UV disinfection and UV/H₂O₂ oxidation: by-product formation and control
UV disinfection and UV/H$_2$O$_2$ oxidation: by-product formation and control
Summary

Due to increased regulations about the drinking water quality and better understanding of the benefits of UV technology in water treatment, a growing number of utilities consider the use of UV disinfection and/ or UV-based oxidation processes. Although knowledge about practical application of UV technology is already considerable, additional information is needed about possible side effects of this technology and how these side effects could be eliminated. To that end, a literature study was conducted establishing the state of knowledge about by-product formation during UV disinfection and UV/ H₂O₂ oxidation. Especially knowledge about hygiene and the toxicity of by-products and degradation products is required to support water utilities in their choice of technology for the inactivation of pathogenic microorganisms (UV disinfection) and for the degradation of organic micro pollutants like pesticides and pharmaceuticals (UV-based oxidation).

Degradation products remain after degradation of the micro pollutants, whilst by-products are formed during reactions with the water matrix. The data about by-product formation described in this report are related to practical conditions of disinfection and oxidation processes.

Considerable information is available about the UV- and UV-oxidation based formation of by-products such as nitrite, assimilable organic carbon (AOC), and bromate. Although limited information has been found about algae growth after UV with respect to hygienic aspects, information about how to reduce algae growth or how to deal with algae growth is available. Data about toxicity (genotoxicity, carcinogenicity) following UV technology is very limited. However, in many publications the applied test conditions related to the data about by-product formation (water quality, UV dose) is lacking. It shows that the level of by-product formation depends strongly on the UV dose and the type of UV lamp applied. Due to the lower UV dose, the level of by-products is typically much lower for UV disinfection compared to UV-based oxidation. By-product formation is also typically lower using low-pressure mercury (LP) lamps compared to the use of medium-pressure (MP) UV lamps.

Nitrite’s adverse effect for blood to carry oxygen may lead to the blue-baby syndrome in infants less than 6 months (methemoglobinemia). Moreover, nitrite may be transformed to nitrosamines which due their adverse effects on human health are regulated compounds. The formation of nitrite occurs through direct photolysis of nitrate which is present in many natural waters. As a measure for biological regrowth, the AOC content of drinking water prior to distribution should be low from a hygienic point of view. Since AOC may lead to biofilm formation, this may give rise to growth of Legionella as well. Bromate has been designated carcinogenic to human. The WHO guideline as well as the European standard for bromate in drinking water is 10 µg/ L. In the Netherlands the bromate level following disinfection may not exceed 5 µg/ L (90% percentile) (Staatsblad van het Koninkrijk der
In cases other than disinfection, e.g. after oxidation, the maximum bromate level is 1 µg/L.

**UV disinfection**

Nitrite formation and AOC are controllable with post GAC during practical application of medium-pressure UV disinfection. It is expected that UV disinfection systems equipped with low-pressure UV lamps could be used without post treatment. Irrespective of the type of UV lamp applied, the nitrite content of the treated water does not exceed the European standard for drinking water (0.1 mg NO$_2$–/L).

UV disinfection does not contribute to genotoxicity at UV doses up to about 90 mJ/cm$^2$. However, there are indications that genotoxicity may be found. Bromate formation does not occur.

**UV/H$_2$O$_2$ advanced oxidation**

Due the high UV dose to effectively degrade organic micro pollutants, nitrite and AOC formation is enhanced treating natural water with MP-UV/ H$_2$O$_2$ oxidation. At nitrate levels >4 mg/L, the nitrite concentration may exceed the European drinking water standard of 0.1 mg NO$_2$–/L. The AOC level after oxidation may be as high as 100 – 140 µg acetate-carbon equivalents per liter. In order to produce biologically stable water post treatment, e.g. BAC filtration, is inevitable. Bromate formation does not occur with UV/ H$_2$O$_2$ oxidation.

In order to reduce estrogenericity, UV/ H$_2$O$_2$ oxidation with both LP and MP UV lamps is effective. Although direct photolysis (no addition of H$_2$O$_2$) effectively reduces the concentration of the compounds involved, estrogenericity through direct photolysis can only be decreased at very high UV doses.

Information about the contribution of UV/ H$_2$O$_2$ oxidation to (geno)toxicity is lacking.

**Gaps in knowledge**

The following gaps in knowledge have been identified:

- What is the formation and removal of toxic compounds due to direct photolysis (UV disinfection and UV/ H$_2$O$_2$) and oxidation (UV/ H$_2$O$_2$)?
- To what extent will nitrite and biodegradable organics be formed during low-pressure UV/ H$_2$O$_2$ oxidation?
- What is the mechanism of nitrite removal during BAC filtration?
- What is the mechanism of hydrogen peroxide degradation in BAC filters?
- What is the maximum H$_2$O$_2$ concentration permitted in drinking water?
- Can UV/ H$_2$O$_2$ oxidation be safely applied on GAC effluent prior to chlorination with respect to chlorinated by-products, AOC levels and removal of H$_2$O$_2$?
# Contents

Summary 1

Contents 3

1 Introduction 4

2 Background 7
  2.1 UV, UV sources and UV dose 7  
  2.2 Formation of AOC 7  
  2.3 Formation of nitrite and bromate 8  
  2.4 Algae growth 9  
  2.5 Toxicity 9  
  2.6 Process conditions and water quality 10

3 Results and discussion 11
  3.1 UV disinfection 11  
    3.1.1 Nitrite formation in practice 11  
    3.1.2 Formation of AOC 13  
    3.1.3 Algae growth 14  
    3.1.4 Toxicity 15  
  3.2 UV/H<sub>2</sub>O<sub>2</sub> oxidation 16  
    3.2.1 Nitrite formation 16  
    3.2.2 Formation of AOC 17  
    3.2.3 Algae growth 18  
    3.2.4 Toxicity 18

4 General discussion 20  
  4.1 Low-pressure versus medium-pressure 20  
  4.2 UV disinfection 21  
  4.3 UV/H<sub>2</sub>O<sub>2</sub> oxidation 21  
  4.4 Removal of AOC, nitrite, and H<sub>2</sub>O<sub>2</sub> 22

5 Conclusions and gaps in knowledge 24

6 Literature 25
1 Introduction

History of UV disinfection
In several European countries, e.g. Germany, France, Norway, Austria, and Switzerland, UV is applied for water disinfection since the 1930's. From the 1970's, UV plants in the Netherlands have been installed for groundwater disinfection, e.g. treatment of Aeromonas, and for secondary disinfection like treatment of GAC filtrate to reduce heterotrophic plate counts (HPC). In the Netherlands, the majority of the plants apply a UV dose between 20 - 40 mJ/cm². Most of these plants are equipped with medium-pressure (MP) UV lamps.

However, UV technology for primary disinfection has been increasingly studied for practical application over the last ten years. This is primarily based on the fact Cryptosporidium parvum oocysts are readily inactivated at low UV doses using in vivo assays (Bolton et al., 1998). This discovery has changed the approach towards application of UV technology for water disinfection. The approach is based on the fact that micro-organisms do not have to be killed, but that inactivation is sufficient. Earlier, a >2 log removal of Cryptosporidium parvum for which a UV dose of about 9,000 mJ/cm² was reported (Campbell et al., 1995). This can now be realized with less than 10 mJ/cm² based on inactivation. Most important is that when a micro-organism is inactivated, it is unable to replicate.

Water utility Evides supplies drinking water to amongst others the city of Rotterdam using UV for primary disinfection. Since 2005 Evides applies a Reduction Equivalent Fluence (REF) of 70 mJ/cm² treating 18,000 m³/h with MP-UV.

Also in the United States there is considerable interest in UV technology for water disinfection. Basis for this is the Long Term 2 Enhanced Surface Water Treatment Rule (LT2 rule) which has the purpose of reducing disease incidents with Cryptosporidium and other pathogenic micro-organisms in drinking water (www.epa.gov). In contrast to chlorine, UV is very effective for the inactivation of Cryptosporidium parvum oocysts (Clancy et al., 2000; Craik et al., 2001; Linden et al., 2001) and Giardia lamblia (Linden et al., 2002). In 2002, the city of Seattle (USA) decided to install UV disinfection aiming at a 3-log inactivation of Cryptosporidium parvum. Seattle Public Utilities provides drinking water to 1.3 million people treating about 28,500 m³/h (180 MGD) with 40 mJ/cm² (Hilmoe, 2002). This system is in operation in Seattle since 2004. Recently, the city of New York has taken UV disinfection with low-pressure (LP) lamps in operation.

UV-based oxidation
UV-based processes for the degradation of micro pollutants have been subject of research for several decades now. However, due to the detection of the pesticide bentazon in Dutch waters, the water utilities in the Netherlands have become seriously interested in technical solutions for the removal of such compounds. Since then, much effort has been put in the analysis of trace organics.
Increasing detection of organic contaminants in the intake water, the interest in UV-based oxidation processes (AOP) is increasing the last few years. In 2004, PWN Water Supply Company North Holland installed the UV/ H₂O₂ oxidation process for disinfection and as a barrier for organic micro pollutants at their treatment location in Andijk, the Netherlands. For this purpose the UV system treats up to 3,000 m³/h at 540 mJ/cm² (0.56 kWh/m³) using 6 mg/L hydrogen peroxide (PWN, 2004).

Application and water quality
Retrofitting existing treatment plants and building new treatment plants with UV disinfection or UV-based oxidation raises questions about the water quality after UV treatment with respect to a safe application of UV technology. Although the risks of applying UV technology for the production of drinking water are very low, special attention should be paid to (geno)toxicity and regrowth (hygiene).

Regulations
Implementation of treatment technologies are related to the water quality of drinking water which has to comply with the European Drinking Water Directive (DWD) 98/ 83/ EC. In principle, WHO guidelines for drinking water are used as a base for the standards in the DWD (www.europa.eu). The Member States of the European Union can include additional requirements or set higher standards.

Although the drinking water quality for consumers in the European Union is protected by the European Drinking Water Directive, strategies against chemical pollution of groundwater (www.ec.europa.eu) and surface water (www.ec.europa.eu) are (separately) described. For the USA , the US EPA developed the Stage 2 Disinfectants By-products Rule (DBP rule). This rule is intended to reduce potential cancer and reproductive and developmental health risks from disinfection by-products in drinking water (www.epa.gov).

Literature study
This study aimed at describing the state of knowledge about by-product formation during UV disinfection and UV/ H₂O₂ oxidation of pre-treated natural water. Known disinfection and oxidation by-products are biodegradable organics, nitrite, and bromate. Furthermore, these DBP’s attention should be paid to toxicity and algae growth due to photosynthesis. The formation of degradation products from organic micro pollutants is not within the scope of this study.

This report gives an overview of the international literature and data made available by Dutch water utilities. The report ends with a description of the most important gaps in knowledge that need to be addressed to ensure a safe application of UV-based treatment processes.
2 Background

2.1 UV, UV sources and UV dose
Light (photons) generated by mercury (Hg) UV sources consists of UV (200 – 400 nm) and visible light (400 – 800 nm). The most important wavelength range for water treatment is 200 – 280 nm (UV-C or germicidal range). Conventional mercury UV sources for water treatment are the low-pressure Hg lamp (LP-UV) and the medium-pressure Hg lamp (MP-UV). The spectrum emitted by MP lamps is in the 200 – 800 nm range whilst LP lamps emit predominantly at 253.7 nm (see Figure 1).

Due to the germicidal effect of UV-C light, mercury UV lamps are applied for disinfection purposes. UV disinfection relies on the inactivation of micro-organisms by dimerisation of the thymine bases in the DNA (Masschelein, 2002; Jagger, 1967). This brings about that micro-organisms cannot replicate which eliminates the risk of infection.

Besides inactivation of micro-organisms, UV light can also be used for degradation of organic micro pollutants. This process is called photolysis. Since the effect of degradation of pollutants by photolysis is too low, a chemical is added to the water producing mainly hydroxyl radicals ($\cdot OH$) through absorption of UV light. The UV/H$_2$O$_2$ Advanced Oxidation Process (AOP) produces the highly reactive hydroxyl radicals by UV irradiation of hydrogen peroxide (H$_2$O$_2$):

$$H_2O_2 \rightarrow 2 \cdot OH \quad (\text{quantum yield } \sim 1 \text{ at 253.7 nm})$$

Using UV/ H$_2$O$_2$ oxidation as a barrier for organic micro pollutants both degradation mechanisms (photolysis and oxidation) run in parallel.

The conventional unit for UV dose is mJ/ cm$^2$. A synonym for dose is fluence (which is in fact a better description; Bolton and Linden, 2003). If the UV dose (or fluence) is related to the inactivation of calibrated micro-organisms, e.g. Bacillus subtilis spores or MS2 phages, the dose or fluence is called Reduction Equivalent Dose (RED) or Reduction Equivalent Fluence (REF).

2.2 Formation of AOC
The formation of biodegradable organics is related to the nature and concentration of dissolved organics in the water. These organics, predominantly consisting of humic and fulvic acids are summarized as Natural Organic Matter (NOM) and expressed/ measured as Dissolved Organic Carbon (DOC).

During UV disinfection, biodegradable organics may be formed through absorption of photons (direct photolysis) or through reaction of hydroxyl radicals with NOM. Formation of hydroxyl radicals during UV disinfection proceeds among others by photolysis of nitrate (Sharpless and Linden, 2001). However, the formation potential of hydroxyl radicals by this route is very limited. Due to the fact that besides NOM also HCO$_3^-$ (bicarbonate) and CO$_3^{2-}$ (carbonate) react effectively with hydroxyl radicals, the formation of biodegradable organics through the radical pathway is negligible. Therefore,
the formation of biodegradable compounds during UV disinfection is expected to proceed through photolysis. Photolysis of natural water results in the breaking of bonds within organic molecules creating smaller organic molecules that are readily assimilable for bacteria. Natural water absorbs mainly at the lower wavelengths in the UV-C region which includes predominantly NOM and nitrate ion. It can be understood from Figure 1 that the wavelength of the incident UV light as well as the UV dose affect the formation level of biodegradables. This implies that the UV source may contribute to the formation level of biodegradables as well. As the absorbance of natural water at 253.7 nm which includes NOM is relatively low, it indicates that the production of biodegradable organics by photolysis using LP lamps will be limited. However, since the organics absorb predominantly in the low wavelength region (200 - 230 nm) one may expect elevated levels of biodegradable organics applying MP lamps (see Figure 1). In contrast to UV disinfection, biodegradable organics during UV/ H\textsubscript{2}O\textsubscript{2} oxidation will be produced through both photolysis and hydroxyl radical oxidation of NOM.

In the Netherlands, drinking water is distributed to the customer without an additional disinfectant like chlorine. Therefore, to ensure that the water is hygienically acceptable, it is imperative that the water is biologically stable. In order to measure the presence of biodegradable organics the AOC (Assimilable Organic Carbon) parameter was introduced (Van der Kooij et al., 1982). The principle of this method is described in Van der Kooij, 1992. AOC in water may lead to an increase of heterotrophic plate counts (HPC) which may result in slime layers (biofilms) on surfaces, e.g. pipe walls. It was concluded that the AOC concentration (P17 and NOX strains) is an index for the biological stability of drinking water, with values <10 µg acetate-C eq/ L indicating a limited growth potential (Van der Kooij, 1992). However, AOC and BDOC tests give no information about the rate of uptake by bacteria and also not about the effect of inorganic ions that may promote the growth, e.g. ammonia, sulphides. This has led to the development of the biofilm monitor determining the biofilm formation rate (BFR) and biofilm formation potential (BFP). At low AOC concentrations, a linear relationship has been found with the BFR (Van der Kooij et al., 1995; Van der Kooij et al., 2003).

2.3 Formation of nitrite and bromate
Nitrite (NO\textsubscript{2}\textsuperscript{−}) is produced by photolysis of nitrate (NO\textsubscript{3}\textsuperscript{−}). Since nitrate is present in most groundwaters and surface waters, nitrite formation has to be taken into account using UV-based treatment processes. Nitrate absorbs predominantly in the 200 - 240 nm wavelength range which makes which leads to nitrite formation with MP lamps but not or very limited with LP lamps (see Figure 1).
Bromate (BrO\textsubscript{3}\textsuperscript{−}) is known to be produced by oxidation of bromide ion (Br\textsuperscript{−}) and is a known potential carcinogen (Kurokawa et al., 1983, 1990; WHO, 2005). Bromide is a constituent of many natural waters. However, UV is not able to convert bromide to bromate. This is also true for UV/ H\textsubscript{2}O\textsubscript{2} treated waters containing bromide (Kruithof et al., 2000; Kruithof et al., 2003). Although the hydroxyl radicals are able to convert bromide into bromate, this process is not completed in the presence of an excess of hydrogen peroxide.
Von Gunten and Oliveras (1997, 1998) showed that the hypobromous acid (HOBr/ OBr⁻) which is formed from bromide by reaction with hydroxyl radicals is effectively reduced to bromide by H₂O₂ which process disables the oxidation pathway of bromide to bromate in the UV/H₂O₂ process.

2.4 Algae growth
Algae are able to develop and grow on spots where they can absorb visible light (photo synthesis) without be irradiated with UV light. In general algae are found in so-called inline UV systems where light from the UV lamps that are perpendicularly positioned to the water flow falls into the piping connected to the UV reactor. Due to the longer wavelengths, visible light travels deeper than UV light. The emission of visible light is characteristic for mercury UV lamps. The extend to which visible light is emitted depends on the light source. About 5% of the emission of low-pressure lamps is visible light whereas this part is about 25% for medium-pressure UV lamps (personal communication UV suppliers).

2.5 Toxicity
The number of papers in literature dealing with toxicity of UV-treated water is limited. Relevant toxic effects are genotoxicity, carcinogenicity and endocrine disruption. Genotoxicity is related to DNA damage which may lead to cancer. Gen mutations are small damages of DNA whereas chromosome aberrations are defined as DNA with severe damage. Compounds causing damage of the chromosomes are called clastogenic. In contrast, carcinogenicity may be the effect of other routes as well. Endocrine disrupting compounds are compounds that disrupt the endocrine system. Toxicity regardless of which kind, is not only caused by degradation products formed during treatment of micro pollutants. Also the formation of
degradation products from NOM, e.g. organic radicals, may contribute to the overall toxicity of treated water.

Studying the effect of water treatment processes on the formation of toxic products the analysis can be done on each individual product or measured as a total effect of the treatment.

A well-known gen mutation assay is the Ames test. This method uses Salmonella typhimurium strains for which the TA98 and TA100 are most applied. The method can be extended by using a mix of metabolizing enzymes (S9). These enzymes may convert unharmful compounds into mutagenic substances as this may occur in the human body.

A substance is defined as mutagenic or genotoxic as the number of induced revertants (mutagenic bacteria in the test using treated water) is significantly higher than the number of spontaneous revertants (mutagenic bacteria in the test using the untreated water). At Kiwa Water Research a substance is defined genotoxic if the number of induced revertants is at least twice the number of spontaneous revertants.

Estrogenic activity due to the presence of Endocrine Disrupting Compounds (EDCs) is caused by natural and/or synthetic estrogens. Many of these compounds originate from humans. These compounds enter the aquatic system mainly by discharge of sewage water on surface water.

2.6 Process conditions and water quality

The nature of by-products and the extend at which these by-products are formed depend on:
- mechanisms: photolysis and/or oxidation;
- UV dose;
- \( \text{H}_2\text{O}_2 \) dose;
- concentration of organic matter, expressed as DOC;
- nitrate ion content;
- concentration of bicarbonate (\( \text{HCO}_3^- \)) and carbonate (\( \text{CO}_3^{2-} \)) as scavengers for hydroxyl radicals.
3 Results and discussion

3.1 UV disinfection
As shown in the previous section the UV dose has a significant effect on the production level of by-products. However, compared to UV oxidation the applied UV dose for disinfection purposes is relatively low. In early years, the UV dose for disinfection of groundwater and GAC effluent was typically 20 – 40 mJ/cm² (Kruithof et al., 1992). Due to increased knowledge of UV sensitivity of natural strains, the UV dose has been raised to 70 mJ/cm² in recent years (Van der Veer, 2002). Moreover, due to the relative insensitivity of viruses, e.g. adenovirus, for UV light there are indications that the UV dose may be further increased (Linden et al., 2005). This section will show that not all parameters are equally affecting the formation of by-products and also which parameters are related to the formation of certain by-products.

3.1.1 Nitrite formation in practice
The formation of nitrite (NO₂⁻) during the application of UV technology can be completely assigned to the irradiation and absorption of UV light by nitrate (NO₃⁻). Data show that the formation of nitrite in water (8.6 mg NO₃⁻/L; UV-T₂₅₄ = 90%, 1 cm) treated with LP-UV was lower than 0.01 mg NO₂⁻/L. The UV dose was not given here. Von Sonntag and co-workers (1992) found a concentration of 0.002 mg NO₂⁻/L after irradiation of water containing 50 mg NO₃⁻/L with LP-UV. The calculated UV dose was 25 mJ/cm². Results of tests performed with a collimated beam apparatus equipped with a LP-UV lamp confirm the extreme low nitrite content of water treated with low-pressure UV lamps: 0.007 mg NO₂⁻/L at a UV dose of 120 mJ/cm² (14 mg NO₃⁻/L).

Not only are the nitrite contents of water treated with MP-UV significantly higher than those treated with LP-UV, there is also a linear relation between the nitrite formation and the nitrate content of the water regardless of the type of lamp (IJpelaar et al., 2006). In water containing 15 mg NO₃⁻/L up to 0.04 mg NO₂⁻/L was produced in a bench-scale UV unit treating the water at a REF of 70 mJ/cm² (UV-T₃₅₄ = 90%, 1 cm). Under the same conditions but at a nitrate content of 8 mg NO₃⁻/L, the nitrite formation reached a maximum of 0.02 mg NO₂⁻/L. However, results of tests with a MP-UV lamp in a collimated beam apparatus with the same water quality under the same conditions show significantly higher nitrite concentrations: 0.11 mg NO₂⁻/L. The initial nitrate concentration was 15 mg NO₃⁻/L and the UV dose was 70 mJ/cm² (established with an IL1700 radiometer connected to a SED240W sensor).

The formation of nitrite can be significantly reduced if the MP UV lamps are provided with quartz sleeves with a cut-off of the lower wavelengths. Bernhardt (1994) showed a nitrite concentration of 30 µg NO₂⁻/L after treating water with 50 mg NO₃⁻/L at a UV dose of 50 mJ/cm² using sleeves with a cut-off at 235 nm. Under exactly the same conditions using quartz
sleeves without a cut-off the nitrite content of the treated water was 0.15 mg NO$_2$–/L.

Table 1: Impact of water quality parameters on nitrite formation during UV disinfection of natural water containing nitrate. Tests were performed with a collimated beam apparatus equipped with a medium-pressure UV lamp. UV dose based on sensor/radiometer readings. (Ijpelaar et al., 2006).

<table>
<thead>
<tr>
<th>Water quality</th>
<th>Nitrate (mg NO$_3$–/L)</th>
<th>DOC (mg C/L)</th>
<th>pH</th>
<th>UV dose (mJ/cm$^2$)</th>
<th>Nitrite (mg NO$_2$–/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.5</td>
<td>3</td>
<td>7.87</td>
<td>20</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>3</td>
<td>7.87</td>
<td>70</td>
<td>0.07</td>
</tr>
<tr>
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<tr>
<td></td>
<td>12.3</td>
<td>4.1</td>
<td>7.00</td>
<td>70</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>12.3</td>
<td>4.1</td>
<td>9.05</td>
<td>70</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>3</td>
<td>7.87</td>
<td>70</td>
<td>0.08</td>
</tr>
</tbody>
</table>

The data presented above confirm that nitrite formation is highly affected by the wavelength-dependent UV light emitted by the mercury UV source (MP vs. LP) and the applied UV dose. If the wavelengths emitted do not correspond with the absorption characteristics of the compound there will be no reaction. Therefore, since the absorption of nitrate at the LP emission line at 253.7 nm is very low, nitrite formation during UV disinfection with LP-UV is negligible, irrespective of the UV dose.

In contrast to LP-UV lamps the emission spectrum of MP lamps corresponds smoothly with the absorption characteristics of nitrate. As a result nitrate may absorb all emitted photons having an energy that corresponds with wavelengths between 200 - ~240 nm. Moreover, this 'availability' of UV light realized with MP-UV to produce nitrite is elevated by increasing nitrate content, pH and UV dose (see Table 1, Ijpeelaar et al., 2006).

The higher nitrate concentrations analyzed in water after irradiation in a collimated beam apparatus is explained by the fact that the complete water volume in the petri dish is irradiated. In contrast, in UV reactors where the water flows through a cylinder equipped with UV lamps nitrate irradiation occurs at a maximum distance of the lamp. According to the Beer-Lambert law this water depth is defined by the UV-T of the water and the nitrate concentration. However, if the distance between the lamps and the reactor wall exceeds this water depth the nitrate present in the water out side these imaginary water cylinder will not be irradiated (Ijpeelaar et al., 2005). As a result the nitrite concentration in the effluent of flow-through systems is often lower than with a collimated beam apparatus.

**Summary**

It can be concluded that the nitrite content of water treated for disinfection purposes up to UV doses of 70 mJ/cm$^2$ fulfills the European drinking water standard for nitrite (0.1 mg NO$_2$–/L) for both LP and MP UV lamps. However, at higher UV dose applying MP UV lamps the nitrite concentration in treated water may exceed this standard.
3.1.2 Formation of AOC

Data from a UV system equipped with LP lamps used to disinfect pre-treated surface water showed an AOC level of 6.6 µg/L (DOC = 2-4 mg/L, UV-T = 83-90%, 1 cm). The UV-dose was about 25 mJ/cm² (unpublished research water utility Vitens, the Netherlands).

In a laboratory-scale study treating surface water with LP-UV (pre-treated with coagulation, sedimentation and rapid sand filtration) the increase in AOC was not significant at REF up to 90 mJ/cm² (IJpelaar et al., 2001). At a REF of 90 mJ/cm² using MP-UV an AOC concentration of 15 µg Ac-C/L was found in surface water pre-treated by rapid sand filtration (2 mg DOC/L; AOC raw water = 7.5 µg Ac-C/L). After irradiation of pre-treated surface water (DOC = 2 mg/L; UV-T = 90%, 1 cm) in a pilot plant (180 m³/h) equipped with MP lamps caused the AOC level was about 10 µg Ac-C/L (REF = 58 mJ/cm²) and ~ 15 µg Ac-C/L at a REF of 95 mJ/cm². This study also showed that the AOC concentration was effectively reduced to < 10 µg Ac-C/L with GAC filtration.

From these data it can be concluded that AOC formation during UV disinfection is not significant at UV doses up to 90 mJ/cm² irrespective of the use of LP-UV and MP-UV.

Research on the formation of biodegradable organics, Greater Cincinnati Water Works (GCWW, Ohio USA) measured AOC levels up to 500 µg/L treating surface water by UV (pre-treatment: sand filtration and GAC filtration) at 40 mJ/cm². Although the same strains (P17 and NOX) are used in this project these numbers are about 50 times higher than the numbers typically found with the Dutch method (Van der Kooij et al., 1982; Van der Kooij, 1992). The AOC level of the raw water in different trials (Summer and Winter water) was about 150 µg/L.

In contrast to the findings described above, the AOC concentrations found in the GCWW study as described by Kashinkuti et al. (2004) were comparable or higher for the tests with LP lamps compared to the AOC levels after treatment with MP lamps. Also the AOC levels appeared to decrease with increasing UV dose. Moreover, the actual numbers are much higher than typically found with the Dutch AOC method. However, the authors concluded that the AOC increases were not supported by a second trial.

Tests measuring biodegradable DOC were performed by Féliers et al. (2003). They reported no remarkably increased BDOC levels using a batch reactor with 4 MP lamps at UV doses up to 4,000 mJ/cm². For these tests four different pre-treated surface water qualities were applied. Unfortunately, specific data about the water qualities applied are not available. However, since three of the water qualities were obtained after ozonation alone or followed by GAC filtration, the water is close to drinking water quality. The fact that no BDOC increase was measured at UV dose up to 4,000 mJ/cm² makes the method at least questionable to be used as a measure for bacterial regrowth.
Table 2: Formation of biodegradable organics expressed as AOC produced during UV disinfection of pre-treated natural waters using medium-pressure and low-pressure UV lamps.

<table>
<thead>
<tr>
<th>Water quality</th>
<th>Nitrate (mg NO₃⁻/L)</th>
<th>DOC (mg C/L)</th>
<th>UV-T₂₅₄ (%), 1 cm</th>
<th>Lamp type</th>
<th>UV dose (mJ/cm²)</th>
<th>AOC/ BDOC (µg Ac-C/L)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>2</td>
<td>90</td>
<td>MP</td>
<td>58 - 197¹</td>
<td>2.8 – 8.2³</td>
<td>90 – 197¹</td>
</tr>
<tr>
<td>3.6</td>
<td>1.7 - 2.4</td>
<td>78</td>
<td>MP</td>
<td>25</td>
<td>7.1³</td>
<td>≤ 3.6⁴</td>
</tr>
<tr>
<td>unknown</td>
<td>unknown</td>
<td>90</td>
<td>MP</td>
<td>20 - 30</td>
<td>not significant</td>
<td>≤ 3.6⁴</td>
</tr>
<tr>
<td>10.6</td>
<td>unknown</td>
<td>90</td>
<td>LP</td>
<td>90¹</td>
<td>not significant</td>
<td>90 – 197¹</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>MP</td>
<td>90</td>
<td></td>
<td>15</td>
<td>90 – 197¹</td>
</tr>
<tr>
<td>unknown</td>
<td>MP</td>
<td></td>
<td></td>
<td>4,000</td>
<td>not significant</td>
<td>90 – 197¹</td>
</tr>
</tbody>
</table>

¹ Reduction Equivalent Fluence (REF)
² AOC concentration after treatment, including AOC concentration in influent water
³ Pilot plant research water utility Evides
⁴ Drinking water installation at location water utility (demonstration plant water utility Brabant Water)
⁵ Bench-scale UV unit, Ijpeelaar et al., 2001
⁶ BDOC method used according to Féliers et al., 2003

Summary
The AOC formation level is lower in systems with LP lamps than with MP lamps. However, it can be concluded that with all lamps and under all conditions of UV disinfection (≤ 100 mJ/cm²) the production of AOC is limited to about 10 µg Ac-C/L (in addition to the AOC level of the raw water).

3.1.3 Algae growth
Algae growth takes place predominantly in UV systems equipped with UV lamps emitting visible light that are placed perpendicular to the water flow (so-called in-line UV systems). In these UV systems the walls of the pipes that are connected to the UV reactor are irradiated only by visible light. Given that the visible light travels deeper than UV light in (pre-treated) natural water and that not all of the algae passing the UV lamps are killed, algae growth may occur on the wall of the pipes.

The level of algae growth in in-line UV systems depends on the following aspects (Beerendonk and Ijpeelaar, 2003):
- concentration of phosphates (Reynolds, 1984);
- type of lamp applied;
- UV transmittance of the water. Due to a low UV transmittance the level of algae growth is often higher in waste water. In addition, waste water is often treated in open channels and therefore accessible for visible light.

Examples of significant algae growth are known in UV disinfection systems equipped with MP UV lamps. However, there are also examples of algae growth in systems equipped with LP lamps. Generally, the extent of algae growth in LP-UV systems is much lower than in MP-UV systems (see...
background section). These systems need to be cleaned with chlorine regularly which puts them out of production.

3.1.4 **Toxicity**

Until recently most toxicity tests have focused on gen mutation assays using the Ames test. Published studies on genotoxicity were performed in Austria and in the Netherlands. Data from UV disinfection studies about changes of endocrine disruption have not been published or are not available.

Early studies with pre-treated surface water subsequently treated with UV did not show genotoxicity in the Ames test. In one of these studies applying a UV dose of 120 mJ/cm², it was unclear what type of UV lamp was used (Zoeteman et al., 1982). The second study revealed no genotoxicity after UV treatment using 20 - 40 mJ/cm² with both low-pressure and medium-pressure UV lamps (Kruithof et al., 1992). Applying Ames (TA98 with S9 mix) on pre-treated surface water in a 180 m³/h pilot plant equipped with medium-pressure UV lamps genotoxicity was not detected at UV doses up to 90 mJ/cm² (REF). However, the data indicated an increase in genotoxicity after UV treatment. According to Haider and co-workers (2002) genotoxicity of groundwater (Ames, TA98 without S9) increased after LP-UV treatment (UV dose up to 80 mJ/cm²). This is in contrast to the data found by IJpelaar et al. (2001). Using a bench-scale UV reactor equipped with a low-pressure UV lamp IJpelaar et al. measured no genotoxicity (Ames: pH7, TA98 without S9) at (calculated) UV doses up to 90 mJ/cm².

Studies carried out by Helma and co-workers (1994) showed no elevated clastogenicity after treating drinking water at a UV dose of 150 mJ/cm². At the same conditions, it was found that ground water prior to and after GAC filtration did show a significant increase of clastogenicity. For these tests the applied UV source was not described. However, Helma and co-workers (1994) reported that increased clastogenicity was measured treating ground water with a low-pressure lamp (no data given about the applied UV dose). In contrast, Haider and co-workers (2002) found no increased clastogenicity after treating different qualities of groundwater in a lab-scale UV reactor equipped with a low-pressure UV lamp up to 80 mJ/cm² (REF).

Although more data are required to explain these results it may be concluded that the measured data largely depend on:
- the water quality;
- the actual UV dose (preferably based on biodosimetry (REF));
- preconditioning of the samples prior to testing.
Summary
It is concluded that data found on formation of toxic products are often contradictory. Detailed information about how the treatment and the toxicity tests were performed is often not available. In spite of these observations it is expected that due to the low UV dose the level of toxicity produced during UV disinfection of pre-treated natural water is low or even negligible. However, this may change if the UV dose is increased in future due to relatively UV-insensitive micro-organisms, e.g. adenovirus.

3.2 UV/H\textsubscript{2}O\textsubscript{2} oxidation
In contrast to UV disinfection, UV/ H\textsubscript{2}O\textsubscript{2} is based on two major mechanisms:
− absorption of UV photons which leads to excitation of molecules which may result in breaking of bonds;
− reaction of organic micro pollutants with hydroxyl radicals that are formed in the reaction between H\textsubscript{2}O\textsubscript{2} and UV photons.
A major difference between UV disinfection and UV/ H\textsubscript{2}O\textsubscript{2} oxidation is the applied UV dose. The UV dose is directly related to the energy input which may be up to about 35 times higher for UV/ H\textsubscript{2}O\textsubscript{2} oxidation (500 – 750 mJ/cm\textsuperscript{2}) than for UV disinfection (20 – 70 mJ/cm\textsuperscript{2}). The higher the energy input the easier molecular bonds are broken. Since besides direct photolysis micro pollutants also strongly react with the in-situ produced hydroxyl radicals in UV/ H\textsubscript{2}O\textsubscript{2} systems the level at which by-products are formed is much higher than in disinfection systems. The question is whether these levels can be satisfactorily controlled during high-quality drinking water production.

3.2.1 Nitrite formation
Nitrite formation only occurs through direct photolysis of nitrate and the formation level depends strongly on the applied wavelengths and UV dose. Therefore, elevated nitrite levels are produced in water treated with UV/ H\textsubscript{2}O\textsubscript{2} oxidation. Treatment of pre-treated surface water in a pilot plant equipped with medium-pressure UV lamps, the nitrite concentrations increased from close to zero to levels between 0.04 and 0.33 mg/ L NO\textsubscript{2}\textsuperscript{-} (UV dose 540 mJ/ cm\textsuperscript{2}; H\textsubscript{2}O\textsubscript{2} dose 6 mg/ L, see Table 3). In general, nitrite formation depends on the nitrate content and pH of the treated water, the applied type of UV lamp and the UV and H\textsubscript{2}O\textsubscript{2} dose (Ijpeelaar et al., 2006). In an MP-UV/ H\textsubscript{2}O\textsubscript{2} collimated beam study Sharpless and co-workers (2003) found that higher H\textsubscript{2}O\textsubscript{2} levels cause elevated nitrite levels.
Summary
It can be concluded that the formation of nitrite during UV/ H$_2$O$_2$ oxidation of water may well exceed the European drinking water standard of 0.1 mg/ L NO$_2$ using MP lamps. However, the nitrite concentration is significantly reduced after GAC filtration. Martijn et al. (2006) showed that matured biological populations in the carbon filters are able to decrease the nitrite content of the water from about 0.18 mg NO$_2$- L to less than about 0.025 mg/ L. Since with virgin carbon the nitrite concentration in the GAC effluent was only about 20% reduced, they concluded that nitrite is biologically converted.

3.2.2 Formation of AOC
The production of AOC during UV/ H$_2$O$_2$ oxidation of pre-treated natural water is much higher than during UV disinfection. Its formation does not only depend on the emission spectrum of the applied UV lamps (see Figure 1) but also on the UV and H$_2$O$_2$ dose. Moreover, the ratio of the concentrations of NOM (as the main precursor of AOC) and nitrate in the treated water may affect the level of biodegradable organics. Due to the fact that both parameters absorb UV light in the 200 – 240 nm wavelength range, NOM and nitrate may compete for UV photons. Increasing the nitrate level from 4.4 mg NO$_3$- L to 7.6 mg NO$_3$- L and DOC from 3.1 mg C/ L to 3.6 mg/ L led to an increase of the nitrite concentration from 0.1 to 0.21 mg NO$_2$- L but an AOC decrease from 106 µg Ac-C/ L to 91 µg Ac-C/ L (pH ~ 7.3; alkalinity (HCO$_3$-) = 129 – 132 mg/ L; UV-T$_{254}$ (1 cm) changing from 86% to 84%). Table 3 shows the data of AOC and nitrite formation during UV/ H$_2$O$_2$ oxidation. It can be seen that the AOC and nitrite formation levels are related to the DOC and nitrate concentrations. In general, increased nitrate levels at fairly constant pH, H$_2$O$_2$ dose and DOC concentration cause increased nitrite levels and decreased AOC levels. This is due to the strong absorbance of nitrate in the 200 – 240 nm wavelength range causing less absorption of UV by NOM.

GAC filtration appears an effective means of reducing the AOC level of the UV/ H$_2$O$_2$ treated water producing biologically stable water. Although the AOC increased from 10 (before treatment) to 40 µg Ac-C eq./ L after UV/ H$_2$O$_2$ oxidation and GAC filtration, Kruithof et al., 2005 reported that the biofilm formation rate of the GAC effluent was about 2 pg/ cm$^2$.day.
Table 3: Nitrite and AOC formation during MP-UV/H₂O₂ treatment of pre-treated surface water. The water was pre-treated with coagulation (FeCl₃) and rapid sand filtration.

<table>
<thead>
<tr>
<th>H₂O₂ (mg/L)</th>
<th>NO₃⁻ (mg NO₃⁻/L)</th>
<th>DOC (mg C/L)</th>
<th>pH</th>
<th>HCO₃⁻ (mg/L)</th>
<th>UV-T (cm⁻¹)</th>
<th>AOC (µg Ac-C/L)</th>
<th>NO₂⁻ (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>4.4</td>
<td>3.1</td>
<td>7.4</td>
<td>132</td>
<td>86</td>
<td>106</td>
<td>103</td>
</tr>
<tr>
<td>4.0</td>
<td>8.0</td>
<td>3.4</td>
<td>7.5</td>
<td>130</td>
<td>86</td>
<td>39</td>
<td>269</td>
</tr>
<tr>
<td>5.4</td>
<td>12.5</td>
<td>3.7</td>
<td>7.0</td>
<td>138</td>
<td>81</td>
<td>70</td>
<td>330</td>
</tr>
<tr>
<td>6.1</td>
<td>7.6</td>
<td>3.6</td>
<td>7.3</td>
<td>129</td>
<td>84</td>
<td>91</td>
<td>205</td>
</tr>
<tr>
<td>6.9</td>
<td>3.4</td>
<td>3.7</td>
<td>7.9</td>
<td>126</td>
<td>83</td>
<td>131</td>
<td>40</td>
</tr>
<tr>
<td>5.9</td>
<td>10.8</td>
<td>4.4</td>
<td>8.0</td>
<td>156</td>
<td>80</td>
<td>27</td>
<td>237</td>
</tr>
</tbody>
</table>

It can be concluded that the level of AOC formation during UV/H₂O₂ oxidation is much higher than during UV disinfection. With MP-UV/H₂O₂ the AOC formation level is strongly related to the nitrate content of the water. Generally, the higher the NO₃⁻ concentration in the influent water the lower the AOC concentration.

3.2.3 Algae growth
In spite of or due to the fact that no publications have been found about algae growth in UV/H₂O₂ systems, it is expected that this phenomenon does not occur in these systems. This is explained by the use of high UV doses in combination with the presence of H₂O₂. It is believed that algae do not survive the extreme conditions in the UV reactor.

3.2.4 Toxicity
A limited number of studies have focused on the analysis of toxic products in UV/H₂O₂ treated water. Early studies showed that bromate formation does not occur under the applied process conditions (Kruithof et al., 2000, 2003). This is due to the fact that hypobromous acid which is the intermediary in the formation of bromate from bromide is converted to bromide by hydrogen peroxide (Von Gunten and Oliveras, 1997; 1998). Precondition is that H₂O₂ is present in excess over hypobromite/hypobromous acid.
Rosenfeldt et al. (2006) studied the effectiveness of UV photolysis (high UV dose) and UV/H₂O₂ for the reduction of estrogenic activity of water associated with the presence of Endocrine Disrupting Compounds (EDCs). In this research the Yeast Estrogen Screen (YES) was used. Rosenfeldt et al. found that LP-UV (UV dose up to about 10,000 mJ/cm²) did not change the estrogenic activity of water with 3 µg/L of 17-a-ethinyl estradiol (EE2). MP-UV reduced about 80% of the initial estrogenic activity but only at a UV dose of 6,000 mJ/cm². For both LP-UV and MP-UV, estrogenic activity due to EE2 is not reduced at UV dose lower than about 2,000 mJ/cm². In contrast, after addition of 5 mg/L H₂O₂ the estrogenic activity (EE2) was decreased for about 95% using about 200 mJ/cm² of UV.
No publications have been found about genotoxicity and carcinotoxicity after treatment of water with UV/H₂O₂.
Summary
UV/H₂O₂ treatment of natural water does not result in the formation of bromate. Estrogenic activity is effectively reduced with UV/H₂O₂ oxidation, but not with UV photolysis without H₂O₂ at high UV dose. Knowledge about the effect of UV/H₂O₂ treatment of natural water on genotoxicity and carcinogenicity is not available.
4 General discussion

Over the last years there is an increased interest in UV technology as a barrier for pathogens and organic micro pollutants in the production of drinking water. The use of UV light for disinfection purposes is very effective for a broad range of micro-organisms. In contrast to chlorine, UV light also effectively inactivates Cryptosporidium parvum oocysts and Giardia lamblia. In case that organic micro pollutants have to be removed as well, UV disinfection is not the appropriate technology. In that case UV oxidation, e.g. UV/H\textsubscript{2}O\textsubscript{2} advanced oxidation, may be applied. Currently, the applied UV dose for disinfection are in the 40 – 70 mJ/ cm\textsuperscript{2} range. Although due to relatively difficult to inactivate micro organisms the UV dose may be increased in the near future, the dose may be up to 35 times lower than required for UV oxidation. However, the effective removal of pathogens and organic micro pollutants with UV technology also induces undesired side reactions. Organic matter and inorganic ions present in natural water also react with UV light and the hydroxyl radicals that are produced in-situ during UV oxidation. This may lead to the formation of by-products (products formed during chemical reaction with the water matrix) like AOC from NOM and nitrite from nitrate. Also degradation products (products resulting from the degradation of the micro pollutants) may be formed. Bromate formation does not occur either during UV disinfection or UV/ H\textsubscript{2}O\textsubscript{2} oxidation. The nature of the by-products and their concentration may differ between water qualities and the type of UV lamp (low pressure, medium pressure) applied. Moreover, due to the elevated UV dose, the concentrations of by-products is generally higher after treatment with UV oxidation. Reviewing literature it must be noted that data are often not complete and therefore difficult to compare. Many papers do not give full information about how the UV dose is determined, the water quality with respect to relevant parameters and the analysis method determining the concentrations of the formed products and the parent compounds.

4.1 Low-pressure versus medium-pressure

Low-pressure UV lamps are more energy efficient, cheaper and have a longer life time than medium-pressure UV lamps. Ultimately, this leads to:

- no or lower levels of by-products;
- lower energy input;
- reduced energy costs.

However, the lamp power of the current LP lamps (up to 0.4 kW) is much lower than the MP lamp power (up to 30 kW). This means that significantly more low-pressure lamps are required treating the same volume of water than medium-pressure lamps. This may result that the size of UV systems equipped with low-pressure lamps is larger than MP-UV systems (larger footprint).
4.2 **UV disinfection**

In general, under the conditions of UV disinfection the formation of nitrite is low. Due to the fact that nitrate hardly absorbs at 253.7 nm, nitrite formation is negligible with low-pressure UV disinfection. Although the nitrite content of water treated with medium-pressure UV lamps is higher than using low-pressure UV lamps, the European standard for nitrite in drinking water (0.1 mg NO\(_2^-/L\)) is not exceeded. Although the extend at which nitrite is produced depends on the initial nitrate concentration, the applied UV dose, and on the pH, it is expected that the European standard will also not be exceeded using poor water qualities.

The AOC data measured after UV disinfection are low, but the differences between LP-UV and MP-UV may be significant. The main cause for this is the difference in the emission spectra of both mercury lamps in relation to the absorbance of DOC (see Figure 1). In many cases the AOC content of the water after LP-UV disinfection is negligible or very low. Therefore, it is expected that UV disinfection with LP-UV lamps could be applied as the final treatment step. However, this is not simply the case using UV disinfection systems with MP UV lamps. Water treated with MP-UV disinfection show increased levels of AOC up to 15 µg AcC eq./L. To measure the biological stability of the water in time, it is recommended to measure the biofilm formation rate (BFR) or the biofilm formation potential (BFP) of the treated water.

Very limited data are available about the increase of toxicity during UV disinfection of water. Most cases using the Ames test show no increased mutagenicity after UV disinfection. In one case an increase was detected (Ames test, strain TA98 without S9), but the increase was not significant.

Algae growth related to UV disinfection appears to occur in the pipes just before and after the reactor. Especially in UV systems with UV lamps configured perpendicular to the water flow, so-called ‘in-line’ systems, algae are found. The extend of algae growth is the strongest with systems with MP lamps. This is due to the fact that up to 25% of the total emission of MP lamps is visible light which stimulates the growth of algae due to photo synthesis. For LP lamps this part is about 5%.

4.3 **UV/H\(_2\)O\(_2\): oxidation**

By-product formation during UV/ H\(_2\)O\(_2\) advanced oxidation may occur through direct photolysis and oxidation with the in-situ produced hydroxyl radicals (·OH).

Due to the fact that nitrate absorbs UV light below 240 nm, nitrite formation takes place using MP UV lamps. Moreover, since the UV dose compared to UV disinfection is much higher, nitrite concentrations up to 3 times higher than the European drinking water standard for nitrite (0.1 mg/ L NO\(_2^-/L\)) have been found. Although data on nitrite formation with LP-UV/ H\(_2\)O\(_2\) oxidation are lacking, it is expected that the nitrite data will be negligible or very low. This expectation is based on the fact that nitrite formation only occurs through direct photolysis. In spite of the fact that higher UV doses are used for UV/ H\(_2\)O\(_2\) advanced oxidation, the extremely low absorbance of
nitrate at 253.7 nm prevents formation of significant amounts of nitrite using LP UV lamps. The AOC content of pre-treated groundwater and surface water will also be much higher after UV/ H₂O₂ oxidation than after UV disinfection. Compared to UV disinfection, AOC formation during UV/ H₂O₂ oxidation is enhanced due to the use of higher UV doses and the fact that both mechanisms (photolysis and oxidation) play a role here. The AOC content of UV/ H₂O₂ treated water may be as high as 140 µg AcC eq./ L (Kruithof et al., 2005).

Information about toxicity of UV/ H₂O₂ treated water is very limited. Recent research showed that estrogenicity due to 17-ß-estradiol and 17-a-ethinyl estradiol measured with Yeast Estrogen Screen (YES) is completely reduced with UV/ H₂O₂ oxidation at acceptable doses. Photolysis is not effective below 2,000 mJ/ cm² (MP-UV) and 12,000 mJ/ cm² (LP-UV). Genotoxic and/ or carcinogenic data of water after UV/ H₂O₂ have not been found.

Algae growth is not established in UV/ H₂O₂ oxidation systems. This is probably due to the high UV dose for oxidation purposes and the presence of hydrogen peroxide.

4.4 Removal of AOC, nitrite, and H₂O₂
In order to remove by-products from the water phase after UV disinfection and UV/ H₂O₂ advanced oxidation, the water requires additional treatment. GAC filtration following UV/ H₂O₂ is effectively applied in practice for the removal of AOC, nitrite and H₂O₂ (Martijn et al., 2006).
AOC in water puts the carbon filters in a bio-active mode. The required Empty Bed Contact Time (EBCT) to obtain biologically stable water after UV/ H₂O₂ treatment was 40 minutes (Kruithof et al., 2003).
The number of publications found about the removal of nitrite from water is limited. Martijn et al. (2006) showed that matured biological GAC filters are effective for the removal of nitrite.
Since only about 10% of the H₂O₂ added to the water to activate the UV/ H₂O₂ oxidation process is converted into hydroxyl radicals, a significant amount of H₂O₂ still has to be removed. Earlier research revealed that activated carbon effectively degrades H₂O₂ into water and oxygen (Kruithof et al., 2000). It was shown that a concentration of 10 mg/ L H₂O₂ is decreased to below the detection limit with an EBCT of less than 10 minutes.
5 Conclusions and gaps in knowledge

Conclusions
An important conclusion from this literature study is that much information is available about by-product formation during UV disinfection and UV/H\(_2\)O\(_2\) oxidation. However, many research results are not fully supported by data about the set-up of the research and the process conditions. Application of UV disinfection and UV/ H\(_2\)O\(_2\) oxidation may result in the formation of undesired by-products. Known substances are nitrite and Assimilable Organic Carbon (AOC). Bromate formation does not occur, either in UV disinfection systems or in UV/ H\(_2\)O\(_2\) systems.

Attempts to reduce estrogenticity, it has been established that UV/ H\(_2\)O\(_2\) oxidation is required to reduce the estrogenic activity in water due to 17-ß-estradiol and 17-a-ethinyl estradiol. Photolysis at acceptable UV dose (≤ 750 mJ/cm\(^2\)) is not effective. However, data about genotoxicity and carcinogenicity after UV/ H\(_2\)O\(_2\) oxidation are needed to establish whether toxicity due to UV technology is an issue.

The formation of by-products is strongly affected by the applied UV dose. Therefore, the concentration of by-products is generally higher after UV/ H\(_2\)O\(_2\) oxidation than after UV disinfection. Secondly, the formation level is generally higher after treatment with medium-pressure UV lamps than with low-pressure UV lamps. Applying low-pressure UV lamps for disinfection the nitrite formation is negligible and the production of AOC limited. For LP-UV/ H\(_2\)O\(_2\) oxidation nitrite formation is expected to be negligible, but data are lacking. Also data are required about the formation of AOC during LP-UV/ H\(_2\)O\(_2\). Nitrite and AOC concentrations vary from significant to very high using medium-pressure UV lamps for UV disinfection and UV/ H\(_2\)O\(_2\) oxidation, respectively.

Algae growth takes place using UV disinfection and especially with UV systems equipped with medium-pressure UV lamps. Based on the available information algae growth does not occur with UV/ H\(_2\)O\(_2\) oxidation.

Gaps in knowledge
This literature study has revealed the following gaps in knowledge
- What is the formation and removal of toxicity due to direct photolysis (UV disinfection and UV/ H\(_2\)O\(_2\)) and oxidation (UV/ H\(_2\)O\(_2\))?  
- To what extent will nitrite and biodegradable organics be formed during low-pressure UV/ H\(_2\)O\(_2\) oxidation?  
- What is the mechanism of nitrite removal during BAC filtration?  
- What is the mechanism of hydrogen peroxide degradation in BAC filters?  
- What is the maximum H\(_2\)O\(_2\) concentration tolerable in drinking water?  
- Can UV/ H\(_2\)O\(_2\) oxidation be safely applied on GAC effluent prior to chlorination with respect to chlorinated by-products, AOC levels and removal of H\(_2\)O\(_2\)?
6 Literature


www.epa.gov/ ogwdw/ disinfection/ lt2/ basicinformation.html
www.epa.gov/ ogwdw/ disinfection/ stage2/ basicinformation.html

UV disinfection and UV/H2O2 oxidation: by-product formation and control Kiwa WR
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