Høgskulen på Vestlandet

Bacheloroppgave

NAB3030

Predefinert informasjon

Startdato:	20-03-2020 09:00	**Termin:**	2020 VÅR
Sluttdato:	06-05-2020 14:00	**Vurderingsform:**	Norsk 6-trinns skala (A-F + Bestått)
Eksamensform:	Bacheloroppgave		
SIS-kode:	203 NAB3030 1 PRO-1 2020 VÅR HAUGESUND		
Intern sensor:	(Anonymisert)		

Deltaker

Kandidatnr.: 335

Informasjon fra deltaker

Tittel *: Ozon som alternativ for behandling av ballastvann

Engelsk tittel *: Ozone as an alternative for ballast water treatment

Navn på veileder *: Sverre Fagerland

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BACHELOR THESIS

Ozon som alternativ for behandling av ballastvann

Ozone as an alternative for ballast water treatment

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Preface

This bachelor thesis is inspired by the Green Shipping subject in the Nautical Science Department of the Western Norway University of Applied Sciences, Haugesund Campus. The subject focuses on solutions for efficient and environmentally friendly shipping. This is a relevant topic for us since we see ourselves having a career within a sustainable maritime industry after graduating.

We realized the ballast water treatment is one of the main environmental problems the marine industry faces, and we wanted to study and find more sustainable technological solutions to manage this issue. Ozone has been widely used for a long time now mainly for drinking water treatment purposes and is found as an element in nature.

During the process of deciding on our research question, we decided to visit the Norwegian Maritime Authority and asked around. We discovered that the people we asked, either had not heard much of ozone or were hesitant about having ozone technology on vessels.

Later, we found that ozone is the main disinfectant used by most of the world's bottling water companies such as Nestle, Coca Cola, Pepsi and many others. So how could it be that the industry was not more positive towards considering using ozone as an alternative for Ballast Water Treatment System (BWTS)? This motivated us to explore the topic further and therefore gave us the research question: "Is Ozone a viable alternative for a Ballast Water Treatment?".

Throughout this study, we have been in contact with several industry professionals who have been able to help us in an incredible way to make this research possible. We would therefore like to warmly thank them. Also, many thanks to our supervisor Mr. Sverre Olav Fagerland who has given us a continuous and very good support during this interesting study and writing process.

Abstract

The worldwide transfer and introduction of invasive species through ballast water has caused significant environmental impact and economic damage. This issue is identified today as one of the principal threats to the world's oceans. (Stone, 2014)
The International Maritime Organization (IMO) and the United States Coast Guard (USCG) have therefore come up with ballast water management regulations which aim to prevent the transfer of non-native organisms into local environments and slowing down the damage to the ecosystem. Now with the IMO D-2 standard, the requirements for the efficiency of Ballast Water Treatment Systems (BWTS) have become more demanding.

Large resources have been used in developing and certifying different BWTS. In this study we have chosen to focus on Ozone Technology and compared this method to some of the other technologies available today, these being Ultraviolet Light (UV) + Filtration, KBAL, Electrochlorination, and Chlorine Dioxide.

The purpose of this Bachelor Study is to find out if ozone is a promising option for treating ballast water according to the new requirements today, and to compare it to the chosen alternative systems. We will also do our best to address some of the challenges regarding efficiency, cost, residual environmental pollution, health and safety problems, space restrictions as well as the handling of the technology and possible chemicals. To answer the research question, a literature study has been used as a method in addition to several interviews to gain a more extensive understanding on how ballast water treatment systems work.

The results conclude that there are many ballast water treatment systems on the market and there is not a simple universal solution that works for all ships. However, ozone technology has developed to a great extent during the last few years, finding better and optimized solutions to produce ozone gas, injecting it into the water with precise doses, off-gas management and safer controls.

Sammendrag

Verdensomspennende overføring og introduksjon av fremmede arter gjennom ballastvann har forårsaket betydelige miljømessige og økonomiske konsekvenser. Dette problemet blir i dag identifisert som en av hovedtruslene mot verdens hav.

Den internasjonale sjøfartsorganisasjonen (IMO) og den amerikanske kystvakten (USCG) har derfor kommet med forskrifter for håndtering av ballastvann som tar sikte på å forhindre overføring av fremmede organismer til lokale miljøer som kan skade økosystemet. Nå med IMO D-2-standarden har kravene til effektivitet av et system blitt mer krevende.

Store ressurser brukes for tiden til å utvikle forskjellige metoder for behandling av ballastvann på skip. I denne oppgaven har vi valgt å belyse bruken av ozon teknologi, samt andre tilgjengelige systemer som brukes til dette formålet, Ultrafiolett Lys (UV) + Filtrering, KBAL, Elektroklorinering, og Klordioksid.

Hensikten med denne oppgaven er å undersøke om ozon er et lovende alternativ for å behandle ballastvann i henhold til de nye kravene i dag, og å sammenligne det med de valgte alternative systemene. Vi vil også ta opp noen av utfordringene når det gjelder kostnader, miljøforurensning, helse- og sikkerhetsproblemer, plassbegrensninger samt håndtering av teknologi eller kjemikalier av mannskap. For å svare på problemstillingen har en litteraturstudie blitt brukt som metode, i tillegg til intervjuer for å få en mer omfattende forståelse av hvordan ballastvann systemene fungerer.

Resultatene konkluderer med at det er mange renseanlegg for ballastvann på markedet, og det er ingen enkel universell løsning som fungerer for alle skip. Imidlertid har ozon teknologi utviklet seg i stor grad i løpet av de siste årene, og funnet bedre metoder for å produsere ozon gass, å tilføre dette i vann, presisjons-dosering, utlufting av rest-ozon, og kontroll systemer, noe som gjør denne teknologien mye mer effektiv.

Glossary

Biocide	Chemical substance intended to destroy, deter render harmless or control harmful organisms
BWMS	Ballast Water Management System
BWTS	Ballast Water Treatment System
By-product	A secondary product from a chemical reaction or manufacture
CE certification	Conformité Européenne, Conformity with health, safety and environment standards for products within the European economic area.
Cl_2	Chlorine
ClO_2	Chlorine Dioxide
DNV-GL	Det Norske Veritas, Norwegian risk and classification company
DO	Dissolved Oxygen
DPB	Disinfection by-product
Eco system	A biological community of interacting organisms
FDA	Food and Drug Administration
Flocculation	A process combining smaller particles into larger flocs
GRAS	Generally Recognized as Safe
HSE	Health, safety, environment
HCL	Hydrogen chloride
IMO	International Maritime Organization
KBAL	Knutsen Ballast Water
KVOC	Knutsen volatile organic compounds

mV	millivolts
NaOCL	Sodium hypochlorite
NM	Nautical Miles
NMA	Norwegian Maritime Authority
O_3	Ozone
ORP	Oxidation Reduction Potential
OSHA	Occupational Safety and Health Administration
Oxidizing	Combining chemical with oxygen
PLC	Programmable Logic Controller
PPM	Parts Per Million
SARS	Severe acute respiratory syndrome
TRO	Total Residual Oxidant
Turbidity	Measure of degree of particles affecting the transparency of the water.
USCG	United States Coast Guard
UV	UltraViolet radiation
Venturi Injector	Reduced fluid pressure when fluid flows through a constricted opening, creating differential pressure and hence vacuum, for O3 gas injection

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1. Introduction

Considering the dramatic situation the world's oceans faces regarding pollution, climate change and the extinction of several aquatic species, it is now more important than ever to conserve the local environments. As the worlds average temperatures rises together with that of the oceans, aquatic species are far more vulnerable than before.

The principal transportation method for international trade is the maritime shipping industry (Thibault, 2011).

For many generations, the worlds vessels have been discharging ballast water containing foreign marine life into sensitive ecosystems, causing immense damage through introducing invasive species which take over and often eliminate part of the local marine life. One recent example is the invasion of Pacific Oysters into the southern coastal waters of Norway (Perrin, 2018).

Another example is the Green Crab invasion of the eastern shores of the United States, which originally were only found on the other side of the Atlantic (Tennessen, 2011).

This can cause reduction in commercial fishing activities and further damage to local tourism industry.

The uptake and discharge of ballast water by ocean-going ships therefore have the possibility to contribute to the worldwide spread of aquatic invasive species, with negative impacts on the environment, economies, and public health.

The global marine industry with its governing bodies has recognized this problem for decades and have gone through various stages in order to adopt laws and regulations controlling the discharge of contaminated ballast water. The IMO D-1 regulation, which is a voluntary measure to change ballast water at high seas, has been a step in the right direction.

International governing bodies such as IMO and USCG have developed guidelines and legislature for how to manage this issue, and deadlines are now also in place for implementing BWTS aboard the worlds fleet. As is estimated today, more than 30.000 vessels around the world still need to be equipped with BWTS. The total cost averages between 0,5 to 2 million US dollars per vessel depending on vessel size (Olofsson, 2019).

The interesting fact from a technology perspective is that there has been a fast development of sustainable product-solutions related to BWTS during the last few years, which is good news for the environment. The quest for finding "greener" options instead of the use of harmful chemicals has been on the forefront of research and development. This is the reason why ozone is such an attractive alternative for treating ballast water. Ozone is an element produced by nature and is described as a triatomic oxygen (O3), which is the most powerful oxidant found in nature (Rowen & Robins, 2020).

1.2 Research question

The research question for this study is:
"Is Ozone a viable alternative for a Ballast Water Treatment?"

It was decided on this research question because of the great importance of keeping our oceans clean through a sustainable and effective BWTS, doing our very best in preventing the extinction of native species, having negative effects on local biodiversity and to avoid the negative impacts on local economies through damages to the fishing and tourist industry.

Ballast water is essential for the safe operation of ships, but it is also one of the principle threats to the world's oceans. Therefore, it was decided to find out if ozone, being a natural and strong disinfectant, can be a good alternative for ballast water treatment today and a sustainable option for the years to come. It will also be determined in this study if ozone for ballast water treatment will qualify for approval according to the new IMO D-2 standards that must be met by 2024.

1.3 Limitations

It is important to acknowledge this study's limitations to have a better understanding of its content. During this project, the numbers of interviews for this study were limited because we were unfortunate enough to have them scheduled during the Covid-19 pandemic of 2020. However, it was fortunately possible to have phone interviews with several industry professionals.
This bachelor study will focus on ozone technology as an alternative for treating ballast water. Ozone works very efficiently in both fresh and saltwater, but this study will focus on saltwater

ozonation. It must be recognized that this has been a very complex topic considering the magnitude of technical and application details.

It has also been decided to limit the number of ballast water treatment systems that will be compared to ozone to make this study more manageable considering the complexity of this topic. Also, due to the recent implementation of these BWTS, not much information has been published regarding the experience so far. Most of the results is based on lab-research testing.

2. Literature

This study is based on research papers from different authors and publishers surrounding the topic of ballast water treatment. The pre-existing literature will be supplemented by interviews to achieve a better understanding of how the ballast water treatment systems operate.

This study is partially based on "How ballast water treatment systems work" published in Marine Insight (Kantharia, 2019). This is short summary of some the different treatments systems used today. As well as researching the challenges of ballast water management compliance (Hawkes & McMenemy, 2016).

To give us a general insight on the different BWTS that are discussed in this study "Technologies for ballast water treatment: A review" (Tsolaki & Diamadopoulos, 2010) is used, in addition to a white paper on "An Overview of Regulations and Ballast Water Treatment Technologies" (Alfa Laval, 2017).

To better understand how ozone reacts in saltwater, a kinetic study of ozone decay and bromide formation is used (Jung, Hong, Kwon, & Kang, 2016).

For a perspective on risks and hazards related to ozone, the "safe installations of ozone systems on ships" (DNV-GL, 2015) is mainly used in addition to The Linde group (The Linde Group, 2014), Ozone solutions (Ozone Solutions, u.d.). These provide information on the risks that can occur when working with ozone technology as well as general advice on usage and health effects of exposure to ozone.

The IMO Ballast Water Management Convention entered into force on the 8 of September 2017. Which sets a new standard for vessels to be implemented in 2024. It can be challenging for ship builders and owners to redesign current vessels or decide on a system that will meet the new standard with as little inconvenience as possible. This research will present a possible alternative and compare with other BWTS in the market.

As for information on the convention and regulations, information will be gathered directly from the source, IMO. There is no better way to gain an understanding and assure correct information than from the government agency enforcing this convention. Some information related to the USCG standards will be gathered from the classification agency DNV-GL.

3. Methodology

3.1 Methodology Choice

To answer the research question:

"Is Ozone a viable alternative for Ballast Water Treatment?" a qualitative method has been applied.

For research as specific and complex as this, it is best suited to use a qualitative method. Qualitative research is a type of research that collects and works with non-numerical data and that seeks to interpret meaning from these data (Crossman, 2020). A qualitative method focuses on words rather than numbers.

There has been an extensive amount of research done around the broad topic of ballast water treatment due to the huge impact on the ocean's local environments. With so much information, there has been significant access to data through online publications, and therefore a limited qualitative study in the form of a literature study has been the approach. Additionally, interviews have been conducted with several industry professionals to achieve a better understanding on how the ballast water treatment systems work.

3.2 Approach

A qualitative method is suitable when you have little knowledge and experience on a topic and can provide a more comprehensive insight because of the great openness of the approach. One also has few restrictions on the information collected and can get the most content out of the literature. This study uses secondary data written and published by others, and not research done ourselves (Jacobsen, 2005). This way it is possible to investigate what people and authors who are central to the topic have said and believe. Since there is a lot of information available about ballast water treatment systems, where literature from different authors have different opinions, it can make this study more challenging, as one must be critical to what is the best information.

This study, in addition to being based on existing research, also has conducted 7 interviews to gain a broader understanding on how the ballast water treatment systems work.

3.3 Critical Source Evaluation

By using a literature-based approach, it is possible to acquire knowledge through research studies published by many different authors. It is then important to determine the reliability of the sources so that the information found is credible.
This bachelor study considers the origin of the source, its purpose and whether it is printed from a neutral point of view or a company trying to sell their products.
As the internet is used to collect all kinds of information, great importance has been given to assessing the quality of the websites used, as well as the date of publication due to the fast development of the technologies mentioned.
To enhance the credibility and reliability of this study, focus on using as many articles and studies possible by reputable organizations such as DNV-GL, IMO, The Norwegian Maritime Authority and the United States Coast Guard has been of the utmost importance.

3.4 Research Ethics

As mentioned above, this study consists mainly of secondary data. Emphasis is made to reference all the literature used to make this study possible, so that it should be easy to verify the information in this study. This is also to respect copyright and credit the authors behind the publications. This has been carried out in accordance with the school's guidelines for source referencing.

4. Ballast Water

4.1 Introduction

Ballast water is kept in onboard tanks, and carried by ships to ensure stability, trim and structural integrity of a vessel during a voyage. When a ship loads cargo, the ballast water is discharged. When a ship unloads cargo, it fills its ballast tanks with water.

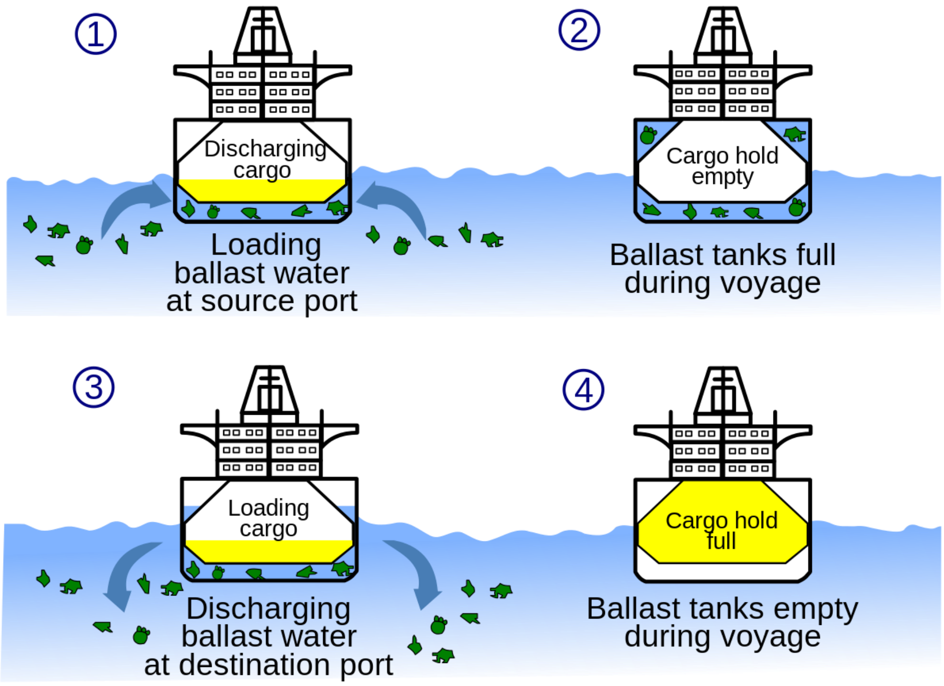


Figure 1: Description of ballasting and de-ballasting process

Ballast water can contain many species of microorganisms, crustaceans, mollusks, phytoplankton, zooplankton, among others. According to Hans Buch Marine these could be introduced to new marine environments and pose a threat to the local marine ecosystems causing severe ecological impact as well as economic problems for coastal communities as follows:

- Compete with local species for food or habitat
- Becoming invasive, and possibly outcompeting the native species
- Alter the habitat in which they live
- Carry diseases or parasites
- Increase the risk that already threatened species will become extinct or displace native species from an area
- Causing a decrease in the local economy based on fishing

One tragic example of an invasive species was the introduction of the 1991 cholera outbreak in South America. An Asian strain of cholera was transported to Peru's coastal waters via ballast water. This virus created a huge negative impact by sickening 300,000 people and killing almost 3,000 (Thibault, 2011).

Invasive aquatic species is one of the five greatest threats to the world's oceans, in addition to overfishing, coastal pollution, temperature-increase and acidification (Stone, 2014)-

It is estimated that around 4000 - 7000 different species are transferred daily via ballast water around the world, and the cost of containing the damage caused by these invasive ocean creatures is approximately $14.2 billion per year in the USA, and €1.2 billion per year in Europe (Hawkes & McMenemy, 2016).
Aquatic invasions are virtually irreversible and, once the newcomers are established, their impacts may also increase in severity over time (David et al., 2013).

4.2 Laws and regulations

The issue of microorganisms in ballast water was first raised by the International Maritime Organization (IMO) in the late 1980's (The International Maritime Organization, 2020). This resulted in the IMO Ballast Water Management (BWM) Convention which entered into force in 2017 (International Maritime Organization, 2017) and the United States Coast Guard (USCG) Ballast Water Management Regulations entering into force in 2012 (DNV-GL, 2020). These aim to prevent the transfer of invasive species in ballast water by imposing limits on the number of viable organisms allowed in ballast water discharges. This requires ships to not only manage, but also treat their ballast water.

The IMO convention entered into force on the 8 of September 2017 and will achieve its goal through the D-1 and D-2 standard.

The D-1, referred to as the exchange standard, requires ships to exchange 95% of their ballast water, 200 nautical miles from nearest land and at a minimum of 200 meters deep. If 200 nautical miles cannot be achieved, it shall be at least 50 nautical miles and 200 meters deep. If depth and distance requirements cannot be achieved at all, the authorities can in waters they have jurisdiction over, designate ballast water exchange zones. This is a special area where ships can empty their ballast water. Ship owners are encouraged to contact port authorities to find out where these zones are.

The D-1 standard, after the convention went into force, is required by all vessels, except for the ones working in local waters and with permanent ballast water in sealed tanks.

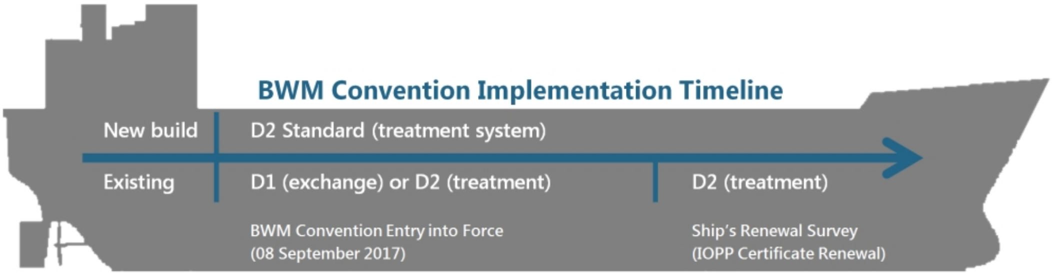


Figure 2: Description of the BWM convention implementation timeline (Smedley, 2016)

The D-2 is referred to as the ballast water performance standard. This specifies the acceptable level of organisms that may be found within discharged ballast water (Maritime and Coastguard Agency, 2018).

By 2024 all ships must meet the D-2 standard. This means that all the vessels, excluding the ones mentioned above, must conform to the D-2 standard, which will involve installing a system to treat the ballast water. The convention does not describe how this must be achieved, only the level of microorganisms present and that no toxic product is released with the ballast water (International Maritime Organization, 2017).

In addition to these two standards, the convention also requires a ballast water management plan to be established for every vessel. This plan contains details for procedures for discharging of ballast water, use of chemicals and regulations for treatment.

This plan is specific to each vessel and in case of D-2 installation, must contain a description of the ballast water system, and the procedures for exchange. It also details an awareness of risks and hazards for crew and environment by using the BWTS and will propose precautionary practices and contingency measures. The vessel is also required to keep a ballast water record book (Singh, 2019).

The convention is international, but some countries have their own standards and regulations such as the USA (DNV-GL).

The USCG has very thorough procedures for a BWTS to gain type approval. The USCG has higher demands than IMO for the treatment of ballast water. For the IMO ballast water elimination process, it is enough that the organisms no longer have the ability to reproduce, but for the USCG every microorganism must be dead upon discharge (United States Coast Guard, 2012), and additional suggestions as described within its operational procedures as follows:

- Cleaning the ballast water tanks regularly to remove all sediments
- Removing fouling from the hull, pipes and tanks on a regular basis
- Rinsing the anchor and the chain when it is retrieved
- Keeping a log for ballast and fouling management.
- Ballast water management plan is required but unlike the international convention it is not required to be approved by a third party.
- Before a vessel arrives at a US port, a call must be sent 24 hours in advance. This call will be answered with instructions on where the vessel can discharge their ballast water before entering the port. (DNV-GL)

4.3 Treatments used today

Before considering any treatment technology, it is necessary to understand certain factors of water quality as well as the legal requirements. The water pumped into a vessel's ballast tanks can vary significantly depending on water turbidity, and it will affect different BWTS in different ways. Specific water characteristics may limit a system's ability to comply in a given situation or cause it to consume more power. The following criteria are important for the shipowner to evaluate and consider when selecting a BWTS:

- Approval Requirements (National & International)
- Overall effectiveness
- Safety
- Cost
- Quality of water where the vessel will operate
- Climate & region
- Salinity
- Environment-friendliness
- Space restrictions
- Ease of operations

Traditionally the use of chemical treatment, seawater chlorination, UV and Filtration to eliminate microorganisms in ballast water has been the norm according to interviewees working with BWTS. Today, the treatment product must achieve the IMO or USGC standards in order be approved, installed and demonstrate that the disinfectants are degradable or removable before the discharge of ballast water.

Most approved BWTS today are based on different technologies, which will be discussed further below (Kantharia, 2019).

4.3.1 Filtration + UV

Both filtration and UV technologies are promising options for treating ballast water but do not meet the D-2 requirements standing alone, unless a UV BWTS is treated two times. A combination of these two technologies is therefore one of the more common treatment methods today. Approximately 50 % of the vessels which have a BWTS installed today use filtration + UV. This process is effective although it is used for vessels that do not require treating high quantities of ballast water (Alcántara, 2018).

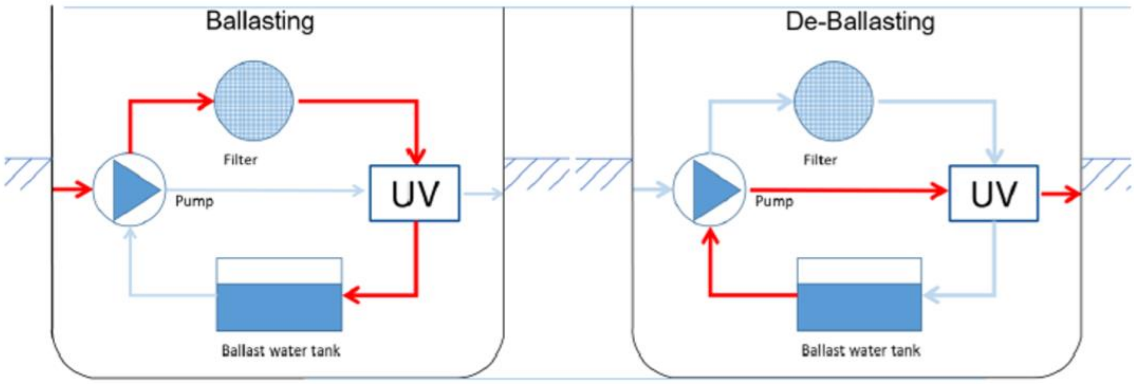


Figure 3. The process of the filtration + UV system

Filtration is a physical treatment of ballast water. It removes solid material, such as suspended particles and larger microorganisms (Tsolaki & Diamadopoulos, 2010), (Alfa Laval, 2017).

Various versions of filtration systems are available. Some are designed and works by leading the water through a series of porous disks or screens. These screens stop any solid material from passing through along with the water. The screens will have to be changed or backwashed on a regular basis so that the filter does not clog up.

With no chemicals this system is eco-friendly. The downside of the filtration process is that it is effective on large materials but traditionally has no possibility of being effective against the smaller microorganisms.

Filtration can help by supplementing other systems by pre-treating the water but cannot work alone since the system will then not reach the D-2 standard.

There has been an interesting development within UV technology over the past years. These products center around lamps emitting ultraviolet rays, which when correctly installed changes the DNA of the microorganisms rendering them harmless and unable to reproduce. This method is successfully used all over the world for drinking water treatment and is effective against most microorganisms (Kantharia, 2019).

This treatment method briefly explained, leads the water through a reactor chamber that is surrounded by UV lamps. A certain reaction-time is required for this process to be effective. After this, the treated ballast water is pumped and moved on for storing or discharged.

UV is only active during the disinfection process, where the water passes the lamps, and does not create any disinfection-residual or by-products after this point. This makes it harmless for the marine ecosystem but means that the system will not treat the inside-surface of the ballast water tanks (Bircher, 2016). One of the principal factors for the effectiveness of UV treatment is the clearness or transparency (turbidity) of the water. This is explained through the ultraviolet ray's need and ability to reach all the way through the water and react with every microorganism. If the water is not clear enough, an adjustment of intensity in the lamps or more powerful lamps are required (Hydro Group) .

Other factors are the concentration of possible chemicals or pollutants in the raw water being treated, organic or non-organic and how much "dirt" is in the water. This could possibly seriously affect the quartz glass and inhibit the UV light transmittance rate (Albatross UV).

Standard UV treatment technology faces a challenge with matching the criteria of the USCG, because it lacks the ability to eliminate every organism. So, it will require excessive UV power to meet the USCG standard, making other systems more lucrative. For the IMO, UV can be used as an acceptable option for the D2 standard, provided that the ballast water is treated two times (Casas-Monroy, et al., 2018).

4.3.2 KBAL

The information for this section is gathered from an interview with two persons working closely with the KBAL system.

KBAL uses no filtration and no chemicals. The system uses however UV technology in combination with a fast drop in pressure creating a strong vacuum. This system has few movable parts, and in Knutsen's own words it avoids downtime, is easy to maintain and runs automatically.

The BWTS from KBAL works by pumping the untreated ballast water up to a pressure vacuum reactor. The water is then quickly and dramatically dropped down in the pressure vacuum reactor and the weight of the water increases the pressure additionally. This causes the water to “boil” at low temperatures, thus eliminating most microorganisms. After the pressure treatment, the water moves on to UV treatment to eliminate any remaining microorganisms before it enters the ballast water tanks. This whole process kills 99.9% of all microorganisms.

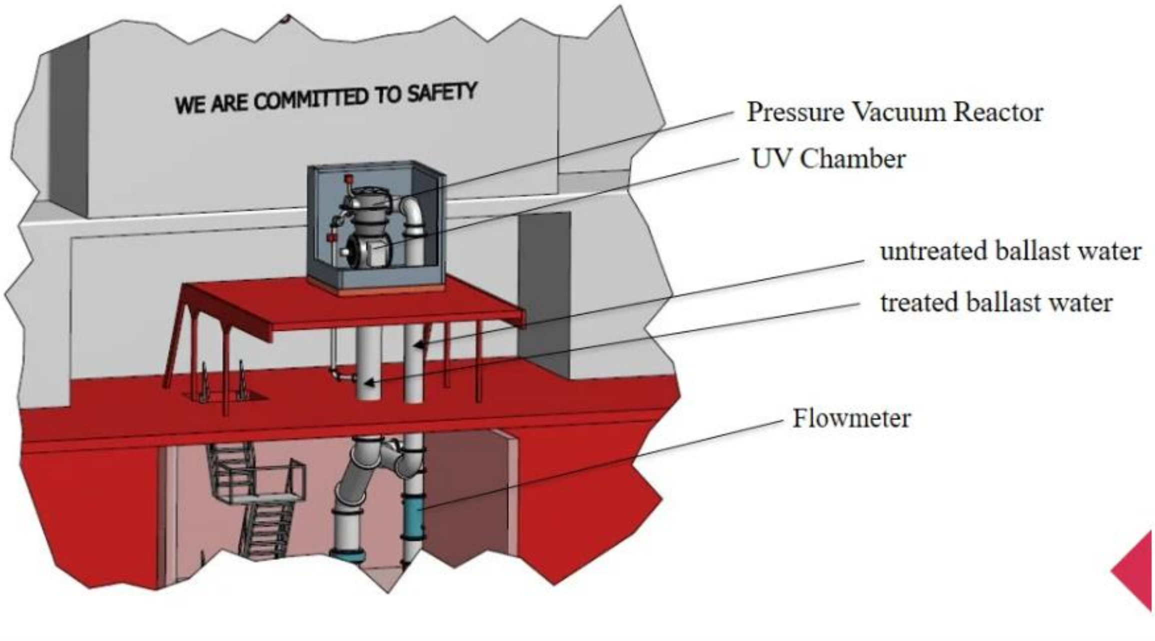


Figure 4: The KBAL System, Picture credit to Knutsen OAS

There is a downside to this system, which is a complex installation due to all the piping required through several decks. It is a challenge to retrofit a ship, so this solution is more convenient in new builds.

KBAL meets the D2 standard and is currently in the process of qualifying for USCG standard as well. In addition to this if desirable, the system can be used to sanitize fresh water.

4.3.3 Seawater Electrochlorination

Seawater Electrochlorination is an approved BWTS technology which oxidizes and eliminates microorganisms and aquatic invasive species through the on-site production of Sodium

Hypochlorite (NaOCl) from the salt present in seawater. This is a highly effective disinfectant and has been used for many years to avoid marine growth in sea chests and seawater piping together with heat transfer systems on marine installations.

It is important to realize that although the term electrochlorination may suggest the presence of chlorine, the generation of sodium hypochlorite is a “diluted bleach” and has nothing to do not with chlorine gas (Apetroaei, et al., 2018), (Tsolaki & Diamadopoulos, 2010). Although this technology has a reputation for safe, convenient, reliable and effective operation, there exists certain practical and operational limitations. These can be summarized as follows:

- When the salinity concentration within the incoming ballast water is low, the efficiency of the electrochlorination system decreases. This in return means that the power consumption will increase to compensate, and at the same time makes it more difficult to produce the required amounts of the Sodium Hypochlorite disinfectant. This method may therefore not be effective in cases where ballast is taken from fresh or brackish water (Ship Insight, 2019).

- The seawater temperature also affects the efficiency of this system, as situations with lower water temperatures will decrease the production of the Sodium Hypochlorite. In order to solve this, usage of the vessels engines needs to support the increase in temperature, which also elevates the installation cost and complexity of the system (Alpha-Purify, 2018).

- The electrochlorination BWTS uses a chemical process which creates a safety-concerns related to the generation of hydrogen and chlorine gases. These two are flammable when mixed. The chlorine gas is also highly corrosive(Tuthill, Avery, Lamb, & Kobrin, 1998). The significance of these dangerous gases needs to be evaluated carefully, as it could pose danger to the crew and a long-term risk to the ballast water tank coatings. (Fradelos, 2018)

4.3.4 Chlorine Dioxide (ClO2)

Another disinfectant used for BWTS worth mentioning is chlorine dioxide. This is a yellow to reddish-yellow manufactured gas that does not occur naturally in the environment and is explosive under pressure. Chlorine dioxide is successful at removing a wide range of organisms, it can be practically delivered at an effective dose under operating conditions, and it decays rapidly to safe, non-detectable limits (Maranda, Cox, Campbell, & Smith, 2013).

Unlike chlorine that tries to react with everything, chlorine dioxide only reacts with living organisms. Chlorine usage can result in toxic byproducts, chlorine dioxide does not. It does not require any additional treatment or neutralization before de-ballasting. This treatment is considered as one of the better options for treating ballast water with higher turbidity (Ship Insight, 2019).

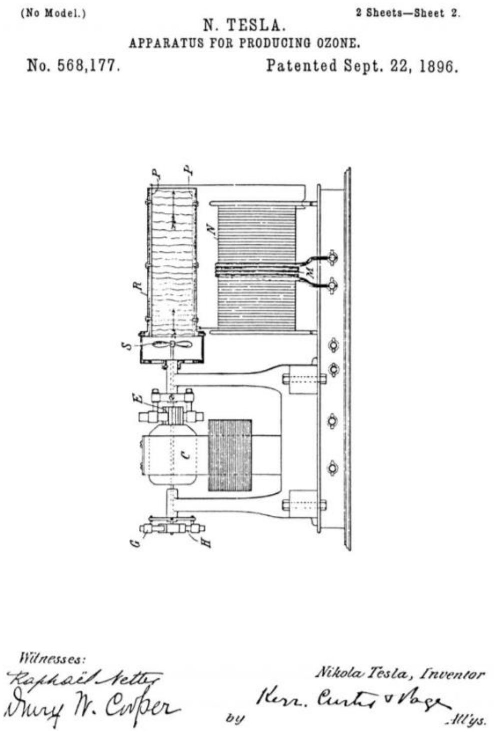
Chlorine dioxide possesses similar hazards to chlorine, but some more severe, such as making fires worse and is also toxic to aquatic life. Chlorine dioxide is also fatal if inhaled and causes severe skin burns and eye damage upon contact (National Library of Medicine).

It is complicated to transport and is therefore usually produced on site. Chlorine dioxide is usually generated in the form of a liquid solution or gas, using hydrochloric acid (HCl) or chlorine which is mixed with sodium chlorite. This means that chemicals need to be purchased, stored onboard the vessel, and the crew needs to be trained to handle these products. This could be considered a downside when considering a BWTS based on chlorine dioxide. (Maranda, Cox, Campbell, & Smith, 2013), (Alfa Laval, 2017).

5.0 Ozone

5.1 Introduction

According to history, Martin Van Marum, a Dutch chemist was the first person to detect ozone gas due to its characteristic smell around his electrifier. However, it was not mentioned by its name until 10 years later in 1840, in a writing of Schönbein, a German scientist. He called this gas 'ozone', which originates from “ozein”, the Greek word for scent. Schönbein performed many studies on the disinfection mechanisms of ozone which made it possible for the first ever ozone generator to be manufactured in Berlin by Von Siemens. Since then, many scientists and engineers have been fascinated by ozone, even Nicola Tesla created several patented ozone generators in his time.



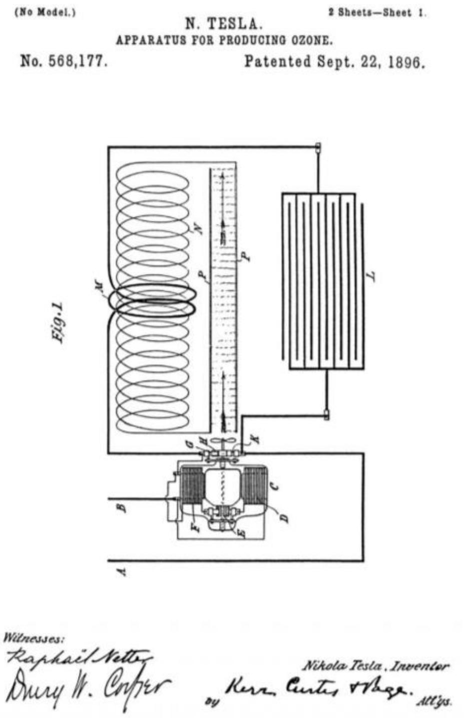


Figure 5: Apparatus for producing ozone by Nicolas Tesla

In 1893, Nice became the 'place of birth of ozone for drinking water treatment' and ozone became a popular choice as a disinfectant for drinking water in Europe. Today, chlorine is preferred over ozone for municipal drinking water disinfection, although ozone has proven to be more powerful against certain microorganisms that have developed resistance to disinfectants (Lenntech).

Ozone has been proven efficient for the disinfection against the SARS virus, where inactivation of the SARS virus was completed during 4 min (Jia-min, Chong-yi, Geng-fu, Yuan-quan, & Rong, 2004).

Also, in Western Norway, a large ozone system to treat the water-reservoir at Langevatn in Rogaland is now being installed by the local operator IVAR (Water World, 2015) .

Today, The Norwegian Maritime Authority, have seen an increase in the use of ozone technology on board many vessels. An example of this is in fishing vessels and live fish carriers using ozonated water to disinfect onboard tanks and pipes (Normex), (Norwegian Maritime Authority, 2015).

5.2 How does Ozone work?

Ozone is a molecule that is made up of three oxygen atoms. It is an unstable blue gas with a powerful odor. Ozone (O3) is also found in nature, produced in two principal ways; through UV-light reacting with the oxygen in the atmosphere to produce the ozone layer, and when lightning strikes during a thunderstorm. Both methods break-up oxygen molecules to form ozone.

Ozone in the ozone layer filters out the UV rays from the sun which are dangerous to life on earth. Today, ozone can be produced for commercial and industrial use, simulating the same methods as nature, but on a much smaller scale (Ozone Solutions, u.d.). Ozone can be effectively used for the disinfection of air and water, the latter is the interest and principal subject of this paper.

It is a strong disinfectant agent with high germicidal properties acting in the inactivation of a wide variety of pathogenic organisms, including bacteria, virus and protozoa. Unlike chlorine, ozone does not form halogenated compounds with organic matter (Botelho da Silva, de Mello Luvielmo, Curtinovi Geyer, & Prá, 2011).

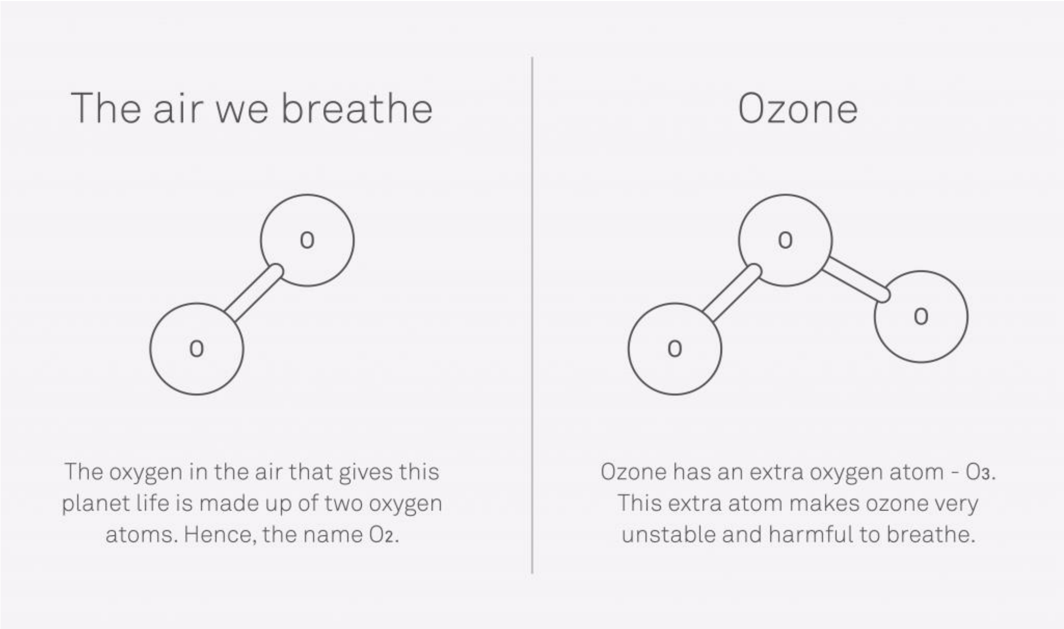


Figure 6: Oxygen vs Ozone

The lifespan of ozone ranges from a couple of minutes to hours depending on its surrounding conditions. Ozone will for example have a longer lifespan in fresh water than in sea water. The Ozone chemistry in seawater is also considerably different to that in freshwater due to the presence of bromide, Br-, in the seawater (Herwig, Perrins, Cordell, & Dinnel, 2006).

When ozone is injected into seawater, multiple powerful reactions take place. Such as the bromide found in saltwater being oxidized by ozone converting it into bromines, like hypobromous acid (HOBr) and hypobromite ion (OBr^-). The interesting result of these produced by-products from the reaction with ozone, is that both these compounds have strong disinfection properties and will effectively kill and eliminate the living organisms in the ballast water (Jung, Hong, Kwon, & Kang, 2016).

5.3 Ozone Generation

The information in this section is mainly gathered from interviews with people working closely with ozone systems.

Ozone is normally produced in a generator through the corona effect. During this process, an ozone generator uses dry air or oxygen as its source gas. By then adding high voltage, the oxygen molecule splits into two oxygen atoms. These atoms can then combine with other oxygen molecules which make a molecule with three oxygen atoms, and thereby making ozone. As mentioned above, the ozone molecule is very unstable and if it does not collide with another oxidizable molecule, it will decompose into oxygen again (Biozone, 2018), (Gromicko).

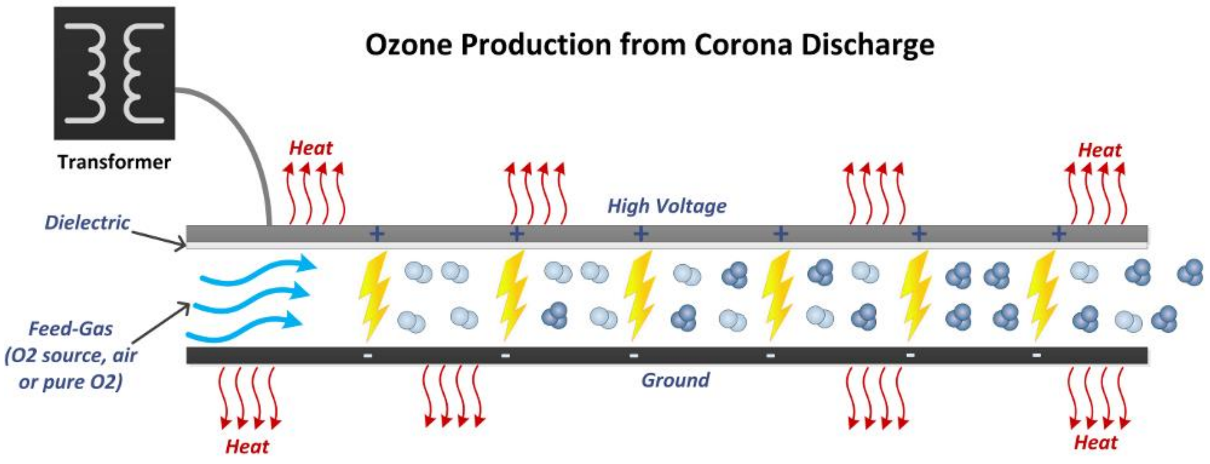


Figure 7: Oxygen passes through the corona discharge and is converted to ozone

There are four main components that must be present when it comes to ozone generating BWTS:

- Feed gas (compressed air, oxygen – or both)
- Ozone generator
- Gas-to-liquid gas transfer (injection system)
- Monitoring and control
- Neutralization

Each of these components will be further discussed below:

5.3.1 Feed Gas Preparation

When ozone is generated through a generator, feed gas is required which is normally based on oxygen which is generated from compressed air.

The compressed air source should be extremely clean and dry in order to achieve good efficiency in the oxygen and ozone generation process. Poor quality air or oxygen leads to contamination of the ozone generator.

5.3.2 Ozone Generator

For BWTS the ozone corona effect is used in generating the gas because it produces higher concentrations of ozone. Oxygen is selected as feed-gas and is flowed through the high-voltage electric corona field produced between conductive and dielectric surfaces.

The ozone concentration produced generally depends on:

- The oxygen purity of the feed gas
- The voltage applied across the reactor cell
- The flow rate of the feed gas through the reactor cell
- The temperature of the feed gas

Therefore, higher purity of oxygen and voltage across the reactor cell, while low flow rates, high concentration of ozone gas will be produced.

5.3.3 Mass Transfer (gas-to-liquid)

During this process, the ozone gas is injected and dissolved into the ballast water. The overall effectiveness of the BWTS depends on this process of injecting and maintaining the gas in the water (Di Bernardo; Dantas 2005). This can be achieved through the following ways:

1. By transferring the ozone gas into the water through a bubble-diffuser method. The devices used are categorized as diffuser stones or diffusor tubes. This method is not very efficient, as efficiency-levels of 40-50% are the maximum achieved. This means half of the ozone gas goes to waste as off-gas into the tanks.

2. Another way is by using a venturi injector. This works by forcing water through a conical body which creates a vacuum or suction through a pressure-drop in the water, so the ozone gets injected, mixed and dissolved into the water. This is by far the most popular method which the industry has adopted during the past 10-15 years, where mass-transfer efficiency-rates of 90-95% are achievable.

3. The most modern and sophisticated method is by using a microbubble generator. During this process, the suction for the ozone gas is created directly in the pump-head, through a variation of hydraulic forces producing pressure ozonated microbubbles. While the above mentioned technologies produce what are called macro-bubbles (bubble size above 1 mm), this technology produces micro-bubbles with a diameter under 50 microns (0,05 mm), which means much more efficiency is achieved from the ozone-gas, not only in terms of high mass-transfer rates of 96-98%, but through these extremely smaller bubbles more contact and ozone half-life is achieved. This means that the ozone will last longer in the water and can reach corners of the ballast water tanks in a more efficient way. The fascinating advantage with this technology producing such small ozone-bubbles, the lifespan of ozone in the water increases and therefore, less ozone is needed to reach a good disinfection level (Galdeano, et al., 2018).

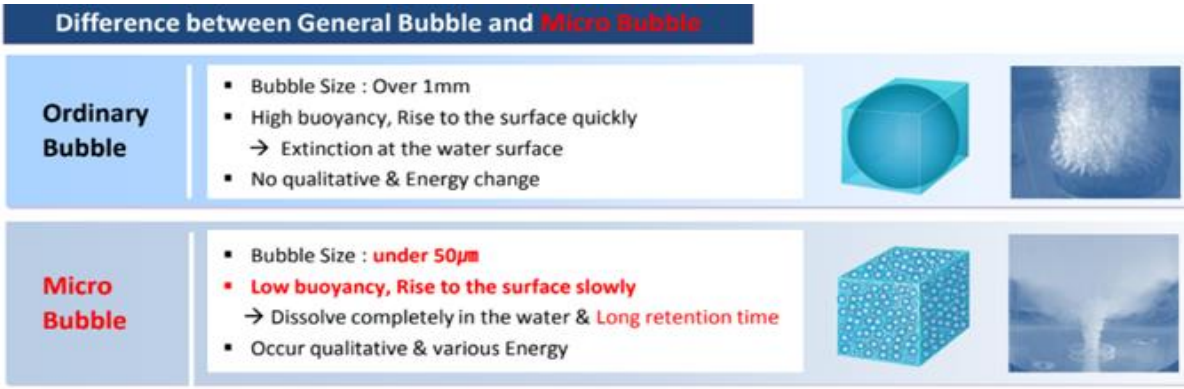


Figure 8: Difference between an ordinary bubble and a microbubble

Other important components and considerations for this mass transfer process is the following:

- Backflow Prevention System: Any gas-delivery system into water, has the potential risk of backflow, which means water backing up into the gas-tubing and destroying the generator. Special check (anti-return) valves are a vital part of any ozone-installation.

- Contact time: For any disinfectant to work properly to kill microorganisms and other living species, dosage and contact-time is required. Dosage has already been discussed above, but contact-time is of equal importance. The combined effect of the are referred to as CT-Value, which is defined as dosage multiplied with contact-time. Most microorganisms and organisms have a defined level of dosage and contact-time which is required to kill them by an oxidant such as ozone.

- Off-Gas management: It is impossible to inject & dissolve all the ozone gas into the water, and a certain percentage will bubble out of the water. If it is a very well-engineered installation, especially when using a microbubble injection-system, this amount of ozone gas can be as low as 5-6%, but it still needs to be removed from the pipe or tank. This can easily be done just after the ozone injection through a vent-valve installed either directly on the pipe, or on a contact-tank. From this vent-valve, the undissolved ozone gas is led to a catalytic ozone destruct system, which will convert the ozone back into oxygen. Any remaining ozone gas in the ballast tanks will easily be ventilated out from the various vent-pipes & ducts in the ballast water tanks onboard the ship. This is especially important to prevent corrosion in the tanks and pipes. As mentioned before, ozone is in fact not corrosive in water, but it is in gas form in the "air".

5.3.4 Monitoring & Control

Ozone gas being such a strong oxidant and disinfectant produced onboard, means that control and monitoring is of utmost importance. Specific exposure levels need to be determined for each species (Grotmol, Dahl-Paulsen, and Totland 2003), and reliable methods to measure ozone in seawater are therefore needed to ensure that lethal limits are not exceeded (Gonçalves & Gagnon, 2018).

There are sensors installed in the water to continuously measure the oxidation power of the ozone. In addition, there are ozone-gas monitors installed in the environment where the ozone generator is installed. These sensors are connected to both visual and audio alarm systems and will shut down the ozone generator if the leak continues and gas-contamination reaches dangerous levels.

For ozone BWTS, the following monitors and control-systems are used:

1. ORP (oxidation reduction potential): As mentioned before, ozone in saltwater has a short lifespan, but it reacts with other oxidants in the water. Therefore, the ozone itself is not easy to measure, so one measures the general oxidation-level in seawater using an ORP system. The most common unit for expressing ORP is millivolts (mV) (Apera Instruments, 2018).

2. Automation: The ORP system is connected to the ozone reactor power supply through a PLC (programmable logic controller), which will automatically control the ozone output through a pre-set point value.

3. Ambient Ozone Detectors: Monitors the ambient ozone-levels in case of gas leaks. A modern ozone system which has been correctly installed according to specifications, has little or no risk for creating a leak by itself.

5.3.5 Neutralization

As explained above, upon injecting ozone into seawater, numerous chemical reactions take place, and new oxidants are formed like bromine. Normally only smaller amounts of bromine compounds remain in the treated water. If the levels are too high, an onboard neutralizer must be used to inject thiosulphate (non-toxic) to reduce them to acceptable levels. The ozone system will in any case normally produce low concentrations of active substances.

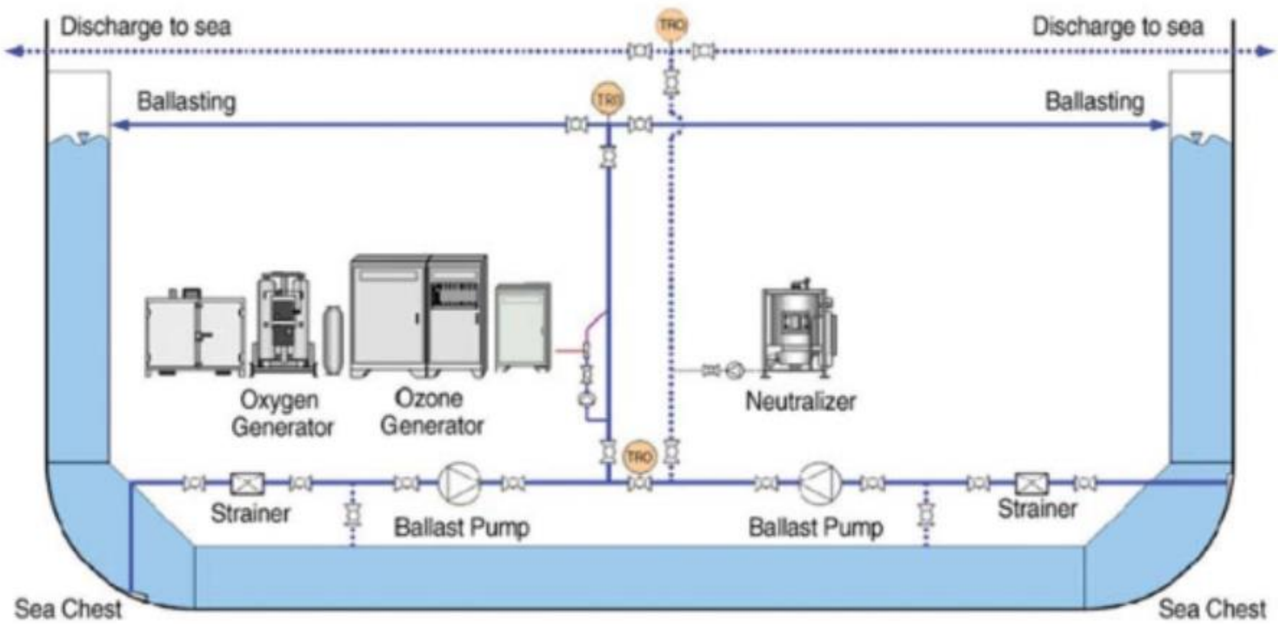


Figure 9: Ozone system for treating ballast water

5.4 Risks and Hazards

The same oxidizing properties that allow high concentrations of ozone to react with organic materials, gives it the ability to react with similar organic material in the human body. If inhaled in high concentration over longer periods of time, ozone gas could cause chest pain, shortness of breath, coughing and throat irritation. Research has shown that people's susceptibility to ozone varies greatly from person to person (Ozone Solutions, u.d.).

As with any strong chemical or toxic gas, there are risks involved. Ozone gas exposure can occur due to leaks from generators, supply hoses or from the water itself if ozone off-gas management and proper ventilation from tanks is not correctly implemented.

In accordance with the Norwegian Maritime Authority Regulations of 1 January 2005 No. 8 concerning working environment, health and safety of persons working on board vessels (The NMA HSE Regulations), there are general requirements for risk assessment regarding the use of new working equipment and new technology in section 2-2 paragraph 1 of these regulations.

This implies that:

- hazards on board shall be identified
- an assessment of the risk represented by the hazard shall be made
- relevant safety measures shall be implemented

As mentioned before, ozone is a powerful reactive substance which means that one should have respect for ozone but not be frightened of it. Ozone is a dangerous chemical according to the Norwegian Maritime Authority HSE Regulations (Norwegian Maritime Authority, 2015).

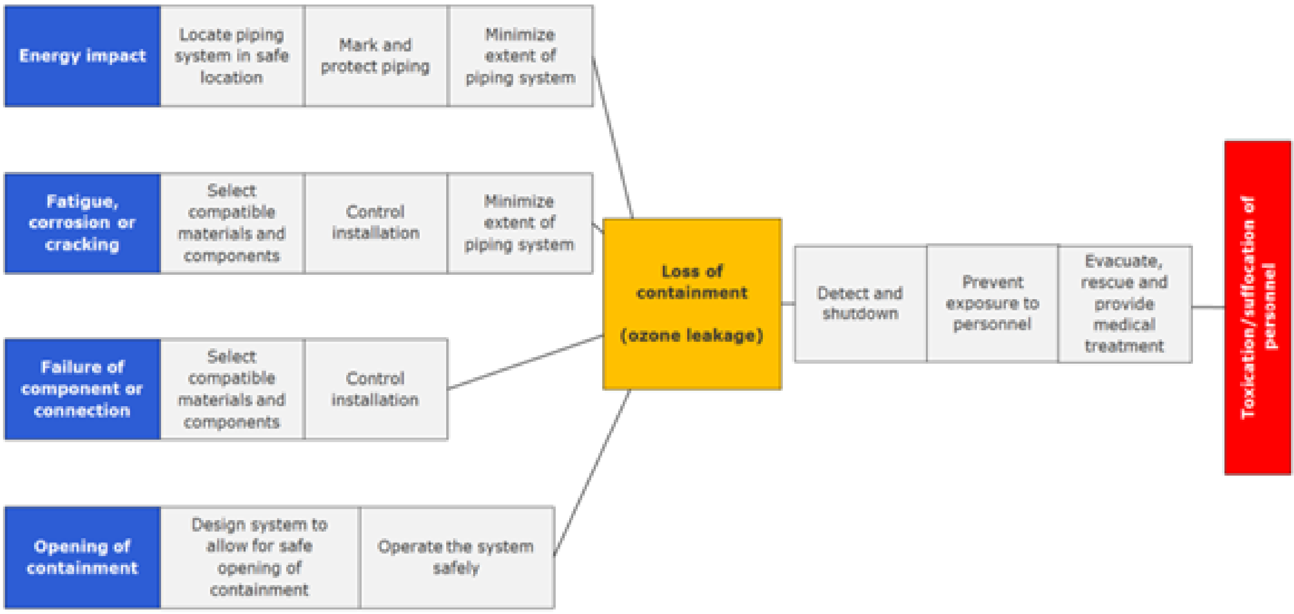


Figure 10: shows a diagram of risks according to DNV

This risk bowtie-diagram above published by DNV, shows the main event in yellow located in the center of the diagram. This shows the possible loss of control or containment over a hazardous ozone gas leakage.

The consequences, marked red at the end of the diagram, can occur after the loss of containment. Recommended actions are labeled in grey to the right in the diagram in case of leaks to protect and if necessary, treat the crew medically.

The possible causes for this situation are located on the far left, marked blue. These are possible situations that can cause ozone leaks but can be avoided through the recommended prevention measures, called mitigation barriers, marked grey to the left in the diagram. These prevention barriers will be of help to reduce possible risks if included and installed correctly following all necessary guidelines (DNV-GL, 2015)

Ozone itself does not burn, but it is crucial to be aware that in contact with combustible substances it will increase the risk of fire due to its oxygen content and can fuel any existing fire significantly (The Linde Group, 2014).

One of the advantages of ozone is that it has a pungent odor much like chlorine. The recognized ozone odor detection threshold is from 0.01 ppm to 0.04 ppm. This is an advantage for quick detection of ozone in the environment and thereby making it easier to avoid. This is one of the principal reasons why very few serious accidents occur with ozone. However, the nose rapidly loses its ability to detect ozone and it is crucial not to only rely on odor as a warning of high ozone concentrations (The Linde Group, 2014).

To safely work with ozone, risks must be identified so accidents can be prevented.

Prolonged breathing in air containing ozone concentrations beyond the permissible exposure limit must be avoided. The 8-hour exposure limit varies from country to country, for instance: 0.1 ppm in the US or 0.2 ppm in the EU (The Linde Group, 2014).

Ozone gas has been classified by the United States Food and Drug Administration (FDA) as a Generally Recognized Safe (GRAS) substance, and as a safe sanitizer of water and food (Galdeano, et al., 2018).

According to The US OSHA (2008) (Occupational Safety and Health Administration) guidelines for ozone in the workplace are:

- 0.1 ppm for 8 hours per day exposure doing light work
- 0.2 ppm for no more than 2 hours exposure
- 0.08 ppm for 8 hours per day exposure doing moderate work
- 0.05 ppm for 8 hours per day exposure doing heavy work

If exposed to a higher dose of ozone during a short period, the effects can be irritation of the throat and coughing. These are not chronic and will disappear within a couple of hours.

As with any toxic gas, it is important to be aware of the emission regulations that are present. An easy way to make sure that the concentrations do not exceed a certain amount is to install an ambient ozone sensor that will set off an alarm when the concentrations are too high. This will be further explained below in the guideline of ozone.

Concentration [ppm]	Duration of exposure	Effect*	Other notables
0.01			Odour threshold
0.1		Minor eye, nose and throat irritation	Maximum 8hr exposure limit (UK, US)
0.10-0.25	2-5hrs	Headache, dry couch and some reduction in lung function	
0.2			Maximum 15min exposure limit (UK)
0.3	2hrs	Reduction in lung function during moderate work for all persons	
>0-6	2hrs	Chest pain	
1.0	1-2hrs	Lung irritation/couching; severe fatigue	
>1.5	2hrs	Reduced ability to think clearly; continuing cough, extreme fatigue may last for two weeks; Severe lung irritation and pulmanory edema (fluid build-up)	Pulmanory edema may have delayed effect
1<ppm<10		Possible coma, and as above. Severe pneumonia may occur at higher levels	
11	15 minutes	Rapid unconsciousness	
50	30 minutes	Fatality expected**	

*Based on observations from actual exposures, except from **
**Based observations on laboratory animals

Source: /5/WorksafeBC 2006, Ozone Safe Work Practices

Figure 11: The table above shows the physical effects of ozone gas on humans according to DNV.

5.5 Guidelines and Regulations

According to The Norwegian Maritime Authority (NMA), there are no particular legal requirements for ozone systems today, but all equipment taken on board and installed must be risk assessed with regard to health, safety and working environment. In accordance with the Regulations of 1 January 2005 No. 8 regarding the work environment, health and safety of the crew working onboard the vessel (Norwegian Maritime Authority, 2015).

When it comes to Ozone, there are several parts of the system to take into consideration for preventing all possible risks. Although there are no legal requirements as mentioned above, there are recommendations to follow such as the guidelines for safe installation of ozone systems on board ships by DNV-GL (2015) as follows:

Piping

- Ozone gas piping systems shall be located in safe locations to prevent damage from dropped or rolling objects.

- Ozone pipes shall be marked to separate them from other piping systems.

- Signs shall be permanently fitted in the space containing ozone piping stating that heavy lifting, implying danger of damage to the ozone pipes, shall not be done during ozone operation.

- The extent of ozone piping shall be minimized as much as possible in order to reduce the possible leakage points.

- A By-Pass (side stream) pipe-system, shall be used to inject the ozone gas into the water instead of using and disrupting the main ballast water pipe. The by-pass pipe is normally of less diameter than the principal ballast water line. Several countries require the by-pass pipe to be protected with another in case of leaks, which is called a "pipe-in-pipe" system, which is a double security in case of a leak.

- The ozone piping shall be pressure and tightness tested in the presence of the surveyor after installation on board.

Ventilation

Possible leakage points should be located as close as possible to extraction fans so that any leakage will immediately be extracted from the space. Ozone piping should as far as possible be located in a space where sufficient air flow is provided. Venting of the ozone piping systems shall not lead to hazardous ozone concentrations on deck, other compartments or in enclosed spaces.

Another recommended safety factor is to locate the ozone generator in a separate treatment room onboard the vessel.

Detectors and Sensors

As mentioned under section 5.3.4, ambient ozone gas monitors are required. In case of environments with poor ventilation, portable ozone and oxygen gas detectors should also be provided. To detect all possible leakage sources in the ozone piping system, there shall be a minimum of two independent means of ozone leakage detection. These are normally located half a meter over ground or deck level due to the fact that ozone is heavier than air, so it tends to sink rather than rise. The alarm connected to these detectors shall be both acoustic, optical, hard-wired and configured to the main ozone generator for immediate shutdown during a leak-detection.

The following situations will trigger alarms-signals:

- Ozone leakage detection
- Emergency stop buttons
- Failure of ventilation system.
- Failure to connect the water system to which the ozone is injected.

Protective equipment and handling

It is also important to implement section 4-1 of the Norwegian Maritime Authority HSE regulations regarding safe use of the equipment by the persons working onboard (Norwegian Maritime Authority, 2015).

Other Important safety measures according to the NMA are:

- everyone on board must be trained in how to act and relate to ozone gas
- there must be available protective aids in case of leak (such as a respirator with active carbon filter)

Operation Manual

Keeping an operational manual for the ozone BWTS is also necessary and it must have CE certification marking which indicates conformity with health, safety, and environmental protection standards for products sold within the European Economic Area. The manual shall be kept on board the ship.

5.6 Efficiency

During the past 30 years ozone has been used as the principal disinfectant and oxidant for the global bottled water industry because "Ozone proved to be the magical disinfectant and oxidant that could disinfect the water, the bottling equipment, the bottle, and the sealed cap of the bottle while also oxidizing any traces of odorous materials that might be present in the water. Then the ozone decomposed to harmless oxygen and thereby disappeared without leaving an undesirable taste or odor behind" (Bollyky, 2002).

Ozone is a very reactive molecule with an immensely powerful oxidizing ability. It is this oxidizing ability that makes ozone such a potent disinfection method. It is between 50 to 100% stronger than chlorine and reacts roughly 3125 times faster as an oxidizer. It has a noticeably short half-life, and because the nature of the ozone molecule is so unstable, it cannot be stored and must be generated on-site (Gad, 2010).

This is a great advantage due to the implementation of higher standards in the industries restricting certain by-products. Unlike chlorine, ozone, if installed and used correctly in regard to dosage, does not leave any by-products, giving it the status of a very environmental and sustainable technology. Ozone is also more effective in dark conditions and environments, which further makes this technology attractive for ballast water treatment (Gonçalves & Gagnon,2018).

Despite its high oxidation power, ozone dissolved in water is less corrosive than chlorinated water (Romanovski, Claesson, & Hedberg, 2020). There are other disinfectants at work in seawater in addition to ozone, which will not corrode the steel inside the ballast tanks either. Several studies confirm this additional advantage of ozone, for example in South Korea, a company called BlueBallast has a technical report proving after many corrosion tests that ozone, if used and installed correctly does not cause corrosion on the tanks. BlueBallast is the only BWTS today to successfully use ozone for ballast water treatment, without combination of other ballast treatment systems or pre-treatment. Their system is also approved by IMO and the USCG (Foster, 2020).

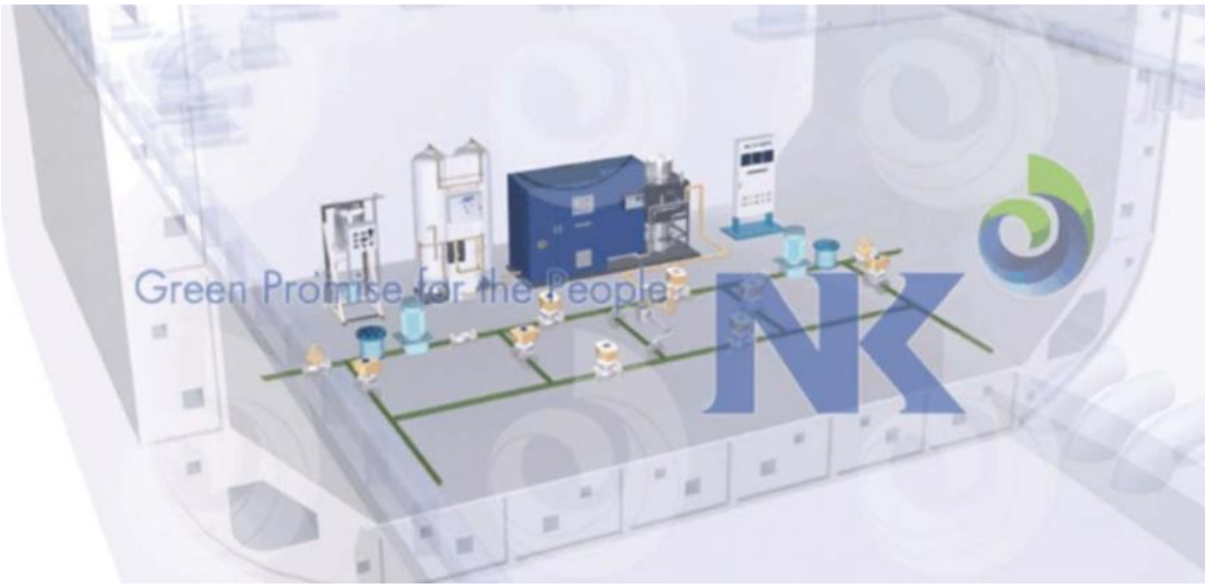


Figure 12: Demonstration of NK-O3 Blue Ballast System onboard for BWT

Figure 13. Shows the successful corrossion testing of the BlueZone BWMS

Ozone treatment also only needs to treat the water once through a single pass-injection system. With the added benefits of being produced onsite using only ambient air and electricity, and it being a natural and sustainable “non-chemical” method is disinfection, this technology is now rapidly gaining headway into many other industrial applications.

A Finnish study with laboratory experiments carried out in both Finland and the UK from 2005 studied ultraviolet light, ultrasound and ozone technologies for onboard ballast water treatment. It is worth mentioning that the ozone technology, like most technologies has evolved and improved after finding more effective ways to inject the gas into the water without losing such a considerable amount of ozone in the process. The systems available today are extremely advanced and secure in comparison to what was available only 5-10 years ago

The results from the onshore studies with considerable reliability for UV, varied between 78-100%, for US treatment between 80-99% and for ozone treatment which turned out to be the highest out of all 3 systems, between 95-100% depending on the organism group, ozone dosages and contact time.

However, during these experiments, no pre-treatment (filter) was used. To achieve the level of organism elimination that is required by IMO, the study suggests that it might be necessary to combine pre-treatment filtering with the main ballast water treatments (J, Rytkönen, Viitasalo, & Leppäkoski, 2006).

A potential advantage of the conditions in ships ballast tanks is that long contact times in the dark enhances the efficiency of using ozone and its other corresponding seawater oxidants. This may result in residual levels capable of removing many organisms, by taking advantage of the much slower residual decay in the dark and the long contact times (Gonçalves & Gagnon, 2018).

So many publications support the use of ozone as a practical and convenient disinfectant for seawater treatment as no chemicals need to be stored and is available to use any time since it is created on-site. Ozone has also proven to be effective in the inactivation of nonindigenous species in ballast water (Nauplii of the brine shrimp Artemia salina, Jureti ć et al. 2011), in the elimination of most pathogens affecting seafood in fresh- and seawater aquaculture systems (salmon, halibut, tilapia, shrimp, etc.) (Gonçalves & Gagnon, 2018).

The section bellow is based mainly on information gathered from several interviewees working with ozone technology.

In order to optimize the efficiency and security of an ozone BWTS, the following technical parameters are important factors which needs to be studied and evaluated before a final purchase decision:

- Ship´s design and capacity
- Ballast water-intake quality

    - Temperature
    - Salinity in the water
- Selection of ozone and oxygen generator
    - Required ozone concentration and dosage
- Possible pre-treatment of incoming water

5.6.1 Ship´s design & capacity

All ships are vastly different in size, which will require specific ozone generator capacity depending on the ballast water tank volume. Sizing the correct system is particularly important, making sure one does not under or oversize. It is normal to have extra ozone capacity when calculating ozone-demand, making sure there is a certain margin of redundancy. Furthermore, just like any engine or generator, one does not want the system to work on 100% of its capacity, but rather between 50-60%.

A major challenge onboard vessels is the available space, which makes it a challenge to fit new additional technology. Today, due to the extensive research & development, the ozone generators available today are much more compact with reduced footprint than only a few years ago. Furthermore, the largest and most energy-demanding component of an ozone-system is the air compressor, which is normally already part of the existing technology onboard the vessel.

The most important part of preparing an ozone ballast water installation onboard a vessel is a clear understanding of the ballast water tank-volume and the design of these. The pump capacity and water flow into the tank are also of great importance.

5.6.2 Ballast Water Intake-Quality

If the water quality in Haugesund or Stavanger is compared with that found in larger ports such as Rotterdam, Los Angeles or Shanghai, there will be high variation in degrees of contamination. While the waters here in Norway are highly transparent and clean, murky and turbid waters are found elsewhere. This enhances the demand for stronger disinfection. A ballast water management system needs to be sized for the worst possible scenario when it comes to water quality, otherwise the system could be consuming most of its water treatment & disinfecting capacities on the general contamination of the water such as oil and organics, instead of the marine organisms it was designed to reduce and/or eliminate in the first place. In addition to adding this water-quality parameter into the calculation, it is also important to factor in water-temperatures into this equation.

- Temperature: High water temperature accelerates the decomposition rate of the Ozone. Temperature has an important effect on Ozone efficiency. In saltwater, the temperature varies from -1 degrees C to 30 degrees C depending on the season and geography. In a study from 2016, temperatures between 2 degrees C and 30 degrees C were investigated in relation to Ozone decay in saltwater. The result showed that as the temperature increased from 2 degrees C to 30 degrees C, the Ozone decay rate constantly increased greatly (Galdeano, et al., 2018).

- Salinity: Salinity: As mentioned earlier during this study, the ozonation process in seawater and freshwater is extremely different due to the bromide found in seawater, the reaction between ozone and bromide produce powerful disinfectants. So, when the salinity in the water increases, the concentration of bromide also increases and therefore less concentrations of ozone is needed to create more disinfectants (Jung, Hong, Kwon, & Kang, 2016).

5.6.3 Selection of Ozone and Oxygen Generator

It is important to choose the right ozone generator depending on what kind of capacity of ballast water you have onboard.

There are several methods for choosing an ozone generator for a vessel. Although ozone companies that use their systems for ballast water treatment also have easy-to-read tables to quick-select the appropriate model, with confirmed details such as dosage and other important specifications of the selected ozone system.

5.6.4 Possible Pre-Treatment of Incoming Water

The ozone generating system with its corresponding oxygen generator, air compressor, gas-to-liquid mass transfer and off-gas management system are all very expensive components and will be greatly wasted if the water it treats is unnecessarily contaminated. A very efficient and to keep the ozone-capacity to a minimum, is to pre-treat the incoming water through a screener and a filtration system. The screener also acts as a security to avoid that items such as plastic bags and other floating debris does not enter the pumps and ozone-injectors which could create serious and time-consuming service. In worst cases, also serious and costly damage to the system itself. There are several screener alternatives on the market, many with automatic cleaning which is essential for autonomous and continued operation.

The main filter will seriously enhance the efficiency of the ozone treatment process, since it physically removes smaller particles and organics, so the ozone will not react with these elements, and rather uses its oxidation power to eliminate the living microorganisms which is the principal purpose of investing in such a system. The filter system can be a very compact system, filtering down to 20 microns or smaller.

6. Costs

6.1 Capital Cost of Technology with Installation, Start-Up & Training

The cost of an ozone ballast water management system depends on several factors. In summary these important considerations can be described as follows:

- Regulations & Relevant Required Certifications
- The Category-type and Size of the vessel
- Existing Ballast Water & Pump System
- Geographical Areas of Operation (Water salinity, temperatures etc)
- Existing Water Treatment & Air Compressor capacity onboard
- Operational and financial situation of the shipowner

Ozone BWTS installation onboard will very often use the existing compressed air capacity onboard. However, for the sake of good order and complete project investment, the cost of the fully featured air-compressor system is included into the estimated costs below.

For the example of this cost-analysis, the following type of vessel is chosen:

- A 921-feet oil-tanker with a ballast water capacity of 52.350 m3 with a breakdown of capital costs for an ozone ballast water management system as follows:

Vessel-Type	Deadweight	Ballast Water Tanks	Filtration Cost USD (optional)	Ozone System Cost USD	Installation	Total USD
Oil-Tanker	165.000 Ton	52.350 m3	545.000	755.000	Included	1.300.000

Estimated capital cost of technology are based on interviews.

6.2 Cost of Operation

1. Supervision
2. Electricity

A modern and fully featured Ozone BWTS is an automated technology platform, integrated into the ship's centralized control system. So, the supervision is minimal, and can be reduced to general overviews and inspection during ballasting and de-ballasting.

Vessel -Type	Deadweight	Ballast Water Tanks	Supervision Costs USD	Electricity Costs	--	Total Annual USD
Oil-Tanker	165.000 Ton	52.350 m3	9.500	15.000	--	**24.500**

Estimated annual cost of operation are based on interviews. The final costs will depend greatly on quantity and service-contract

6.3 Cost of Maintenance

Consumables:

- Filters, Dryers for Air Compressor(s) & Air Cooling (Oxygen & Ozone Generators)
- Solenoid, Pneumatic (air) & Backflow Prevention Valves
- Ozone Off-Gas Management & Destruct

One of the many great attributes of the ozone BWTS is that it produces ozone gas from the ambient air, which is its principal consumable together with electricity to produce this strong disinfectant. The air compressor requires periodical check and change of its incoming and outgoing air filters. In addition, the coalescent filters which removes oils and humidity (condensation) are especially important to replace.

The oxygen generator includes various valves at work, both in the solenoid (electric) and pneumatic (air) valve categories. The ozone gas backflow prevention valves also need periodic cleaning and replacement, in addition to the off-gas management systems requires changes in its Ozone destruct material annually.

Vessel-Type	Deadweight	Ballast Water Tanks	Filter & Dryer Cost USD	Valve Costs USD	Ozone Off-Gas Costs USD	Total USD
Oil-Tanker	165.000 Ton	52.350 m3	2.500	4.000	6.500	**13.000**

Estimated annual cost of maintenance are based on interviews. The final costs will depend greatly on quantity and service-contract

A common misconception with ozone is that since it is such a strong oxidant, it will increase corrosion in the ballast water tanks and therefore add a higher maintenance cost. If the ozone system is installed correctly, the ozone should stay in the water and therefore not be a problem to the corrosion of the tanks.

6.4 Service of Core Components

- Ozone Reactor Cell & Power Supply Components
- Zeolite for Oxygen Generators
- ORP Sensor(s)

Although a modern certified Ozone System is manufactured from the very best components and materials, and designed to work 24/7, scheduled service needs to be programmed so that the core components of the systems need to be serviced or replaced. This depends very much on which condition and environment the vessel operates in. The ozone reactor and power supply components which converts the O2 molecule to the O3 molecule very seldomly needs to be replaced. These are replaced only if there has been a serious water leak from above decks or similar. The zeolite material inside the oxygen generator unit can practically last forever if the compressed air is clean and filter replaced. The table below shows a “worst-case-scenario” In any case all these items must (both above and below which are described in the tables) should be present onboard the vessel as part of the spare part stock.

Vessel-Type	Deadweight	Ballast Water Tanks	Ozone Reactor Cost USD	Zeolite Cost USD	ORP Sensor Costs USD	Total USD
Oil-Tanker	165.000 Ton	52.350 m3	18.500	12.000	9.500	40.000

Estimated annual service of core component prices are based on interviews.

7. Comparison of ozone and other treatment systems

This table is based partially on information mentioned in section 4.3 and interviews with industry professionals on the following systems:

	Ozone	Filtration + UV	KBAL	Electrochlorination	Chlorine Dioxide
	Effective Treatment	Effective Treatment	High Ballast Flow Rate	High Ballast Flow Rate	Effective Treatment
	Works in all salinities	Works in all Salinities	Works in all Salinities	Effective Treatment	Works in all Salinities
+	Low Power Consumption	Low purchase Price	Minimal Maintenance	Low Power Consumption	Minimal Power Consumption
	High Ballast Flow Rate	Chemical Free	Chemical Free		High Ballast Flow Rate
	Chemical Free				
	Can work without a filter				
	Needs Separate Treatment Room	Low Ballast Flow Rate	Complex Installation through several decks	Dependent on Salinity	Cost of Chemicals
	Higher purchase price	Treatment at discharge (only UV)	Hard to retrofit older vessels	Hydrogen & Chlorine Gas as by-product must be managed	Needs separate treatment room
-	Requires Compressed Air	Costly replacement of UV lamps	Requires large UV systems	High CAPEX	Logistics and storage of chemicals
	Complex Technology with Sophisticated Gas-Sensor	Issues with growth on quartz lamps (marine biofouling)		Produces by-products and needs to be neutralized before discharge	Requires special training of personal
	Bi-Products produced if over-ozonation occurs	Corrosion issues in +18 degree C waters		Time-consuming maintenance through cleaning of electrodes	Needs gas-sensors
	Can be corrosive to metal in ballast tanks			Loss of effectiveness in cold waters	Can be corrosive to metal in ballast tanks

8. Discussion

This Bachelor-project is based on the literature by different authors who have written about Ballast Water Treatment Systems (BWTS). Most of the research found is about systems that have been in the market since the ballast water management convention came to force. As described in this study, all technologies have developed incredibly during the last years and will continue to do so. This makes BWTS interesting, especially because several of these advancements are much more sustainable than before. So many new technological advancements have improved the efficiency of these ballast water treatment systems such as injecting ozone into the water via microbbubles. All in all, much better BWTS are going to be installed during the next couple of years as the deadline's approaches. It is easy to detect a favorite among the different alternatives offered, and several companies we have approached will say their system is the best. Writing this study with a focus on being as objective as possible in our findings was therefore a major concern.

This study has found misconceptions about using ozone as a BWTS, especially the claim that it causes corrosion inside the ballast tanks. This technology has through formal tests been proven to be far less corrosive than other treatments methods. If correctly installed and used correctly, an ozone BWTS will not cause corrosion inside the ballast water tanks. It is important to mention that the BlueBallast ozone system for ballast water treatment has been approved by IMO and the USCG.

An aggressive approach to communicate directly with leading industry experts and ozone manufactures provided the necessary updated technical background information to make sure this study is up to date. All the references and interviews concluded, that ozone is extremely effective as an oxidant and disinfectant in seawater, and it will remove all of the unwanted organisms in the ballast water as long as the dosage and injection-process is configured correctly for the kind of vessel and water-characteristics to be treated.

Due to the fact the ozone gas is produced from the oxygen in the ambient air and electricity, it is very practical while environmentally friendly at the same time. Another interesting advantage is that through ozone and its additional oxidants it produces in seawater a strong residual effect is created, which is carried throughout the complete interior section of the ballast water tanks. This will eliminate fouling, biofilm and general microbiological growth and cross-contamination inside the tanks. The downside of ozone technology is its high investment cost (Capital Expenditure – CAPEX), and the requirement of its own treatment room.

According to a research study in 2005 of ballast water that analyzed the efficiency between ultrasound, ultraviolet and ozone, it was clear that ozone was by far the most efficient in removing microorganisms. This was without using any pre-treatment of the water and ozone managed to still remove 95-100% of the microorganisms. In the same study, UV proved to be between 78-100% efficient in clear water. UV efficiency relies on how clear the water is so the light can go through and disinfect. The effects of the UV will therefore be restricted in more turbid waters, which requires using a filter. UV also uses high levels of energy when the light intensity is increased if there are a lot of microorganisms to remove.

Filtration + UV is a clean and ecological treatment alternative, which produces no chemical by-products. It has a much lower initial capital expenditure than ozone and is quite easy to operate. Advancements in both filtration and UV technology will show some great improvements in the near future. This will hopefully enhance the ballast flow volume and include better automatic cleaning of the UV Quartz housing, which are serious limitations of the current technology. Lamp life is also expected to improve during the next few years.

The Norwegian KBAL technology is very innovative and belongs to the sustainable clean technology-category. It can work in all degrees of salinity, work with high ballast flowrates. This is a very new an unproven technology, so further experience is required to determine its operational effectiveness and level of maintenance. As a minus it cannot guarantee full disinfection, and as so, requires additional disinfection power from a UV system. Furthermore, this package required a complex installation, which runs through several decks, which could be a major obstacle on an older vessel with less space.

Saltwater Chlorination is a common technology and has been used inside marine seachests and cooling towers for many years. It requires low power consumption and uses the salt in seawater as its base to produce the disinfectant. Today’s technology can work with high water flowrates. It is furthermore a proven effective disinfectant against most microorganisms. The weak issue with this technology is that it requires salt to function and produce its chlorine compound Sodium Hypochlorite (NaOCl). Many ports around the world have brackish water such as Gothenburg, the largest port in Scandinavia. Furthermore, this technology produces hydrogen gas which is explosive, and smaller amounts of chlorine gas which is very toxic.

Chlorine Dioxide is an efficient disinfectant and is used around the world. In order to produce chlorine dioxide gas, hydrochloric acid (HCl) is normally used together with sodium chlorite. These chemicals need to be stored onboard, and the crew needs to be trained to handle these dangerous substances. For longer voyages at sea, this technology does not seem practical, as larger amounts of chemicals needs to be stored very safely. Further, like ozone, it produces a gas, but much more dangerous and with a higher degree of toxicity than ozone. The Chlorine Dioxide gas is also very corrosive to metals.

9. Conclusion

There are many BWTS on the market today, and there is no ideal and perfect universal system covering all vessels. As mentioned during this study, the choice of a system depends on national and international requirements, the type and size of the vessel, the geographical location of operation together with several other factors.

After extensive research and conversations with various industry experts, it is clear that ozone technology is an efficient, and sustainable BWTS. It is a powerful and convenient disinfectant for the incoming ballast water, it will also produce a residual effect which is of great benefit to avoid further organic growth and cross-contamination within the large volume of the ballast tanks. Ozone is a proven technology which is produced onboard using only ambient air and electricity, and it is available to use anytime.

This study has also found several misconceptions about using ozone as a BWTS, especially the claim that it causes corrosion inside the ballast tanks. This technology has through formal tests been proven to be far less corrosive than other treatments methods. If correctly installed and used correctly an ozone BWTS will not cause corrosion inside the ballast water tanks.

Despite its advantages, ozone technology has still not achieved its maximum potential. The products are still among the more expensive options in the market, and they are rather complex systems that require precise configuration and regular maintenance. Additional situations are at risk, such as potential gas leaks if the installation is not up to standards, and the required safety monitoring equipment is not calibrated or functioning properly. Due to this, a separate treatment room is required for the ozone generator installation.

To answer the research question "Is Ozone Technology a viable alternative for a Ballast Water Treatment System? The answer is a clear yes. Ozone performs very well in all types of vessels, water, temperature and environmental conditions, making this technology a highly interesting alternative for a BWTS now and in the future.

10. Suggestions for Further studies:

1. Micro and Nano-Bubble (MNB) technology for further gas-to-liquid mass-transfer efficiency
2. Water-Cooled vs Air Cooled Ozone Generator System
3. Better use of existing Compressed Air Resources onboard to "feed" O_2 & O_3 System
4. Using Ozone followed by UV to create "Advanced Oxidation"
5. Using latest generation of automated Screen Filters before O_3 injection to boost performance
6. Using alternative technologies to "neutralize" the ballast water during discharge (UV+TiO_2)

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Attachement 1: Interview Guide

Intervjuguide

Ved veiledning fra NSD, omhandler intervjuguiden en oversikt over spørsmål som vil bli dekket under intervjuet, samt oversikt over team som vil bli dekket. Merk at spørsmålene ikke er begrenset til disse, derimot er tema som vi bli dekket begrenset til disse 2 tema.

Tema som skal dekkes under intervju:

1. Ballastvann:

-Ballast vann definisjon og bruksområde.

-Hva betydning har ballastvann for miljøet?

-Hva er regelverket for ballastvann behandling pr dags dato?

-Hvordan blir regelverket for fremtiden?

-Hvordan avviker reglene i USA?

-Hvordan foregår ballastvannbehandling pr dags dato?

-Hva må til for at behandlingsanlegg skal være tilstrekkelig for fremtiden?

-Vurderes ozon som fremtidig behandlingsanlegg?

2. Behandlingsanlegg:

-Mest brukte behandlingsanlegg i dag? Hvorfor?

-Hvordan fungerer det? Kjemisk? Fysisk?

-Hvor effektivt er anlegget? Energieffektivt?

-Hvor mye rom krever anlegget? Lagring?

-Hvordan er anlegget å bruke i praksis på fartøy? Vanskelig for mannskap?

-Hvilke risiko og farer fører anlegget med seg? Hva må gjøres for å motvirke?

-Er ozon vurdert som en fremtidig løsning? Hvorfor?

-Hvordan ser fremtiden ut?

Attachement 2: Consent Form

Vil du delta i forskningsprosjektet

"Ozon som alternativ for behandling av ballastvann"?

Dette er et spørsmål til deg om å delta i et forskningsprosjekt hvor formålet er å samle kunnskap om ozon renseanlegg ombord. I dette skrivet gir vi deg informasjon om målene for prosjektet og hva deltakelse vil innebære for deg.

Formål
Lære om ozon renseanlegg ombord på fartøy. Hvordan det fungerer, hvordan det anvendes og om det har utvidete bruksområder.

Hvem er ansvarlig for forskningsprosjektet?
Høyskolen på vestlandet, maritim avdeling er ansvarlig for prosjektet.

Hvorfor får du spørsmål om å delta?
De bes om å deltakelse på grunnlag av at vi ser på din kunnskap som nyttig for vår undersøkelse av tema.

Hva innebærer det for deg å delta?
Dersom de ønsker å delta vil vi holde personlig intervju. Vi vil stille deg spørsmål knyttet til tema for å få en bedre forståelse. Intervjuet vil bli tatt opp for å gjøres skriftlig på et senere tidspunkt. Lydopptaket vil ikke publiseres.

Det er frivillig å delta
Det er frivillig å delta i prosjektet. Hvis du velger å delta, kan du når som helst trekke samtykke tilbake uten å oppgi noen grunn. Alle opplysninger om deg vil da bli anonymisert. Det vil ikke ha noen negative konsekvenser for deg hvis du ikke vil delta eller senere velger å trekke deg.

Ditt personvern – hvordan vi oppbevarer og bruker dine opplysninger
Vi vil bare bruke opplysningene om deg til formålene vi har fortalt om i dette skrivet. Vi behandler opplysningene konfidensielt og i samsvar med personvernregelverket.

- *Lydopptaket vil obevares på en server for HVL der bare studentene som jobber*

Hva skjer med opplysningene dine når vi avslutter forskningsprosjektet?
Prosjektet skal etter planen avsluttes *[5. mai. 2020]. Etter endt prosjekt vil lydopptaket destrueres. Transkiptet vil inkorporeres i slutt produktet og sluttproduktet vil publiseres som bachelor oppgave.*

Dine rettigheter
Så lenge du kan identifiseres i datamaterialet, har du rett til:

- innsyn i hvilke personopplysninger som er registrert om deg,
- å få rettet personopplysninger om deg,
- få slettet personopplysninger om deg,
- få utlevert en kopi av dine personopplysninger (dataportabilitet), og
- å sende klage til personvernombudet eller Datatilsynet om behandlingen av dine personopplysninger.

Hva gir oss rett til å behandle personopplysninger om deg?
Vi behandler opplysninger om deg basert på ditt samtykke.

På oppdrag fra *Høyskolen på Vestlandet* har NSD – Norsk senter for forskningsdata AS vurdert at behandlingen av personopplysninger i dette prosjektet er i samsvar med personvernregelverket.

Hvor kan jeg finne ut mer?
Hvis du har spørsmål til studien, eller ønsker å benytte deg av dine rettigheter, ta kontakt med:

- *Høyskolen på Vestlandet* ved *Sverre Fagerland. Eventuelt student Patrick Fanebust på p.fanebust@hotmail.com*
- NSD – Norsk senter for forskningsdata AS, på epost (personverntjenester@nsd.no) eller telefon: 55 58 21 17.

Med vennlig hilsen

Prosjektansvarlig(Veileder): Sverre Fagerland *Eventuelt student: Patrick Fanebust*

Samtykkeerklæring

Jeg har mottatt og forstått informasjon om prosjektet Ozon som alternativ for behandling av ballastvann, og har fått anledning til å stille spørsmål. Jeg samtykker til:

☐ å delta i *intervju*
☐ at intevjuet blir tatt opp

Jeg samtykker til at mine opplysninger behandles frem til prosjektet er avsluttet, ca. *[oppgi tidspunkt]*

(Signert av prosjektdeltaker, dato)