing cake layer. It shows more than 60% of contribution from the cake layer. The least contributors are colloidal and solutes components (colloidal and solutes components are sources for severe pore blocking in the process), while inorganic matter accounts for more than 20% of the cake layer. The adsorption and deposition of macromolecules matter in the wastewater results in the formation of a highly dense cake layer (Zhang et al. 2006). Figure 3 illustrates the membrane fouling phenomenon.

The foulants that affect membrane fouling can be categorized into three categories; inorganic foulants, organic foulants and biofoulants. Inorganic foulants are a group with cations and anions that precipitate in to the membrane surface or inside the membrane pores (Z. Wang et al. 2008). The high concentration of inorganic substances in the wastewater results in a severe inorganic fouling in the membrane (Arabi and Nakhla 2008). Where it is essential to use chemical cleaning. Organic foulants such as organic biopolymers, humic substances, different kind of proteins, polysaccharides, etc. The organic foulants included in the metabolic products of bacteria are called extra polymeric substances (EPS). The organic fouling is comparatively difficult to remove and biopolymers are important foulants in the organic fouling process (X. M. Wang and Li 2008). Biofoulant includes micro-organisms and some compounds that are produced by microorganisms. The fouling process create according to microorganisms growth, deposited and metabolisms on the membrane surface (Meng et al. 2007).

In order to optimize the production efficiency it is important to optimize the operational parameters as mentioned above.

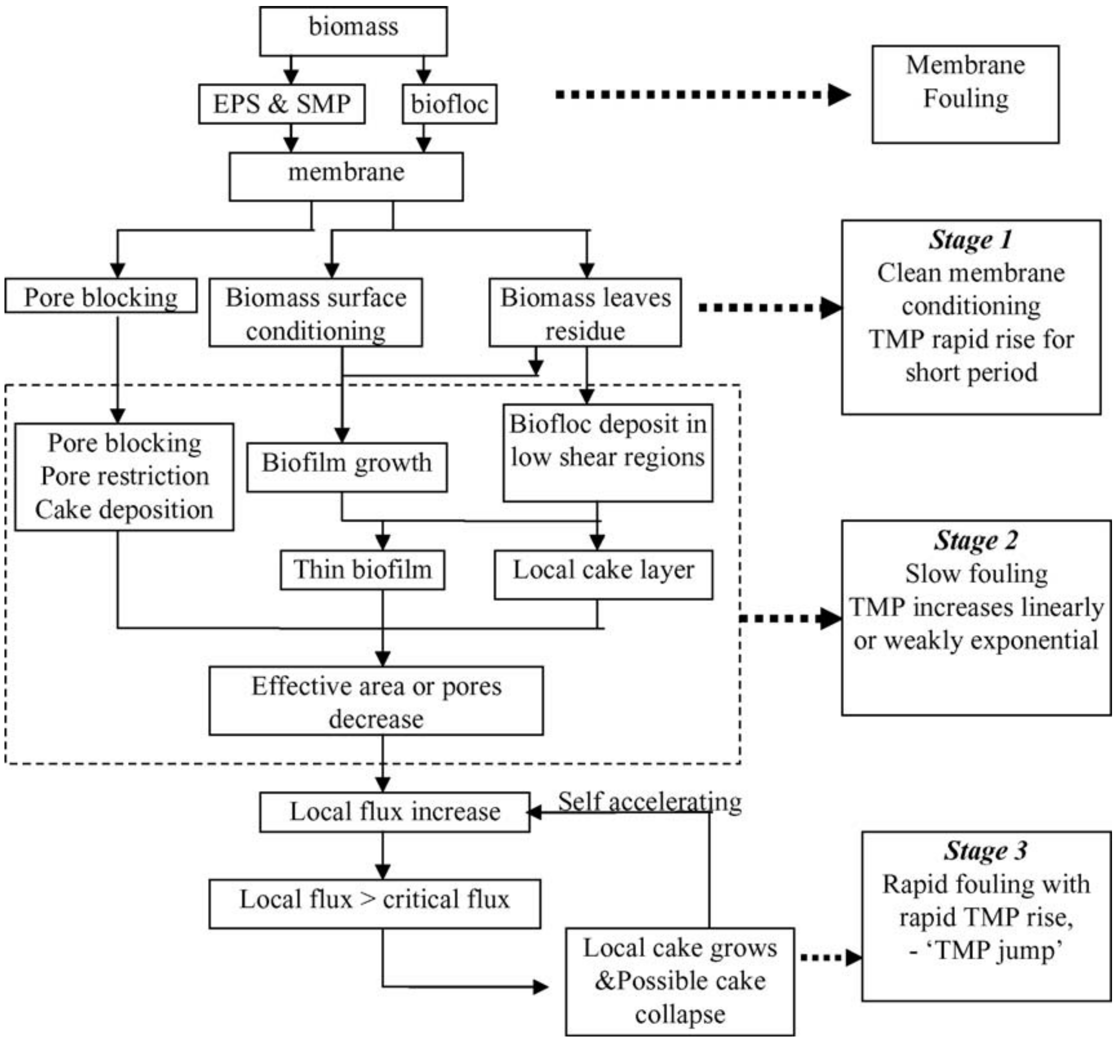

Figure 3: **MBR fouling mechanism map—the three stages of fouling** (Zhang et al. 2006)

2.3 Operational optimization approaches in Biofilm Membrane BioReactor

A wastewater treatment plant's ambition is to increase the treatment efficiency to a maximum level in an economically feasible way. However, when operating a treatment plant, the major practical barrier is the economically costly membrane fouling. All the possible actions that help in mitigating or ceasing membrane fouling is crucial to address when aiming to optimize the operating parameters in the treatment process. When planning to optimize the operating parameters, among several aspects, one of the most important aspects is critical flux. Critical flux provides a quantitative value in finding out the level that a plant can run its filtration process without irreversible fouling. Another aspect that helps to increase the treatment efficiency of a treatment plant includes membrane cleaning, which can be done both physically and chemically.

The aim of this study was to answer the following overall question: "How to optimize operating conditions, using different operating parameters in a pilot–scale MBBR-MBR system situated at Norwegian University of Life Sciences (Norwegian: *Norges miljø- og biovitenskapelige universitet,* (***NMBU)***" This was to be answered in light of the following two operational objectives.

1. Understanding and experimental determination of critical flux
    a. Develop and implement protocol for critical flux test for the current system configuration.
    b. Treatment efficiency optimization through economical aspects.
2. Comparison study of different membrane cleaning protocols.
    a. Develop and implement protocol for membrane cleaning in place (CIP)
    b. Optimization of physical cleaning methods for current system configuration.

In addition, a problem of foaming in BMBR system has been investigated and inputs for system design optimization provided.

3 Materials and Methods

Biofilm Membrane BioReactor pilot plant: Figure 4 shows a demonstration of the pilot-scale BMBR plant used in this study. The whole plant consists of five chambers: wastewater feed /equalization chamber (Chamber I), two MBBR chambers (Chamber II and III), MBR/ separation chamber (Chamber IV) and permeate chamber (Chamber V). Each chamber has 100 l capacity. Chamber II, III and IV is continuously aerated. And return sludge circulates directly from Chamber IV to Chamber II. In Chamber IV, three ceramic membrane modules are horizontally-parallel placed.

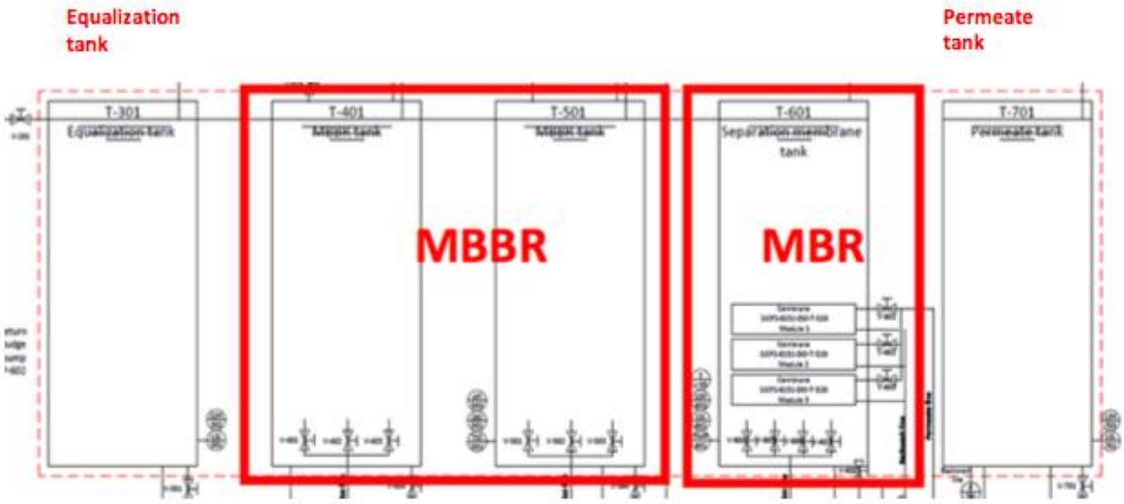

Figure 4: Schematic diagram of BMBR pilot plant

Ceramic membrane elements : The ceramic membrane modules are placed in chamber IV as depicted in figure 4. The membrane specifications are given in table 1.

Table 1: Membrane specifications of the ceramic membrane (Cembrane A/S n.d.)

Model SiCFM-0826-SO-T-250-M1	
Active membrane surface	0,826 m^2
Number of flat sheets	12
Distance between sheets	6mm
Aerator module	PP diffuser with 2mm perforation
Maximum water flow	870 ltr/hour
Maximum suction pressure	-700 mbar
Maximum backwash pressure	3 bar
Operating temperature	5-80^{o} C
Cleaning methods	Backwash/Ozone/High pressure jet/Chemical cleaning
Pore size	0,1 µm

A new membrane was installed in December as the pilot plant got damaged in August. The new membrane specifications were also same as the previously used membrane but the membrane surface was 1.242 m^2

Household wastewater: The plant receives wastewater from student dormitories at NMBU in Ås and the influent was mixed in a composition of 10:1 grey water and black water solution.

Operation, performance monitoring and analysing the pilot plan

The following operational conditions were followed during the operation period

- All operations in the pilot plant were fully automated.
- Level sensors were used in order to control the liquid level in the chambers. When the wastewater level in the membrane tank falls below the lower sensor, the filtration was stopped (standby mode to protect the membranes).
- When TMP exceeds 400 mbar-vacuum in filtration mode or 1 bar-pressure in backwash mode, peristaltic pump was stopped and chemical cleaning provided.
- Permeate pump was operated with ramp-ups and ramp-downs of 10 s.
- MLSS in the membrane unit was kept <12 g/L by recirculation of sludge from membrane chamber to aeration chamber (if there was any chance to exceed)
- When the system was operating with 1 or 2 active membrane modules, to balance the operation, the order of active modules alternate in a frequency of about one hour.

Number of modules	**Filtration area, m^2**	**Theoretical flux (gross), LMH**	**Theoretical capacity (gross)**	
			m^3/h	**m^3/d**
1	0.276	150	0.04	0.96
2	0.552	300	0.08	1.92
3	0.828	450	0.12	2.88

– When permeate tank was empty (by level switch), BW was stopped or not started.
– Measured continuously: Total suspended solids, pH, temperature, water level.
– The following data was continually monitored and stored.
  - daily inflow
  - operation times
  - trans-membrane pressure
  - membrane flux (gross = pump capacity, net = membrane capacity, considering BW)
  - permeability = specific flux / TMP –(was normalized to 20^0C)

Analysis on daily basis: MLSS, TSS, COD, VSS and permeate turbidity was measuered according to the standard methods given in the book *Standard Methods for the Examination of Water and Wastewater* American Public Health Association.by Rice, E. W., Bridgewater, L., Association, A. P. H., Association, A. W. W., & Federation, W. E. (2012).

The pilot plant was installed in February 2017 and data was continually collected since 08/02/2017. In the meantime, operational parameters were changed to optimize the system efficiency. The data was collected from 01/07/2017 to 22/12/2017 and has been used in this master thesis analysis. Old data was also used when necessary.

4 Results and Discussions

4.1 Critical Flux in BMBR plants

4.1.1 Background

The concept of critical flux was proposed by R.W. Field, D.X. Wu, J.A. Howell 1995. Critical flux is generally regarded as the flux above which cake or gel formation by particles or colloids occur (John A. Howell 1995). Van der Marel et al. 2009 writes that "critical flux is a quantitative parameter in understanding MBR process and its application determines filterability of different sludge mixtures". Generally, critical flux is determined by direct observation (Li et al. 1998), mass balance (Madaeni, Fane, and Wiley 1999), or pressure profiles (Le Clech et al. 2003, Diez et al. 2014). However, a single or precise agreed protocol for critical flux determination does not exist, and the lack of this protocol acts as a barrier when comparing research data (Le Clech et al. 2003). Le Clech et al. 2003 the research group has summarized the definitions of critical flux as used in past research, rewritten in table 2.

Table 2: Definitions of critical flux with method of determination

Critical flux definitions	Method of determination	Restriction	Reference
Stable operation for long period	Observation of TMP and flux behavior	Initial flux decline not taken into account	(John A. Howell 1995)
Transition between pressure-dependent and pressure-independent flux	Hydraulic tests (changes in TMP for different fluxes)	Short-term experiment	(Bouhabila, Aïm, and Buisson 1998)
Inertial lift velocity (*V*IL)	Determination of *V*IL	Based on theoretical model	(Kwon and Vigneswaran 1998)
No material deposition	DOTM	Soluble deposition not visible	(Bouhabila, Aïm, and Buisson 1998)
No material deposition	Mass balance	Soluble deposition not visible	(Bouhabila, Aïm, and Buisson 1998)
Stable operation (constant specific flux) from the start-up	Flux-step method	Short-term experiment	(Cho and Fane 2002)
Limiting flux	Stepwise increase of TMP	Less fouling control	(Defrance and Jaffrin 1999)

According to Hai and Yamamoto 2011 "the typical value of critical flux in MBR plants ranges from 10 to 30L/h.m^2 depending on membrane properties (Bottino et al. 2009), flow regime, side stream or submerged type (Judd S. J. 2010), aeration rate (Guglielmi G., Chiarani D. 2007) (J. A. Howell, Chua, and Arnot 2004), module configuration and microbial characters (Z. Wu et al. 2008)".

Critical flux for irreversibility is when the the cake or gel formation layer cannot be removed by physical cleaning methods, where irreversible fouling has occurred and where chemical cleaning has to be used (Bacchin, Aimar, and Field 2006).

Since the "critical flux" *(J_c)* concept was introduced by Field et al 1995, it has been operated and practiced to avoid membrane fouling in membrane processes. They mention that "the critical flux hypothesis for microfiltration is that on start-up there exist a flux below which a decline of flux with time does not occur; above it, fouling is observed". Two distinct forms have been established. "The strong form is that a flux exists which is equivalent to the corresponding clean water flux at the same time as TMP. The weak form is that on startup a constant flux is rapidly established and maintained during the startup of the filtration, but not necessarily equal to the clean water flux" (Field et al. 1995). The most applied hypothesis is the weak form. This is due to the high presence of organic and inorganic substances, such as many colloids and ESPs, in the mixed liquor in a MBR, increasing the opportunity for fouling to occur (Le Clech et al. 2003).

Among the different methods that are available to measure critical flux (Table 2), van der Marel et al. 2009 has introduced an improved flux step method. In this method membrane is operated at a higher flux, followed by a fixed lower flux for equal time durations before it goes to the next higher flux level (Navaratna and Jegatheesan 2011), also shown in figure 5.

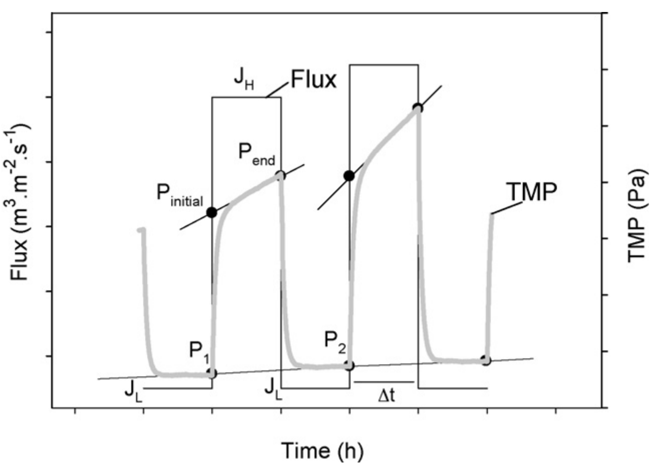

Figure 5: Improved flux step method (van der Marel et al. 2009)

The improved flux-step method applies successive fluxes up to a maximum flux and back in the same way as the common flux-step method. Total fouling rate was calculated (including both reversible and irreversible fouling) by change in TMP with time (dtmp/dt). According to figure 5, before J_L and after J_H (P_1 and P_2, respectively) TMP values have been used to calculate the irreversible fouling rate.

$$Total\ fouling\ rate, F_{total} = \frac{dR_{total}}{dt} = \frac{P_{end} - P_{initial}}{\eta JL}\frac{1}{\Delta t}$$

$$Irreversible\ fouling\ rate, F_{irr} = \frac{dR_{irreversible}}{dt} = \frac{P_2 - P_1}{\eta JL}\frac{1}{\Delta t}$$

R is the resistance, *P* is the pressure, *J* is the flux, η is the viscosity of the permeate which was corrected to a temperature of 20 ◦C and *t* is the flux-step duration (s).

4.1.2 Development of experimental protocol for Critical Flux determination in BMBR plants

Most of the past research has used flux step method to calculate critical flux level. In that process the flux has increased step wise. Each step is conducted as it comes to a constant flux value. Within one flux step none of the cleaning is applied. Cleaning has been applied when it goes from one step to the next step. Furthermore, one flux step length is short (in minutes). In that way the flux step where fouling occurs can easily be identified.

This research focused on identifying the critical flux behaviour when a plant runs long term with constant flux, in a condition where the cleaning treatments are combined into the treatment process. In other words, this was run as the same as the flux step method while applying cleaning methods (in the same way it would run in the plant) in to each flux step. Furthermore, flux length was increased by around 12 hours, and the following protocol was used.

Protocol for critical flux

- An integrity test* has to be done to check the product for leakages.
- At the separation chamber MLSS level should be maintained more than 5g/l when it runs for critical flux test. (more than 10g/l increases fouling problems)
- Operation parameters (given below) should be similar to general running parameters, which include physical cleaning methods to remove irreversible fouling.
- Operation parameters: filtration length – 300s; after each filtration cycle apply relaxation (only relaxation) for 80 seconds. After each 10th cycle, apply backwash. Here below is the procedure for applying backwash after each 10th cycle. *Relaxation I – 20(s); degas length 5(s) with 30Hz; backwash length 8(s) with 60Hz speed; Relaxation II – 60(s); pressure release 10(s)* respectively.
- Start filtration with lowest possible pump speed 10Hz for a long duration (for ex:10-12 Hours)
- Increase the pump speed for the next level (depends on operation process, wastewater characteristics; for example by 2 Hz), after maintaining the filtration duration go to the next speed level
- Continue filtration with increasing pump speeds level up to 10 levels (10 steps) (filtration height/pump speed level and length should be same in all 10 steps). (Stop criteria - if TMP increase over TMP_{OPT})
- When going from one flux level to the next flux level backwash should be applied.
- Record flux, TMP development and temperature at each step.
- Highest possible flux where no fouling occurs should be identified from filtration profiles:

$$\text{FLUX} = f\left(\frac{dTMP}{dt}\right)$$

* A bubble test and critical flux test with fresh water were conducted as integrity test for new membrane.

4.1.2.1 Results and discussion

None of the leakages were identified by the integrity test with bubble test conducted for new membranes (fig 6 and 7).

Results from the critical flux test done as an integrity test with tap water are provided in figure 8. Test was started from 15Hz and increased by 5Hz in each step until it reached 65Hz as 3 replicates. According to the protocol developed, the experiment was planned to run for 10 flux levels (10 pump speeds). Unfortunately we could run only 4 flux levels; 24LMH, 26LMH, 28LMH and 30LMH. At the 30LMH, TMP reached its maximum level and the filtration process stopped. Recorded data are graphically explained in figure 9 and figure 10.

Figure 6: Side view of the integrity test

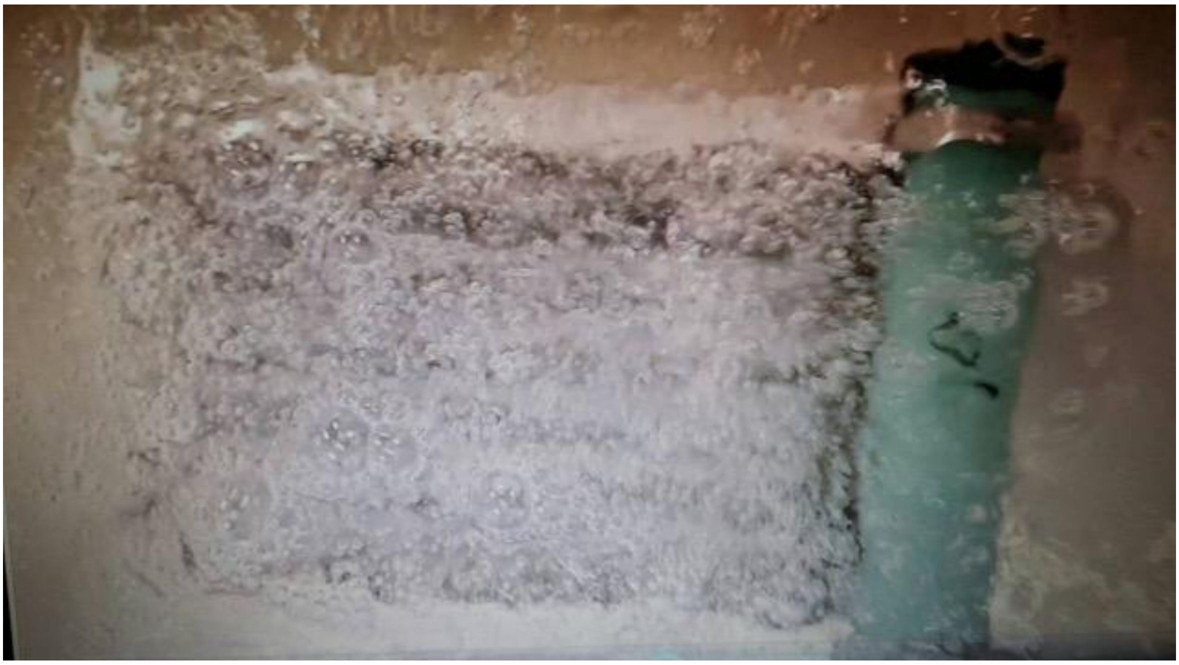

Figure 7: Top view of the integrity test

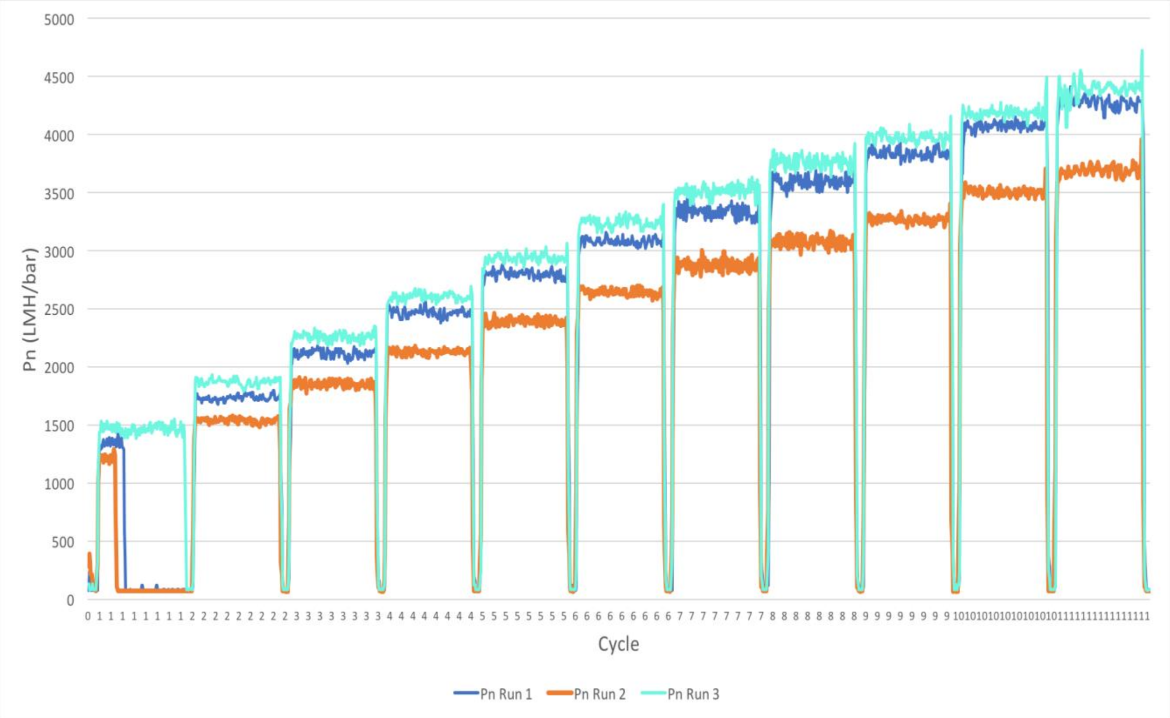

Figure 8: Flux test with tap water-critical flux base line (Data in detail : Annex IV)

Referring to Fig. 8, a constant TMP pattern under 24LMH and 26LMH can be observed. When it comes to the beginning of 28LMH, TMP pattern instability was observed. Furthermore, this instability arose when it nears 30LMH. Reason for the TMP stability at 24LMH, 26LMH and instability at 28, 30LMH might be due to the fouling phenomenon. In another way it can be interpreted as all the foulants have been removed by relaxation. Reason for an instable TMP pattern at 28LMH and 30LMH might be due to foulants that reduces the membrane filtration ability. Averaged final TMP at each flux level from 24 to 30LMH was 121, 142, 277, 418 mbar respectively. It was clearly seen from figure 10 that an averaged final TMP jump has taken place from 26LMH. Considering Iorhemen, Hamza, and Tay 2016 studies the TMP jump leads to permeability reduction. Therefore it can be assumed 26LMH with the TMP jump, accumulation of colloidal particle has taken place on the membrane surface (same observation has already been reported by (Le Clech et al. 2003). At 26LMH, the following values were observed: Average permeability - 227, average TMP - 116mbar and average initial cycle fouling - 11.2 mbar/min, average normalized flux 26.269 LMH/bar. At 28LMH average permeability - 144, average TMP: 227mbar, average initial cycle fouling 30.5 mbar/min and average normalized flux 24.975 LMH/bar. The average initial cycle fouling increase from 11.2 to 30.5mbar/min is visible when the flux changes from 26LMH to 28LMH. This confirms that fouling has occurred from flux level 28LMH.

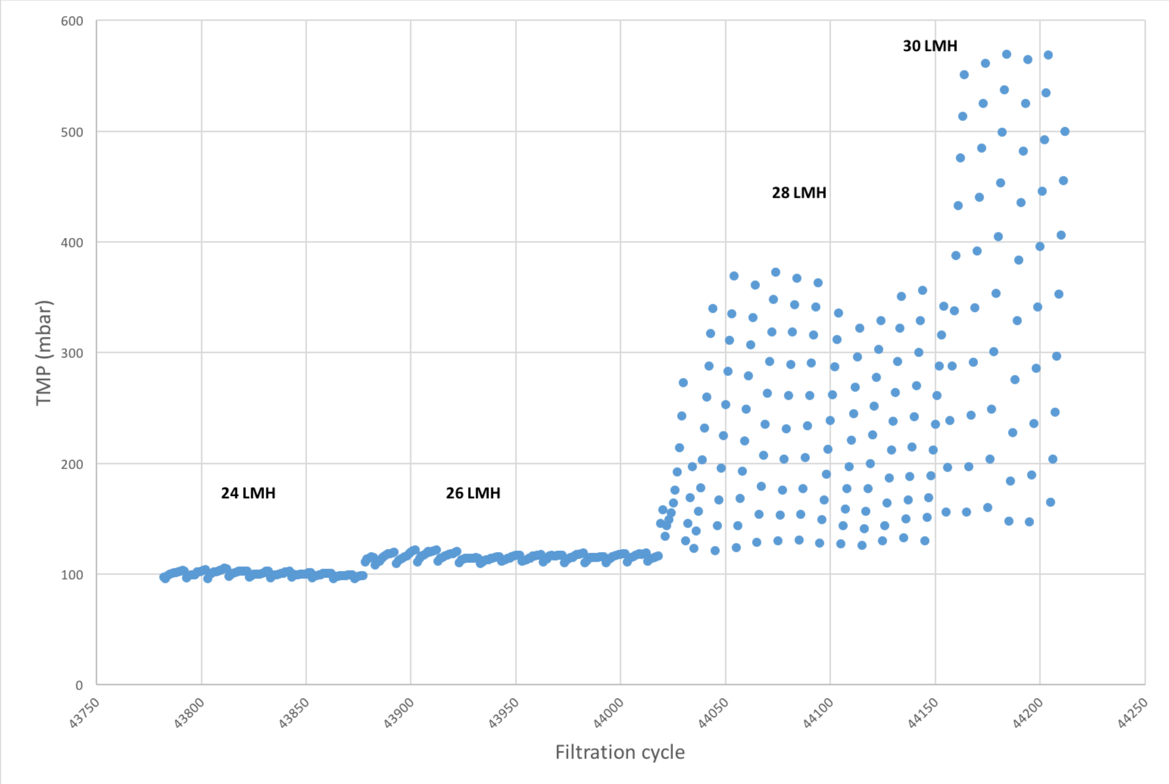

Figure 9: TMP behaviour in filtration cycle with respect to flux level 24, 26, 28 and 30LMH (Data detail Annex V)

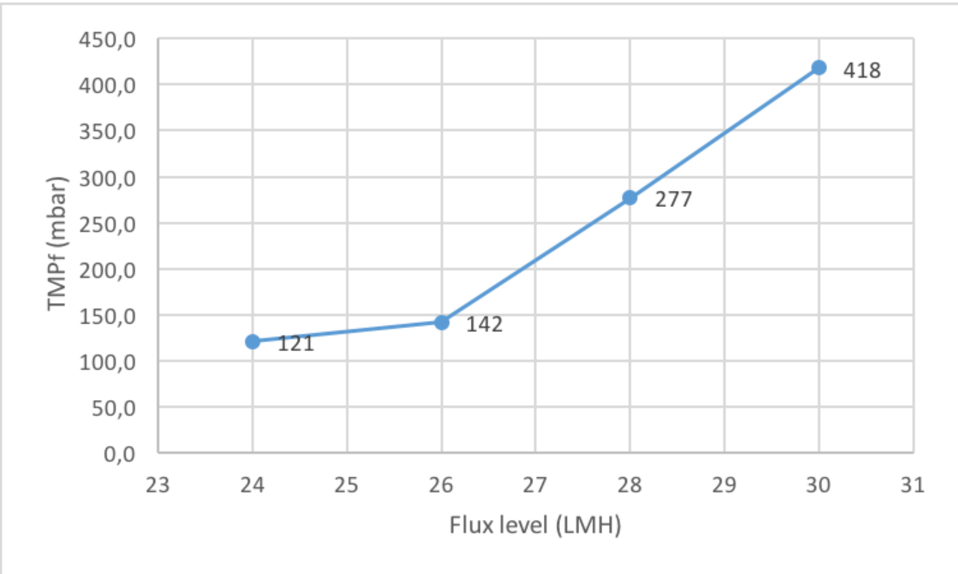

Figure 10: Relation between average final TMP with flux levels

It was important to find the actual time where fouling occurs at 28LMH. This was done using improved flux method (van der Marel et al. 2009), following discussion and figure explanations. According to figure 11 and figure 12, fouling was visible from the 4-5 cycle at 28LMH. At the same time, initial TMP value at 1-3 cycles are mostly similar and comparatively increase when it comes to 4-5 cycles, which means foulants have not been removed by relaxation before it goes to the next cycle. Therefore, this experiment confirms that fouling has taken place from the 4th cycle at the 28LMH pump speed, only with relaxation.

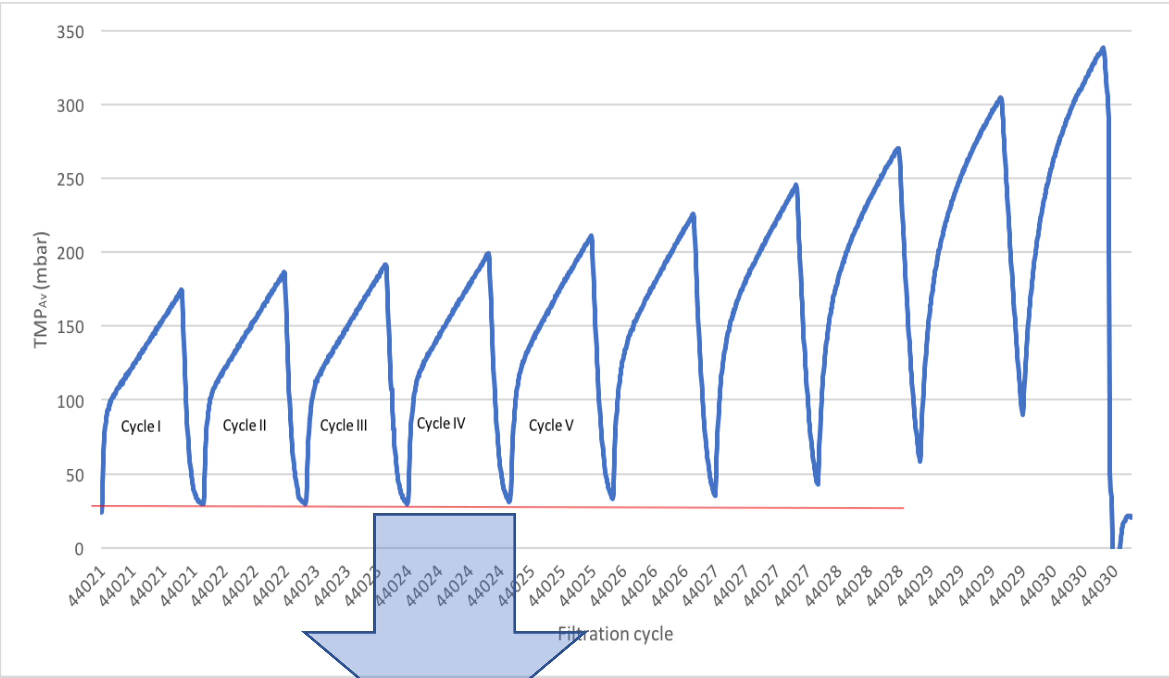

Figure 11 Detail TMP profile with 28LMH pump speed level (Annex VI)

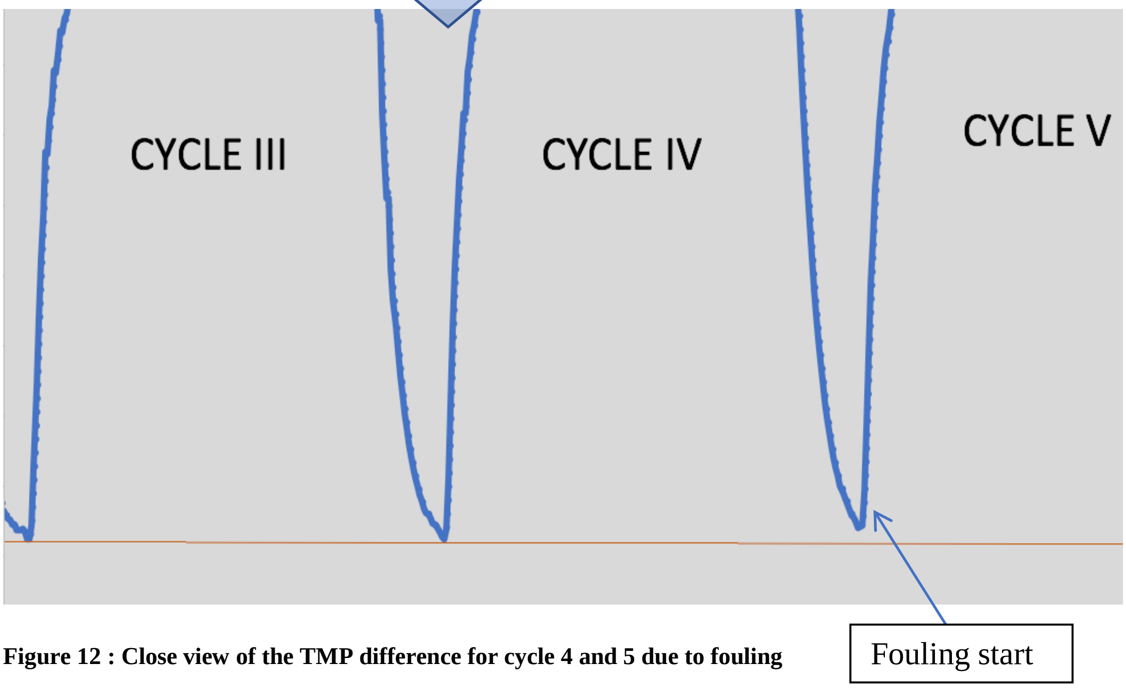

Figure 12 : Close view of the TMP difference for cycle 4 and 5 due to fouling

This following discussion was based on backwash treatment. Figure 13 has shown TMP variation at the beginning of 28LMH and from the end section of 30LMH. Just after backwash treatment, a constant initial TMP pattern is visible until the end of 30LMH. This confirms that fouling has been removed in all four LMH levels by backwash.

This emphasizes that fouling has occurred only when using relaxation under this experimental conditions.

It is important to find out the critical flux for the whole physical treatment process (both for backwash and relaxation) when optimizing treatment plant operations. In order to do that a small change in the protocol is needed. Applying backwash after each 5^{th} cycle instead of each 10^{th} cycle is proposed, maintaining TMP around 300mbar.

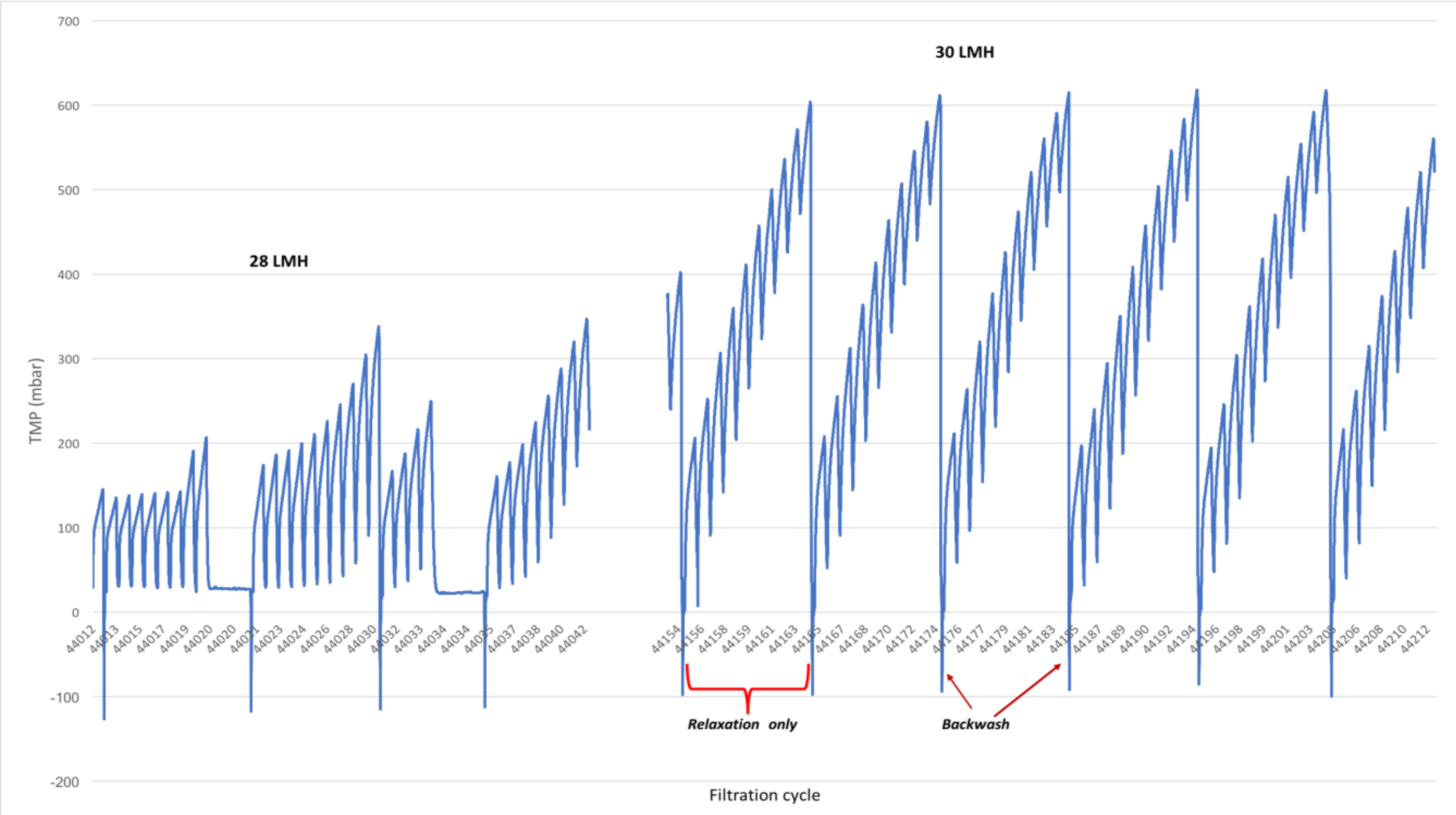

Figure 13: Relationship between TMP with respect to the 28LMH (at the beginning) and 30LMH (at the end) when using relaxation and backwash as physical treatments

4.1.3 Treatment efficiency optimization through Critical Flux and economical aspects

When we analyze the plant in economical perspective, the target should be to increase the net flux to a maximum level in terms of low energy and chemical consumption. Merely increasing the gross flux will not be useful in this perspective. When selecting treatments we also have to think how to optimize the operational efficiency in an economically feasible way. As we discussed above, when running a treatment plant practically, the main concept is increasing the treatment efficiency through real time treatment optimization. In this experiment backwash has been used for the whole treatment period. From figure 13 it is observable that no TMP fluctuation takes place under 24LMH and 26LMH flux levels with backwash when compared to 28LMH and 30LMH flux levels. This proves relaxation itself has had the ability to remove fouling in 24LMH and 26LMH flux levels. According to figure 15 it maintains a high permeability level in stable flux level at 24LMH and 26LMH. Both figures emphasize that application of backwash for this level is not necessary. These findings are helpful for planning the pilot plant optimization in an economical way.

Fouling that could not be removed by relaxation itself results in drastically reduced membrane permeability (fig. 15), starting from 26LMH onwards where it needs to use backwash treatment. If the plant needs to run over 26LMH flux levels, backwash treatment frequency should be increased while maintaining maximum final TMP 300-350 (in a cycle). However, backwash is not needed to be applied after each cycle.

In table 3, critical flux data obtained from the experiment has been compared with the pilot plant data from March 2017 to May 2017 (when the plant ran as normal) with regard to net flux and gross flux percentage changes. From March 2017 to May 2017 net flux production efficiency in filtration, Net flux/ gross flux (NF/GF) was 30.2%. During this period backwash has taken place after each cycle as depicted in the table. Under the experiment, period net flux production efficiency in filtration was 47.9 %, 47.7 %, 45.9% and 46.9 % for 24,26,28,30 LMH flux levels. Therefore, with increased number of backwash and length of backwash, a net flux reduction is observed with an increase in energy consumption. This observation is important when optimizing the backwash in an effort to enhance net flux production efficiency in filtration.

Table 3: 2017 net flux production efficiency in filtration in different time periods

Period	**Gross flux LMH**	**Net Flux LMH**	**Filtration time (S)**	**Relaxation 1**	**Backwash (s)**	**Relaxation 2**	**Net Flux/ Gross flux**
March - May 2017	45.13	13.63	300	30	20 after each cycle	120	30.2%
Critical flux in December	24LMH	12.5	300	20	8 for each 10^{th} cycle	60	47.9 %
	26LMH	13.6	300	20	8 for each 10^{th} cycle	60	47.7 %
	28LMH	14.5	300	20	8 for each 10^{th} cycle	60	45.9%
	30LMH	15.9	300	20	8 for each 10^{th} cycle	60	46.9%

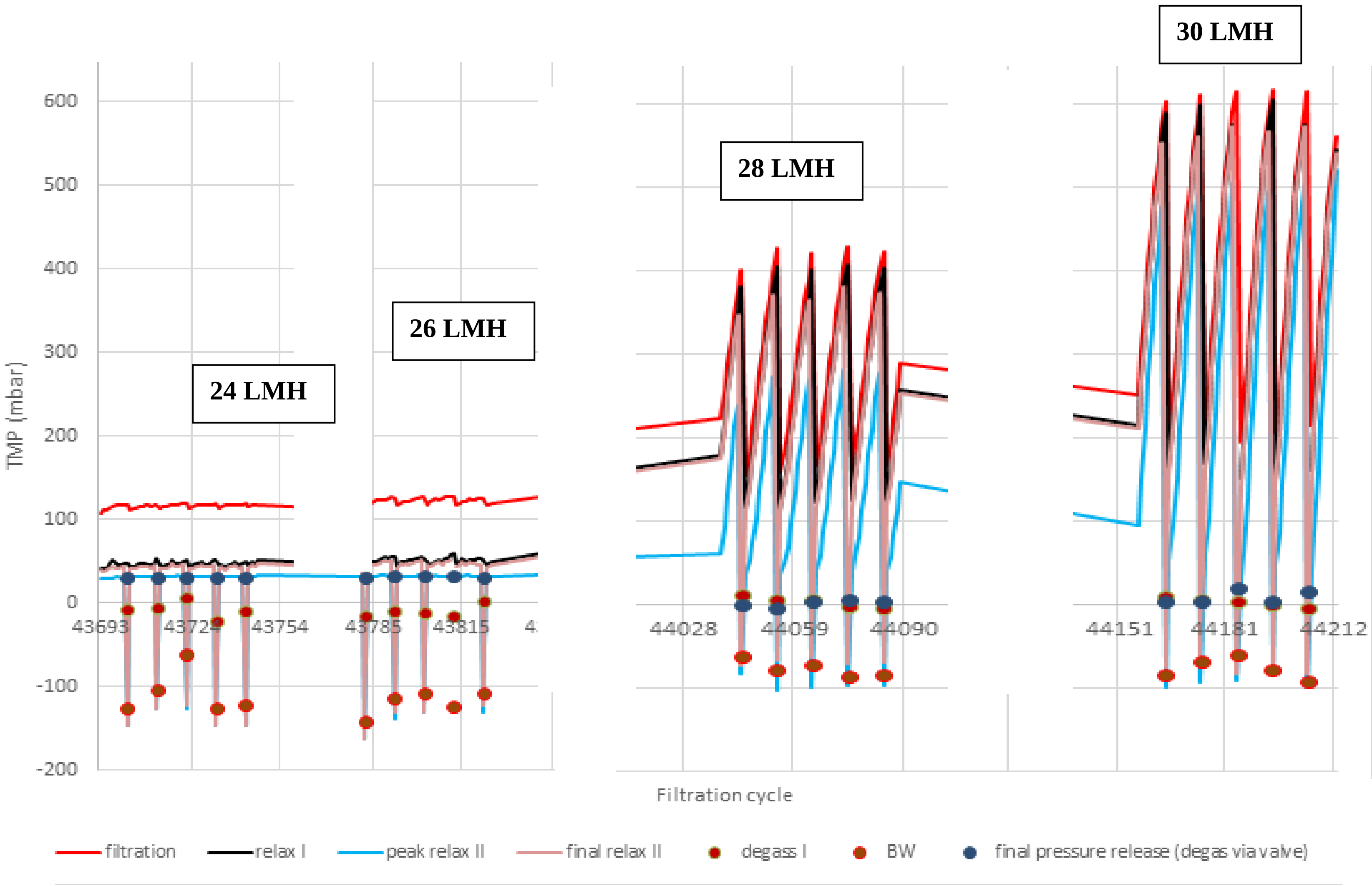

Figure 14: Relationship between TMP variation with different cleaning treatment methods used under different flux levels 24, 26, 28, 30 respectively

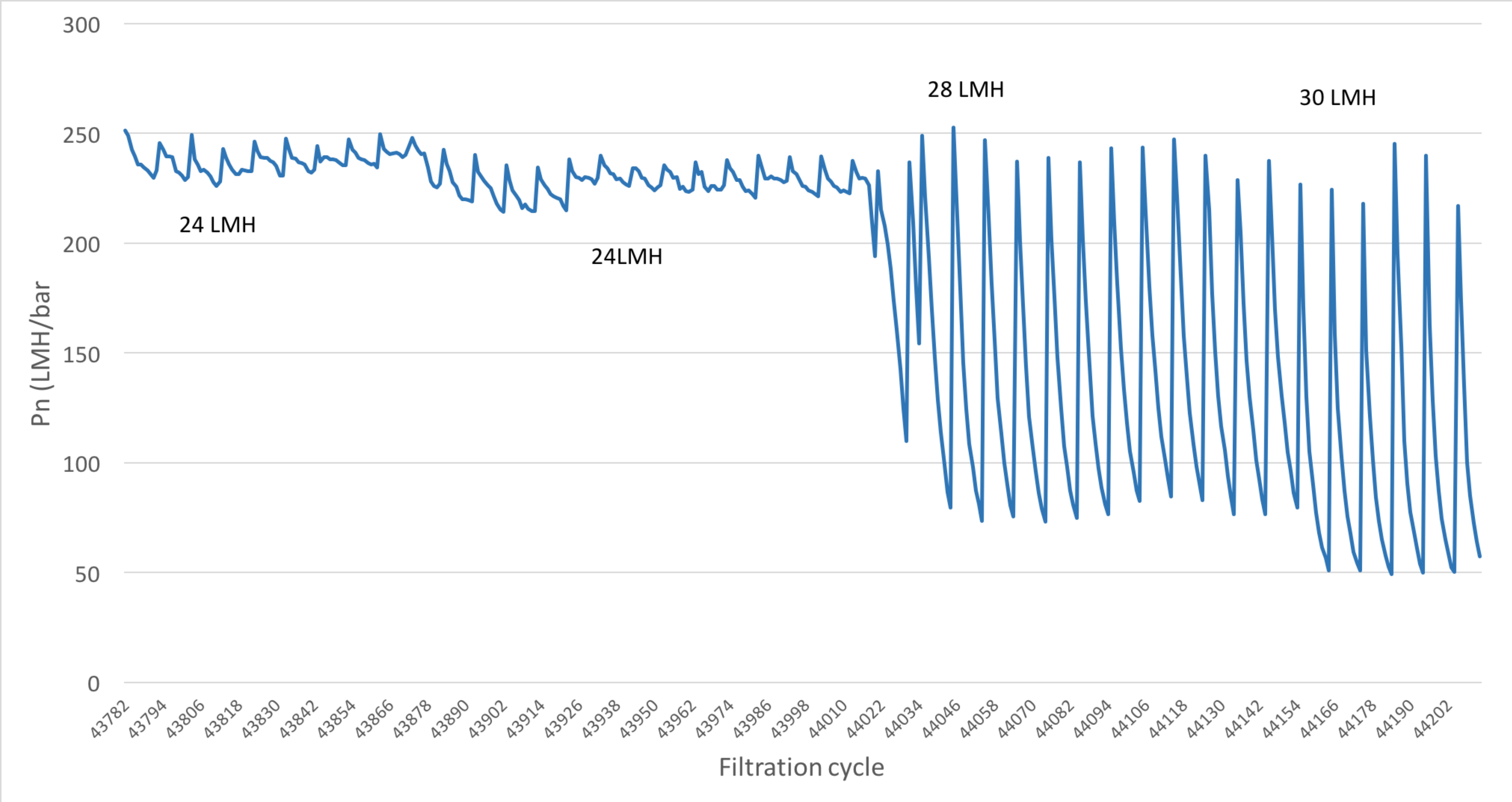

Figure 15: Relationship between permeability variation with different flux levels 24, 26, 28, 30 respectively (Data detail : Annex V)

4.1.4 Conclusion

The protocol used in the experiment was only useful to find the critical flux for relaxation. Critical flux could not be found for both relaxation and backwash. Plant can run only by relaxation when the flux is at 24LMH and 26LMH. At 28, 30 LMH backwash is needed. It is suggested to maintain backwash after 5th cycle instead of 10th cycle, to increase the filterability. Critical flux for the whole physical treatment process (both for backwash and relaxation) need to be identified through further tests.

Economic benefits can only be gained when running 26, 26LMH by relaxation, and by introducing backwash after 28 and 30LMH. Net flux production efficiency in filtration through the experiment period increased up to 50% compared to the period from March to May 2017 where it was 30%.

4.2 Comparison study of different membrane cleaning protocols

4.2.1 Chemical cleaning

4.2.1.1 Background

Normally there are two kinds of fouling, namely hydraulically reversible fouling and hydraulically irreversible fouling. Hydraulically reversible fouling is defined as fouling that can be removed by a hydraulic wash, physical cleaning like backwash, air sourcing etc., while hydraulically irreversible fouling due to adsorption and/or chemical bonding between membrane and foulants can only be removed by chemical cleaning. Hydraulically irreversible fouling is mainly due to intra-pore fouling. Therefore chemical cleaning is a method used to remove foulants that cannot be removed by other cleaning methods (Chang et al. 2002), (Hai and Yamamoto 2011). In spite of the many drawbacks when using chemicals for cleaning, such as inconvenience during storage, transportation, preparation and production of contaminants, reduced lifetime and efficiency of the membrane, and environmental issues related to the waste chemical disposal, the chemical mechanism is still being used in many plants (Lu, Du, and Lipscomb 2009), (Hai and Yamamoto 2011). Table 4 shows different commercially available cleaning agents and their cleaning effects. (You et al. 2006), (Grelot et al. 2010).

Table 4: Different commercially available cleaning agents and their cleaning effects

CHEMICAL	Cleaning Effect
Citric Acid, HCL, HNO_3	Solubilization, chelatation
NaOH	Solubilization, hydrolysis
NaOCl, H_2O_2	Oxidization, disinfection
Enzymes, surfactants, chelating agents	Emulsification, dispersion, chelatation Surface conditioning

Removal of foulants such as organic foulants is mainly done by sodium hypochlorite NaOCl. Inorganic foulants, precipitated salts or scalants can be cleaned by acid (nitric, phosphoric, hydrochloric, sulphuric and citric or caustic soda etc. (Mohammadi, Moghadam, and Madaeni 2003), (Hai and Yamamoto 2011). Metal chelating agents, surfactants and enzymes can also be used. Further disinfectants (O_3), oxidants (H_2O_2, $KMnO_4$) or sequestration agents (EDTA) can also be used for chemical cleaning of membranes (Lin, Lee, and Huang 2010). Even though many types of cleaning agents exist, NaOCl are used by a majority. This is due to its availability, affordability and disinfection ability. Authors Hai and Yamamoto 2011 highlights that the typical range for cleaning in MBR ranges for NaOCl varies from 1000 to 3000 mg/L. Membranes can be damaged if they are continuously exposed to NaOCl. Citric acid has been found to be an effective cleaning agent for inorganic fouling removal in MBRs (Vallero, Lettinga, and Lens 2005), (Porcelli and Judd 2010). Research by Lateef, Soh, and Kimura 2013 using municipal waste water observed that when using both NaOCl and citric acid ability to mitigate, membrane fouling was high.

Chemical cleaning is carried out in two ways; offline cleaning, and cleaning in place (also known as recovery cleaning/ intensive cleaning). (Zhang et al. 2006) Offline cleaning is when membrane modules are taken out of the bioreactor and immersed in a tank of cleaning reagent, or membrane modules are immersed directly in membrane tank full of cleaning agent after draining off sludge. This can be done once intermittently by several months or by several years. In the other method, cleaning in place (CIP), a cleaning reagent is injected into the membrane in reverse to normal filtration while the membrane modules are still submerged in bioreactor (Wei et al. 2010). CIP cleaning interval depends on process properties and is easier and simpler.

Chemical cleaning effectiveness depends on two major factors. They are physical parameters of the detergent solution and deposited foulants and chemical actions. Physical parameters such as temperature, pressure flow and time. Chemical actions can be defined as the nature of the cleaning agent, detergent concentration, pH and ionic strength (Blanpain-Avet, Migdal, and Bénézech 2009). Efficiency of chemical cleaning can be increased by providing an optimal temperature. A high temperature below the membrane's maximum temperature can increase the cleaning efficiency (Arnal, García-fayos, and Sancho 2009). In general, permeate flux and TMP is used to check the effectiveness of the cleaning process after cleaning at defined operating conditions. Liikanen, Yli-Kuivila, and Laukkanen 2002, has explained a cleaning efficiency through evaluating the flux recovery and the fouling ratio (Liikanen et al., 2002; Chen et al., 2003) and it is calculated as given below.

Flux recovery = J_c / J_0 (1) Fouling ratio = J_f / J_0 (2)

J_{c} - the flux after cleaning
J_0 - the flux of the virgin membrane
J_f - the flux for the fouled membrane.
J_{w} - the water flux density
The flux recovery, Resistance removal, defined as (Madaeni et al., 2001):
$FR(\%) = [(J_c - J_w) / (J_0 - J_w)]\cdot 100$

Among the few researches conducted in this area, a three step chemical cleaning treatment was found for the filtration of fish press liquor using ceramic membranes. An alkali (NaOH), acid (HNO3) and disinfection stage (NaOCl solution + NaOH) was applied to restore the initial water flux after the ultrafiltration operation (Pérez-Gálvez et al. 2011). The initial cleaning stage with alkali has been efficient to restore the membrane permeability of the overall recovery of the membrane flux. Efficiency of this alkali stage is due to its ability to hydrolyze, solubilize and remove the protein deposits (Hai and Yamamoto 2011). A poor cleaning efficiency was observed in the second stage where they used acids. This might be due to physico-chemical interactions between nitric acid and the fouling deposits remaining on the membrane surface after the alkaline cleaning (Blanpain-Avet, Migdal, and Bénézech 2009). Furthermore, they conclude that the oxidation of the organic compounds to other groups which exhibit higher a hydrophilicity, such as aldehydes, ketones or carboxylic acids, illustrate a lower adhesion to the membrane material.

4.2.1.2 Protocol for CIP

A two-step cleaning treatment, involving NaOCl and citric acid was applied to restore the permeate flux after the periodic filtration process. The complete cleaning sequence is as follows. NaOCl was used to remove organic matter and citric acid treatment was used to remove the inorganic matter.

Procedure

- Filtration cycle stop
- Remove all the sludge from the membrane chamber using drainage pump and store the sludge in another aeration tank to reuse after cleaning.
- Stop sludge supply to the membrane chamber.
- Wash the membrane chamber using tap water until it removes all the sludge. This washing should be done at least three times.
- Fill the membrane chamber with tap water and start aeration for about 1 – 5 minutes until the residual sludge gets loose.
- Remove the sludge – water mix from the membrane chamber
- If there is any residual sludge, wash with tap water.
- Start the permeate backwash with alkaline. Backwash should be done until it covers the upper module in the membrane chamber with NaOCl solution. Reason for this is to remove the bound organic matter hidden at the intra-pores of the membrane.
- Dose the chemical to the backwash permeate line (final NaOCl concentration in backwash solution (permeate + chemical) should be a 0.5 - 1%)
- After backwash period, start aeration for 2 minutes to mix the chemical.
- Soak the membrane modules in the NaOCl solution at least 2 hours (time depends on membrane fouling intensity) to remove or lose cake layer on the membrane.
- After 2 hours start aeration for 5 minutes, then discharge the solution and wash the membrane chamber with tap water.
- Dose the citric acid to the permeate line and start the permeate backwash with citric acids. Backwash should be done until it covers the upper module in the membrane chamber with citric acid solution. Reason for this is to remove the bound inorganic matter hidden at the intra-pores of the membrane.
- Soak the modules in acid solution for 2 hours (time depends on membrane fouling intensity)
- Discharge and wash it with tap water

- Start the permeate pump backwash to clean the lines several times with permeate and again wash the separation chamber using tap water until it reaches pH level between 5-6 (solution pH shows how efficiently chemicals remove from chamber and backwash line. If there are any chemicals in the chamber it could badly affect the bacteria population after restarting the process.)
- Fill the stored sludge for the chamber again and restart the filtration process.
- Flux recovery percentage calculation by the following equation.
    - Flux recovery percentage = $J_c / J_0 * 100$

J_c - the flux after cleaning
J_0 - the flux of before cleaning

- Recovery from initial value = $J_c / Ji * 100$

J_i - first stable operation at the beginning of the pilot plant installation

4.2.1.3 Results and Discussion

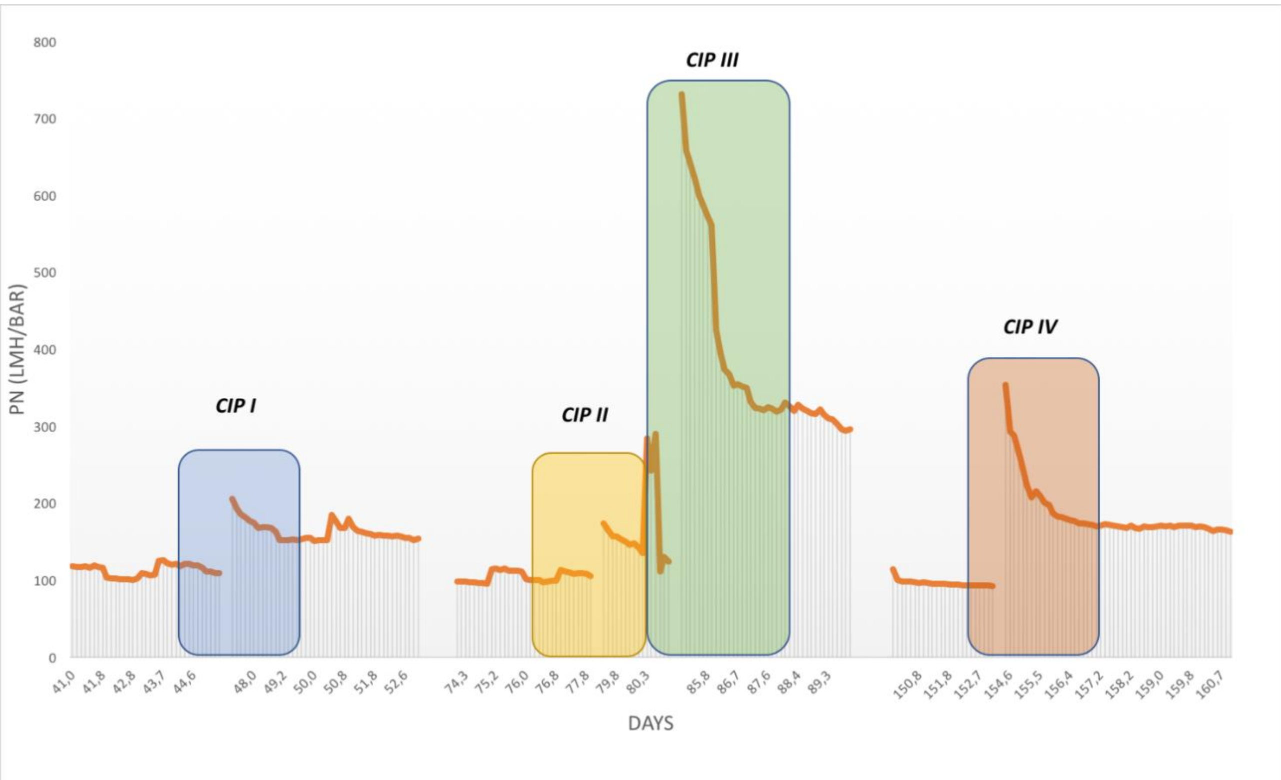

Figure 16: Normalized permeability (Pn) value before and after CIP as a function of time – pilot plant (Data detail Annex VII)

Figure 16 summarizes the data continuously taken (231 days) taken from the pilot plant from 08/02/2017 until 26/09/2017. During the whole period 4 cleaning in place (CIP) were conducted and TMP and flux behavior parameters were determined. Among the 4 CIPs the first two were cleaned only by NaOCl 0.5 - 1% solution. Both NaOCl 0.5 - 1% and 5% citric acid were used respectively for the last two CIPs. Among the last two CIPs, CIP III was done by "chemical bath method" (in annex II). For CIP IV above mentioned protocol was used. Cleaning intervals were as follows; from establishment of the treatment plant to CIP I was 50 days. Hereafter, the time interval between two CIPs was 30days, 7 days and 65 days respectively.

Normalized permeability (Pn) value before cleaning at the CIP I was measured 115LMH/bar and then Pn was increased 152 LMH/bar after chemical cleaning. CIP I's recovery percentage was 32.3% and the recovery from membrane initial normalized permeability value (350 LMH/bar – first stable operation at the beginning of the pilot plant installation) was 43.5%. For CIP II, Pn value before cleaning was measured as 107 LMH/bar and increased up to 148 LMH/bar. Recovery percentage was 38.3% and the recovery from membrane initial normalized permeability value was 42.3%. When comparing recovery percentage (before and after chemical cleaning) obtained from tests carried out during the whole period, a lower recovery percentage can be observed in CIP I and CIP II. In both CIP I and CIP II the cleaning agent was NaOCl solution only. Mohammadi, Moghadam, and Madaeni 2003 defines that an alkaline solution such as NaOCl have the ability to remove only organic foulants, which means that the inorganic foulants that were in the wastewater were not been removed by the chemical solution used in CIP 1 and CIP II.

When looking at the CIP III Pn before cleaning was measured as 124 LMH/bar and increased up to 335 LMH/bar; recovery percentage was 170% and the recovery from membrane initial Pn value was 95.7%.

The Pn value before cleaning at the CIP IV was measured 93LMH/bar and the Pn was increased 177.4 LMH/bar after chemical cleaning. CIP IV's recovery percentage was 90.7% (fig 17) and the recovery from membrane initial normalized permeability value (350 LMH/bar) was 50.7%.

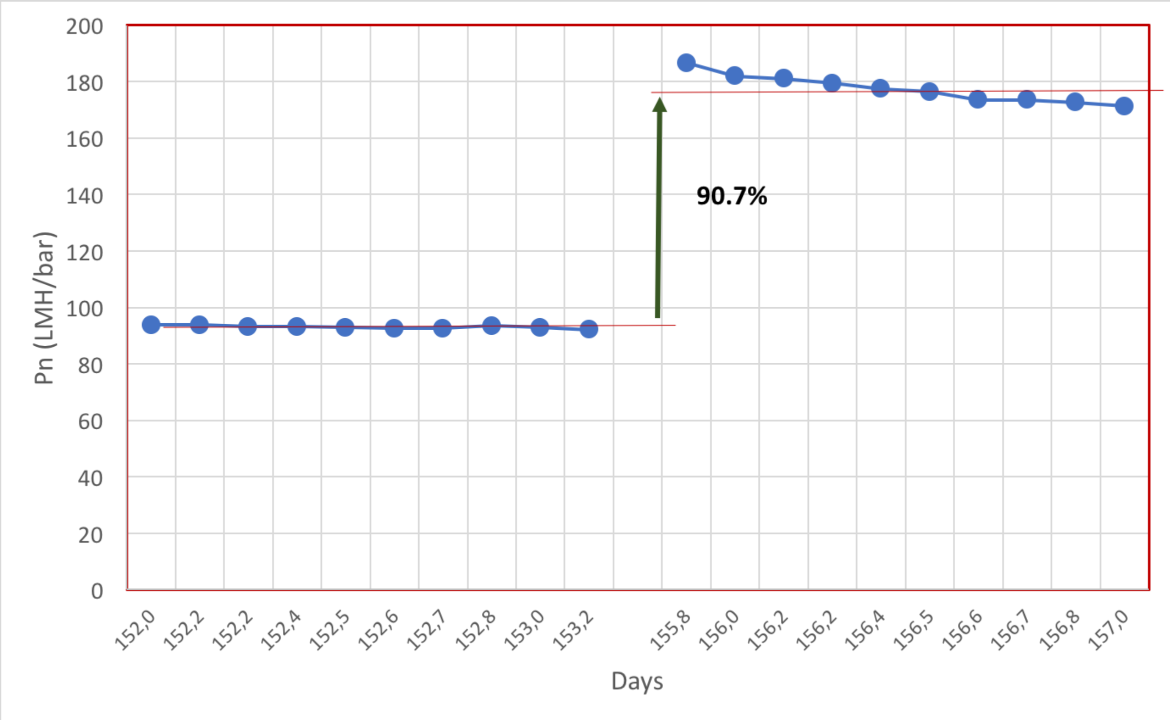

Figure 17: Recovary percentage between CIP IV (Data detail Annex VIII)

In our experiment both NaOCl and citric acid was used as a cleaning agent in CIP III and CIP IV. Mohammadi, Moghadam, and Madaeni 2003 reported acid (nitric, phosphoric, hydrochloric, sulphuric and citric or caustic soda etc.) as a cleaning agents that have the ability to clean inorganic foulants, precipitated salts or scalants. We already know that NaOCl removes organic compounds. This emphasizes that both organic and inorganic solutions have been eliminated by using NaOCl and citric acid solutions in CIP III and CIP IV. Therefore CIP III and CIP IV both show high recovery percentages when compared to CIP I and CIP II.

When looking at CIP III and CIP IV, even though same chemicals have been used, the application process was different. CIP III shows a high recovery percentage, 170% when compared to CIP IV 90.7%. The reason for this difference cannot only be placed on the different application methods used in cleaning. The difference could e.g. be due to a short time period between CIP II and CIP III (one week).

4.2.2 Physical cleaning

4.2.2.1 Background

Backwash: Main operation in backwash technique is the trans membrane pressure that periodically is inverted by the use of a secondary pump, so that permeate flows back into the feed, lifting the fouling layer from the surface of the membrane (Franken 2009). An optimal backwashing duration, frequency and intensity are key factors in order to prevent rapid fouling and a fast increment of TMP. N. Yigit et al. 2011 found that membrane resistance can be reduced ~160% after backwash and furthermore reports that backwash effectively diminishes reversible fouling due to pore blocking and cake layer formation. A backwash can be conducted by using several methods such as permeation, chemicals, air, clean water, and other mediums (Hai and Yamamoto 2011).
Another concept is named backwash hammer. Here, a high pressure water column is applied to backwash (between 1-2 bar).

Aeration: This is the most widely practiced way to remove fouling. The mechanism used is to vibrate the submerged membrane mechanically and remove sludge foulants on the membrane (Hai and Yamamoto 2011), even though technically it demands huge amounts of energy (Judd 2008). Due to its easiness in installation and operation, this mechanism is vastly use in membrane filtration fouling control (Hai and Yamamoto 2011). However, an aeration control must consider several important factors including cost, effectiveness, and optimization during an MBR operation (Yusuf, Abdul Wahab, and Sahlan 2016). Aeration makes a change in the polarized layer concentration that forms near the membrane, where it significantly enhance the permeate flux (Cheng and Lee 2008). However, this method has a maximum limit of where it can work effectively. Beyond that limit, fouling resistant cannot be removed successfully. Same results have been found by Lie and research group where they found that high air flow has no significance on the flux (Lei, Li, and He 2011). (Yusuf, Abdul Wahab, and Sahlan 2016) further emphasizes that high aeration can cause breakages on the flock, resulting in rapid irreversible fouling and a low quality of the nitrification process. Research also emphasizes that low aeration is also not suitable for membrane filtration (Jun Wu and He 2012), (Yusuf, Abdul Wahab, and Sahlan 2016).

Relaxation: Hai and Yamamoto 2011 explains relaxation as an introduction of a pause on the throughput of the membrane with a maintained air source, which results in a concentration gradient on the surface of the membrane that drives the cake formation to the surrounding mix liquor. This technique is only applicable when removing reversible fouling. In order to help fouling removal, a longer relaxation time is needed to enhance the permeate flux (Zuo et al. 2010). Relaxation effectiveness was studied with a backwash technique by Rahimi et al. where it was found that a relaxation technique was comparable with a backwash technique in terms of a TMP increment.

Degassing: The extraction of dissolved gases and volatile compounds from water is called degassing (Vorsana 2012). Process water may contain volatile compounds, or odorants, such as ammonia, acetone, methylethylketone (MEK), and volatile organic compounds (VOCs). A research done through using reverse osmosis (RO) filtration by (Rzechowicz and Pashley 2007) found that when water permeates through porous membranes, under a large hydrostatic pressure difference, the opportunities for vapor and dissolved gas cavitation is high. This will restrict water flow through the membrane void spaces. A very high pressure (30–100 atm) is used to force the water through the voids at a reasonable rate where the voids easily become clogged, which is also very costly.

4.2.2.2 Application of different physical cleaning methods:

The main objective in the experiment was to investigate suitable physical cleaning method combinations for current the pilot plant and optimize under current operation configurations. For this task data was collected for 55 days. The data was divided in to 11 sub periods and tested in 8 sub periods according to different combinations of physical cleaning methods. The methods used were backwash, relaxation, degassing, de-pressurizing and backwash hammer. During this period the pilot plant was operated under fixed filtration pump speed (10Hz) and filtration time (300s). After each filtration, membrane was cleaned by physical cleaning before going to the next filtration cycle. One filtration time 300s includes both filtration time plus time for physical cleaning. Temperature, flux, turbidity and TMP were measured as a function of time. The order of the physical cleaning methods applied in the experiment was relaxation I, degassing, backwash, relaxation II and depressurization respectively.

4.2.2.3 Results and discussion

The effectiveness of fouling removal is measured from the following equation. Initial and final TMP values of the filtration cycle i, and filtration duration Δt of each cycle should be taken (Yusuf, Abdul Wahab, and Sahlan 2016).

$$\text{Reversibility } \% = \frac{TMP_i^{Final} - TMP_{i+1}^{\ initial}}{\Delta t}$$

Table 5 shows the way of using different kinds of physical cleaning methods in different combinations during the experiment. Eight combinations were used (from A-H).
Table 5 shows that the reversibility percentage has been calculated for the eight combinations (A-H) using the above equation to predict the effectiveness of fouling removal.
Trends of permeate turbidity and the permeability have been presented as a function of time, with respect to the combinations of physical cleaning methods in figure 17. The following discussion is based on using figure 17 and table 5 in this report.

Table 5: Combinations of physical cleaning methods used in the experiments

Physical cleaning methods	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
No of days	11.7	3.4	4.6	4.6	2.9	9.6	3.4	9.5
Relaxation I (s)	5	5	5	5	5	20	20	20
Degassing speed (Hz	60	60	60	30	30	30	30	30
Degassing length (s)	20	30	30	30	30	10	10	10
BW speed (Hz)	60	60	60	60	90	90	80	80
BW-hammer (bar)	-	-	-	-	-	-	1.5	1.2
BW Length (s)	10	10	10	10	7	7	7	7
Relaxation II (s	120	110	60	40	60	50	50	50
De-pressurization (s)	-	-	-	20	20	10	10	10
Total time for cleaning	155	155	105	105	122	97	97	97
Reversibility % (annex III)	**132.8**	**165**	**231**	**234**	**230**	**215**	**251.3**	**270.8**

Physical cleaning combinations C, D, E, F, G, H has given more than ~200% reversibility, among them G, H has shown more than ~250%. When looking at the turbidity in figure 18 a high turbidity trend can be seen in A, B, C, D, E combinations with low turbidity in F,G and beginning of H. A very high turbidity is observed at the end of H.
A high relaxation time has been used under relaxation II as one of the physical treatments in both A & B (duration of 120 seconds in A and 110 seconds in B). According to past

research (Zuo et al. 2010) a longer relaxation time has helped fouling removal. But in this experimental condition in A & B, high time duration in relaxation II has not given a positive effect in fouling removal based on the above reversibility calculation.

When considering permeability B, C, D, E combinations and F has shown a stable pattern. When considering turbidity B, C, D, E combinations were higher than F combination (Fig : 18).

In G, H backwash hammer has been introduced. Showing more than ~250% effectiveness of fouling removal/ reversibility in G, H may be due to the effect of backwash hammer. Furthermore, a strange turbidity pattern in H was observed where it starts with low turbidity that increases up to 6 NTU at the end. This was due to accumulation of sludge at the permeate chamber, as shown in figure 21. Furthermore, it was observed that the membrane connectors (a plastic connector that helps to fix the membrane itself to the membrane module) had been damaged (fig 19). Therefore, sludge entered the permeate chamber through the permeate line.

Reasons for this may be the application of the backwash hammer as one of the physical cleaning methods in combination G. A high pressure was used for this application at the beginning, 1.5 bar at the combination ‘G’. With combination ‘H’ pressure was up to 1.2 bar (table 5). It can also be seen that introducing backwash hammer with high pressure shortly triggers the permeability, followed by a drastic decrease. It is understandable that the introduction of backwash hammer to combination ‘G’ has subjected an unbearable pressure to the plastic connectors. Due to high pressure, those connectors were damaged. Also, it can be seen in figure 20 that sludge has entered the membranes pores, thereby blocking those small pores. Blocking the membrane pores can be possible reasons for the reduction of permeability due to the application of the backwash hammer. The backwash hammer can be a good physical cleaning method. However, the above incident makes the assessment of this proposition not possible due to unavailable data. Therefore, the method can also be viewed as a failure.

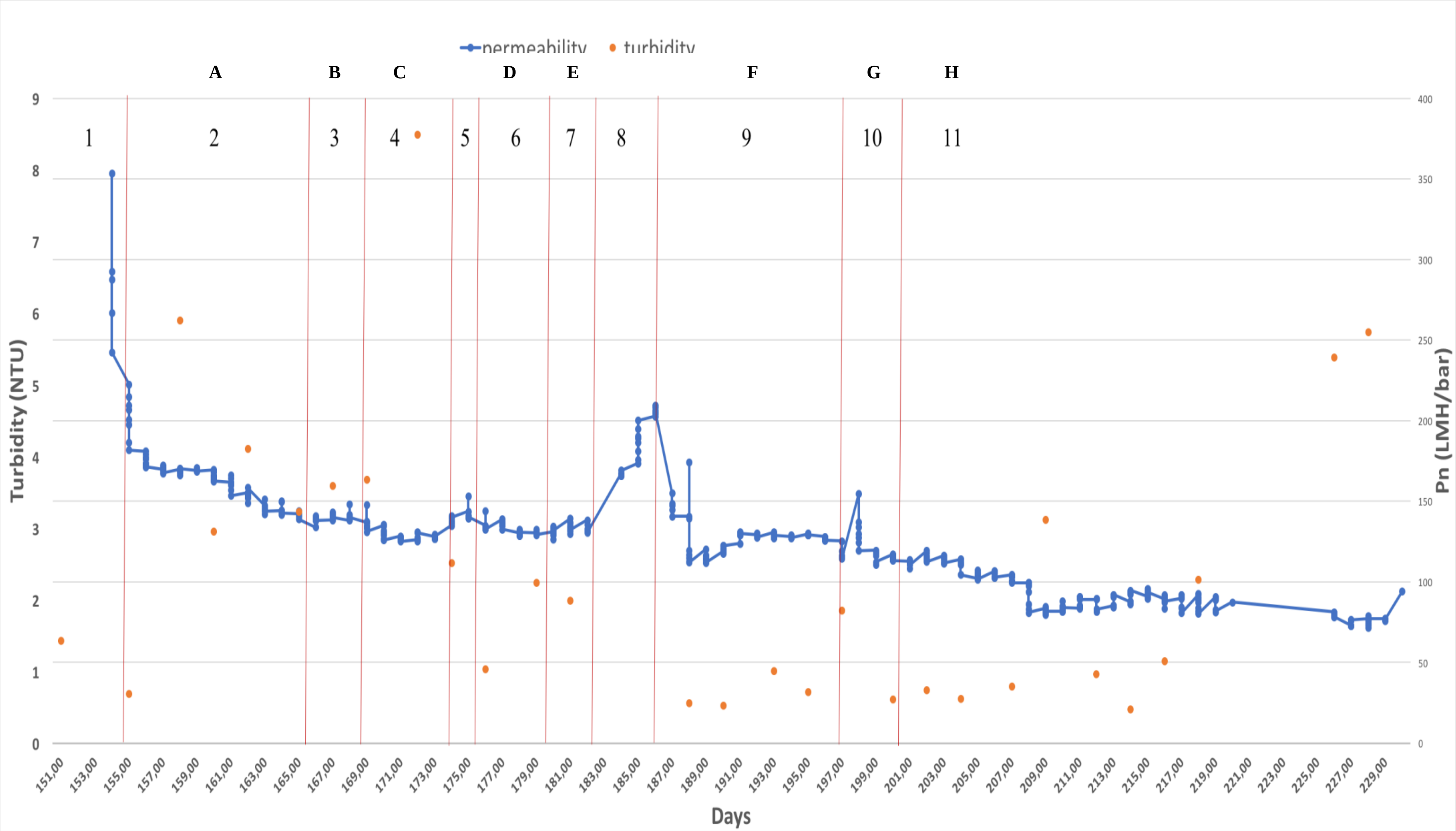

Figure 18: Relationship between permeate turbidity, permeability with respect to time according to different types of physical cleaning method combinations

(Data detail Annex IX)

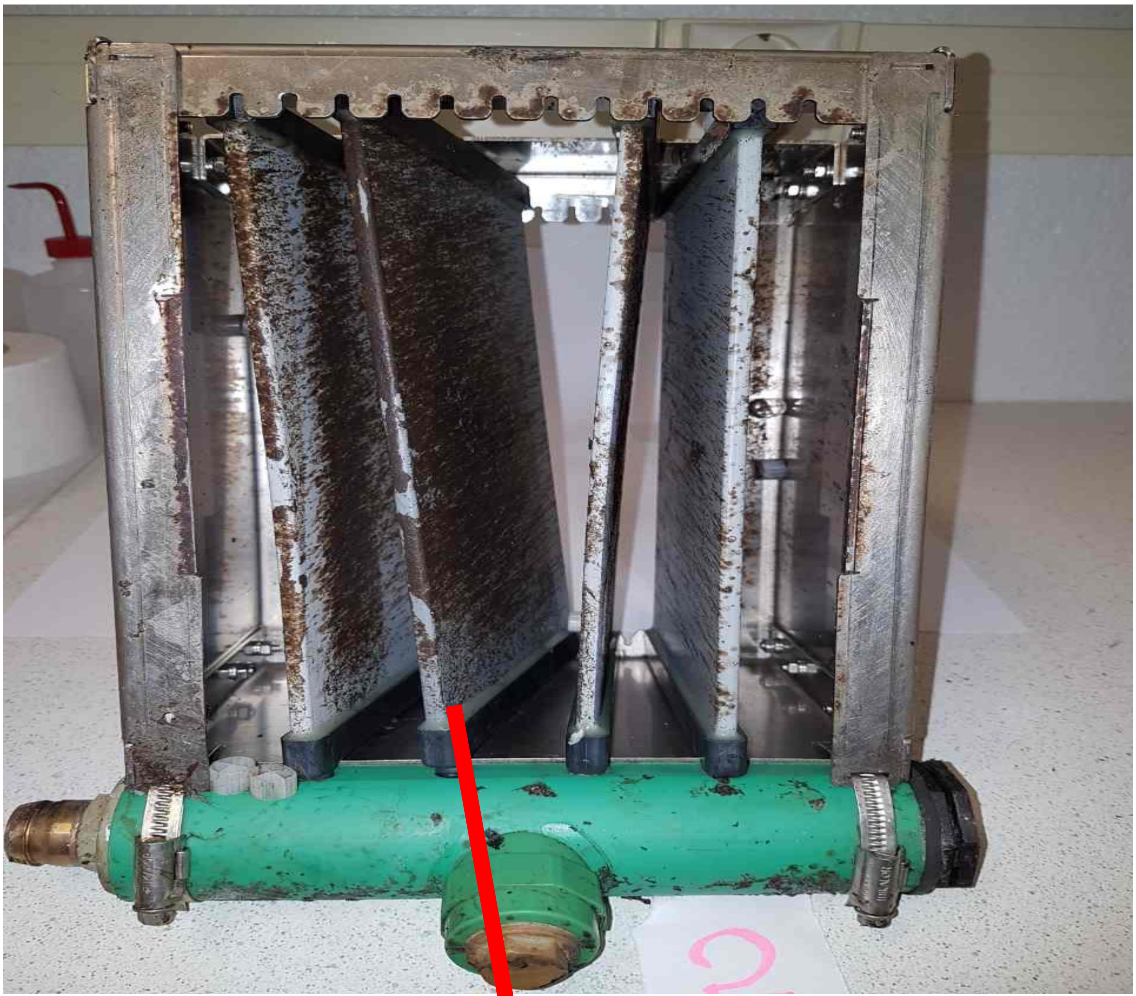

Figure 19: Damaged membrane

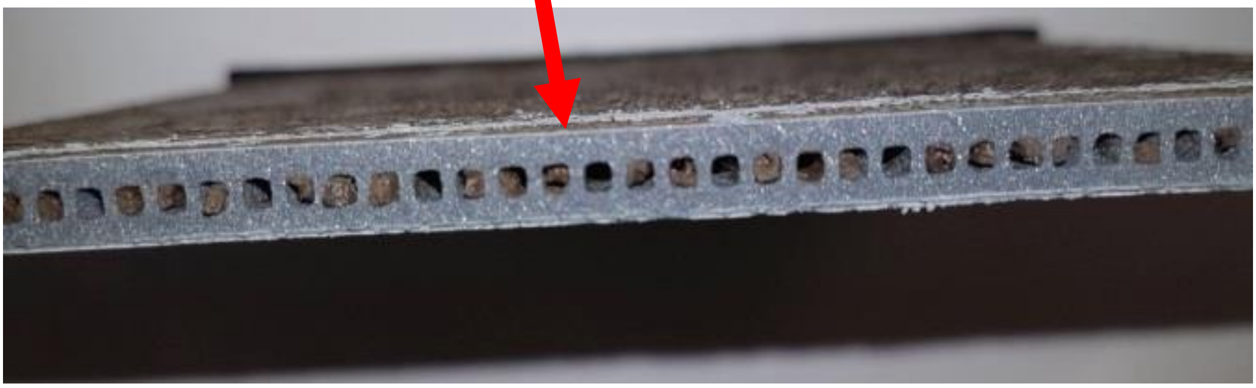

Figure 20: Pore blockage due to sludge accumulation

Figure 21: Sludge collection at the permeate tank

Despite the expensiveness of the ceramic membranes, successful application in aggressive conditions (high temperature and pressure) have recently been observed (Zielińska and Galik 2017). This is further emphasized in the above observations in this thesis research. All the membrane module surfaces were observed through stereomicroscope and no damage was identified. Further, membranes were tested for the bubble test and no damage was identified. During the backwash hammer, high pressure was been applied to membranes. Despite the damage to the plastic connectors, no damage was observed on the membrane surfaces. Furthermore, this pilot plant has from the start been in continual use for different kinds of research purposes. The membranes have undergone several stress conditions within a short period of time. As no other damage could be found, it further confirms that ceramic membrane surfaces can bear high pressure and stress conditions.

4.2.3 Conclusions

The conducted research confirms that the protocol used in this experiment (CIP IV) for chemical cleaning and chemical bath (CIP III) has given good results when both NaOCl and an acid solution are applied together.

High fouling removal ability (200 % reversibility), low turbidity and reasonable permeability were the outcomes of the E, F, G, H combinations. Among them G, H showed over ~250% reversibility with backwash hammer.

Backwash hammer can either be a good physical cleaning method or not. However, due to the damage on the membranes due to high pressure effect, this assessment could not be completed. Further research/tests should be done in this area.

Observations through stereomicroscopic test and bubble test gave results underlining that no damages took place on the studied profiles, confirming that ceramic membrane can bear high pressure and aggressive conditions under treatment.

4.3 Problem of foaming in BMBR systems

4.3.1 Background

The occurrence of periodic foaming in wastewater treatment plants is a common phenomenon. Foaming is not only a problem in conventional activated sludge systems, but also in membrane bioreactors. (Cosenza et al. 2013), (Di Bella and Torregrossa 2013), (Capodici et al. 2014). Foaming is described as a floating biomass and is presented as a viscous layer on the surface of wastewater treatment plant tanks that produce serious operational problems. In particular, there exists two kinds of foaming; biological foaming and chemical foaming. According to Judd and Judd 2010, biological foaming is mainly attributable to the non-balanced F/M ratio, and chemical foaming is attributable to the shock load caused by the synthetic surfactants. The non-balanced F/M ratio favors the foam-forming filamentous hydrophobic micro-organisms metabolism (Davenport and Curtis 2002). Microscopic examination of activated sludge has shown that biological foam is generally enriched with gram-positive filamentous bacteria (Kragelund et al. 2007), (Petrovski, Seviour, and Tillett 2011). These filamentous bacteria synthesize and excrete hydrophobic compounds that increase the hydrophobicity of the activated sludge. This is the key factor in controlling the formation of foam and stabilizing the scum (Petrovski,

Seviour, and Tillett 2011). Foaming by Nocardioform and Microthrix parvicella has been reported in nutrient removal plants and they are considered as the principal cause of foaming (Wanner, 1994). Bacterial strains such as the Eikelboom Type 0092 have been found during foaming occurrence and they are defined as “not famous foam-forming bacteria” (Henze et al. 2008).
Despite the very limited literature found on the relationship between foaming and fouling, (Nakajima and Mishima 2005) and (Di Bella, Torregrossa, and Viviani 2011) have investigated the relationship that occurs between the biological conditions of an MBR and the foam formation on the fouling phenomenon. Membrane permeability is influenced by the high hydrophobicity of foam, increasing both (extracellular polymeric substance) EPS content and filamentous bacteria that directly influence the sludge hydrophobicity. Thus, the sludge properties that induce foam formation may provide some indications on the sludge tendency to induce fouling and vice versa (Judd S. J. 2010). Thus, foaming leads to a significant decreasing of biological performances that results in a decrease in membrane filtration efficiency (Campo et al. 2017). Furthermore, formation can promote due to high aeration intensity in MBR systems, required for membrane scouring (Nakajima and Mishima 2005). In the MBR system, membrane module submerged tank may act as a “foam trap” and the recirculation of trapped foam makes foaming worse (Wanner, 1994; Jenkins et al., 2004). However, the research done by Di Bella et al. (2010) found formation in the MBR pilot plant mainly due to the high EPS concentration in the aerated tank with a negligible influence of filamentous micro-organisms. New management strategies such as Intermittent Aeration (IA) has enhanced the proliferation of foam-forming microorganisms as filamentous bacteria (Campo et al. 2017). The IA process consists of alternating aerobic and anoxic phases within the same stirred reactor. The implementation of such management strategy allows achieving the ammonia oxidation as well as the nitrate reduction saving energy. Indeed, the air supply necessary to the bioreactor result decreased and also the absence of return activated sludge rich in nitrates from nitrification to de-nitrification helps highlight the IA as a cost effective solution. However, the presence of the anoxic phase can seriously impact in the strains development favoring the proliferation of foam-forming microorganisms like filamentous bacteria.

There is a possibility of the foam layer to exceed thickness of 1 m and damage the foam removal system, affecting and sinking the effluent quality. In MBRs, the foaming phenomenon may lead to solids loss (in case of overflowing) often overlooked during MBR design (Henze et al. 2008). Furthermore, it is difficult to control the concentration of the sludge in the aeration tank, due to significant qualities of mixed liquor suspended solids (MLSS) trapped inside the foam. Due to rapid decay of foam, foul odour generates in warm countries.

Finding literature that presents a reachable approach for quantifying the risk to MBBR plants when foam forms on the aeration surfaces has proven to be difficult.

To reduce membrane fouling, BMBR have recently been introduced and it has the potential to reduce foulants such as EPS.

4.3.2 Dealing with foaming

A separate data collection did not taken place in order to identify the foaming behaviour. The following discussion is mainly based on the practical experiences gained during the research period, linking with theory and the performed research.

During the research period foaming was observed 2 times in the pilot plant; once in June 2017 and again in December 2017. The pilot plant collects the influent from the student dormitories at the Norwegian University of Life Sciences situated in Ås. The period when foaming occurred for the first time (June) was a time when students left the campus for their summer vacation, making the number of students living in dormitories were few. The organic load received to the pilot plant was reduced during this time.

Figure 22: Foaming in the separation chamber

The second time, foaming was observed in December 2017. All the functions in the pilot plant had been stopped for 2 months due to the accident and the need to replace membranes. This foaming was observed few days after restarting the plant. This can be attributed to the change of the F/M ratio in the load. To operate the plant in a proper way there must be a balance in food coming to the bioreactor and micro-organisms in the bio reactor. Due to the system changing a change might have happened in the micro-organisms in the bio reactor, leading to high F/M ratio. Therefore, bacteria function has increased and rapid multiplication and dispersion may have taken place. Due to high dispersion, a high F/M ratio makes an environment where the bacteria will not form a good, large dense floc. which triggers foaming (Rick@thewastewaterblog.com 2016). In other terms, this is biological foaming created due to operational condition changes. Judd S. J. 2010 also mentions in his findings that “biological foaming is mainly attributable to the non-balanced F/M ratio”.

Foaming brings many negative impacts such as obscure level sensors, greatly hindered plant operations, possibility of contaminating the permeate tank while overflowing from the separate tank (fig. 23), difficulty to do visual observations (fig. 22), spilling of foams that result in slippery and dirty floor areas, increased housekeeping, generating and spreading pathogens that can cause public health problems, and complex problems in process control. The main objective in this MBBR-MBR pilot plant is to complete preliminary experiments and then transfer the technology to crew ships' wastewater treatment. When thinking about crew ships loading patterns, they undergo strong variations with time regarding no crew and with crew. Therefore, foaming is an important area for further studies to reach the objective of the pilot plant.

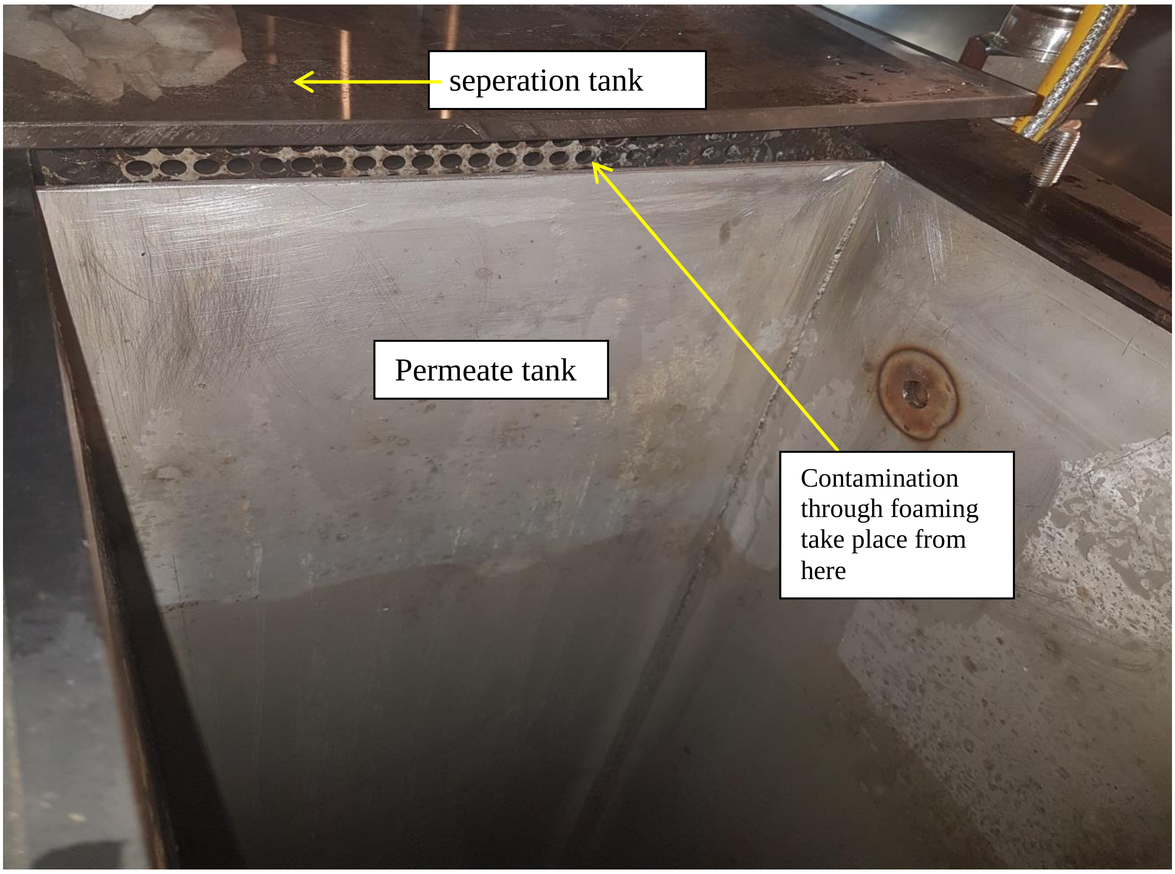

Figure 23: Side view of the permeate tank

4.3.3 Conclusion

It can be understood from the conducted experiments that imbalance in F/M ratio highly affects the foaming behaviour, causing difficulty in handling, health, operational problems.

5 Conclusion

Biofilm Membrane BioReactor (BMBR) is a promising technological combination of MBBR and MBR with advantages such as high quality effluent, process intensification robustness, reduced footprint, cost efficiency, flexibility etc… However, membrane fouling and requirement of high energy acts as huge barrier to extensive use of the technology. As a way to control above barriers and to optimize the production efficiency, a collective plan considering critical flux, better combination of physical and chemical cleaning and mitigating foaming was considered in designing Biofilm Membrane BioReactor (BMBR) in this research.

From the findings, the net flux production efficiency in the pilot plant could be increased by 20% by the developed protocol of critical flux determination through maintaining fouling and keeping system efficiency by optimizing the treatment conditions. Fouling could be controlled by relaxation itself under the working flux 24-26LMH. With increasing flux level to 28, 30LMH better filtration could be obtained by introducing backwash treatment making the process economically viable.

Filtration done both with NaOCl solution and citric acid has given very high recovery percentages (170% and 90%) compared to the treatments done only with NaOCl (42% and 43%). This emphasizes that both NaOCl and the acid solution needs to remove organic and inorganic foulants. It confirms that the protocol used in this experiment (CIP IV) for chemical cleaning and the chemical bath (CIP III) gives good results when both NaOCl and citric acid solution are applied together.

Cake layer formation and pore blocking was controlled resulting ~250% reversibility with the physical cleaning treatment combinations used with backwash hammer (G and H) (table 5). Combinations C, D, E, F, G and H also result 200 % reversibility. Considering both turbidity and permeability E, F, G combinations are better than the other combinations.

Research finding from this study opens new paths for more research for optimization the treatment efficiency in BMBR. The developed protocol of critical flux determination from this research was only useful to find the critical flux for relaxation. However, critical flux that suited both relaxation and backwash was not found. Therefore, it is proposed to repeat the protocol test with some adjustments as highlighted in annex I to find critical flux for both relaxation and backwash. Further, relaxation itself cannot remove foulants when flux

goes over 26LMH, where backwash becomes necessary. It is suggested to maintain backwash after 5th cycle instead of 10th cycle, to increase the filterability.
The suggestion to reduce the number of cycles between two backwash treatments should also be considered with regard to an economic analysis through net flux production efficiency before implementation.
In the physical cleaning, effectiveness in using backwash hammer could not highlight either claim due to the damages on the plastic connectors on the membrane due to high pressure effect. Further research/ tests should be done in this area.

Foaming is a typical problem in wastewater treatment and can be approached by both changing reactor construction and controlling exact operational parameters. Physical construction of a separation wall between permeate tank and separation chamber can avoid contamination while overflowing. It is suggested to maintain a balance F/M ratio during the whole period even though the influent quality can change vastly with students availability at NMBU.

Because no damage could be identified (through stereomicroscopic test and bubble test) on the membrane surfaces, research confirms that ceramic membrane can bear high pressure and aggressive conditions. If the plastic connectors could be made by any other highly durable material, effectiveness and usage of ceramic membranes would arguably be high.

6 Annex

Annex 1

Protocol for critical flux

- An integrity test has to be done to check the product for leakages.
- At the separation chamber MLSS level should be maintained at more than 5g/l when it runs for critical flux test. (According to literature, more than 10g/l increases fouling problems)
- Start filtration with lowest possible pump speed 10Hz for a long duration (e.g. 10-12 Hours)
- Operation parameters; filtration length – 300s; after each filtration cycle apply relaxation (only) for 80 seconds. After each 5th cycle, apply backwash. The following is a procedure for applying backwash after each 5th cycle: Relaxation I – 20(s); degas length 5(s) with 30Hz; backwash length 8(s) with 60Hz speed; Relaxation II – 60(s); pressure release 10(s).
- Increase the pump speed for the next level (depends on operation process, wastewater characteristics; e.g. by 2-5 Hz), after maintaining the filtration duration go to the next speed level
- Continue filtration with increasing pump speeds for up to 10 pump speed levels (10 steps) (filtration height/pump speed level and length should be same for all 10 steps). (Stop criteria is - if TMP increase over TMP_{OPT})
- When going from one flux level to the next flux level, backwash should be applied.
- Record flux, TMP development and temperature at each step.
- Operation parameters similar to general running parameters include physical cleaning methods to remove irreversible fouling.
- Highest possible flux where no fouling occurs should be identified from filtration profiles:

$$\text{FLUX} = f\left(\frac{dTMP}{dt}\right)$$

Annex 1I

Chemical Cleaning

Reagents in use

- NaOCl 100 – 1000 ppm (active chlorine) + NaOH to Ph 10-11
- Citric acid 0.2%

Chemical bath (CIP)

- Filtration cycle stops
- No sludge supply to the membrane chamber
- Sludge is pumped out of the membrane chamber with draining pump
- Membrane chamber to be filled with permeate to the level, covering membrane modules completely
- Module is aerated in permeate for 30min to loosen residual sludge
- Sludge-water mixture to be discharged
- Membrane chamber to be filled with permeate again to the level, covering membrane modules completely.
- Permeate pump starts pumping permeate backwards and dosing pump starts dosing reagent simultaneously.
- Reagent is dosed until the required concentration is reached (to be calculated and programmed)
- Aeration to be provided for 30 sec to mix the chemical
- Membrane modules to be soaked for 2 hours (can be increased up to 12 hours)
- Cleaning solution is discharged with draining pump
- The chamber to be washed with permeate, controlled by pH

*Permeate wash to be provided between hypochlorite and acid cleaning

Annex 1II

Table 6: Reversibility calculation

Combination	TMP Initial	TMP Final	Time	Reversibility %
A	7,6	220	155	137
B	5,1	262,5	155	166
C	12,1	280,9	105	256
D	10,9	263,6	105	241
E	18.5	262,3	122	200
F	16	271,8	97	264
G	7,8	304,3	97	306
H	13	332,5	97	330

Annex IV

cycle	Pn Run 1	Pn Run 2	Pn Run 3
0	79,1	285,0	130,8
0	118,6	356,3	130,2
0	237,7	390,2	86,1
0	196,8	319,2	86,4
0	78,7	212,8	86,1
0	78,7	213,8	86,4
0	78,7	143,1	130,2
0	79,1	107,4	86,4
0	79,6	106,9	86,4
0	79,1	106,9	86,4
0	80,1	107,8	86,8
0	80,6	71,9	86,8
1	79,1	171,3	166,2
1	79,1	301,9	326,9
1	797,0	1006,4	1157,7
1	1020,8	1132,2	1225,2
1	1293,9	1231,4	1437,9
1	1294,1	1207,7	1449,2
1	1323,2	1229,2	1531,4
1	1302,4	1238,7	1519,5
1	1328,9	1219,9	1443,5
1	1372,6	1180,5	1443,5
1	1318,8	1194,0	1507,7
1	1318,8	1243,5	1507,7
1	1332,3	1243,5	1470,0
1	1342,6	1198,5	1475,7
1	1377,9	1207,7	1531,4
1	1327,2	1224,6	1519,5
1	1339,2	1219,9	1470,0
1	1394,1	1167,3	1473,7
1	1367,4	1184,9	1473,7
1	1322,2	1238,7	1464,3
1	1347,8	1224,6	1501,9
1	1383,3	1201,7	1442,1
1	1372,6	1184,9	1475,7
1	1332,3	1253,2	1505,0
1	1332,3	1289,5	1458,7
1	1372,6	1236,3	1447,6
1	1367,4	676,9	1437,9
1	1317,2	427,5	1499,1
1	1342,6	108,8	1519,5
1	1427,6	73,2	1458,7
1	1405,1	72,5	1447,6
1	1317,2	72,5	1507,7
1	1307,3	72,9	1481,5
1	1341,7	72,5	1415,8
1	1383,3	72,2	1415,8
1	1317,2	72,2	1470,0
1	1311,5	72,5	1429,1
1	1291,9	72,5	1436,6
1	599,4	72,5	1394,5
1	403,1	72,5	1416,8
1	81,3	73,2	1470,0
1	81,3	73,5	1410,4
1	81,0	72,5	1389,2
1	81,2	72,5	1399,8
1	81,3	72,2	1464,3
1	81,3	71,9	1453,1
1	82,3	72,2	1424,9
1	81,7	72,5	1421,3
1	81,3	72,5	1465,3
1	81,6	72,9	1501,9
1	81,6	72,9	1453,1
1	81,3	72,5	1454,0
1	81,6	72,9	1499,1
1	82,0	73,2	1458,7
1	82,0	72,5	1386,4
1	82,0	72,5	1400,6
1	81,6	73,2	1415,8
1	81,6	73,2	1465,3
1	81,6	73,2	1471,0
1	82,0	73,5	1416,8
1	82,0	72,9	1426,8
1	82,0	72,9	1482,5
1	123,0	72,5	1458,7
1	123,0	72,5	1436,6
1	82,3	72,5	1447,6
1	82,0	72,5	1497,1
1	81,6	72,2	1453,1
1	81,6	72,2	1436,6
1	81,2	72,5	1447,6
1	81,2	72,2	1470,0
1	82,0	71,9	1470,0
1	82,0	72,2	1448,5
1	82,0	72,9	1490,0
1	81,6	72,9	1520,6
1	81,2	73,2	1519,5
1	81,2	73,2	1454,0
1	81,2	72,5	1430,4
1	81,2	72,2	1459,6
1	81,8	72,2	1487,3
1	81,2	72,2	1481,5
1	81,6	71,9	1501,9
1	82,5	71,6	1513,6
1	123,0	71,9	1482,5
1	122,4	72,5	1470,0
1	81,8	73,5	1513,6
1	81,2	72,9	1526,5
1	81,6	71,9	1520,6
1	81,6	72,2	1519,5
1	81,8	72,5	1465,3
1	82,1	72,5	1475,7
1	81,8	72,2	1519,5
1	81,2	72,2	1520,6
1	82,9	72,9	1464,3
1	82,3	72,9	1421,3
1	82,1	72,2	1499,1
1	81,2	72,2	1494,3
1	81,4	73,2	1465,3
1	81,4	73,2	1470,0
1	82,1	73,5	1416,8
1	82,5	73,2	1481,5
1	82,0	72,5	1488,4
1	82,1	72,5	1437,9
1	82,1	72,2	1476,8
1	82,1	72,5	1532,6
1	82,5	72,9	1502,9
1	82,9	72,9	1465,3
1	82,1	72,9	1500,2
1	81,4	72,5	1551,0
1	82,1	72,2	1500,2
1	82,1	72,9	1433,3
1	82,1	73,2	1405,9
1	82,5	72,5	1432,3
1	83,2	71,9	1458,7
1	82,5	72,2	1432,0
1	81,7	72,9	1459,6
1	81,8	72,9	1476,8
1	82,1	72,9	1529,2
1	82,1	72,9	1497,1
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1	82,1	72,5	1421,3
1	83,5	71,9	1500,2
1	84,0	72,5	1446,2
1	84,0	72,5	782,4
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1	82,9	71,9	86,2
1	83,1	72,2	88,0
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1	83,1	72,9	88,8
1	82,1	72,2	88,5
1	82,1	72,2	88,1
2	81,8	355,7	85,8
2	119,9	553,2	163,9
2	961,2	1381,1	1206,4
2	1235,9	1463,9	1457,7
2	1701,0	1551,7	1884,0
2	1735,7	1546,1	1909,3
2	1770,5	1557,4	1902,8
2	1745,2	1557,4	1902,8
2	1725,2	1535,0	1873,8
2	1737,9	1540,5	1831,0
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2	1730,0	1529,5	1880,8
2	1712,7	1558,4	1895,8
2	1694,3	1552,8	1895,8
2	1731,5	1552,8	1844,7
2	1731,5	1558,4	1850,6
2	1731,5	1546,1	1831,0
2	1719,0	1557,4	1831,0
2	1731,5	1540,5	1860,0
2	1737,9	1546,1	1866,9
2	1719,0	1563,1	1860,0
2	1725,2	1563,1	1853,2
2	1750,8	1511,5	1860,0
2	1725,2	1506,0	1895,8
2	1706,5	1540,5	1895,8
2	1712,7	1546,1	1895,8
2	1700,4	1540,5	1917,0
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2	1725,2	1524,0	1866,9
2	1719,0	1535,0	1866,9
2	1719,0	1546,1	1866,9
2	1736,3	1569,6	1873,8
2	1731,5	1528,0	1866,9
2	1725,2	1533,6	1866,9
2	1685,3	1539,3	1887,9
2	1679,1	1533,6	1887,9
2	1719,0	1533,6	1902,1
2	1719,0	1539,3	1916,6
2	1730,0	1568,9	1895,0
2	1719,0	1568,9	1880,8
2	1725,2	1546,1	1880,8
2	1730,0	1551,7	1880,8
2	1736,3	1557,4	1873,8
2	1691,4	1551,7	1880,8
2	1708,5	1546,1	1873,8
2	1691,4	1522,5	1880,8
2	1725,2	1522,5	1866,9
2	1725,2	1551,7	1873,8
2	1742,7	1522,5	1837,8
2	1731,5	1511,5	1831,0
2	1737,9	1563,1	1853,2
2	1742,7	1568,9	1866,9
2	1755,5	1568,9	1895,0
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2	1731,5	1544,9	1866,9
2	1731,5	1580,5	1866,9
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2	1742,7	1544,9	1924,2
2	1719,0	1533,6	1882,9
2	1712,7	1568,9	1866,9
2	1737,9	1551,7	1909,9
2	1755,5	1540,5	1924,2
2	1776,8	1511,5	1902,1
2	1776,8	1511,5	1887,9
2	1731,5	1563,1	1860,0
2	1737,9	1574,7	1853,2
2	1744,3	1546,1	1853,2
2	1744,3	1546,1	1839,7
2	1710,1	1563,1	1826,3
2	1714,8	1551,7	1826,3
2	1750,8	1546,1	1791,2
2	1757,3	1551,7	1797,7
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2	1755,5	1517,0	1853,2
2	1768,6	1551,7	1880,8
2	1768,6	1540,5	1880,8
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2	1762,0	1557,4	1833,0
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2	1781,8	1500,6	1833,0
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2	1730,0	1535,0	1873,8
2	1744,3	1535,0	1909,9
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2	1717,5	1511,5	1817,5

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2	1731,5	1522,5	1895,8
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2	1717,5	1533,6	1902,8
2	1723,7	1533,6	1902,8
2	1730,0	1546,1	1873,8
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2	1796,6	1544,9	1887,9
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2	1723,7	1557,4	1909,9
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2	1730,0	1544,9	1880,8
2	1763,9	1432,1	1909,3
2	1775,2	1269,5	1908,8
2	1099,9	322,1	990,9
2	774,0	214,7	660,9
2	161,5	71,6	131,0
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2	82,2	70,9	87,3
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2	81,8	70,3	87,3
2	81,1	70,3	87,3
2	80,4	70,3	86,8
2	80,4	70,3	86,4
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3	191,2	668,4	392,5
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3	1412,4	1699,5	1819,7
3	2015,2	1845,1	2201,5
3	2026,5	1877,7	2192,2
3	2098,1	1871,1	2215,7
3	2142,6	1819,9	2250,3
3	2157,8	1832,4	2276,8
3	2120,1	1886,2	2301,3
3	2087,5	1866,6	2282,9
3	2131,4	1832,4	2243,9
3	2142,6	1877,7	2276,8
3	2105,4	1884,4	2284,9
3	2070,4	1884,4	2274,7
3	2098,1	1911,5	2274,7
3	2102,2	1884,4	2250,3
3	2094,8	1851,6	2260,2
3	2142,6	1817,2	2274,7
3	2105,4	1836,3	2266,5
3	2142,6	1877,7	2250,3
3	2157,8	1845,1	2311,6
3	2127,5	1826,1	2294,9
3	2112,7	1906,2	2293,1
3	2127,5	1832,4	2276,8
3	2109,6	1774,1	2294,9
3	2135,0	1832,4	2274,7
3	2087,5	1845,1	2231,6
3	2102,2	1838,8	2284,9
3	2139,8	1838,8	2282,9
3	2139,8	1877,7	2213,0
3	2109,6	1884,4	2250,3
3	2117,1	1813,7	2258,4
3	2165,5	1832,4	2254,2
3	2120,1	1845,1	2237,0
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3	2150,2	1853,8	2334,9
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3	2142,6	1845,1	2252,7
3	2150,2	1826,1	2271,2
3	2183,2	1847,4	2309,7
3	2167,9	1886,2	2204,4
3	2142,6	1864,6	2210,8
3	2147,5	1838,8	2252,0
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3	2109,6	1851,6	2254,2
3	2076,1	1864,6	2262,3
3	2098,1	1832,4	2278,5
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3	2142,6	1845,1	2184,1
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3	2132,2	1851,6	2262,3
3	2102,2	1838,8	2270,3
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3	2124,6	1858,0	2268,3
3	2094,8	1851,6	2282,9
3	2065,8	1891,1	2235,9
3	2120,1	1849,3	2270,3
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3	2127,5	1838,8	2228,0
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3	2086,9	1875,8	2293,1
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3	2135,0	1838,8	2228,0
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3	2094,8	1858,0	2311,6
3	2080,2	1819,9	2266,5
3	2051,6	1845,1	2243,9
3	2033,5	1897,9	2212,2
3	2109,6	1864,6	2243,9
3	2102,2	1823,5	2268,3
3	2072,4	1829,9	2243,9
3	2054,9	1891,1	2212,2
3	2076,6	1877,7	2254,2
3	2065,8	1845,1	2270,3
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3	2109,6	1884,4	2262,3
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3	2091,4	1897,9	2238,4
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3	2132,2	1838,8	2280,3
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3	80,1	70,6	87,6
3	80,1	70,6	87,6
3	80,4	69,1	88,0
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3	80,1	70,6	88,0
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4	80,8	167,7	124,5
4	153,6	381,9	279,2
4	1423,0	1561,8	1699,7
4	1808,6	1777,3	2047,2
4	2443,1	2114,5	2524,2
4	2474,9	2107,4	2548,6
4	2500,4	2148,9	2564,1
4	2532,4	2163,5	2572,9
4	2506,6	2127,3	2572,9
4	2484,4	2141,7	2597,7
4	2483,3	2127,3	2572,9
4	2426,2	2113,2	2564,1
4	2500,4	2168,8	2642,0
4	2509,0	2147,1	2623,8
4	2474,9	2141,7	2590,6
4	2474,9	2134,5	2608,6
4	2483,3	2106,2	2642,0
4	2474,9	2093,4	2614,8
4	2515,2	2170,9	2579,3
4	2491,8	2156,2	2538,1
4	2449,9	2127,3	2581,7
4	2433,5	2141,7	2608,6
4	2410,4	2113,2	2572,9
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4	2409,3	2086,4	2564,1
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4	2489,7	2134,5	2632,9
4	2481,3	2134,5	2623,8
4	2517,7	2127,3	2572,9
4	2500,4	2161,5	2538,1
4	2441,3	2086,4	2570,6
4	2417,3	2086,4	2588,1
4	2426,6	2121,7	2622,6
4	2418,1	2148,9	2596,9
4	2466,0	2163,5	2608,6
4	2466,5	2156,2	2590,6
4	2449,9	2128,9	2632,9
4	2451,5	2094,5	2623,8
4	2482,8	2100,4	2605,8
4	2483,3	2100,4	2596,9
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4	2500,4	2141,7	2632,9
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4	2402,3	2134,5	2636,1
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5	2774,0	2405,0	2883,2
5	2774,0	2389,5	2931,4
5	2810,9	2397,2	2971,1
5	2783,0	2405,0	2951,1
5	2820,2	2428,7	2973,6
5	2810,6	2412,8	2974,0
5	2822,8	2381,8	2963,6
5	2822,8	2420,7	2905,3
5	2832,1	2444,7	2943,9
5	2801,3	2436,6	2911,9
5	2810,6	2397,2	2911,9
5	2801,3	2374,2	2855,0
5	2801,3	2359,0	2924,8
5	2810,6	2397,2	2983,6
5	2841,5	2420,7	3016,0
5	2841,5	2428,7	2963,6
5	2832,4	2423,3	2934,2
5	2792,1	2384,7	2943,9
5	2764,9	2412,8	2944,3
5	2810,6	2374,2	2953,7
5	2832,1	2397,2	2943,9
5	2822,8	2397,2	2973,6
5	2850,9	2381,8	2914,9
5	2813,6	2374,2	2934,2
5	2747,1	2412,8	2983,6
5	2792,1	2412,8	2984,1
5	2774,0	2428,7	2993,6
5	2774,0	2394,4	2943,9
5	2779,7	2348,4	2905,6
5	2761,1	2389,5	2943,9
5	2792,1	2452,8	2924,5
5	2829,2	2436,6	2883,5
5	2783,0	2428,7	2951,1
5	2747,2	2420,7	2902,6
5	2792,1	2355,9	2943,9
5	2783,0	2386,6	2993,6
5	2801,3	2428,7	2983,6
5	2774,0	2420,7	2963,6
5	2810,6	2378,9	2943,9
5	2783,0	2340,9	2973,6
5	2783,0	2397,2	3003,8
5	2819,9	2436,6	3034,7
5	2819,9	2412,8	2973,6
5	2810,6	2405,0	2953,7
5	2783,0	2394,4	2914,9
5	2795,3	2352,7	2905,3

5	2777,3	2386,6	2943,9
5	2813,6	2436,6	2934,2
5	2850,9	2371,2	2905,3
5	2860,3	2363,5	2895,5
5	2829,2	2374,2	2895,8
5	2792,1	2407,7	2943,9
5	2810,9	2423,3	2964,1
5	2738,5	2400,0	2953,7
5	2729,5	2431,1	2924,5
5	2783,0	2389,5	2886,6
5	2819,9	2366,6	2902,3
5	2783,0	2405,0	2902,3
5	2764,9	2381,8	2953,7
5	2774,0	2381,8	2934,2
5	2832,1	2371,2	2934,2
5	2832,1	2355,9	2914,9
5	2747,2	2355,9	2943,9
5	2738,3	2402,3	2953,7
5	2764,9	2378,9	2944,3
5	2783,0	2363,5	2934,5
5	2738,3	2378,9	2915,1
5	2747,1	2389,5	2905,6
5	2743,5	2378,9	2934,2
5	2734,6	2420,7	2943,9
5	2855,1	2270,2	3063,1
5	2830,8	2004,8	2983,0
5	1625,8	597,7	1247,0
5	1070,7	388,5	602,0
5	157,9	106,4	127,4
5	118,1	70,9	85,2
5	120,0	70,9	85,2
5	120,7	70,9	85,0
5	78,7	70,3	85,3
5	79,3	70,0	85,6
5	82,8	105,9	85,6
5	81,7	140,6	85,6
6	80,4	589,9	120,5
6	115,1	944,0	297,7
6	1499,7	2311,3	2057,3
6	1996,8	2433,0	2541,3
6	2960,0	2658,5	3138,8
6	3000,5	2683,8	3169,5
6	3021,5	2692,3	3220,8
6	3070,2	2675,4	3241,2
6	3109,5	2666,9	3272,3
6	3119,4	2675,4	3282,9
6	3119,4	2692,2	3251,9
6	3079,9	2675,4	3251,9
6	3032,8	2666,9	3283,5
6	3060,9	2633,7	3251,9
6	3129,4	2650,2	3241,2
6	3129,4	2658,5	3282,9
6	3099,7	2642,3	3282,9
6	3109,6	2667,1	3261,9
6	3089,7	2666,9	3282,8
6	3079,9	2650,2	3304,1
6	3109,5	2584,4	3272,3
6	3079,9	2608,6	3230,8
6	3080,3	2658,5	3272,3
6	3070,2	2649,9	3251,4
6	3060,6	2625,0	3261,9
6	3051,0	2608,6	3293,4
6	3051,0	2633,2	3251,9
6	3051,0	2649,9	3220,8
6	3079,9	2625,0	3282,9
6	3079,9	2625,0	3251,4
6	3109,4	2658,5	3160,2
6	3079,6	2650,2	3190,2
6	3109,5	2625,0	3283,5
6	3109,5	2633,2	3200,3
6	3070,2	2675,4	3231,1
6	3051,0	2658,5	3220,8
6	3051,0	2675,4	3160,4
6	3060,6	2683,8	3210,5
6	3070,1	2633,7	3210,6
6	3089,7	2625,5	3210,6
6	3070,2	2683,8	3221,0
6	3109,6	2650,2	3231,3
6	3159,5	2641,9	3231,1
6	3139,6	2650,2	3241,4

6	3109,5	2617,4	3283,7	6	242,0	106,9	169,9	7	3358,6	2994,2	3504,6
6	3099,6	2617,4	3273,1	6	161,3	70,9	127,4	7	3328,0	2994,2	3529,3
6	3070,2	2650,2	3200,3	6	81,0	70,6	84,6	7	3309,6	2870,3	3529,3
6	3060,6	2641,9	3231,3	6	81,0	70,6	84,6	7	3329,9	2879,0	3496,6
6	3079,9	2641,9	3200,3	6	80,0	70,6	84,2	7	3369,0	2941,4	3540,4
6	3099,6	2683,8	3169,8	6	79,6	70,6	84,2	7	3369,0	2923,3	3562,6
6	3060,6	2683,8	3159,4	6	81,7	70,3	84,2	7	3350,5	2810,9	3515,4
6	3070,2	2625,5	3169,5	6	82,5	105,5	84,6	7	3379,0	2819,2	3493,9
6	3079,6	2633,7	3220,8	7	81,0	396,5	263,6	7	3389,8	2916,5	3551,4
6	3050,3	2625,0	3220,8	7	81,4	742,3	600,1	7	3387,4	2889,7	3573,9
6	3070,2	2633,7	3220,8	7	1394,4	2307,3	2370,2	7	3387,4	2836,1	3496,6
6	3099,6	2633,7	3220,8	7	1931,1	2525,0	2785,5	7	3429,4	2853,1	3475,2
6	3050,3	2675,4	3284,3	7	3148,0	2898,6	3416,3	7	3328,0	2932,3	3585,2
6	3090,1	2650,2	3273,8	7	3214,2	2941,4	3488,5	7	3307,9	2905,4	3562,6
6	3119,4	2650,2	3241,5	7	3329,9	2820,4	3521,4	7	3381,8	2836,1	3483,3
6	3070,2	2666,9	3251,9	7	3360,9	2820,4	3467,0	7	3381,8	2861,7	3483,3
6	3079,9	2633,7	3314,8	7	3319,8	2939,1	3443,5	7	3259,9	2854,6	3562,6
6	3050,3	2625,5	3251,4	7	3299,6	2885,9	3507,5	7	3240,5	2828,9	3529,3
6	3069,8	2625,0	3210,4	7	3421,6	2810,9	3540,4	7	3360,9	2879,0	3504,6
6	3060,6	2649,9	3272,3	7	3403,0	2844,6	3485,9	7	3403,0	2914,4	3537,2
6	3089,7	2633,2	3241,1	7	3289,6	2896,6	3499,4	7	3289,6	2828,9	3604,1
6	3139,6	2625,0	3230,8	7	3321,3	2879,0	3532,4	7	3259,9	2812,0	3529,3
6	3060,6	2666,7	3304,1	7	3392,4	2870,3	3529,3	7	3382,4	2898,6	3454,0
6	3051,0	2641,5	3273,1	7	3392,4	2905,4	3496,6	7	3350,5	2898,6	3496,6
6	3079,9	2641,5	3304,2	7	3269,8	2896,6	3540,6	7	3269,8	2853,1	3573,9
6	3089,7	2666,7	3336,5	7	3269,8	2879,0	3529,3	7	3269,8	2820,4	3559,2
6	3050,3	2607,9	3220,6	7	3421,6	2923,3	3485,9	7	3411,0	2889,7	3507,5
6	3050,3	2599,7	3200,3	7	3381,8	2916,5	3485,9	7	3329,9	2880,8	3562,6
6	3099,4	2608,6	3241,1	7	3259,9	2846,0	3573,9	7	3307,9	2853,1	3496,6
6	3069,8	2616,7	3261,9	7	3300,7	2844,6	3573,9	7	3338,2	2861,7	3454,0
6	3060,2	2616,7	3315,0	7	3483,5	2905,4	3464,6	7	3389,8	2916,5	3507,5
6	3060,0	2633,2	3293,5	7	3472,6	2941,4	3464,6	7	3369,0	2898,6	3529,3
6	3079,7	2608,6	3282,9	7	3336,2	2863,3	3540,4	7	3269,8	2837,4	3518,4
6	3089,4	2650,2	3272,3	7	3360,1	2846,0	3529,3	7	3299,6	2820,4	3496,6
6	3129,6	2683,8	3272,3	7	3411,0	2905,4	3393,7	7	3381,8	2934,7	3543,6
6	3079,6	2683,8	3282,9	7	3379,4	2896,6	3422,7	7	3318,5	2925,6	3608,0
6	3050,8	2608,6	3230,8	7	3288,0	2819,2	3551,4	7	3299,6	2802,6	3515,4
6	3060,4	2641,5	3241,1	7	3299,6	2795,3	3540,4	7	3301,2	2826,3	3504,6
6	3070,2	2616,7	3282,9	7	3421,6	2889,7	3404,0	7	3301,2	2953,1	3570,4
6	3032,0	2617,4	3304,1	7	3389,8	2889,7	3456,3	7	3241,6	2962,4	3634,4
6	3079,9	2692,3	3261,9	7	3319,8	2812,0	3551,4	7	3261,2	2861,7	3555,9
6	3079,8	2700,8	3241,5	7	3360,9	2812,0	3485,9	7	3301,2	2846,0	3526,3
6	3022,6	2641,9	3305,2	7	3350,5	2872,0	3467,0	7	3261,2	2889,7	3585,2
6	3060,6	2616,7	3251,9	7	3340,2	2889,7	3499,4	7	3241,6	2863,3	3562,6
6	3040,7	2701,0	3241,5	7	3309,6	2844,6	3488,5	7	3289,6	2836,1	3393,7
6	3031,1	2683,8	3262,5	7	3319,8	2844,6	3521,4	7	3329,9	2870,3	3404,0
6	3050,3	2658,5	3169,8	7	3358,6	2914,4	3485,9	7	3271,1	2914,4	3608,0
6	3099,4	2683,8	3179,9	7	3348,4	2887,8	3499,4	7	3251,4	2879,0	3596,5
6	3089,7	2666,9	3190,1	7	3372,0	2778,0	3499,4	7	3329,9	2933,1	3467,0
6	3089,9	2608,6	3169,8	7	3350,5	2834,7	3456,3	7	3498,1	2803,1	3565,2
6	3119,4	2658,5	3210,5	7	3340,2	3003,5	3507,5	7	2811,3	902,6	1954,2
6	3089,7	2650,2	3220,8	7	3329,9	2994,2	3551,4	7	2173,5	572,6	1280,1
6	3021,6	2633,7	3210,5	7	3360,9	2861,7	3592,8	7	329,0	106,9	215,3
6	3040,7	2633,7	3231,1	7	3371,3	2870,3	3526,3	7	203,4	107,4	129,7
6	3060,0	2658,3	3272,7	7	3281,1	2939,1	3540,4	7	121,5	71,3	86,1
6	3070,2	2625,0	3231,1	7	3261,2	2879,0	3573,9	7	121,0	71,3	85,7
6	3109,6	2616,7	3210,6	7	3319,8	2827,6	3464,6	7	122,1	72,5	86,9
6	3129,4	2649,9	3231,4	7	3379,4	2861,7	3464,6	7	122,1	72,9	86,9
6	3089,7	2658,5	3221,0	7	3317,9	2907,5	3540,4	7	80,7	72,2	86,9
6	3089,7	2658,5	3210,6	7	3288,0	2880,8	3540,4	7	80,7	72,2	86,9
6	3069,8	2649,9	3241,4	7	3389,8	2836,1	3404,0	8	122,1	406,9	162,7
6	3040,7	2649,9	3241,5	7	3371,3	2854,6	3424,7	8	122,1	773,2	412,5
6	3070,2	2576,5	3220,8	7	3279,6	2887,8	3510,3	8	627,9	2510,2	2531,2
6	3119,4	2584,4	3200,3	7	3259,9	2861,7	3488,5	8	1104,6	2747,0	3007,5
6	3109,6	2641,5	3210,6	7	3329,9	2828,9	3412,4	8	3240,5	3016,4	3679,4
6	3109,6	2616,7	3190,1	7	3340,2	2879,0	3433,1	8	3397,9	3051,6	3782,2
6	3139,6	2641,5	3200,3	7	3288,0	2914,4	3581,5	8	3462,0	3078,5	3765,6
6	3129,5	2625,0	3262,5	7	3288,0	2887,8	3551,4	8	3509,4	3051,6	3721,1
6	3060,0	2584,4	3231,1	7	3338,2	2914,4	3485,9	8	3675,5	3062,8	3858,1
6	3099,6	2600,5	3241,5	7	3317,9	2923,3	3504,6	8	3653,4	3098,5	3869,9
6	3079,9	2625,0	3262,5	7	3289,6	2854,6	3540,4	8	3610,0	3072,9	3681,8
6	3070,2	2608,7	3241,5	7	3309,6	2870,3	3518,4	8	3620,8	3037,0	3702,0
6	3079,6	2616,7	3251,9	7	3371,3	2896,6	3494,4	8	3670,5	3075,1	3782,2
6	3079,6	2666,9	3294,4	7	3329,9	2907,5	3504,6	8	3599,3	3125,9	3834,5
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6	3041,4	2608,6	3180,1	7	3328,0	2819,2	3529,3	8	3658,2	3048,4	3765,6
6	3109,5	2683,8	3384,7	7	3390,6	2898,6	3485,9	8	3599,3	3139,1	3793,7
6	3160,7	2475,0	3396,7	7	3338,2	2941,4	3540,4	8	3578,2	3139,1	3759,4
6	2066,6	673,9	1515,9	7	3279,6	2802,6	3548,2	8	3603,6	3016,4	3777,0
6	1433,6	425,6	964,3	7	3329,9	2794,4	3515,4	8	3620,8	3033,9	3840,4

8	3536,6	3111,4	3765,6
8	3546,9	3107,6	3783,1
8	3550,6	3098,5	3823,1
8	3519,6	3102,2	3817,2
8	3550,6	3051,6	3710,1
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8	3544,0	3025,1	3714,7
8	3586,4	3016,4	3759,4
8	3522,2	3157,9	3816,9
8	3561,1	3157,9	3782,2
8	3659,5	3033,9	3703,6
8	3648,6	3042,7	3702,0
8	3540,2	3139,1	3736,9
8	3523,1	3111,4	3703,6
8	3631,6	3028,1	3777,0
8	3648,6	3054,8	3834,5
8	3592,9	3105,9	3699,2
8	3603,6	3075,1	3666,8
8	3627,0	3115,2	3834,5
8	3605,7	3143,2	3834,5
8	3670,6	3045,3	3704,5
8	3618,9	3050,9	3725,7
8	3567,7	3139,1	3822,9
8	3598,5	3115,2	3805,8
8	3647,2	2967,6	3811,7
8	3597,2	3025,1	3834,6
8	3540,2	3148,5	3863,8
8	3578,2	3078,5	3804,4
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8	3614,4	3125,9	3743,2
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8	3546,9	3042,7	3794,4
8	3536,6	3060,5	3805,8
8	3629,9	3039,6	3716,5
8	3675,5	3022,2	3738,4
8	3554,5	3063,9	3840,4
8	3554,5	3054,8	3805,8
8	3575,7	3107,6	3681,8
8	3592,9	3116,7	3713,1
8	3582,3	3124,5	3777,0
8	3575,7	3082,0	3710,1
8	3571,7	3010,6	3782,2
8	3582,3	3051,6	3816,9
8	3636,2	3115,2	3710,1
8	3692,9	3115,2	3727,4
8	3523,1	3124,5	3777,0
8	3512,8	3148,5	3836,4
8	3653,4	3084,1	3743,2
8	3636,2	3066,1	3771,8
8	3502,5	3105,9	3736,9
8	3550,6	3105,9	3702,0
8	3687,9	3075,1	3681,8
8	3610,0	3102,2	3692,7
8	3509,4	3109,7	3834,5
8	3550,6	3082,0	3798,5
8	3595,1	3051,6	3752,9
8	3574,2	3078,5	3811,3
8	3624,6	3045,9	3691,0
8	3647,2	3019,3	3703,6
8	3605,3	3078,5	3805,3
8	3620,8	3105,9	3816,9
8	3636,2	3001,9	3749,5
8	3626,8	2984,6	3738,4
8	3550,6	3139,1	3769,5
8	3582,3	3167,4	3770,8
8	3614,4	3037,0	3636,8
8	3571,7	3037,0	3699,2
8	3610,0	3157,9	3799,8
8	3642,4	3139,1	3765,6
8	3578,2	3096,7	3777,0
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8	3614,4	3019,3	3765,6
8	3636,2	3001,9	3783,1
8	3536,6	3060,5	3828,8
8	3536,6	3105,9	3834,5
8	3592,9	3045,9	3783,1
8	3603,6	3019,3	3714,6
8	3623,3	3120,6	3811,3
8	3557,2	3120,6	3787,0
8	3626,8	3001,9	3688,3
8	3582,3	3042,7	3699,2
8	3588,7	3120,6	3846,3
8	3582,3	3093,1	3805,3
8	3582,3	3007,8	3754,4
8	3561,1	3001,9	3792,9
8	3675,5	3096,7	3792,9
8	3675,5	3096,7	3783,1
8	3502,5	3069,5	3736,9
8	3512,8	3063,9	3759,4
8	3714,5	3060,5	3692,7
8	3669,4	3066,1	3660,2
8	3561,1	3078,5	3810,8
8	3616,0	3082,0	3786,5
8	3599,3	3013,4	3660,2
8	3588,7	3045,9	3686,4
8	3598,7	3133,8	3764,5
8	3597,2	3100,4	3741,8
8	3663,2	3122,0	3846,3
8	3718,9	2900,9	3922,0
8	2329,7	847,5	2170,6
8	1229,3	534,4	1422,6
8	244,1	104,6	210,1
8	163,5	105,0	168,1
8	121,0	70,9	83,7
8	81,4	70,6	83,7
8	80,7	69,7	84,2
8	80,0	69,7	83,7
8	80,3	70,9	83,3
8	80,7	71,6	83,7
9	82,5	390,6	193,6
9	116,5	756,5	535,4
9	1775,8	2600,2	2765,9
9	2373,7	2921,6	3245,2
9	3661,9	3220,6	3969,9
9	3765,1	3248,1	3979,5
9	3808,6	3293,8	3958,8
9	3802,6	3256,8	4019,0
9	3863,0	3293,8	3924,9
9	3878,9	3322,1	3972,8
9	3845,5	3270,9	4007,4
9	3851,8	3303,2	3995,8
9	3908,5	3234,2	4002,7
9	3829,6	3220,6	4002,7
9	3924,4	3248,1	3928,9
9	3936,0	3289,6	3963,2
9	3834,5	3280,3	3974,7
9	3867,7	3276,0	3903,9
9	3829,6	3276,0	3993,4
9	3807,7	3234,4	4016,7
9	3807,7	3285,4	4019,0
9	3807,7	3304,4	4016,7
9	3818,6	3299,1	4019,0
9	3829,6	3299,1	3995,8
9	3863,0	3299,1	4046,9
9	3802,6	3243,3	4058,7
9	3813,6	3289,6	3947,5
9	3824,7	3299,1	3995,8
9	3858,2	3261,7	4054,4
9	3897,0	3280,3	4042,5
9	3807,7	3280,3	4016,7
9	3796,8	3261,7	4028,5
9	3863,0	3280,3	3995,8
9	3874,3	3299,1	3981,8
9	3878,9	3270,9	3958,8
9	3856,6	3261,7	3947,5
9	3905,0	3308,5	3968,0
9	3845,5	3312,6	3979,5
9	3824,7	3280,3	3931,3
9	3802,6	3280,3	3933,9
9	3807,7	3270,9	3968,0
9	3840,7	3289,6	3942,7
9	3807,7	3280,3	3920,0
9	3807,7	3261,7	3942,7
9	3829,6	3261,7	3984,3
9	3802,6	3248,1	3993,4
9	3878,9	3238,9	4019,0
9	3901,6	3280,3	3972,8
9	3885,6	3252,5	3958,8
9	3829,6	3289,6	4019,0
9	3878,9	3304,4	3942,7
9	3949,4	3294,9	3968,0
9	3748,6	3252,5	3954,1
9	3780,9	3341,3	3972,8
9	3791,7	3284,5	3970,3
9	3818,6	3275,2	4005,0
9	3818,6	3261,7	3942,7
9	3786,0	3243,3	3942,7
9	3770,1	3257,3	3968,0
9	3818,6	3243,6	3931,3
9	3874,3	3252,9	3951,7
9	3851,8	3197,9	3949,4
9	3851,8	3257,3	3951,7
9	3863,0	3294,9	3963,2
9	3770,1	3280,3	4088,4
9	3770,1	3280,3	4028,5
9	3807,7	3257,3	3954,1
9	3807,7	3238,9	3945,2
9	3863,0	3225,2	3965,6
9	3840,7	3225,2	3998,0
9	3796,8	3257,3	4014,4
9	3840,7	3276,0	3945,2
9	3867,7	3299,1	3920,0
9	3834,5	3261,7	3954,1
9	3829,6	3299,1	3892,6
9	3818,6	3289,6	3920,0
9	3818,6	3243,3	3954,1
9	3818,6	3280,3	3920,0
9	3823,5	3234,2	3970,3
9	3840,7	3243,3	3993,4
9	3856,6	3266,6	4009,4
9	3780,3	3248,1	4019,0
9	3801,8	3248,1	3977,2
9	3818,6	3276,0	3977,2
9	3786,0	3318,1	3993,4
9	3829,6	3270,9	4019,0
9	3807,7	3229,7	3958,8
9	3786,0	3266,6	3993,4
9	3878,9	3276,0	4024,1
9	3890,2	3285,4	3977,2
9	3807,7	3238,9	3979,5
9	3818,6	3238,9	3977,2
9	3851,8	3276,0	3995,8
9	3818,6	3266,6	4028,5
9	3775,2	3211,6	4032,8
9	3770,1	3229,7	3947,5
9	3818,6	3252,9	3954,1
9	3854,2	3216,1	3977,2
9	3901,6	3285,4	3954,1
9	3834,5	3276,0	3942,7
9	3881,3	3234,2	3936,2
9	3913,0	3270,9	3950,1
9	3878,9	3261,7	3947,5
9	3940,3	3270,9	3947,5
9	3906,1	3303,2	3958,8
9	3856,6	3270,9	3970,3
9	3812,6	3270,9	4009,4
9	3834,5	3289,6	3986,3
9	3812,6	3285,4	4000,4
9	3823,5	3280,3	3970,3
9	3851,8	3285,4	3897,6
9	3818,6	3252,9	3870,4
9	3840,7	3207,0	3963,2
9	3851,8	3225,2	3908,8
9	3807,7	3257,3	4015,6
9	3793,0	3299,1	3984,2
9	3866,5	3318,1	3963,2
9	3840,7	3280,3	3988,8
9	3829,6	3261,7	3984,3
9	3829,6	3280,3	3947,5
9	3791,7	3402,1	4000,5
9	3903,9	3115,7	4156,8
9	2780,1	694,1	3126,5
9	1895,3	416,5	2259,4
9	358,4	69,7	334,7
9	199,1	104,1	208,3
9	79,3	105,9	85,6
9	79,3	106,9	86,3

9	79,6	70,3	126,6
9	80,3	70,0	126,6
9	80,0	70,0	84,1
9	80,0	70,3	125,0
10	122,1	780,9	117,8
10	187,2	1000,0	252,0
10	2112,3	3055,6	2411,7
10	2752,4	3203,1	3063,5
10	3649,5	3444,4	4096,1
10	3664,2	3504,5	4165,2
10	3890,5	3494,9	4254,9
10	3936,2	3456,9	4230,9
10	4100,8	3568,5	4180,3
10	4032,9	3588,4	4180,3
10	4066,6	3543,6	4180,3
10	4100,8	3553,5	4145,4
10	4115,5	3526,7	4175,5
10	4081,3	3546,2	4183,6
10	4066,6	3501,6	4242,9
10	4063,1	3521,1	4192,1
10	4063,1	3553,5	4145,4
10	4051,8	3514,2	4180,3
10	3999,7	3523,9	4192,1
10	4010,7	3533,7	4192,1
10	4036,4	3485,3	4168,6
10	4044,0	3523,9	4133,9
10	4089,3	3543,6	4168,6
10	3985,0	3523,9	4122,4
10	4051,8	3485,3	4183,7
10	4097,6	3514,2	4180,3
10	4071,1	3523,9	4133,9
10	4086,0	3475,8	4133,9
10	4112,4	3514,2	4133,9
10	4127,1	3553,5	4157,0
10	4044,0	3504,5	4215,8
10	4112,4	3514,2	4145,4
10	4089,3	3533,7	4133,9
10	4021,7	3453,8	4183,6
10	4055,3	3463,3	4180,3
10	4040,5	3472,8	4203,9
10	4055,3	3479,3	4180,3
10	4105,8	3489,0	4168,6
10	4063,1	3472,8	4207,1
10	4051,8	3482,3	4207,1
10	4029,3	3533,7	4160,4
10	4089,3	3523,9	4207,1
10	4066,6	3553,5	4160,4
10	4069,9	3546,2	4195,3
10	4058,7	3494,9	4222,3
10	4081,3	3494,9	4230,9
10	4066,6	3523,9	4252,0
10	4077,9	3533,7	4180,3
10	4112,4	3466,3	4195,3
10	4127,1	3456,9	4207,1
10	4089,3	3472,8	4183,6
10	4112,4	3511,4	4195,3
10	4089,3	3511,4	4157,0
10	4089,3	3472,8	4168,6
10	4039,0	3533,7	4192,1
10	4100,8	3456,9	4165,2
10	4077,9	3517,0	4177,0
10	4115,5	3566,0	4215,8
10	4115,5	3521,1	4273,1
10	4036,4	3472,8	4186,9
10	4092,6	3475,8	4187,1
10	4153,6	3514,2	4183,6
10	4104,1	3492,0	4148,9
10	4077,9	3472,8	4111,0
10	4040,5	3497,8	4203,9
10	4029,3	3504,5	4227,8
10	4040,5	3531,0	4245,8
10	4112,4	3540,9	4198,5
10	4104,1	3523,9	4160,4
10	4104,1	3475,8	4145,4
10	4055,3	3514,2	4200,7
10	4089,3	3456,9	4239,9
10	4112,4	3482,3	4246,1
10	4112,4	3492,0	4172,0
10	4055,3	3485,3	4157,0
10	4055,3	3485,3	4145,4

10	4044,0	3492,0	4207,1
10	4066,6	3531,0	4230,9
10	4150,4	3523,9	4195,3
10	4081,3	3466,3	4219,0
10	4104,1	3453,8	4183,6
10	4124,0	3472,8	4222,3
10	4055,3	3504,5	4230,9
10	4089,3	3536,4	4172,0
10	4100,8	3479,3	4183,6
10	4021,7	3479,3	4195,3
10	4077,9	3492,0	4168,6
10	4044,0	3511,4	4192,1
10	4112,4	3514,2	4133,9
10	4100,8	3543,6	4145,4
10	4055,3	3553,5	4180,3
10	4077,9	3523,9	4180,3
10	4112,4	3482,3	4219,0
10	4112,4	3501,6	4180,3
10	4100,8	3531,0	4107,4
10	4029,3	3482,3	4073,4
10	4044,0	3450,7	4180,3
10	4066,6	3501,6	4195,3
10	4066,6	3501,6	4198,7
10	4077,9	3533,7	4195,3
10	4032,9	3492,0	4195,3
10	4044,0	3501,6	4195,3
10	4077,9	3501,6	4195,3
10	4100,8	3531,0	4210,5
10	4055,3	3501,6	4172,0
10	4077,9	3444,4	4195,3
10	4112,4	3501,6	4230,9
10	4070,0	3482,3	4203,9
10	4063,1	3489,0	4168,6
10	4051,8	3521,1	4145,4
10	4066,6	3514,2	4267,0
10	4044,0	3504,5	4192,1
10	4044,0	3523,9	4180,3
10	4044,0	3523,9	4168,6
10	4128,8	3523,9	4133,9
10	4092,6	3485,3	4157,0
10	4047,5	3453,8	4234,1
10	4077,9	3501,6	4195,3
10	4089,3	3511,4	4183,6
10	4100,8	3521,1	4126,0
10	4112,4	3707,6	4361,8
10	4066,6	3407,6	4494,7
10	3708,0	851,3	2426,8
10	3093,3	532,0	1575,8
10	366,2	72,5	256,7
10	284,8	72,9	171,9
10	81,0	107,8	85,2
10	81,2	107,4	84,8
10	80,0	70,9	85,2
10	80,5	71,3	85,2
10	82,1	70,9	85,2
10	82,1	70,9	85,2
11	83,8	650,6	85,9
11	115,5	1139,6	118,8
11	1946,3	3108,4	2050,1
11	2615,2	3310,3	2714,3
11	4068,8	3587,9	4173,6
11	4181,9	3599,8	4338,6
11	4270,0	3618,9	4496,9
11	4319,2	3618,9	4496,9
11	4251,5	3661,7	4408,9
11	4262,9	3702,8	4395,0
11	4288,2	3683,1	4222,9
11	4288,2	3671,5	4257,0
11	4274,5	3679,5	4319,1
11	4251,5	3679,5	4329,2
11	4249,2	3669,6	4420,8
11	4237,7	3669,6	4371,3
11	4260,7	3626,4	4066,1
11	4258,6	3636,2	4066,1
11	4240,1	3679,5	4388,8
11	4290,3	3721,1	4352,8
11	4360,4	3683,1	4214,0
11	4372,3	3673,4	4211,0
11	4408,4	3683,1	4240,6
11	4372,3	3642,4	4315,0

11	4297,7	3677,6	4406,9
11	4262,9	3677,6	4420,8
11	4274,5	3669,6	4513,4
11	4251,5	3669,6	4525,6
11	4309,4	3722,8	4458,8
11	4333,0	3712,8	4383,1
11	4288,2	3722,8	4263,0
11	4348,6	3702,8	4274,6
11	4325,0	3693,0	4265,7
11	4313,4	3681,3	4280,0
11	4240,1	3689,4	4472,5
11	4251,5	3659,8	4512,0
11	4295,6	3689,4	4554,6
11	4295,6	3699,4	4525,6
11	4274,5	3744,4	4397,0
11	4311,4	3744,4	4431,0
11	4325,0	3702,8	4390,9
11	4348,6	3702,8	4417,0
11	4360,4	3659,8	4397,0
11	4311,4	3679,5	4371,2
11	4274,5	3657,8	4373,4
11	4309,4	3667,7	4373,4
11	4297,7	3699,4	4333,9
11	4237,7	3699,4	4357,3
11	4283,9	3722,8	4378,9
11	4249,2	3764,6	4355,1
11	4274,5	3754,5	4345,6
11	4301,9	3744,4	4347,9
11	4325,0	3673,4	4420,8
11	4325,0	3652,0	4458,8
11	4334,9	3709,4	4432,9
11	4309,4	3689,4	4457,1
11	4260,7	3699,4	4408,9
11	4215,0	3701,1	4397,0
11	4272,3	3732,8	4420,8
11	4272,3	3742,9	4410,8
11	4321,2	3764,6	4444,9
11	4334,9	3722,8	4447,3
11	4334,9	3691,2	4336,2
11	4323,1	3701,1	4336,2
11	4323,1	3687,6	4359,5
11	4286,0	3648,0	4383,1
11	4217,5	3657,8	4383,1
11	4244,5	3657,8	4371,3
11	4148,3	3699,4	4383,1
11	4148,3	3691,2	4406,9
11	4286,0	3694,7	4392,9
11	4262,9	3724,4	4404,9
11	4299,8	3711,1	4431,0
11	4311,4	3721,1	4444,9
11	4288,2	3638,3	4420,8
11	4339,1	3638,3	4444,9
11	4240,1	3699,4	4444,9
11	4251,5	3699,4	4444,9
11	4258,4	3732,8	4422,7
11	4223,9	3722,8	4397,0
11	4212,5	3753,0	4431,0
11	4201,2	3763,2	4418,9
11	4260,7	3691,2	4371,3
11	4274,5	3721,1	4359,5
11	4186,6	3648,0	4395,0
11	4197,6	3616,7	4406,9
11	4290,3	3657,8	4371,3
11	4260,7	3669,6	4371,3
11	4235,3	3734,4	4347,9
11	4189,9	3724,4	4347,9
11	4212,5	3726,0	4381,0
11	4251,0	3734,4	4345,6
11	4334,9	3630,7	4399,4
11	4311,4	3621,1	4371,3
11	4299,8	3609,3	4408,9
11	4313,4	3640,3	4408,9
11	4292,6	3659,8	4408,9
11	4288,2	3638,3	4457,1
11	4286,0	3709,4	4359,5
11	4286,0	3689,4	4333,9
11	4215,0	3669,6	4333,9
11	4226,3	3669,6	4383,1
11	4226,3	3679,5	4385,2
11	4226,3	3657,8	4437,2

11	4274,5	3679,5	4397,0
11	4313,6	3689,4	4397,0
11	4274,5	3701,1	4420,8
11	4274,5	3701,1	4432,9
11	4251,5	3773,5	4383,1
11	4262,9	3763,2	4383,1
11	4262,9	3702,8	4383,1
11	4203,7	3722,8	4359,5
11	4242,1	3751,5	4457,1
11	4192,5	3719,5	4432,9
11	4313,4	3628,6	4422,7
11	4325,0	3628,6	4399,0
11	4288,2	3711,1	4420,8
11	4286,0	3691,2	4444,9
11	4286,0	3732,8	4383,1
11	4286,0	3732,8	4395,0
11	4290,3	3956,6	4632,8
11	4274,5	3598,8	4725,5
11	4015,8	851,3	2527,6
11	3345,1	496,6	1630,7
11	490,4	106,4	254,4
11	326,9	106,4	170,4
11	123,1	71,6	82,6
11	83,2	71,6	81,9
11	83,9	71,3	81,9
11	83,9	71,9	82,2
11	83,2	71,9	83,0
11	82,5	71,6	83,0

Annex V

filtration Cycle	TMP avg	permeability
43782	97	251,2
43783	96	249
43784	98	242,5
43785	100	239,5
43786	101	235,8
43787	101	235,9
43788	101	234,3
43789	102	233,2
43790	103	231,6
43791	104	229,9
43792	103	233
43793	97	245,7
43794	98	242,5
43795	100	239,4
43796	100	239,6
43797	99	239,2
43798	102	232,7
43799	102	232,1
43800	103	230,7
43801	104	228,8
43802	104	230,2
43803	96	249,4
43804	100	238,1
43805	101	235,7
43806	102	232,9
43807	102	233,3
43808	103	232
43809	104	230,3
43810	104	227,9
43811	105	226
43812	105	228
43813	98	243
43814	99	238,7
43815	101	235,9
43816	101	233,5
43817	102	231,5
43818	103	231,5
43819	102	233,3
43820	103	233,2
43821	103	232,7
43822	103	232,9
43823	97	246,1
43824	98	241,9
43825	100	239,2
43826	100	238,9
43827	100	238,9
43828	100	237,6
43829	101	236,8
43830	101	235,3
43831	103	230,6
43832	103	230,6
43833	97	247,6
43834	99	242,9
43835	99	239
43836	100	238,4
43837	100	236,7
43838	100	236,4
43839	101	235,9
43840	102	232,7
43841	102	232
43842	103	233,6
43843	98	244,3
43844	100	237,2
43845	100	239,3
43846	100	239,2
43847	100	238,2
43848	100	238,1
43849	100	237,8
43850	100	236,4
43851	101	235,5
43852	102	235,4
43853	97	247,3
43854	98	242,5
43855	99	241,2
43856	99	238,7
43857	100	238,1
43858	101	237,8
43859	101	236,6
43860	101	235,8
43861	101	236,2
43862	101	234,3
43863	96	249,5
43864	98	243
43865	98	241,5
43866	99	240,5
43867	99	241
43868	99	241,2
43869	99	240,6
43870	99	239,1
43871	99	240,1
43872	99	243,7
43873	96	247,9
43874	97	244,4
43875	98	242,2
43876	98	240,4
43877	98	240,9
43878	111	234,4
43879	114	228,2
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Annex VI

FIL.

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44030	264,3
44030	265,5
44030	266,6
44030	267,8
44030	269
44030	270,1
44030	271,1
44030	273
44030	273,6
44030	274,8
44030	275,9
44030	277,1
44030	278,3
44030	279,2
44030	280,4
44030	281,1
44030	282,3
44030	282,9
44030	284,5
44030	285,2
44030	286,5
44030	287,5
44030	288,7
44030	289,6
44030	290,4
44030	291,5
44030	291,8
44030	293,1
44030	293,5
44030	294,9
44030	295,8
44030	297,1
44030	298,2
44030	298,6
44030	299,5
44030	299,9
44030	301,1
44030	301,7
44030	303,1
44030	303,6
44030	304,6
44030	305,2
44030	306,1
44030	306,5
44030	307,2
44030	308,5
44030	308,8
44030	309,7
44030	309,4
44030	310,3
44030	310,5
44030	311,5
44030	312,4
44030	313,3
44030	314,1
44030	314,4
44030	315,2
44030	315,7
44030	317,2
44030	317,7
44030	318,9
44030	319
44030	319,7
44030	320,5
44030	321,7
44030	322,5
44030	323
44030	323,7
44030	323,8
44030	324,9
44030	325,6
44030	326,6
44030	327
44030	327,7
44030	328,2
44030	328,9
44030	329,8
44030	330,4
44030	331,5
44030	332
44030	332,9
44030	333,2
44030	333,8
44030	334
44030	334,2
44030	334,2
44030	334,9
44030	335,8
44030	336,1
44030	337
44030	337,4
44030	338,3
44030	338,2
44030	335,1
44030	330,2
44030	324,8
44030	319,7
44030	315,9
44030	309,3
44030	305,3
44030	300,1
44030	291,3
44030	199,4
44030	98,4
44030	50,5
44030	37,9
44030	34,7
44030	28
44030	9,7
44030	-5,4
44030	-28,8
44030	-48,7
44030	-67,3
44030	-94,2
	-
44030	115,2
	-
44030	104,6
44030	-82,8
44030	-49,2
44030	-26,7
44030	-16,9
44030	-9,5
44030	-4,9
44030	0,2
44030	4,8
44030	7,2
44030	9,7
44030	12,6
44030	14,1
44030	15,5
44030	16,7
44030	17,6
44030	17,8
44030	18,5
44030	19,3
44030	20,6
44030	21
44030	21,1
44030	21,1
44030	21,4
44030	21,4
44030	21,3
44030	21,2
44030	21,1
44030	20,7

Annex VII

days	Pn av(LMH/bar)
41,0	118,3
41,2	117,1
41,3	116,5
41,4	117,7
41,6	115,4
41,7	119,0
41,8	116,6
41,8	115,7
42,0	102,7
42,2	102,2
42,3	101,5
42,4	100,4
42,6	100,8
42,7	101,0
42,8	99,9
42,9	101,4
43,0	108,5
43,2	108,3
43,3	105,4
43,4	106,7
43,6	124,9
43,7	125,3
43,8	121,9
43,9	120,3
44,0	121,1
44,2	117,9
44,3	120,7
44,4	120,4
44,6	118,5
44,7	119,2
44,8	115,4
45,0	110,9
45,2	110,6
45,3	109,3
45,4	109,1
47,0	205,5
47,0	192,1
47,1	185,1
47,1	181,0
47,1	176,8
48,0	174,0
48,2	167,8
48,3	168,6
48,4	168,9
48,6	167,1
48,7	162,6
49,0	151,5
49,2	151,8
49,3	151,8
49,4	152,7
49,6	151,8
49,7	152,8
49,8	154,6
49,8	154,5
50,0	151,0
50,1	151,4
50,2	151,5
50,3	151,8
50,6	184,1
50,7	175,7
50,8	167,8
50,8	167,3
51,0	179,6
51,2	168,7
51,3	163,3
51,4	162,6
51,6	160,5
51,7	159,2
51,8	157,7
51,8	158,5
52,0	157,5
52,0	157,5
52,2	156,7
52,3	157,1
52,4	156,3
52,6	154,6
52,7	154,5
52,8	151,5
52,8	153,6
74,0	98,3
74,2	98,2
74,3	97,7
74,4	97,0
74,6	97,3
74,7	96,1
74,8	96,2
74,8	94,9
75,0	113,5
75,2	114,4
75,3	113,2
75,4	114,7
75,6	111,4
75,7	111,5
75,8	111,5
75,8	111,3
76,0	101,2
76,2	100,2
76,3	99,8
76,4	100,1
76,6	97,0
76,7	98,0
76,8	99,3
76,8	98,8
77,4	113,1
77,5	110,9
77,6	109,6
77,7	108,2
77,8	108,7
77,8	109,3
77,8	108,3
77,9	105,2
79,8	173,1
79,8	164,8
79,8	156,9
79,8	156,6
79,9	153,0
79,9	149,3
79,9	145,6
80,0	147,4
80,0	141,9
80,2	135,0
80,3	283,3
80,4	241,9
80,6	289,7
80,7	111,0
80,8	130,0
80,8	124,0
85,7	730,7
85,7	657,5
85,7	641,4
85,8	622,1
85,8	599,2
85,8	587,3
85,8	571,7
85,9	561,0
86,0	425,0
86,2	393,4
86,3	372,9
86,4	367,6
86,6	352,4
86,7	354,7
86,8	351,2
86,8	349,6
87,0	331,6
87,2	323,3
87,3	322,1
87,4	320,5
87,6	324,1
87,7	322,1
87,8	318,8
87,8	321,3
88,0	330,1
88,2	325,3
88,3	319,9
88,4	327,9
88,6	322,8
88,7	319,1
88,8	316,6
88,8	315,8
89,0	321,1
89,2	314,7
89,3	309,8
89,4	308,8
89,6	302,6
89,7	295,6
89,8	293,6
89,8	295,3
150,2	113,5
150,2	100,0
150,4	98,3
150,5	97,5
150,6	97,5
150,7	97,1
150,8	96,4
151,0	96,5
151,2	96,1
151,2	95,3
151,4	94,7
151,6	94,7
151,7	95,4
151,8	93,7
152,0	93,7
152,2	93,8
152,2	93,2
152,4	93,2
152,5	92,8
152,6	92,6
152,7	92,5
152,8	93,4
153,0	92,8
153,2	92,1
154,5	353,7
154,6	292,8
154,7	287,8
154,8	266,9
155,0	242,5
155,2	222,6
155,2	206,8
155,4	215,0
155,5	209,5
155,6	200,8
155,7	197,5
155,8	186,6
156,0	181,9
156,2	181,1
156,2	179,4
156,4	177,5
156,5	176,3
156,6	173,6
156,7	173,5
156,8	172,6
157,0	171,3
157,2	169,8
157,2	170,1
157,4	172,5
157,5	171,1
157,6	171,0
157,7	169,9
157,8	168,9
158,0	167,5
158,2	170,1
158,2	167,9
158,4	166,4
158,5	169,5
158,6	168,9
158,7	168,9
158,8	169,8
159,0	170,4
159,2	169,2
159,2	170,2
159,4	168,5
159,5	171,0
159,6	170,2
159,7	170,5
159,8	170,3
160,0	168,9
160,2	169,6
160,2	168,0
160,4	166,2
160,5	163,3
160,6	165,5
160,7	165,4
160,8	164,0
161,0	162,5

Annex VIII

Days from start	Pn(LMH/bar)
152,0	93,7
152,2	93,8
152,2	93,2
152,4	93,2
152,5	92,8
152,6	92,6
152,7	92,5
152,8	93,4
153,0	92,8
153,2	92,1
Chemical cleaning	
155,8	186,56
156,0	181,92
156,2	181,08
156,2	179,4
156,4	177,47
156,5	176,33
156,6	173,58
156,7	173,54
156,8	172,56
157,0	171,32

Annex IX

No of days from start	Permeability	Turbidity
151,83		1,427
154,49	353,72	
154,62	292,78	
154,66	287,84	
154,83	266,92	
155,00	242,54	
155,16	222,58	
155,25	206,75	
155,41	214,95	
155,50	209,45	
155,62	200,75	
155,67	197,49	
155,83	186,56	0,69
156,00	181,92	
156,17	181,08	
156,25	179,4	
156,41	177,47	
156,50	176,33	
156,62	173,58	
156,66	173,54	
156,83	172,56	
157,00	171,32	
157,16	169,75	
157,25	170,08	
157,42	172,53	
157,49	171,11	
157,62	170,95	
157,66	169,86	
157,83	168,9	
158,00	167,45	
158,16	170,06	
158,25	167,86	
158,41	166,38	
158,50	169,45	
158,62	168,94	
158,67	168,91	
158,83	169,83	5,907
159,00	170,35	
159,16	169,2	
159,25	170,2	
159,41	168,51	
159,50	170,95	
159,62	170,18	
159,66	170,53	
159,83	170,27	
160,00	168,87	
160,16	169,55	
160,25	168,01	
160,42	166,17	
160,49	163,3	
160,62	165,52	
160,66	165,36	
160,83	164,03	2,957
161,00	162,48	
161,16	162	
161,25	160,14	
161,41	161,27	
161,50	160,84	
161,62	166,33	
161,67	164,3	
161,83	156,89	
162,00	153,52	
162,16	155,2	
162,25	155,14	
162,41	151,96	
162,50	152,78	
162,62	155,58	
162,66	153,62	
162,83	148,88	4,11
162,99	158,41	
163,16	147,11	
163,25	147,63	
163,42	145,23	
163,50	151,35	
163,62	144,99	
163,66	145,13	
163,83	142,21	
164,00	143,84	
164,16	144,29	
164,25	144,27	
164,41	149,6	
164,50	142,62	
164,62	141,98	
164,67	141,89	
164,83	150,34	
165,00	142,8	
165,16	142,32	
165,25	144,15	
165,41	142,17	
165,50	142,23	
165,62	142,27	
165,66	140,9	
165,83	141,35	3,23
165,99	138,86	
166,16	134,03	
166,25	141	
166,41	139,27	
166,50	138,95	
166,58	139,09	
166,66	138,64	
166,83	140,07	
167,00	138,09	
167,17	138,47	
167,24	143,24	
167,41	140,93	
167,50	142,02	
167,62	140,77	
167,67	141,04	
167,83	141,73	3,597
168,00	140,17	
168,16	138,1	
168,25	148,35	
168,41	141,64	
168,50	139,82	
168,62	141,13	
168,66	140,44	
168,83	141,01	
168,99	140,01	
169,16	136,97	
169,25	147,95	
169,41	136,57	
169,50	137,66	
169,62	134,81	
169,66	134,6	
169,83	133,12	3,683
170,00	131,03	
170,16	134,92	
170,25	131,15	
170,41	129,12	
170,50	129,39	
170,62	135,78	
170,66	131,85	
170,83	126,76	
171,00	125,91	
171,16	128,47	
171,25	128,09	
171,42	126,87	
171,50	125,99	
171,62	127,85	
171,66	126,39	
171,83	125,92	
172,00	125,2	
172,16	126,14	
172,25	126,6	
172,41	126,25	
172,49	131,05	
172,62	126,77	
172,66	127,55	
172,83	125,41	8,497
173,00	130,47	
173,16	128,13	
173,25	127,61	
173,41	129,57	
173,49	128,1	
173,62	126,66	
173,66	126,89	
173,83	126,78	
174,00	128,07	
174,16	135	
174,25	137	
174,41	137,8	
174,50	140,8	
174,62	136,2	
174,67	136,7	
174,83	139,7	2,517
175,00	139,9	
175,16	143,8	
175,25	153,3	
175,50	139,3	
175,62	140,5	
175,66	141,1	
175,83	140,9	
176,00	140,5	
176,16	135	
176,24	134,7	
176,41	144	
176,50	133,3	
176,62	132,5	
176,66	133,8	
176,83	132,8	1,038
177,00	132,9	
177,16	139	
177,25	137,5	
177,41	136	
177,50	135,2	
177,62	135,6	
177,66	136,4	
177,83	135	
177,99	132,6	
178,16	130,3	
178,25	131,4	
178,50	129,6	
178,62	128,8	
178,66	132,4	
178,83	128,8	
178,99	131	
179,16	130,4	
179,25	131,1	
179,41	132,7	
179,50	130,8	
179,62	131	
179,66	131,3	
179,83	130,8	2,237
179,99	129,2	
180,16	131,3	
180,25	134,5	
180,41	130,4	
180,50	129	
180,62	129,5	
180,66	126,6	
180,83	133,2	
181,00	131,9	
181,16	139,3	
181,25	136,6	
181,41	136,9	
181,50	129,8	
181,62	134,9	
181,66	133,6	
181,83	131,8	1,99
182,00	132,3	
182,16	138,4	
182,25	135,7	
182,41	131,9	
182,50	131,4	
182,62	132,9	
182,66	132,4	
182,83	131,2	
183,00	130,5	
184,41	167,5	
184,50	166,6	
184,62	165,8	
184,66	165,7	
184,83	166,9	
185,00	169,3	
185,16	173,6	
185,25	176	
185,41	181,3	
185,50	186,4	
185,62	189,2	
185,66	190,3	
185,83	194,9	
186,00	200,2	
186,16	202,7	
186,25	204,7	
186,41	209,6	
186,50	209,1	
186,62	205,4	
186,66	208,5	
186,83	204,6	
187,00	206,5	
187,50	155,2	
187,62	148,6	
187,66	147,5	
187,83	144,8	
188,00	140,7	
188,16	140,6	
188,25	139,6	
188,41	174,3	
188,50	119,7	
188,62	116,7	
188,66	114,9	
188,83	112,5	0,557
189,00	112,2	
189,16	120,4	
189,25	116,6	
189,41	113,8	
189,50	116,5	
189,62	114,5	
189,67	114,5	
189,83	112,3	
190,00	111,9	
190,16	119,1	
190,25	117,7	
190,41	118,8	
190,50	119,2	
190,62	120,1	
190,66	120,7	
190,83	122,5	0,53
190,99	122,5	
191,17	123,8	
191,25	129,2	
191,41	129	
191,50	130,6	
191,62	129,1	
191,66	130,8	
191,83	130,9	
191,99	130,2	
192,16	129,3	
192,24	129,9	
192,41	130,2	
192,50	129,7	
192,62	129,7	
192,66	128	
192,83	128,8	
193,00	127,7	
193,16	131	
193,24	129,7	
193,41	128	
193,49	127,7	
193,62	127,3	
193,66	127,7	
193,83	128,5	1,007
194,00	129	
194,16	128,2	
194,25	128,9	
194,41	128,6	
194,50	127,1	
194,62	127,5	
194,66	128,7	
194,83	127,7	
195,00	127,5	
195,16	129,7	
195,25	129,2	
195,41	129,4	
195,50	130,1	
195,62	129,5	
195,66	129,6	
195,83	129,1	0,716
196,00	129,2	
196,17	128	
196,25	126,5	
196,41	127,8	
196,50	127,7	
196,62	126,2	
196,66	126,1	
196,83	126,5	
197,00	125,7	
197,16	125,3	
197,24	119,10	
197,41	115,70	
197,50	116,60	
197,62	114,50	1,853
198,25	154,9	
198,41	137,3	
198,50	133,9	
198,62	129,7	
198,66	127,4	
198,83	124,5	
199,00	119,4	
199,16	119,6	
199,25	118,6	
199,41	116,7	
199,50	118	
199,62	116,7	
199,66	116,3	
199,83	110,6	
200,00	112,4	
200,16	117	
200,25	116,3	
200,41	116,9	
200,50	113,2	
200,62	117,3	
200,66	114,6	
200,83	114,9	0,608
201,00	113,30	
201,16	112,70	
201,25	113,7	
201,41	112,4	
201,50	113,1	
201,62	113	
201,66	112,7	
201,83	108,3	
201,99	110,6	
202,16	119,4	
202,25	118	
202,41	116,2	
202,50	115,7	
202,62	114	
202,66	114,7	
202,83	113,3	0,741
203,00	112,5	
203,16	116,4	
203,25	111,5	
203,42	115	
203,50	115	
203,62	114,8	
203,66	113,9	
203,83	111,7	
203,99	111,8	
204,16	114,1	
204,25	114	
204,41	111,4	
204,50	110,8	
204,62	112,1	
204,66	111,6	
204,83	111,8	0,6233

205,00	104,4	
205,16	102,1	
205,25	103	
205,41	102,9	
205,50	107,4	
205,62	105,30	
205,66	104,20	
205,83	105,60	
205,99	101,70	
206,16	106,50	
206,25	105,60	
206,41	103,40	
206,50	105,30	
206,62	106,80	
206,66	106,60	
206,83	102,70	
207,00	102,80	
207,16	104,50	
207,25	104,20	
207,42	103,80	
207,50	103,00	
207,62	100,10	
207,66	100,20	
207,83	100,90	0,7903
208,00	99,50	
208,16	99,50	
208,25	99,50	
208,41	97,70	
208,50	98,30	
208,62	93,70	
208,66	86,20	
208,83	83,20	
209,00	81,00	
209,16	83,70	
209,25	81,70	
209,41	80,90	
209,50	79,80	
209,62	83,50	
209,66	84,60	
209,83	81,80	3,1233
210,00	81,60	
210,16	81,60	
210,25	81,50	
210,42	82,80	
210,50	85,00	
210,62	88,20	
210,66	82,90	
210,83	84,7	
211,00	84,1	
211,16	83,7	
211,25	85,6	
211,42	84,7	
211,49	90,5	
211,62	84,4	
211,66	90,7	
211,83	90,8	
212,00	89,2	
212,16	89,2	
212,25	89,5	
212,41	81,7	
212,49	81,5	
212,62	89,8	
212,66	82,1	
212,83	83,2	0,9617
213,00	83	
213,16	85,4	
213,25	84,3	
213,41	85,1	
213,50	85,5	
213,62	91,9	
213,66	90,7	
213,83	91,6	
214,00	92	
214,16	87,7	
214,25	86,5	
214,41	86,1	
214,50	88,2	
214,62	92,4	
214,66	93,6	
214,83	93,9	0,4777
215,00	94,8	
215,16	90,8	
215,25	90,4	
215,41	95,7	
215,49	94,6	
215,62	89,6	
215,66	92,7	
215,83	93,8	
216,00	93,6	
216,16	89,5	
216,25	87,5	
216,41	91,9	
216,49	91,2	
216,62	83,7	
216,66	90,2	
216,83	88	1,15
217,00	88	
217,16	89,7	
217,25	90,6	
217,41	91,8	
217,50	91,8	
217,62	83,8	
217,67	91,1	

217,83	84,3	
218,00	80,8	
218,16	92,3	
218,25	92,7	
218,41	89	
218,50	90,5	
218,62	87,5	
218,66	83,8	
218,83	81,9	2,28
219,00	80,4	
219,16	90,6	
219,25	90	
219,41	82,5	
219,50	82,7	
219,62	88,7	
219,66	82,2	
219,83	81,2	
220,00	81,7	
220,16	87,4	
226,41	81,3	5,39
226,49	79,3	
226,62	78	
226,66	80,8	
226,83	80,30	
226,99	78,40	
227,16	72,90	
227,25	73,20	
227,41	72,60	
227,50	76,20	
227,62	72,60	
227,66	76,10	
227,83	76,00	
227,99	76,60	
228,16	77,10	
228,25	75,90	
228,41	74,20	
228,49	71,60	
228,62	73,30	
228,67	79,00	
228,83	76,60	5,74
229,00	77,20	
229,16	77,20	
229,24	75,90	
229,41	76,50	
230,03	94,20	

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