ADVANCED OXIDATION PROCESSES FOR EFFLUENT TREATMENT IN PHARMACEUTICAL INDUSTRY

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Abstract. In India, the dominating source for emissions of degradable organic substances to water is the Pharmaceutical API manufacturing industry. The organic substances increase oxygen consumption in the recipient which subsequently threatens aquatic species. Improved process engineering, process closures and use of external treatments have in recent years drastically lowered the Total Dissolved Salts (TDS), Total Suspended Solids (TSS), Biological Oxygen Demand (BOD). However, the Chemical Oxygen Demand (COD) has not been reduced to the same extent, as some organic substances are more persistent and must be treated with more advanced techniques. Chemic al precipitation, which can bind large parts of the remaining COD into solid matter, making it possible to be removed from the effluent by various separation technologies, contributes to an efficient COD removal. However, the direct operating cost for the treatment is high as large amount of chemicals are used in the process, and large quantities of sludge generated.In the near future Indian Pharmaceutical Manufacturing industry will have to meet new regulatory demands on COD discharges, and will have to meet stringent discharge demands. It is therefore of interest to review alternative treatments in regards to technical, environmental and economic feasibility in the treatment of Pharmaceutical Manufacturing units wastewaters. Much interest has been shown for Advanced Oxidation Processes (AOP's), which is why these techniques have been evaluated in this thesis. The first part of the report consists of a literature review where processes with the following oxidants have been reviewed.

Keywords: Advanced Oxidation Treatment, Ozone, Wastewater Treatment, COD, Pharma Manufacturing Industry

Introduction: In India, the dominating source for emissions of degradable organic substances to water is the Pharmaceutical API Manufacturing industry. The organic substances increase oxygen consumption in the recipient which subsequently threatens environment. During recent decades, much effort has been put on lowering the Biological Oxygen Demand (BOD) in the effluents, using various biological treatments. However, some organic Solvents & Chemical substances that are discharged from the Manufacturing units are more persistent and must be treated with more advanced techniques. For that reason Chemical Oxygen Demand (COD) has become a more relevant effluent pollution parameter in the Pharmaceutical Manufacturing industry worldwide. COD is a measure of the chemical oxygen demand where an oxidizer is used to degrade the more persistent organic matter. Improved process engineering, process closures and use of external treatments have in recent years drastically lowered the TDS, TSS, BOD However, the COD emissions have not decreased to the same extent and must therefore be further reviewed. Chemical precipitation, which can bind large parts of the remaining COD into solid matter, making it possible to be removed from the effluent by various separation technologies, contributes to an efficient COD removal. However, a major draw back with this type of treatment is the generation of large quantities of sludge which is difficult to dewater (consumes a lot of energy) and generates large quantities of waste. In the near future Indian Pharmaceutical Manufacturing industry will have to meet new regulatory demands on COD discharges, and will also meet very stringent discharge demands. It is therefore of interest to review alternative treatments in regards to technical, environmental and economical feasibility in the treatment of Pharmaceutical API Manufacturing Industry wastewaters.

Objectives: The aim with this thesis is to find a potential oxidation process for COD removal from Pharmaceutical API Manufacturing unit effluents that can be used in the near future to meet the emission standards. The first objective will be to review and compare advanced oxidation technologies and methods, and based on literature information assess their technical, environmental and economical feasibility in the treatment of Pharmaceutical API Manufacturing unit effluents.

Secondly, the objectiveis to confirm the assumptions and demonstrate the actual performance of a selected technologyin laboratory on actual effluent.

Characterization of wastewater: Wastewater characterized by approved methods (i.e., pH by pH Electrode, COD by HACH COD track, BOD by HACH BOD track, TSS by Gravimatory, Millipore, and TDS by Gravimatory, watt man).Characteristics of wastewater in various stages has been characterized and tabulated in table below.

Sl.No	Parameter	Unit	HTDS effluent from Process	LTDS from Process &Utilities	Stripper Outlet/MEE feed	MEE Condensate	MBR/ Microbial Outlet	RO permeate	Polishing RO permeate
1	pH		7.75	7.91	6.58	8.52	7.96	6.91	6.84
2	COD		54105	7712	43148	28951	12318	2071	1535
3	BOD		15846	3103	10206	3128	652	2	0
4	TSS	mg/Lit	114	1862	263	24	364	0	0
5	TDS		42202	7703	43814	1981	3372	3235	32
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5	TDS		42202	7703	43814	1981	3372	3235	32

Present Method's of Waste water treatment in API Manufacturing Unit:

As shown in figure 1, in API manufacturing site, ZLD plant consists three units, such as;

(i)   HCS treatment unit
(ii)   LCS treatment unit and
(iii)   Effluents recycling unit.

The HCS treatment unit consists a solvent stripper, followed by a MEE (Multiple Effective Evaporator) and an ATFD (Agitated Thin Film Drier). The LCS were fed to Solvent stripper, where mixed solvents were stripped and collected in top distillate collection tank. Stripper processed effluent collected from stripper column bottom fed to MEE, where maximum liquid extracted and condensate collected to condensate collection tank. The concentrate collected form MEEfed to ATFD, and condensate generated during ATFD operations were collected to condensate collection tank and salts generated was disposed to TSDF (Transport Storage Disposal Facility).

The condensates from condensate collection tanks were transferred to Low concentration wastewater collection tanks for further treatment.

system which removes suspended solids to zero in permeate. The tanks and setters bottom drains were collected in sludge collection tank and which was fed to sludge decanting system. The sludge generated during this process was disposed to TSDF. The permeate collected from MBR system fed to RO system which filters the wastewater through semipermeable membrane. The permeate generated from RO system fed to Polishing RO, where wastewater polished to portable water quality. Polished water was recycled to Utilities for use and rejects generated in the process was sent to MEE for

unit comprises a wastewater equalization system, followed by a biological system Sequential Batch Reactor (SBR) and a Membrane Bioreactor (MBR). The third unit was a wastewater recycling unit where semipermeable(Reverse Osmosis) membranes used to filter the wastewater to recycle.

Wastewater flow and treatment in experimental ZLD Effluents generated from various sources has been collected in HCS and LCS collection tanks. Wastewater collected in HCS collection tanks Effluents collected in Low concentration streams collection tanks were fed to Equalization cum neutralization system where all effluents were equalized to uniformed and neutralized to required pH (6.5 to 8.5). After

neutralization and equalization process, effluents fed to SBR which is a fill and draw activated sludge process and where microbial cells reduces the Organic load. SBR processed wastewater was passed through Decant tank followed by Lamella clarifier to remove settable solids. The overflow of Lamella clarifier   was   fed   to   MBR

treatment. Effluent flow quantity was followed as per system design. The entire system and individual units performance was investigated with the help of physical, chemical and biological parameters in various intervals (i.e., end of the day 1, 2, 3, 4, 5... and 30).Values were considered after stabilizing the system.

Effluent Characteristics and Hydraulic Loads :
Characteristics of effluents in various stages of plant operations are presented in table 4.1.1. Loads of raw effluents fed to the system was within the designed specifications. Hydraulic loads fed to the various

system were presented in figure 1. Forease of discussion, henceforth, loads of all parameters, viz.,COD, BOD, TDS and TSS are presented in terms of **kilograms per day** (KPD) based on average volumes of fed to individual systems.

Performance of HCS treatment unit: As shown in fig.1 and 2, a huge reduction in loads were achieved in HCS treatment system. 890 KPD of COD reduced in stripper alone out of 2184 KPD, also in MEE system, it was 1966 KPD out of 1294. As shown in fig. 2, a significant quantity of TDS was reduced in MEE (i.e., 1629.6 KPD, out of1705.1 KPD).The BOD also reduced in the quantity of244 and281.2 KPD (out of 640.4 KPD) in Stripper and MEE respectively. However there is an increase of TSS in stripper outlet. It was due to formation of precipitates during initial heating process of effluents

Performance of LCS treatment unit: The LCS system consists SBR and MBR, where biological operations are made possible to oxidize Organic matter and remaining organic matter removed through MBR respectively .As sown in fig. 1 and 2, there was a reduction of 168.7 KPD of BOD in SBR, where it was 33.7 KPD in MBR. The total BOD treated wastewater in industrial premises after RO polishing of MBR outlets.

quantity reduced to 8.2 KPD from 210.6 KPD in LCS treatment system. SBR is an activated sludge process for treatment of waste water where separate tanks are not required for aeration and sedimentation. This type of systems are typically suitable for small scale processes. In the present investigation, TSS quantity was reduced to "ZERO" after LCS treatment unit, where 78 and 23.4 KPD of TSS reduced in SBR and MBR systems correspondingly. Pharmaceutical wastewater treatment studied by a membrane bioreactor(MBR) process in southern Taiwan, the investigation reported that there is no suspended solids in outlet of MBR. However, there was no mush significant reduction in TDS as LCS treatments unit was not designed for reduction of TDS loads. Although in the present investigation, the designed LCS treatment unit made comfort to effluent recycle unit. In similar, a laboratory study conducted with MBR system in China with wool mill wastewater shown excellent effluent quality which was useful for recycle. An investigation made with MBRpost treatment of secondary wastewater contains 80% textile and 20% of municipal wastewater to recycle
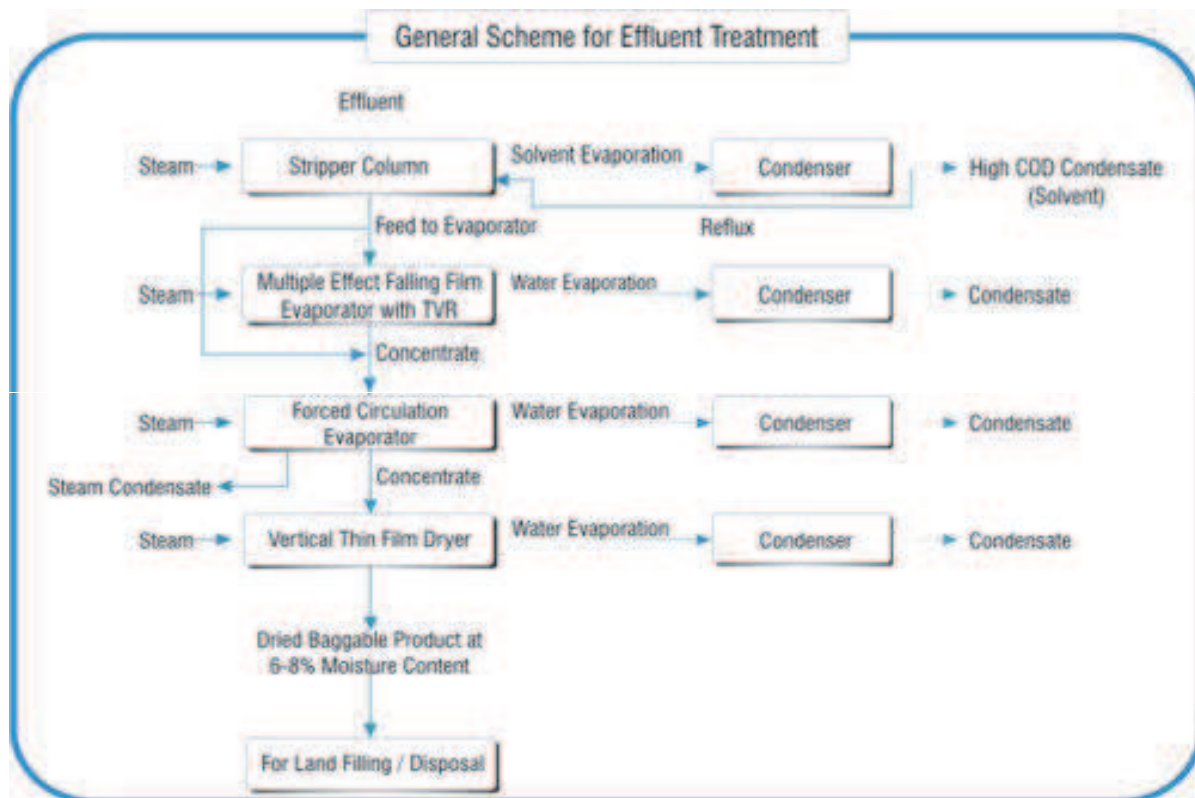
Performance of Effluents recycling unit: The quantity of TDS present in LCS treatment unit outlet was reduced to 1.3 KPD after polishing RO treatment with quality of 32 ppm. The total quantity of TDS fed

to the primary RO system was 207.8 KPD and it was reduced to15.0 KPD in permeate. As revealed in table 1, the recycle water generated after polishing RO contained COD of 1532 ppm and TDS of 32 ppm, and

other parameters (BOD and TSS) were "ZERO ppm" in quality. The effluent recycling unit was in key role of making effluents to portable quality. However the pressure driven RO system cannot be used to feed raw water asit was designed for tertiary treatment of effluents to generate recycle water.

The system designed for recycle of effluents has shown marveloutcome in generation of high quality permeate. The overall loads reduction was 99.2 percent in TDS, 80% percent in COD and 100 percent in both TSS& BOD,. The studies relieving that the designed ZLD unit can be used effectively to treat TDS, TSS & BOD but there is still a gap in reducing COD as per the statutory needs. API manufacturing unit effluents, which helps to meet statutory requirements and reduce concerns on ground water depletion.

Oxidation Process

In recent years, advanced oxidation processes (AOP's) have been widely developed as promising and efficient methods for the treatment of water and wastewater containing toxic and recalcitrant organic pollutants. Compared with other processes, AOP's offers several particular advantages such as

High efficiency

Easy operation

Less production of residuals and toxic by- products at the end of treatment.

The term oxidation refers to the transfer of one or more electrons from a reductant (electrondonor) to an oxidant (electron acceptor), which leads to a change in the chemical composition of both the reductant and oxidant (Kommineni et al., 2008). In the past, chemical oxidation have been used to reduce concentrations of residual organics, remove ammonia, control odors, and for disinfection purposes. Today, chemical oxidation processes are recommended for improving the treatability of refractory organic compounds, to reduce the inhibitory effects of certain compounds to microbial growth and to eliminate the toxic compounds that might affect the microbial growth and aquatic flora in the recipient. (Eddy and Metcalf, 2003)

Recently, a series of new oxidation methods for wastewater purification called Advanced Oxidation Processes (AOP), have received an increased attention as tertiary treatments for Pharmaceutical effluents. These types of processes are utilizing combinations of several different oxidizers, and are based on formation of hydroxide radicals (OH*). The radicals are then used to reduce/destroy dissolved organic compounds, aromatic compounds, toxic compounds, detergents, pesticides and many more. (Munter, 2001)

The AOP concept was first introduced by Glaze et al. (1987), and defined as:*"Near ambient temperature and pressure water treatment processes which involve the generation of hydroxyl radicals (OH*) in sufficient quantity to affect water purification".*

These type of water treatments are sometimes called the *"water treatment processes of the 21st century"*, because if applied in a right place, contaminants concentrations can be significantly lowered (Munter, 2001). Many systems are qualified under the broad definition of AOP, and there are many technologies available to produce OH* radicals in the aqueous phase.

Reaction Mechanisms: During oxidation, spices with one unpaired electron, namely radicals, are formed. The radicals tend to be very reactive and are followed by further oxidation reactions between the radical and other organic or inorganic reactants, until thermodynamically stable products are formed. Ideally, the end-products of complete oxidation are carbon dioxide (CO_2) and water (H_2O), Reaction below. However, this might not always be feasible, because very large amounts of chemicals and energy are required. (Kommineni et al., 2008, Bijan and Mohseni, 2005)

[1] **OH* + Contaminants → Intermediates →Co_2 + H_2O +End product:** AOPs can generally be divided under two different categories; photo-chemical and non photochemical processes. In the latter one OH* radical formation is initiated when oxidizing agents such as O_3, H_2O_2 are applied to the wastewater. Photo-chemical processes are based on same type of oxidizers, but in a combination with UV irradiation. Some systems are also used in a combination with catalysts and pH adjustments to proceed or increase the rate of reaction. (Goi,2005)

Once generated, the OH* radical can in principle attack all organic and inorganic compounds, and depending on the nature of the substrate, three types of attacks are possible (Munter, 2001, Siitonen, 2007):

1. The OH* radical can steal a hydrogen atom from the pollutant (alkenes, alcohols etc.).

2. The OH* radical can add itself to the pollutant (aromatics, olefins, etc.)

3. The OH* radical can transfer its unpaired electron to other substrates (carbonates, bicarbonates etc.).

Alkenes are treated most efficiently since the double bond is very susceptible to OH* radical attack. Saturated molecules are harder to oxidize, and will thus react at much slower rates, because there is no simple chemical pathway for the mineralization to occur (Gogate andPandit, 2004a). One of many possible reaction pathways is presented in Reaction [2-5], where Rrepresents the carbon chain in the pollutant molecule. (Seneviratne, 2007)

[2] $\qquad H_2R + OH^* → H_2O +HR$

[3] $\qquad HR^* + O_2 → HRO^*_2$
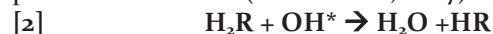
[4]   HRO*$_2$→ R + HO*$_2$
           Decomposition A
[5]   HRO*$_2$→ RO + OH*
   **Decomposition B**
The OH* radical is very unstable and will self-terminate in a short time period, see Reaction [6].
[6]   OH* + H$_2$O* → O$_2$ + H$_2$O
           Termination
Of the many properties that can be used to characterize redox reactions, the Electrochemical Oxidation Potential (EOP) is most commonly used, and is presented forsome common oxidizing agents in Table 5.1 . The higher EOP, the better oxidizing characteristics and apart from fluorine ,the OH* radical is one of the most active oxidants known, with an EOP of 2.80. (Eddy and Metcalf, 2003)

Ozone (O$_3$): The use of **O$_3$** as a chemical oxidant has been suggested in the latest literature as a potential technique for COD, AOX and colour removal from Pharmaceutical effluents. O3 is a toxic gas with characteristic irritating and pungent odor. The molecule is relatively polar (dipole moment of 0.5337 D), has a specific weight of 2.1 kg/m3, and a boiling point of -111.5°C. (Siitonen, 2007)
When **O$_3$** decomposes in water, a complex chain of reactions occur that result in formation of OH* and superoxide (O2 *) radicals according to Reaction [as below] (Seneviratne, 2007). Hoigné et al. (1985) as cited in Hulse (2002), reported that for every decomposed O3 molecule, 0.65 molecule of OH* is formed.

O$_3$+ OH- ---> O$_2$*$^-$ +HO$_2$
O$_3$ + O$_2$*$^-$ ---> O$_3$*$^-$ + O$_2$
O$_3$*$^-$ ----> HO$_3$*$^-$
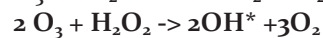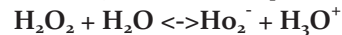H O$_3$*$^-$ ----> OH* +O$_3$
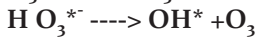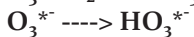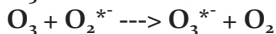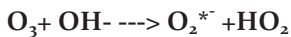
Direct oxidation with O3 on the other hand, is selective and restricted to unsaturated aromatic and aliphatic compounds and to particular functional groups with high electron density (N, P, O or S). All types of reactions may occur simultaneously, but depending on conditions and composition of the wastewater, one or another reaction pathway will dominate.

Peroxone (H$_2$O$_2$/O$_3$): O$_3$ can be combined with H$_2$O$_2$ to enhance the transformation of O$_3$ to OH* in aqueous phase and the treatment is then called peroxone. H$_2$O$_2$ has been used in industrial wastewater treatment for destruction of formaldehyde, phenols, detoxification of cyanide, hypochlorite and for removal of sulphides. (Gogate and Pandit, 2004a)
H$_2$O$_2$ is a weak acid that is fed from an aqueous solution, which in combination with water partially dissociates into hydroxide anions (HO2-), see Reaction [below]. H$_2$O$_2$ is a powerful oxidizer with an EOP of 1.78, a boiling point of 150.2°C and is totally miscible with water (USPeroxide,2008). H$_2$O$_2$ in itself

does not react especially fast with O3, HO2 - ions on the other hand, react much faster and form OH* radicals, see Reaction [below]
H$_2$O$_2$ + H$_2$O <->Ho$_2$$^-$ + H$_3$O$^+$
O$_3$ + Ho$_2$$^-$ ->OH* +O$_2$$^-$ + O$_2$
2 O$_3$ + H$_2$O$_2$ -> 2OH* +3O$_2$
It can be noticed that that two O$_3$ molecules produce two OH* radicals, which means that a larger quantity of radicals are produced for the same concentration of oxidant in the presence of H$_2$O$_2$ compared to O$_3$ used alone. Oxidation with H$_2$O$_2$ alone has not been recommended in literature since the efficiency is proved to be low. Here is a combination with O$_3$ and/or UV a significantly better alternative.
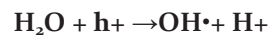
Photocatalytic Oxidation: Mechanism of oxidation of pollutant depends on generation of highly reactive free radicals and its subsequent attack on the pollutants. Rate of generation of free radicals is much faster when a catalyst is used.
The two methods of oxidation are:
Photochemical oxidation: UV + Hydrogen peroxide:
Photocatalytic oxidation: Use of solid photocatalyst such as TiO2:
Mechanism of Free radical generation: Adsorption of the pollutant molecules on the catalyst surface is the rate-controlling step
Semiconductor catalyst +hv → e$^-$ + h$^+$
H$_2$O + h+ →OH•+ H+
Pollutant (in adsorbed state) + OH•→ Intermediates
**Intermediates (also in adsorbed state) + OH• → CO$_2$ + H$_2$O**
When illuminated with light of energy higher that the band gap irradiate on TiO2 particles or films, •OH would be produced in the photocatalytic system. The generated holes (h+) and •OH are most important species for organic compounds degradation in the reaction system (Wang and Chen, 011). Typical catalysts used are Titanium dioxide, Zinc oxide, Selenium oxide, Zinc sulphide, Cadmium sulphide

Fenton´s reagent (Fe^{2+}/H$_2$O$_2$): A rather old catalytic oxidative method (first recognized in the 1960s), is the Fenton´s process, which utilizes H$_2$O$_2$ in a combination with ferrous iron (Fe^{2+}) catalyst (Sevimli, 2005). This type of treatment has been applied for detoxification, discoloration, odor removal and for destruction of non-biodegradable effluents from different sources
Iron salts such as ferrous sulphate (FeSO$_4$) or complexed iron such as Goethite (FeOOH) are used as source of Fe^{2+} (Sevimli, 2005). H2O2 reacts with Fe^{2+} to form the unstable iron-oxide-complex, also called the Fenton´s reagent, which in turn reacts to form OH* according to Reaction
Fe^{2+} +H$_2$O$_2$ -> Fe^{3+} + OH$^-$ + OH*: The produced ferric ion (Fe^{3+}) will partly act as a flocculant and react with

the water to from hydroxides, which in turn adsorb the colloidal particles by sweep coagulation and form larger flocks that easily can settle. The ferric ion will partly also react with H_2O_2 and/or O2 *- to regenerate Fe^{2+} as seen in Reaction [below]. Iron will thus be cycled between ferric and ferrous oxidation states until H_2O_2 is completely consumed

$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + O_2^{*-} + 2H^+$

$O_2^{*-} + Fe^{3+} \rightarrow Fe^{3+} + O_2$
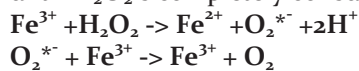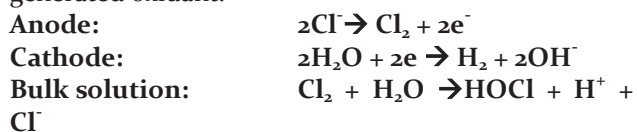
Hydrogen Peroxide + Ultraviolet Light (H_2O_2 /UV)

UV irradiation can also be combined with H_2O_2. As in O3/UV process, the oxidation occurs through either direct photolysis with H2O2 or indirect photolysis with OH* radicals. The radicals are produced when H_2O_2 is exposed for UV radiation in water according to Reaction

H_2O_2 -hv--> $2OH^*$ wave length <300 nm:

Photo-Fenton´s Process (Fe^{2+}/ H_2O_2 /UV): The Fenton´s process which was discussed earlier in this report can also be combined with UV irradiation and is then referred to as the photo-Fenton's process. This treatment has shown a great potential for mineralization of recalcitrant organic compounds and is based on similar reaction mechanisms as explained in Section 0, but in presence of UV light. As a consequence, a higher and faster OH* production rate is accomplished in comparison to the conventional Fenton´s process, see Reaction [below]. (Catalkaya and Kargi, 2007)

$Fe^{3+} + H_2o \rightarrow hv \rightarrow Fe^{2+} + H^+ + OH$: As mentioned earlier, H2O2 has a low extinction coefficient below 300 nm. In contrast, Fenton´s reagent has a relatively large extinction coefficient, allowing mineralization even by visible light (up to 600 nm). (Munter, 2001).

Electrochemical treatment: In the electrochemical process, the pollutants are destroyed by either a direct or an indirect oxidation process. In a direct anodic oxidation process, the pollutants are first adsorbed on the anode surface and then destroyed by the anodic electron-transfer reaction. Organic compounds are destroyed by application of the required potential. In an indirect oxidation process, strong oxidants such as hypochlorite/chlorine, ozone, and hydrogen peroxide are electrochemically generated. The pollutants are then destroyed in the bulk solution by an oxidation reaction of the generated oxidant.

Anode: $2Cl^- \rightarrow Cl_2 + 2e^-$
Cathode: $2H_2O + 2e \rightarrow H_2 + 2OH^-$
Bulk solution: $Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$

$HOCl \rightarrow H^+ + OCl$: All of the oxidants are generated in situ and are utilized immediately. Among the oxidants, generation of hypochlorite is cheaper, and most of the effluents have a certain amount of chloride. The electrochemical treatment involves the application of an electrical current to the effluent to convert chloride to chlorine/hypochlorite. The chlorine/hypochlorite oxidizes the pollutants and is then reduced to a chloride ion.

Equipment and Reactor Designs: A number of devices can be used to transfer oxidants into aqueous solutions, and often relatively simple reactor designs are employed. It is however not always easy to determine which type of system that yields the most efficient oxidation for a given pollutants. Some general suggestions and considerations in process design are presented in following section.

Ozone Systems: Ozone is typically produced electrically on-site from either air or pure liquid oxygen due to its very short half-time ($\approx$10min) (Kreetachat et al., 2007, Esplugas et al., 2002). The latter one is often preferred due to higher costs associated with dehumidification of air. In addition, higher quantities of O3 can be produced from pure oxygen (14% O2 by weight compared to 2% O2 by weight), and less energy is needed relative to compressed air. (Kommineni et al., 2008) Generated O3 gas is fed from the base of the ozone contact reactor, with help of gas diffusers or injectors, see Figure 5 (Kreetachat et al., 2007). The gas is allowed to diffuse through the reactor, which often is of a plug flow type or a continuously stirred one, until it reacts or escapes through the top (Kommineni et al., 2008). A major disadvantage of ozone diffusers is that they are easily clogged with suspended solids and precipitates, which is why O3 often is injected with side stream injectors. Side injections facilitate higher mixing efficiency, but can at same time lower the contact times, resulting in poor gas diffusion. The transfer efficiency of O3 in aqueous phase is generally increased with smaller bubble sizes (bigger interfacial area) and longer contact times between O3 and the effluent. Continuous ozonation is needed due to the short half-life of O3, and static mixers are sometimes incorporated into the reactor to increase the transfer efficiencies of O3 in the liquid (Gogate and Pandit, 2004a). An off-gas decomposer is placed above the contact reactor to collect and thermally destruct excess O3 into O2 with use of a catalyst. Automatic control and monitoring systems are installed to re gulate feed rates, pH and other parameters. (Kommineni et al., 2008)

Ozone system with oxygen storage tank and thermal off-gas destructor.
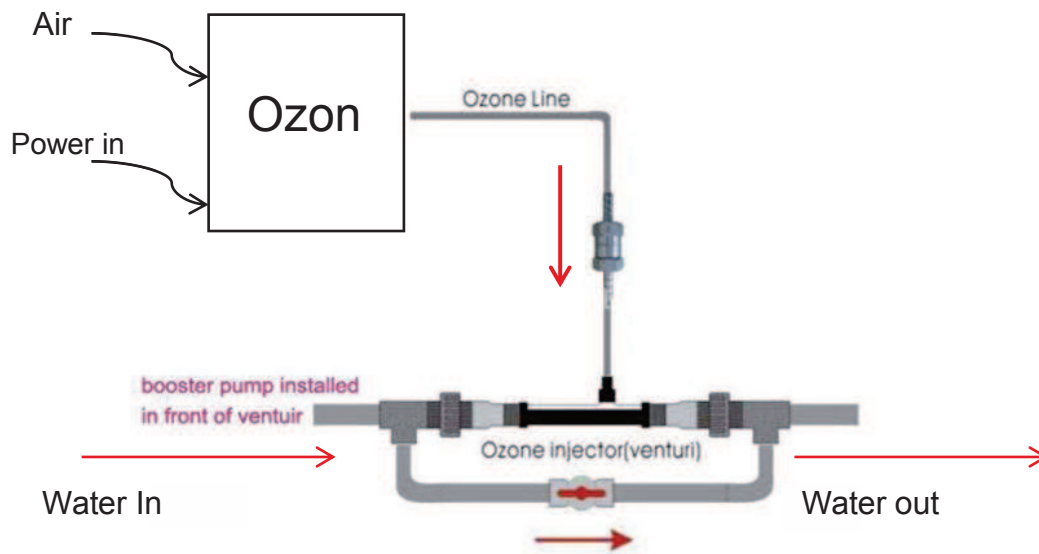
Peroxone Systems: H_2O_2 is a relatively low-priced and readily available chemical, and produced by oxidation of alkylhydroanthraquinones or by electrolysis of ammonium bisulphate, which typically consumesaround 7.7 kWh per kg H_2O_2 produced (Munter, 2001). For wastewater treatment 30-50% H_2O_2solutions are recommended, higher concentrations (70%) will increase the reaction rates, butare not very safe because they can produce detonable mixtures during storage (Gogate andPandit, 2004a). Similar process design and equipment is used in peroxone systems as for O_3systems. It is much easier to dissolve and mix in H_2O_2 into the wastewater than O_3. However, thestability of H_2O_2 in the aqueous phase is very low, and the introduction of H_2O_2 into the systemmust therefore be carefully evaluated. The most traditional way to inject the oxidants is with asingle reactor module. H_2O_2 and O_3 are then injected in a single point through a diffuser andallowed to bubble through the contactor at atmospheric pressure. (Buratovich-Collins andBowman, 2000)

Photo-chemical Systems: The reactor used for UV radiation is typically of a plug flow, and can either be an open channel ora closed vessel. Different light sources can be used to produce UV irradiation; Low pressure mercury vapour lamps (LP-UV), Medium pressure mercury vapor lamps (MP-UV) and Pulsed UV xenon arc lamps (P-UV). (Goi, 2005)The difference among the different lamps lies in the output spectra. The LP-UV and MP-UV lamps produce a series of line outputs, while P-UV lamps produce continuous output spectra. The LP-UV lamps are the most electrically efficient, but MP-UV lamps have recently gained lots of attention because

of their greater potential for direct photolysis and wider wavelength spectrum. The P-UV lamps have not been studied as extensively due to their short life times. The lamps are often equipped with quarts sleeves and cleaning systems in case of highconcentrations of fouling agents. (Kommineni et al., 2008)The UV lamps are arranged in different ways in the reactor, depending on scale of waterapplication. A system designed for large scale wastewater applications (water flows over 1000m3/h), would typically consist of one single reactor vessel equipped with several UV lampsarranged perpendicularly to the wastewater flow. The reaction vesselis filled with wastewater between the reactor walls and lamp system. The more wastewater tobe treated, the more lamps are used. Generally, no cooling system is needed for systemshandling large volumes of effluent, since heat transfers from the lamps are very low (<1°C).(Kommineni et al., 2008)

Photo-catalytic Systems: The photo catalytic process with TiO_2 can be carried out in a slurry reactor with suspended TiO_2particles, or in a supported catalytic reactor. In the suspended form, very fine particles (<1μm) of solid TiO_2 are dispersed with stirrers into the liquid phase. The formed slurry is then directly or indirectly irradiated with UV light, and the reactor is often aerated with O_2 to hinder electron/hole recombination. The suspended form is not recommended for large-scale applications due to opacity problems and fouling of the equipment. In addition, catalyst particleshave to be separated from the treated liquor after oxidation, which introduces high operatingcosts. (Gogate and Pandit, 2004a).

A more common design is the supported photo catalyst, where a carrier material is wash coated with TiO_2 catalyst particles. The biggest advantages with the supported catalyst system are the crystalline

configuration and stability of the TiO2 film in the reacting media, and that no advanced catalyst separation is needed after the treatment. However, this type of system requires a larger reactor volume, can be very sensitive to erosion, and mass transfer problem scan sometimes limit the catalyst performance. (Gogate and Pandit, 2004a)UV lamps are placed inside the reactor in various configurations, and the liquid to be purified is illuminated with light at wavelengths just below 400 nm. An efficient reactor should be able to attain a uniform irradiation of the entire active area, which for large scale designs can be a major problem because of high pollutant concentrations and occurrence of high turbidity. The TiO2catalyst can often be recovered and reutilized for many cycles after treatment. (Legrini et al.,1993, Gogate and Pandit, 2004a)

Interfering Compounds: It is in most cases very hard to obtain a complete mineralization of contaminants, i.e. an oxidation into CO_2 and H_2O. The main reason for this is that there are many interfering compounds present in the wastewater that act as radical scavengers, hence blocking there action pathways and lowering the reaction rates. Thus, very high amounts of chemical oxidants are needed to obtain concentrations at the treatment goals. Industrial wastewater will generally contain different types of salts which are present in ionized forms. The OH* radical reactions are unselective and presence of organic or inorganic content other than pollutants of concern will affect the degradation processes negatively. Compounds like nitrates (NO_3^-), nitrites(NO_2^-) and chlorides (Cl^-) will hinder the OH*radical formation during UV oxidation because they adsorb light at similar wavelengths (200-300 nm). Presence of scaling agents such as ferrous(Fe^{2+}) and magnesium (Mg^{2+}) salts may result in fouling of UV lamps. Phosphates (PO_4-3),carbonates (CO_3^{2-}), bicarbonates (HCO_3^-) and sulphates (SO_4^{2-}) in the source waters have the potential to act as scavengers, but the reactions with OH* radicals are considered very slow and can therefore be neglected for most systems, see Reaction. (Munter, 2001).

$OH* + HCO_3^- \rightarrow OH^- + HCO_3*$ **Inhibitor:**
$OH* + CO_3^{2-} \rightarrow OH^- + CO*_3^-$ **Inhibitor:**

Advantages and Disadvantages of Different AOPs:
Advantages and disadvantages of presented oxidation processes are summarized in Table 7.

Table 7: Advantages and disadvantages of different oxidation processes.

Oxidation Process	Advantages	Disadvantages
O3	Selective at pH≤4 towards unsaturated aromatic and aliphatic compounds, and functional groups with high electron density · Supplemental disinfectant	O3 must be produced electrically on-site due to its very short half-time (»10min) Steady state concentration of O3 in water is often much lower than the saturation concentration · O3 solubility sensitive for temperature change · Off-gas treatment system for O3 destruction needed · Energy and chemical intensive process
H2O2/O3	A more powerful system than H2O2 or O3.used alone . Reduced operating costs as lower dosage of O3 is needed (compared to O3 used alone) · H2O2 is totally miscible with water · Supplemental disinfectant	O3 must be produced electrically on-site due to its very short half-time (10min).Steady state concentration of O3 in water is often much lower than the saturation concentration .O3 solubility sensitive for temperature change .H2O2 can produce detonable mixtures at very high concentrations .H2O2 itself can start act as a radical scavenger at very high concentrations .Post-treatment of residual H2O2 might be needed .Off-gas treatment system for O3 destruction needed
Fenton´s process	Energy efficient since it does not require any electricity beyond the feed pumps and mixers .No off-gas treatment needed, since no gaseous emissions are formed	Large buffer tanks with H2O2, FeSO4, and H2SO4 needed An iron extraction system required to remove residual iron from the treated water. Pre- and post pH adjustments required because process is operated at low pH · Fenton´s reagent is very corrosive and reactor must be coated with an acid-resistant material

O3/UV	More powerful system than O3 and UV used alone Supplemental disinfectant	O3 must be produced electrically on-site due to its very short half-time (10min).Steady state concentration of O3 in water is often much lower than the saturation concentration · O3 solubility sensitive for temperature change · Off-gas treatment system for O3 destruction needed · UV light penetration negatively affected by turbidity · System sensitive to NO3 -, NO2 - and Cl- because they adsorb light in the same wavelength · Fe2+ and Mg2+ presence may result in fouling of UV equipment · Lamp failures can potentially contaminate treated water with Hg · Very energy and chemical intensive process
H2O2/UV	More powerful system than H2O2 and UV used alone H2O2 is totally miscible with water No off-gas treatment needed since no gaseous emissions are formed · Supplemental disinfectant	H2O2 can produce detonable mixtures at very high concentrations.H2O2 itself can start act as a radical scavenger at very high concentrations · Post-treatment of residual H2O2 might be needed · UV light penetration negatively affected by turbidity · Sensitive to NO3 -, NO2 - and Cl- because they adsorb light in the same wavelength · Fe2+ and Mg2+ presence may result in fouling of UV equipment · Lamp failures can potentially contaminate treated water with Hg
Photo-Fenton´s process	A higher and faster OH* production rate accomplished in comparison to the conventional Fenton´s process Fenton´s reagent has a relatively large extinction coefficient, allowing mineralization even by visible light (up to 600 nm) · No off-gas treatment needed since no gaseous emissions are formed	Large buffer tanks with H2O2, FeSO4, and H2SO4 needed. An iron extraction system required to remove residual iron from the treated water Pre- and post pH adjustments required because process is operated at low pH Fenton´s reagent is very corrosive and reactor must be coated with an acid-resistant material · UV light penetration negatively affected by turbidity · Sensitive to NO3 -, NO2 - and Cl- because they adsorb light in the same wavelength · Fe2+ and Mg2+ presence may result in fouling of UV equipment · Lamp failures can potentially contaminate treated water with Hg
TiO2/UV	More powerful system than UV used alone Can be executed at higher wavelengths (400nm) compared to other UV processes, possibility to use sunlight or near UV light · No off-gas treatment needed since no gaseous emissions are formed · Catalyst can often be recovered and reutilized for many cycles after treatment	Catalyst sensitive for fouling .Slow reaction rate If suspended TiO2 particles are used, catalyst separation step is needed after treatment · If supported TiO2 is used, system can be very sensitive to erosion · Potential for quick TiO2 activity loss, requiring on-site storage of catalyst · Aeration is needed to prevent electron-hole recombination · Lamp failures can potentially contaminate treated water with Hg

Degradation Principles and By-products: The degradation of contaminants can be divided into four categories depending on extent of oxidation:

1. Primary degradation - A structural change in parent compound
2. Acceptable degradation - Degradation into intermediates with low toxicity
3. Complete degradation - Degradation into CO_2 and H_2O
4. Unacceptable degradation - Degradation resulting in increased toxicity

(Eddy and Metcalf, 2003)

Technologies Assessment and Comparison: Each AOP is first evaluated in terms of reliability, flexibility, stability and energy efficiency, and then a discussion is brought up regarding the placement of the AOP technology in the wastewater treatment plant.

Mechanical Reliability: Processes that have a simple construction and contain a limited number of moving parts are considered more mechanically reliably because they probably will require less regular in section and maintenance. The O3 and the H2O2/O3 processes receive a high mechanical rating because of their relatively simple system configuration. However, inspection might still be required, especially for ozone generators and diffusers. Photo-chemical processes with O3 and/or

H_2O_2 receive a medium rating as they contain a number of specialty parts (UV lamps, quartz sleeves etc.) which require periodic inspection and replacement to prevent fouling and Hg leakage (UV lamp failure). The Fenton´s process and the TiO_2/UV process get a low score in terms of mechanical reliability, since they need to be carried out under specifically controlled pH conditions and stirring. The Fenton´s process must be carried out in four treatment steps, which means that several pumps and stirrers have to be incorporated. Close monitoring and control is especially important for theTiO_2/UV system due to potential for rapid activity loss.

Flexibility: Flexibility is referred to as the quality of a system to be adaptable to handle large fluctuations in influent wastewater flow rate and load. This is a very important property because the load will most likely change due to variations in production rate. A technology that is flexible should beable to handle fluctuations with no major impact on treatment efficiency. Systems like O_3, H_2O_2/O_3, O_3/UV, H_2O_2/UV, will receive a high rating in terms of flexibility as the dosages of chemicals and/or UV light can easily be adapted and adjusted to respond to changing flow rate and load. The UV and/or chemical dosages can also be varied for the TiO_2/UV and the Fenton´s processes and reactions are most likely carried out in semi-batch reactors that can handle large fluctuations. Yet a medium rating is suggested, because more advanced adjustments are needed. In the Fenton´s process, all four process steps must be adapted to cope with changes in the flow rate. In the TiO_2/UV process, the amount of catalyst might be in adequate for a certain flow rate. This means that more catalyst might have to be incorporated into the reactor, which likely only can be done during process stop.

Stability: Some systems will require some kind of pre and/or post treatment for adjustment and control of temperature, alkalinity, interferences and by-products. A system that has a low stability and a high need for modifications in the process will receive a low rating and a system that has a good ability to alter such parameters itself will receive a high rating.

For example, the Fenton´s process will most likely require pre- and post-adjustment of pH since the process is carried out at low pH. Moreover, a post-treatment for extraction of residual iron might be mandatory in order to prevent the release of iron to the recipient. Supported TiO_2systems may require pre-treatment of effluents containing high concentrations of inorganic constituents to avoid fouling of active sites in catalyst. A catalyst separation unit must also often be included when TiO_2 is used in suspended form to remove TiO_2 particles from the treated wastewater. The TiO_2/UV and the Fenton´s process will therefore receive a low rating. Processes that are utilizing H_2O_2 will receive a medium rating, because presence of excess H_2O_2in the treated wastewater might sometimes require post-treatment. O_3 based systems (O_3,H_2O_2/O_3, O_3/UV) will receive a medium rating as they ordinarily will require an air permit for O_3emissions and an off-gas treatment system to collect and destruct excess O_3 into O_2. Automatic control and monitoring systems are also necessary to regulate temperature and thus the solubility of O_3 in aqueous phase.

Energy Efficiency: Energy efficiency is generally rated low for systems that are utilizing O_3 in combination with UV, because of the high amount of electricity needed in ozone generator(s) and lamps. In addition, the low solubility of O_3 in water will decrease the efficiency since more gas has to be produced on-site and bubbled though the reactor. Systems that are using O_3 or UV in combination with other oxidants (TiO_2 or H_2O_2) do not require same amount of electricity and are therefore rated medium in terms of energy efficiency. Forexample, the H_2O_2/UV system will require electricity for the UV lamps, but H_2O_2 is generally not limited by mass transfer limitations. The Fenton´s process is the most energy efficient AOP since it does not require any electricity beyond the feed pumps.

Overview of Rating: In Table 6.1 , the ratings for each oxidation process in terms of mechanical reliability, flexibility, stability and energy efficiency are summarized.
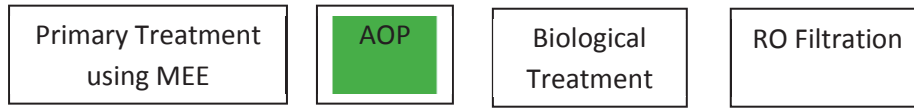
Table 6.1 : Overview of rating for different oxidation processes in terms of mechanical reliability, flexibility, stability, and energy efficiency.

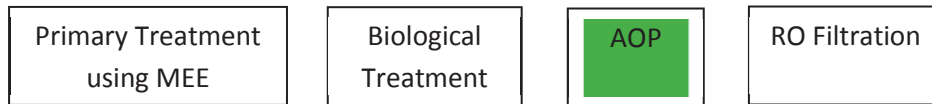| Sl. No	Oxidation Process	Mechanical Reliability	Flexibility	Stability	Energy Efficiency
1	O3	High	High	Medium	Low
2	H2O2/O3	High	High	Medium	Medium
3	O3/UV	Medium	High	Medium	Low
4	H2O2/UV	Medium	High	Medium	Medium
5	TiO2/UV	Low	Medium	Low	Medium
6	Fenton´s process	Low	Medium	Low	High

Placement of AOP in the Treatment Plant: It can be discussed about where the optimal placement of the oxidation technology is in the wastewater treatment plant. Different positions in the plant will result in different degrees of effectiveness, costs and maintenance, because the chemistry and pollutant concentrations will vary throughout the treatment line. There are generally two potential locations mentioned in the literature; before (1) alternatively after a biological treatment (2), see Figure 12.

Option 1

| Primary Treatment using MEE | AOP | Biological Treatment | RO Filtration |

Option 2

| Primary Treatment using MEE | Biological Treatment | AOP | RO Filtration |

Option 1 is an appropriate method to enhance biodegradability. Wastewater containing toxic and inhibitory compounds can be pre-treated to generate biodegradable intermediates, which then are treated biologically. However, due to the high volume of discharged effluent, very large reactors would be required, along with significant amount of expensive chemicals.

Option 2 seems like a more promising option because the treatment plant would be very flexible to variations in wastewater quality output, which can arise from production problems orchange of raw material. Costs are minimized because the wastewater has already been biologically purified to the maximum possible extent, and much lower oxidant dosages would be needed. However, COD removal will simultaneously increase the BOD level in the discharged effluent, but the effect could potentially be minimized with recirculation of effluent to biological treatment or installation of a subsequent RO Filtration stage. If O_3 is used in the AOP step, the O_2gas that is produced when excess O_3 is thermally destructed in the off-gas decomposer couldpotentially directly be supplied to the oxygen requiring biological system.

Table 5.1 : Electrochemical Oxidation Potential (EOP) for some common oxidizing agents. (Eddy and Metcalf, 2003)

Sl. No	Oxidizer	EOP [eV]
1	Fluorine (F_2)	3.06
2	Hydroxyl radicals (OH*)	2.80
3	Ozone (O_3)	2.08
4	Hydrogen peroxide (H_2O_2)	1.78
5	Chlorine (Cl_2)	1.36
6	Chlorine dioxide (ClO_2)	1.27
7	Oxygen (O_2)	1.23

Conclusion: The oxidation technology, and especially treatment with ozone, offers several advantages in comparison to chemical treatment used today. For example, pollutants are destructed rather than concentrated or transferred into a different phase, which means that COD, colour and toxicity is decreased without the need to handle large amounts of sludge. The processes are often very flexible concerning water quality variations and the possibility to control the quality contents of the residual wastewater is high.

The experimental results indicate that treatment with ozone is an efficient method for elimination of COD from Pharmaceutical API Manufacturing unit wastewaters. A relatively high COD reduction 41 % to 53% was achieved for all wastewaters with an applied ozone dosage of 0.2g O_3/L, without an appreciable impact on other parameters such as pH TSS & TDS. There are indications that the nature of the wastewater has an impact on the COD removal efficiency is easier to oxidize. The combination with hydrogen peroxide did not show any further COD reduction compared to ozone treatment alone, thus confirming the results Ko et al. showed in their study in 2009.

However, the total cost is very high in comparison to chemical treatment(precipitation/flocculation) even though there are indications of cases when treatment with ozone can be profitable (e.g. if the cost for sludge handling increases in the future, price for chemicals increases and electricity price decreases). There are also some uncertainties regardingthe system and there is no clear evidence that toxic by-products are not formed. More research must be done and more full-scale installations must be reported before the Pharmaceutical API Manufacturing industry is willing to invest in oxidation technology. An interesting approach is the attempt to develop an even better designed treatment option as oxidation and subsequent biofiltration as nearly "one" tertiary treatment unit.

Recommendations: Much research has been done within the field of advanced oxidation processes and

there is no doubt that these methods work and are efficient for COD elimination in Pharmaceutical API Manufacturing Unit wastewaters. It is more a question about how much people are willing to pay for the technique. However, there is still no one who has managed to characterize the water matrix completely inorder to determine whether hazardous by-products are formed or not. This thesis provides a good overview of the different effluent parameters and how they are changing throughout the oxidative treatment, but a survey on molecular level would be required in the future for a complete characterization.

It would also be of interest to investigate how the TSS concentration of a wastewater is affecting the COD reduction for a specific ozone dosage, as suspended particles probably will influence on the treatment efficiency. This aspect is important to consider for a full scale implementation in order to make a complete dimensioning and to know if pre- or post-clarification is required in the treatment plant. However, in able to investigate that, the test equipment must be developed to manage high concentration of solids in pumps and injectors without clogging the system.

An increase in turbidity is seen for all wastewaters tested in this study at ozone dosages above 0.15 g O_3/L, and even if no obvious particles are seen in the final effluent; the filter paper is clogged easily and fast in the TSS analysis. This observation should be further examined because it may indicate that ozone can be used in the future to improve the flocculation ability of wastewaters.

The wastewater quality is unique for every unit in the world as there are variations in product lines, design and legislation. In this study only two types of wastewaters are tested. It would be preferable to test even more wastewaters in order to find out how ozone is reacting with different types of water. For example, a CETP wastewater would be suitable for such a study.

One part of the economic study in this thesis is based on a subsequent biofiltration stage al though no experimental trials are conducted. Here, it is desired to follow up with testing inorder to find out how large portion of the BOD and COD actually is removed in such step. Finally, it is of interest to test the actual performance of other AOPs as well, and not only O_3 and O_3 in combination with H_2O_2 as in this study.

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