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# Abstract

The introduction of invasive marine species into new environments through ships' ballast water, attached to ships' hulls and via other vectors has been identified as one of the four greatest threats to the world's oceans. Different treatment methods have been proposed for onboard ballast water treatment options to reduce this effect, among those also ultraviolet light (UV), ultrasound (US) and ozone (O3) treatments. The literature survey that was carried out during the first phase of the project indicated that all of the methods have potential for ballast water treatment and numerous reports were available presenting the research activities carried out around the world. The technology that has been studied most widely appears to be UV, whereas US seems to have very limited application in terms of ballast water treatment. In addition to single technologies, the combinations of US + UV and UV + hydrogen peroxide ($H_2O_2$) were also tested as part of the hurdle experiments.

During the first phase, the methods were tested under laboratory both in Finland and the UK. After an evaluation of the laboratory test results, onshore trails were carried out in Tvärminne, Finland, in order to confirm the proper operation of the devices and to obtain information about the efficiency of the treatment options against the organisms in the Baltic Sea marine environment. The effects on phytoplankton and bacteria were not studied.

The results from the laboratory trials were partly confusing due to the various scale effects related to the test system and thus the results were difficult to explain. The results from Tvärminne onshore trials, with considerable reliability for UV, varied between 78–100%, for US treatment between 80–99% and for ozone treatment 95–100% depending on the organism group, flow rate and ozone dosages. The combination of US and UV achieved mortality rates of between 97–100% and the combination of UV + $H_2O_2$ between 94–100%. Even in those cases where 100% mortality was observed, the requirements for the maximum allowable number of viable organisms per water volume set by IMO were not necessarily confirmed due to the relatively small sampling volume. It must also be emphasised that only moderate (200–1,600 l/h) flow rates were used. During the trials in the UK, a possible modification of ballast water properties and contents by the treatments was also identified. Ozone treatment causes a significant increase in Redox potential with possible consequences on metal corrosion,

coatings and gaskets. However, these effects can be minimised by careful material selection.

Costs evaluations were carried out in order to provide rough estimations of treatment costs for each treatment option on two different case study ships. It appears that the costs for treated ballast water varies between 0.045–0.11 €/m$^3$ for UV treatment, for US 0.39–0.43 €/m$^3$ and for ozone 0.20–0.24 €/m$^3$. The effect on the shipping costs due to the treatment varies between 1–14% per voyage for these case study ships. These values represent the cost evaluation for a full-scale application based on the current level of treatment technology available. It is more likely that treatment costs would lower due to technology development. It must be kept in mind that different source and background information has been available for each study and therefore reasonable comparison between the methods is difficult.

In most of the cases, the treatment processes are not predictable due to the different water properties and operational aspects. Therefore, further studies and full-scale trials are required in order to optimise the process conditions for each treatment technology. One option for the testing and evaluation of various treatment methods could be container installations, where treatment processes would be designed for full-scale flow rates and water volumes. This option would also enable different marine environments to be included in the test programme. In addition to the secondary treatment options, primary treatment options, i.e., filters and cyclons, should also be included since many secondary treatment options require primary treatment in order to perform efficiently. In addition to the treatment technologies, the sampling and analysing methods also need to be developed in order to ensure reliable results and easy-to-use samplers for the ship’s crew.

The long-awaited guidelines for test and performance specifications adopted in the IMO MEPC 53 meeting in July 2005 standardised the testing procedures and provides technology developers and manufacturers with a uniform approach to the challenge.

# Foreword

The introduction of invasive marine species into new environments through ships' ballast water, attached to ships' hulls and via other vectors has been identified as one of the four greatest threats to the world's oceans. The other three are land-based sources of marine pollution, overexploitation of living marine resources and the physical alteration or destruction of marine habitat.

This publication describes the activities carried out by VTT Industrial Systems and Åbo Akademi University in terms of laboratory and onshore test trials as part of the Martob-project including a consideration for full-scale installations. The laboratory experiments were carried out in Finland and the UK in 2002 and the onshore trials were conducted in Tvärminne (Finland) in two phases, autumn 2002 and 2003. A summary of the progress achieved during the IMO MEPC53 meeting held in London in July 2005 regarding ballast water management issues is also included in this publication.

The study was partly financed by the EU under the Competitive and Sustainable Growth (GROWTH) Programme, funded by European Commission, Directorate-General for Energy and Transport. National funding was provided by Fortum Ltd., The Finnish Maritime Administration, The Ministry of Transport and Communications of Finland, the Finnish Ministry of the Environment, Acomarin Engineering Ltd. and VTT Industrial Systems. The progress of the project was closely followed by the executive group with representative from each financing body.

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Espoo, November 2005

Authors

# Contents

# 1. Introduction

Ballast is any material used to weight and/or balance an object. An example is the sandbags carried on conventional hot-air balloons, which can be discarded to lighten the balloon’s load, allowing it to ascend. Ballast water is therefore water carried by ships to ensure stability, trim and structural integrity. In the era of old sailing ships, gravel and stones were typically utilised as ballasting material and remnants of deballasting activities such as exotic flora can be found in several locations around the world.

The introduction of invasive marine species into new environments through ships’ ballast water, attached to ships’ hulls and via other vectors has been identified as one of the four greatest threats to the world’s oceans. The other three are land-based sources of marine pollution, overexploitation of living marine resources and the physical alteration/destruction of marine habitat.

There is growing concern over the damage to the aquatic ecosystem caused by the immigration of non-indigenous species. It is estimated that 3–7 billion tonnes of ballast water is transported by shipping activities annually, and ballast water has been recognised as a major vector in the transplant of aquatic species across biogeographical boundaries.

The transfer of species in ballast water started in the late 1800’s. However, during the past decades, the transfer of organisms via ballast water has increased due to the changing pattern of shipping, whereby ships are specialised in a trade (tanker, ore or grain carrier, liquefied gas carrier) and carry goods one way only, making return journeys empty of cargo but with ballast water. Faster transit times and larger volumes of ballast water associated with modern shipping increase the likelihood that organisms will survive the journey in ballast water. Among these organisms, there will inevitably be new problematic ones.

Extrapolations from what is known about the behaviour of non-indigenous species (NIS) in their native range may be risky. Thus, any release of ballast water or a single NIS can be considered “ecological roulette” (Carlton & Geller, 1993). Several of the NIS recorded in north-western European waters are known to adversely affect human life, causing an economic impact and (small-scale) health effects. Therefore, the pervasive feeling that “it won’t happen here because we are different” (Cairns & Bidwell, 1996) is false and misleading. One of the main goals in the science of invasion biology is to understand and minimise, if possible, the economic and ecological impact of non-native nuisance species that become established. Aquatic nuisance species (ANS) are defined as “non-indigenous species that threaten the diversity or abundance of native species, the ecological stability of infested waters or commercial, agricultural, aquacultural or recreational activities dependent on such waters" (Aquatic Nuisance Species Task Force, 2000).

Europe has the longest coastline of all of the continents in the world. Shipping trade and activities have long been a major industry in Europe. Currently, European Economic Area (EEA) ship owners represent about 40% of the world's merchant fleet. 90% of the EU's external trade and 40% of trade by volume between the member States are carried by sea. As a consequence, hundreds of non-indigenous species from different parts of the world have been introduced into European waters, particularly Northern Europe, through ballast water. Although many of them have not had any serious effects on the ecosystem, some have created serious problems and incurred considerable costs in remedial actions.

This publication describes the activities carried out by VTT Industrial Systems and Åbo Akademi University in terms of laboratory and onshore test trials during the Martob-project including a consideration for full-scale installations. The reports from each Work Package were produced as internal project documents. A summary of the latest progress in the IMO MEPC work related to ballast water management issues is also included.

# 2. Martob-project

Onboard Treatment of Ballast Water and Application of Low-sulphur Marine Fuel (MARTOB), was a three year project with a value of €3.5 million under the Competitive and Sustainable Growth (GROWTH) Programme, funded by European Commission, Directorate-General for Energy and Transport. The following objectives were defined for the project:

- investigation of methodologies and technologies for preventing the introduction of non-indigenous species through ships' ballast water
- development of design tools and treatment equipment to be used in the further development of ballast water treatment techniques
- assessment of the effectiveness, safety, and environmental and economic aspects of current and newly developed methods
- development of cost-effective (capital and operating), safe, environmentally friendly onboard ballast water treatment methods that have minimal impact on a ship's operations
- production of guidelines for crew training and criteria for selecting an appropriate ballast water management method
- assessment of the financial, technical and operational effects of a sulphur cap on marine bunker fuel in European waters, and propose a verification scheme to ensure compliance with a sulphur cap from all players in the market
- help to facilitate the introduction of an important sulphur emission abatement measure without the unintentional distortion of competition in the shipping market.

The ballast water treatment technologies tested within the project by various project partners were High Temperature Thermal Treatment, De-Oxygenation, Ultraviolet light, Ultrasound, Ozone and Oxicide treatments and Advanced Oxidation technology. In addition to the single technologies, the combination of two or more treatment methods was also studied as hurdle technology.

The project involved 25 partners from eight European countries and started in April 2001. The project was coordinated by the School of Marine Science and Technology, University of Newcastle upon Tyne, UK and was terminated at the end of June 2004.

# 3. International Convention for the control and management of ships' ballast water and sediments

## 3.1 General

The international Convention to prevent the potentially devastating effects of the spread of harmful aquatic organisms carried by ships' ballast water was adopted by the International Maritime Organization (IMO) at an international conference held in February 2004 at IMO Headquarters in London. The Convention requires all ships to implement a Ballast Water and Sediments Management Plan. All ships will have to carry a Ballast Water Record Book and will be required to carry out ballast water management procedures that meet a given standard. Parties to the Convention are given the option to take additional measures that are subject to criteria set out in the Convention and to IMO guidelines. The Convention will enter into force 12 months after ratification by 30 States, representing 35% of the world's merchant shipping tonnage.

Ships constructed before 2009 with a ballast water capacity of 1,500–5,000 $m^3$ must conduct ballast water management that, at least, meets the ballast water exchange standards or the ballast water performance standards until 2014, after which time it must at least meet the ballast water performance standard.

Ships constructed before 2009 with a ballast water capacity of $\leq$ 1,500 or $\geq$ 5,000 $m^3$ must conduct ballast water management that, at least, meets the ballast water exchange standards or the ballast water performance standards until 2016, after which time it must at least meet the ballast water performance standard.

Ships constructed in or after 2009 with ballast water capacity $\leq$ 5,000 $m^3$ must conduct ballast water management that, at least, meets the ballast water performance standard. Ships constructed in or after 2009 but before 2012, with a ballast water capacity $\geq$ 5,000 $m^3$ must conduct ballast water management that, at least, meets the ballast water performance standard. Ships constructed in or after 2012, with a ballast water capacity $\geq$ 5,000 $m^3$ must conduct ballast water management that at least meets the ballast water performance standard.

Other methods of ballast water management may also be accepted as alternatives to the ballast water exchange standard and ballast water performance standard, provided that such methods ensure at least the same level of protection to the environment, human health, property or resources, and are approved in principle by IMO's Marine Environment Protection Committee (MEPC).

In Regulation D-5, it is stated that at a meeting of the Committee held no later than three years before the earliest effective date of the standard set forth in regulation D-2, the Committee shall undertake a review that includes a determination of whether appropriate technologies are available to achieve the standard, an assessment of the criteria listed on the next page, and an assessment of the socio-economic effect(s) specifically in relation to the developmental needs of developing countries, particularly small island developing States. The Committee shall also undertake periodic reviews, as appropriate, to examine the applicable requirements for ships described in regulation B-3.1 as well as any other aspect of Ballast Water Management addressed in an Annex, including any Guidelines developed by the IMO. This means that by the end of 2005, the review must be conducted (Fig. 1).

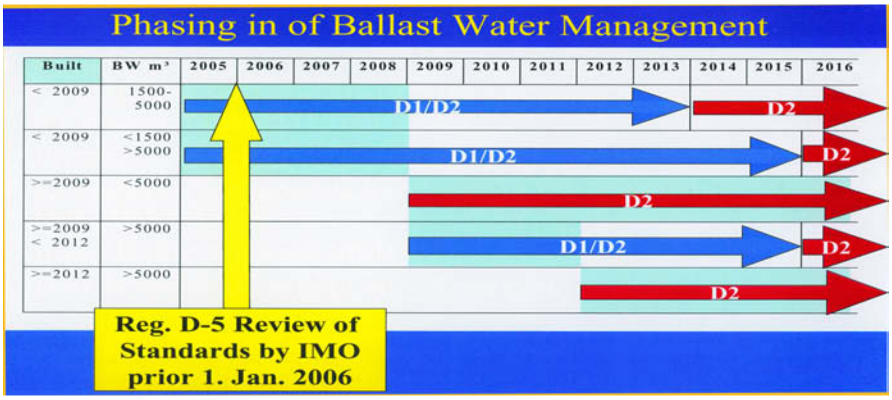


*Figure 1. Time scale for the implementation of the International Convention for the Control and Management of Ships' Ballast Waters and Sediments (Gollasch, 2004).*

Such reviews of appropriate technologies shall also take into account:

- safety considerations relating to the ship and the crew
- environmental acceptability, i.e., not causing more or greater environmental impacts than they solve
- practicability, i.e., compatibility with ship design and operations
- cost effectiveness, i.e., economics
- biological effectiveness in terms of removing, or otherwise rendering not viable, harmful aquatic organisms and pathogens in ballast water.

## 3.2 Ballast Water Exchange Standard

In Regulation D-1 of the Convention, the requirements for the Ballast Water Exchange Standard are defined as follows:

- Ships performing ballast water exchange in accordance with this regulation shall do so with an efficiency of at least a 95% volumetric exchange of ballast water.
- For ships exchanging ballast water using the pumping-through method, pumping through three times the volume of each Ballast Water tank is considered to meet the standard described in the previous paragraph. Pumping through less than three times the volume may be accepted provided the ship can demonstrate that at least a 95% volumetric exchange is met.

The Committee may form a group or groups to conduct the review(s). The Committee shall determine the composition, terms of reference and specific issues to be addressed by any such group formed. Such groups may develop and recommend proposals for the amendment of the Annex for consideration by the Parties (IMO, 2004).

## 3.3 Ballast Water Performance Standard

In Regulation D-2, the requirements for the Ballast Water Performance Standard have been defined as the following (IMO, 2004). Ships conducting ballast water management in accordance with this regulation shall discharge

1. less than 10 viable organisms per $m^3$ of greater than or equal to 50 μm in minimum dimension
2. less than 10 viable organisms per ml of less than 50 μm in minimum dimension and of greater than or equal to 10 μm in minimum dimension
3. less than the following concentrations of indicator microbes, as a human health standard:
    - toxicogenic *Vibrio cholerae* (serotypes O1 and O139) with less than 1 Colony Forming Unit (cfu) per 100 ml or less than 1 cfu per 1 g (wet weight) zooplankton samples
    - *Escherichia coli* less than 250 cfu per 100 ml
    - intestinal *Enterococci* less than 100 cfu per 100 ml.

## 3.4 Recent progress in the IMO MEPC work concerning Harmful Aquatic Organisms in Ballast Water

### *General*

The 53rd meeting of the Marine Environmental Protection Committee (MEPC) was held at IMO Headquarters in London from 18 to 22 July 2005. The session was attended by delegations from 88 member countries and numerous UN and inter- and non-governmental organisations. The Committee noted that from 1 June 2004 to 31 May 2005, eight countries (Argentina, Australia, Brazil, Finland, Maldives, The Netherlands, Spain and Syrian Arab Republic) have signed the Ballast Water Management Convention, and the Maldives became the first Contracting Party after depositing its instrument of ratification on 22 June 2005. The Convention will enter into the force 12 months after ratification by 30 States representing 35% of the world's merchant shipping tonnage.

### *Adopted Guidelines in the MEPC 53 meeting*

Before the MEPC meeting, the Ballast Water Working Group (BWWG) hold an intersessional meeting from 11 to 15 July 2005, where documents submitted for MEPC 53 and relating to harmful aquatic organisms were reviewed. As the result of discussions and negotiations during these two meetings, the following five Guidelines were adopted:

- Resolution MEPC.123(53) – Guidelines for Ballast Water Management Equivalent Compliance (G3)
- Resolution MEPC.124(53) – Guidelines for Ballast Water Exchange (G6)
- Resolution MEPC.125(53) – Guidelines for Approval of Ballast Water Management Systems (G8)
- Resolution MEPC.126(53) – Procedure for Approval of Ballast Water Management Systems that make use of Active Substances (G9)
- Resolution MEPC.127(53) – Guidelines for Ballast Water Management and Development of Ballast Water Management Plans (G4).

*The Guidelines for Ballast Water Management Equivalent Compliance (G3)* applies to pleasure craft used solely for recreation or competition or craft used primarily for search and rescue of less than 50 metres in overall length and with a maximum ballast water capacity of eight cubic metres. Few exceptions are included in the Guidelines regarding the uptake or discharge of ballast water and sediments, and precautionary practices to minimise the uptake or transfer of harmful aquatic organisms and pathogens.

*The Guidelines for Ballast Water Exchange (G6)* applies to all those involved with ballast water exchange (BWE) including, ship-owners and operators, designers, classification societies and shipbuilders. Operational procedures and guidance reflecting the issues highlighted in these Guidelines should be reflected in the ship's ballast water management plan. The Guideline defines responsibilities, ballast water exchange requirements, safety precautions associated with BWE, and crew training and familiarisation issues.

*The Guidelines for Approval of Ballast Water Management Systems (G8)* applies to the approval of Ballast Water Management Systems (BWMS) in accordance with the Convention and to BWMS intended for installation onboard all ships required to comply with Regulation D-2. The goal of these Guidelines is to ensure a uniform and proper application of the standards contained in the Convention. The Guidelines are to be updated as the state of knowledge and technology so requires.

The purpose of the Guidelines (G8) is to

- define test and performance requirements for the approval of BWMS
- assist Administrations in determining appropriate design, construction and operational parameters necessary for the approval of BWMS
- provide a uniform interpretation and application of the requirements of Regulation D-3
- provide guidance for equipment manufacturers and ship owners in determining the suitability of equipment to meet the requirements of the Convention
- assure that BWMS approved by Administrations are capable of achieving the standard of Regulation D-2 in land-based and shipboard evaluations.

The requirements of the Convention relating to the approval of BWMS used by ships are set out in Regulation D-3. Regulation D-2 stipulates that ships meeting the requirements of the Convention by meeting the ballast water performance standard must meet the discharge criteria described in chapter 3.3 of this publication.

The land-based and shipboard approval requirements for BWMS specified in the Guidelines (G8) can be summarised as follows:

- The manufacturer of the equipment should submit information regarding the design, construction, operation and functioning of the BWMS in accordance with Part 1 (see next page). This information should be the basis for the first evaluation of suitability by the Administration.

- The BWMS should be tested for Type Approval in accordance with the procedures described in parts 2 and 3.
- Successful fulfilment of the requirements and procedures for Type Approval as outlined in Parts 2 and 3 should lead to the issuance of a Type Approval Certificate by the Administration.
- When a Type Approved BWMS is installed onboard, an installation survey according to section 8 "Installation survey and commissioning procedures" should be carried out.

The technical specifications in the Guidelines details general technical requirements that a BWMS should meet in order to obtain Type Approval. These specifications cover Ballast Water Management Systems, Ballast Water Treatment Equipment, and Control and Monitoring Equipment. Besides typical document requirements for the plan approval process, approval and certification procedures, installation requirements, and installation survey and commissioning procedures are defined in the Guidelines (G8).

The annexes of the Guidelines (G8) provide test and performance specifications for BWMS approval and contain the following:

- Part 1: Specifications for Pre-test Evaluation of System Documentation
- Part 2: Test and Performance Specifications for Approval of BWMS
- Part 3: Specification for Environmental Testing for Approval of BWMS
- Part 4: Sample Analysis Methods for the Determination of Biological Constituents in Ballast Water.

During the MEPC meeting, one issue that contrived intensive discussions was the need for onboard testing during the type approval of Ballast Water Management Systems. The Committee noted that 15 delegations participating in the Working Group supported the retention of biological efficacy within onboard testing, two delegations could not support this approach and four delegations expressed their reservation regarding the practicability of such testing. The proposals for removing the provisions relating to that issue were based on assumptions that retaining the biological efficacy within onboard testing would delay the implementation of the Convention due to its impracticability, high costs and inconclusive results. Supporters of the opposite point of view argued that rigorous and complete testing onboard, before commercialisation, is the only guarantee that a certain ballast water system works. After extensive debate, the Committee agreed to retain the biological efficacy within onboard testing.

*Procedure for the Approval of Ballast Water Management Systems that make use of Active Substances (G9)* describes the approval and withdrawal of approval of Ballast

Water Management systems that make use of Active Substances to comply with the Convention and their manner of application as set out in Regulation D-3 of the "International Convention for the Control and Management of Ships' Ballast Water and Sediments". The objective of this procedure is to determine the acceptability of Active Substances and Preparations containing one or more Active Substances and their application in Ballast Water Management systems concerning ship safety, human health and the aquatic environment. This procedure is provided as a safeguard for the sustainable use of Active Substances and Preparations.

This procedure is not intended for the evaluation of the efficacy of Active Substances. The efficacy of Ballast Water Management systems that make use of Active Substances should be evaluated in accordance with the "Guidelines for Approval of Ballast Water Management Systems".

The goal of the procedure is to ensure proper application of the provisions contained in the Convention and the safeguards required by it. As such the procedure is to be updated as the state of knowledge and technology may require. New versions of the procedure will be circulated by the Organization following their approval.

*Guidelines for Ballast Water Management and the Development of Ballast Water Management Plans (G4)* objectives are to assist Governments, appropriate authorities, ships masters, operators and owners, and port authorities, as well as other interested parties, in preventing, minimizing and ultimately eliminating the risk of introducing harmful aquatic organisms and pathogens from ships' ballast water and associated sediments while protecting ships' safety in applying the International Convention for the Control and Management of Ships' Ballast Water and Sediments.

These guidelines consist of two parts:

- Part A: "Guidelines for Ballast Water Management", which contains guidance on the general principles of Ballast Water Management
- Part B: "Guidelines for the development of Ballast Water Management Plans", which contains guidance on the structure and content of Ballast Water Management Plans required by Regulation B-1 of the Convention.

The Guidelines apply to all ships and to Flag Administrations, port States, coastal States, ship owners, ship operators, ships' personnel involved in Ballast Water Management, ship designers, ship builders, classification societies as well as other interested parties (IMO, 2005a).

### *Results of the activities conducted by the Ballast Water Review Group*

During the previous MEPC meeting (MEPC 52), the establishment of a Ballast Water Review Group was agreed in order to determine whether appropriate technologies are available to achieve the ballast water performance standard required under Regulation D-2 in MEPC 52/24, paragraph 2.21.5. The review would also include an assessment of safety considerations related to the ship and the crew, environment acceptability, practicability, cost effectiveness, biological effectiveness, and the socio-economic effects specifically in relation to the developmental needs of developing countries, particularly small-island developing States. MEPC 52 also developed a set of recommendations for the conduct of the review and invited Members and observers to submit relevant information according to these recommendations to facilitate the review during the MEPC 53 meeting.

A total of six documents were submitted providing information on ballast water management technologies already developed or under development. As the result of the technology mapping, 13 potential BWM technologies were identified (Table 1).

*Table 1. Potential BWM technologies identified in the technology mapping (IMO, 2005b).*

| **Manufacturer** | **Technology** |
|---|---|
| Alfa Laval & BenRad, Sweden | Filtration + AOT (Advanced Oxidation Technology) |
| Alan Taylor & Associates, Australia | Heat treatment |
| Browning Transport Management “Aquahabistat” (AHS), USA | De-oxygenation |
| Ecochlor Inc., USA | Chemical disinfection |
| Environmental Technologies Inc., USA | Filtration + sonic radiation |
| Hamann New Modular BWM Systems, Germany | Hydrocyclon separation + chemical disinfection |
| Hyde Marine Inc., USA | Filtration + UV |
| Marenco Group, USA | Filtration + UV |
| Marine Technology Institute Co., Japan | Physical disruption/killing |
| MEPI, USA | Filtration, Bromine and Oxidation |
| NEI Treatment Systems, LLC, USA | De-oxygenation |
| Nutech O3 Inc., USA | Ozone |
| OptiMarin AS., Norway | Hydrocyclon separation + UV |

It should be noted that the list above is not an extensive one since some developers or companies may have products under development targeting the market before October 2008 although not mentioned in the list. Based on the technology mapping, it appears that the combination of filtration or hydrocyclon as primary treatment and ultraviolet light as secondary treatment have the most R&D efforts at the moment. Also, various filtration options seem to have an established position as primary treatment options.

Based on the data provided, the Review Group came to the conclusion that the varieties of systems being tested onboard have the potential to meet the criteria of safety, environmental acceptability and practicability. Therefore, it is reasonable to expect that ballast water management technologies and type-approved systems will be available to meet the review criteria of Regulation D-5.2 by October 2008 (IMO, 2005a).

# 4. Activities conducted during the project

## 4.1 General

This chapter provides a summary of the activities carried out by VTT Industrial Systems and Åbo Akademi University during the project. The literature survey was performed during the initial phase of the project and the data was updated during the last phase. The laboratory test trials were conducted in two steps, first in Finland and later in the UK in 2002. Onshore test trials were executed in two phases in 2002 and 2003 in Finland. The results from the onshore test trials were evaluated against the IMO standard. During the upscaling stage, experience gained from the onshore test trials was utilised. Also, various references providing information on economical issues and full-scale experiments were considered.

## 4.2 Literature survey

### 4.2.1 Ultraviolet light technology

UV treatment is a validated technological option for waste, aquaculture, drinking and process waters. It achieves disinfection by inducing the photochemical changing of biological components within micro-organisms, and more specifically by breaking chemical bonds in the DNA and RNA molecules and proteins in the cell. Its application for the treatment of ballast water seems promising, although the need of combining this method with a first step of a form of mechanical separation such filtration or hydrocyclone is deemed to be necessary due to interference with turbidity and sediment, usually present in ballast water, and the shielding of smaller organisms by larger ones.

The turbidity and presence of sediments in ballast water can have a significant effect on the effectiveness of UV treatment. This means that preliminary filtration or hydrocyclone treatment at around 20 μm will generally be necessary before UV treatment (Jelmert, 1999).

UV does not present any health or safety concerns for the crew or the vessel. However, some attention has to be given to two facts: UV lamps can release toxic mercury if they break and if an organism irradiated with UV rays manages to survive the treatment, the possibility of genetic mutations exists.

UV has already found application onboard ships in combination with a primary treatment of hydrocyclone separation (see chapters 3.4 and 4.6.4) and it seems to have a great deal of potential as a secondary treatment technology for ballast water treatment.

### 4.2.2 Ultrasound technology

Ultrasonic treatment is a relatively new technology in ballast water treatment. Two types of ultrasound exist, low intensity, which is not used to disinfection, and power ultrasound. Ultrasound is generated by a transducer, which converts mechanical or electrical energy into high frequency vibrations.

The effect of ultrasound is based on physical and chemical changes in the destruction of organisms and the rupture of cell membranes, resulting from cavitation, the intensity of which is influenced by frequency, power density, exposure time and properties of the treated water.

Ultrasonic technology has been utilised in various applications in water treatment and the food industry in order to control micro-organisms. Traditional ultrasound technology has been applied to low flow rates, typically 225–375 l/min. Experimental ultrasound systems have been applied to control parasites such as *Giardia* and *Cryptosporidium*, but no efficiency data was found in the scientific literature. No results have been reported from large scale pilot plants using ultrasound disinfection.

One ultrasound technology application, referred to as High Power Ultrasound Process, shows promising and economically reasonable results. Compared to other systems, it generates more intensive cavitation. Thus, a reduced exposure time is required and higher flow rates are possible with circular configuration of cylinder sets.

The efficiency of ultrasound treatment can be increased by filtration, but the balance between the exclusion of the larger and hardier organisms and the retention of particulate matter must be determined due to the effective action of ultrasound technology. Ultrasonic treatment devices are relatively robust against average shipboard conditions. Equipment corrosion should not be a problem. Regarding operational aspects, some training of the crew is required.

Safety concerns relating to ultrasound technology are possible noise from the transducer, yet unknown effects upon the structures of a vessel and to the personnel affected by the exposure to ultrasound. It has also been suggested that cavitation may cause physical damage to the structure and coating of the ballast tanks. One safety matter is the heat generated in the transducer if the cooling water system fails.

Only a limited number of cost estimates were available while writing the publication. Ultrasound technology does not seem to have any known environmental concerns. Some experiments with sonic radiation combined with filtration as a pre-treatment have been conducted during the last years (see chapter 3.4).

### 4.2.3 Ozone technology

Ozone has so far been used mainly in onshore applications, i.e., the disinfection of drinking water and water in swimming pools, control of microbiological contamination in aquaculture, aquaria, and power plant cooling systems. In industrial applications, ozone is not used to eliminate microbial populations, but rather to limit population growth.

Ozone is unstable at atmospheric pressure and thus it must be generated onsite. It is also a greenhouse gas and is toxic in high concentrations. The three modules of an ozone plant are a generator, ozone contact chamber and ozone destructor. Ozone is generated using UV light or the corona discharge process. In the contact chamber, ozone is introduced into water and the main purpose of the destructor is to limit the amount of ozone to be stripped out into the air. Once ozone has been introduced into water, three main processes affect the release of ozone: reaction with water impurities, decomposition and stripping into the atmosphere.

Ozonisation of seawater differs primarily from the ozonization of fresh water. The reactions with bromide and the reactions caused by an elevated pH alter the chemistry in salty water. Ozone oxidises bromide, which both consumes ozone and generates bromine. The half-life of ozone in the seawater is only 3.5 sec. due to the presence of bromide. The composition of coastal water increases the ozone demand. Ballast water also contains corrosion products that exert an ozone and bromine demand.

Contact time is essential in the disinfection process. The relationship between disinfectant concentration and contact time is represented empirically as Cn.tp = constant. The relationship shows that the same result, for a given organism, can be achieved with a high concentration of disinfectant for a short contact time or with a low concentration of disinfectant for a long contact time. In addition, some contact time is also required for the disinfectant to work. C.t values are specific to organisms, pH and temperature.

Costs estimations of ballast water treatment techniques vary due to ship design, ship purpose and trading routes. Thus, cost estimations must be based on individual ships and their trading patterns, on the required level of organism removal for that trading pattern and over the lifecycle of the vessel. The estimates of capital costs (1996) for onboard ozone plant range between USD 0.4 million to 20 million, depending on the ballast loading rate and required ozone dose (Oemcke & van Leeuwen, 1998). Additional capital expenditure is also required for pre-treatment.

Occupational aspects must be taken into account in terms of health and safety at work. Ozone treatment may increase the corrosion rate or the consumption of sacrificial anodes.

The efficiency of ozone treatment increases if the ballast water treatment system has a primary treatment, for example, filtration or hydrocyclons, in order to reduce the amount of particles in the water. Pre-treatment would not be possible in in-transit treatment, but might be beneficial for treatment during ballasting. The experiments conducted onboard S/T Tonsina (see chapter 4.6.6) did not include any primary treatment and suggested that ozone treatment has the potential for onboard ballast water treatment.

## 4.3 Laboratory test trials in Otaniemi (Finland) and in Newcastle (UK)

### 4.3.1 Introduction

The main objectives for the laboratory test trials were to design and develop the proposed methods and demonstrate their effectiveness against the selected organisms. UV, US and ozone methods were tested in two test phases. The preliminary test phase was carried out in Espoo, Finland, in April–May 2002. The aim of the preliminary test trials was to establish the operational parameters for the Newcastle test trials and to study the effectiveness of the methods against *Artemia salina* and algae. The second test phase took place in Newcastle, UK, in June 2002, as part of the joint test trials for Martob-project. In addition to the biological analysis, the possible modification of ballast water properties and contents was also identified. The economical and environmental aspects and risk and safety effects were also evaluated.

### 4.3.2 Ultraviolet light treatment unit

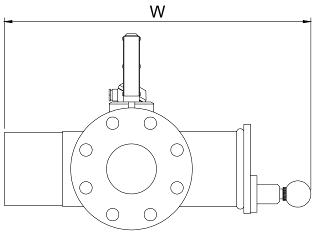
The UV device used in the laboratory test trials was provided and manufactured by Berson Milieutechniek BV, Netherlands (Fig. 2). The Berson InLine 5 UV disinfection unit has one 316L stainless steel irradiation chamber with a total length of 460mm. The internal diameter is 56mm. Inside the chamber, one B410 Berson MultiWave® lamp is mounted perpendicular to the flow and enclosed by a quartz sleeve. The lamp is a medium pressure mercury gas discharge lamp manufactured by Berson BV. Its electric power is 350W. UV output is 200–400 nm or germicidal UV output is 210–320 nm. UV output power is 58 W and operation gas pressure is 2–3 bar. The technical specifications of the device have been indicated in Tables 2 and 3.

UV lamp is placed inside the contact chamber.

*Figure 2. Ultraviolet light device in the test rig.*

*Table 2. Technical specification of the UV chamber of a Berson InLine 5 disinfection unit.*

| **UV chamber HXK1** | |
|---|---|
| Type | BersonInLine® |
| Material | Stainless steel 316L, ac. to AISI |
| Internal finish | Dairy ($Ra_{max}$ 1.0 μm) |
| Connections | NW40 DIN2576 |
| Number of lamps | 1* B410, BersonMultiWave® UV lamp |
| Sample tap connections | No |
| Drain plug | Yes |
| Air relieve valve | No |
| UV sensor | Yes |
| Cleaning mechanism | No |
| Degree of protection | IP54 |
| Pressure test | 15Bar |
| Pressure operational | 10Bar |
| Dimensions (H x W x D) | 460 x 390 x 300 mm |
| Weight dry | 10kg |
| Weight wet | 12kg |



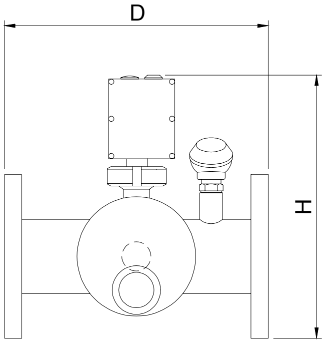
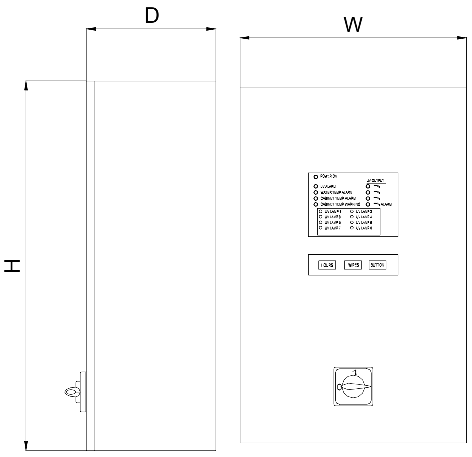


*Table 3. Technical specification of the power/control module of a Berson InLine5 disinfection unit.*

| **Power/control module 410VL1ECU** | |
|---|---|
| Material | painted steel |
| Degree of protection | IP54 |
| Dimensions (H x W x D | 600 x 380 x 210 mm |
| Weight | 15kg |
| Required power supply | 230V/50Hz |
| Connected power | 500 W |
| Safety door switch | yes |
| UV intensity indication | yes |
| UV alarm with relay | yes |
| Temperature control | no |
| Cabinet temp. control | yes |
| Hour counter | yes |
| Energy control | no |



### 4.3.3 Ultrasound treatment unit

The US device used in the laboratory and onshore test trials was designed and constructed by Acomarin Engineering Ltd, Naantali, Finland (Fig. 3). The device was equipped with a dr. Hielscher UIP 2000 Ultrasonic Processor, including generator, transducer and sonotrode, which is made of titanium. The processor is exclusively designed for the purposes of disintegration (e.g., cell disruption, emulsifying, homogenising), thermoplastic molding, coating-lacquer removal, intensive surface cleaning, wire cleaning, cutting, drilling, lapping and compressing, used in industry or sonochemistry laboratories. The amplitude is adjustable and equipped with an automatic frequency scanning system. The generator and transducer are housed separately and the processor is dry-running protected. The technical specifications of the UIP 2000 Processor have been listed in Table 4.

*Table 4. Technical specification of UIP 2000 Ultrasonic Processor.*

| | |
|---|---|
| Power supply | 3 AC 400 V, AC ±10%, 10A, 48 ... 63 Hz |
| Fuse | 10 A time-lag primary (generator), 2A fan processor |
| Effective output power | 2000 W |
| Efficiency | > 85% |
| Power control range | 20% to 100% continuously adjustable |
| Operating frequency | 20 kHz |
| Freq. control range | ± 1 kHz |
| Operational safety | cont. operational proof, even within air |
| Safety classification / Degree of protection | Generator: I, earthed equipment<br>Processor: IP65 |
| R.F.I. suppression / susceptibility | complies with EN 55011<br>complies with EN 50082-2 |
| Permissible environmental conditions | operational temperature + 5 to + 40 °C<br>10 to 90% relative humidity non-condensing |
| Weight | approx. 15 kg |
| Dimensions (W x H x D, max.) | Processor: 475 x Ø115 mm<br>Generator 600 x 400 x 550 mm |

The UV and US devices were built in the same test rig in order to test single technologies and also to test the combination of US and UV as a part of hurdle technologies (Fig. 3).

*Figure 3. Left: Ultraviolet light and ultrasound devices mounted in the same aggregate. The US transducer is mounted inside the stainless steel box. Right: The ozone device rig during the Espoo trials.*

### 4.3.4 Ozone treatment unit

The ozone device was designed and manufactured by ProMinent Dosiertechnik GMBH, Germany. The type of ozone device was an Ozonfilt® OXVa Type 1, and it was mounted in a solid stand made out of metal (Fig. 3).

The system (Table 5) produces ozone from a gas containing oxygen, usually ambient air, like in these test trials, or pure oxygen. The gas is passed through an electronic field produced between two electrodes. The air is treated to ensure it is dry and free from dust particles. Part of the oxygen in the air is converted into ozone in the electrical field. The air stream, which now contains ozone, is then fed to the contact tank for dissolving in water requiring disinfection.

*Table 5. Technical information of the ozone device.*

| **Electrical connections** | |
|---|---|
| Power consumption for ozone generation | < 0.15 kW |
| Power factor | 0.7 cos f |
| Mains power supply | 230 V / 50 Hz |
| Enclosure rating | IP 43 |
| Switch input, pause (XPs) | Isolated, load: +15 V/max. 10 mA |
| Switch input, ozone warning device (XOz) | Isolated, load: +12 V/max. 1.5 mA |
| Standard signal input, Ozone reference value (XmA) | Isolated, resistance +1.7 V at +20 mA, input current |
| Alarm output (XUsr) | Isolated, change-over: 230 V/max. 8 A, free contact |
| **Mixing equipment module** | |
| Flow volume for OZVa, Type 1 | 0.5–3 m³/h |
| Raw water connector for OZVa Type 1 | DN 32 |
| Raw water temperature | < 35 °C |
| Pressure range in raw water pipe | 0.2–2 bar |
| **Total dimensions** | |
| Width | 1190 mm |
| Height | 1300 mm |
| Depth | 305 mm |
| **Weight** | 70 kg |
| **Compressor accessories** | |
| Compressor mains power supply | 230 V / 50 Hz |
| Average power consumption at max. operating pressure | 0.18 kW |

### 4.3.5 Results

In the Espoo trials, brine shrimp *Artemia salina* and algae were used as target organisms. Artificial sea water (salinity 30–35 ppt, average temperature 18 °C) was used. A centrifugal pump was used when the water was introduced to the treatment process. The total reduction of *Artemia* achieved was 43–60% with ozone treatment. The highest reduction rate was achieved with the slowest flow rate and with the maximum ozone dosage (150 l/h, ozone dosage of 5 g/h). The contact times were short enough to have an impact only on activity rates but not on the mortality rates of *Artemia*. Mortality rates increased rapidly with increasing contact time. With US treatment, total reduction rates of 84–100% were achieved; the best results were obtained with a flow rate of 200 L/h and with a maximum transducer amplitude of 50%. Regarding ultraviolet treatment, a maximum reduction rate of 78% was achieved with a flow rate of 200 l/h and with an ultraviolet dose of 563 $mJ/cm^2$.

The combination of US and UV was also tested as a part of hurdle technology. The result of the total reduction of *Artemia* was 82–99%, with the best results achieved with a flow rate of 400 L/h and with a maximum US amplitude and ultraviolet dose of 281 $mJ/cm^2$. Each test run was carried out only once; therefore, the results should be regarded as indicative. The algae culture used in the test trials was corrupted, thus the results were abandoned.

The test trials in Newcastle were carried out in early June 2002 in the facilities provided by Newcastle University. The test arrangements were the same as in the Espoo trials, excluding the composition of the artificial sea water and the utilisation of the centrifugal pump. Standard seawater was prepared for all tests using de-ionised water added with Tropic Marine salt and the target organisms, i.e., *Nereis virens, Acartia tonsa, Tisbe battagliai, Alexandrium tamarense* and *Thalassiosira pseudonana.* During the first three and a half days, a centrifugal pump was used but after realising that the pump itself was eliminating all of the zooplankton, a gravity system was used to supply the water.

The mortality attained by the US treatment was always below 40% for all tests. The ultraviolet method did not inactivate more than 56% of the zooplankton. The highest value for the ozone treatment was 89%, eliminating *Nereis*. In terms of hurdle technology, better performance of the filter (125 µm) + US + UV test compared to the US + UV seems apparent, mainly for *Acartia* and *Tisbe*. As an overall observation, excluding the use of the filter, *Acartia* was the most resistant of the three species and *Nereis* the least.

Phytoplankton results showed that ozone was the most effective at reducing chlorophyll *a* levels with a reduction rate of 97% (flow rate 200 l/h, ozone dosage 5 g/h). US achieved the highest reduction rate of pheophytin, 67%, with a flow rate of 400 l/h and an amplitude of 50% with an after-flushing sample. The highest reduction rate for chlorophyll *a* levels with US, 71%, was also achieved with a flow rate of 400 l/h and an amplitude of 100%. With UV treatment, the highest reduction rate of chlorophyll *a*, 56%, was achieved with a flow rate of 300 l/h and an ultraviolet dose of 375 mJ/cm$^2$. The highest reduction rate of pheophytin, 33%, was achieved with a flow rate of 900 l/h and an ultraviolet dose of 125 mJ/cm$^2$, with an after flushing sample. The hurdle technology, US combined with UV, achieved a reduction rate of 68% with chlorophyll *a* levels and a 46% reduction of pheophytin (flow rate 300 l/h, US amplitude 100%, UV dose 375 mJ/cm$^2$). The combination of filter (125 µm), US and UV achieved a reduction rate of 57% of chlorophyll *a* level and a 52% reduction rate of pheophytin (flow rate 300 l/h, US amplitude 100%, UV dose 375 mJ/cm$^2$) at best.

In addition to the biological effectiveness of the methods, the possible impact of the treatment method on the ballast water properties and contents were also found. UV causes a slight increase in Redox potential (short-term effect) with possible consequences on metal corrosion, coatings and gaskets. Regarding the US method, no risk of corrosion increase or risk with respect to coating or the gaskets was identified. The ozone method causes a significant increase in Redox potential (short-term effect) with possible consequences on metal corrosion, coatings and gaskets.

Along with the biological effectiveness and corrosion-related matters, the economical aspects (preliminary cost calculations), environmental (impacts through discharge to receiving water, energy consumption, chemical spills, materials used) and risk and safety effects were evaluated. Regarding the economical issues, the estimated cost for UV was 0.11, for US 0.28 and for ozone 0.22 €/m$^3$ of treated ballast water. US treatment increased the water temperature by about 5–6 °C. None of the discharges of the methods include substances identified as "priority hazardous substances". UV and US treatments require additional pipelines that may cause breaks and ballast water leaks. UV lamps contain mercury that would result in damages in case of breakage. The possible hazard with ozone treatment would encompass a larger area since the ballast water is treated in the ballast tanks.

### 4.3.6 Discussions

The system configuration used in the laboratory tests was designed for macro-scale testing on board or onshore. Therefore, the available amount of water during the Newcastle trials was insufficient in order to enable a designed function of the devices. The preliminary test phase in the Espoo and Newcastle test trials showed that the apparatus worked as designed when enough water was available. The pre-pumping system that altered the test results was removed and replaced by a gravity water supply system. This arrangement could slightly remedy the source of error but there were still concerns regarding the accuracy of analysis. The lack of pressure caused alterations to the design principles, and piping and valves caused errors due to the low flow rates.

The strategy for onshore test trials was based on the experiences gained from the laboratory test trials. The duration of test runs with US and UV should be longer than in laboratory scale tests in order to minimise the technical sources of errors, i.e., piping, fittings, valves and shortage of water. The use of ambient Baltic Sea water would enable the access to an unlimited amount of water and thus the errors caused by too little water could be reduced. Also, the link to the actual marine (brackish) environment would be evident. The design of the ozone treatment process should also be changed: the contact time should be extended and the device modified in order to monitor ozone dosage per volume of water versus contact time. Various ozone dosages and contact times should be studied.

The results from Espoo and Newcastle test trials were partly promising and encouraging, but also partly difficult to explain. Therefore, the US and UV systems needed to be tested with a continuous flow and of long enough duration and also with various pressure levels. Ozone treatment also needed to be studied with longer contact times to determine mortality rates versus ozone dosage and contact time. Larger scale test trials were inevitable to find out the proper limits for adjustments and efficiency, otherwise scaling to the full-scale dimension would be very difficult.

## 4.4 Onshore test trials in Tvärminne (Finland)

### 4.4.1 Introduction

The laboratory test trials conducted previously in the project offered some promising results regarding the efficiency of the UV, US and ozone technologies in inactivating the target organisms. However, the results comprised inconsistence and uncertainty and it was therefore decided to carry out onshore test trials in order to confirm the designed operation of the devices and to achieve reliable results in respect to the target organisms present in the Baltic Sea's brackish-water environment. It is worthwhile keeping in mind that many (if not most) of the ports worldwide are located at river mouths and, consequently, the ballast water that is loaded in many cases is brackish- or even freshwater.

The onshore test trials were conducted utilising the facilities provided by the Tvärminne Zoological Station, West Gulf of Finland. VTT was responsible for the technical installations and Åbo Akademi University carried out the sampling and analysing. The trials were carried out in two phases, September–October 2002 and August–September 2003. The test water was extracted directly from the sea utilising a peristaltic pump or a membrane pump to ensure a water volume large enough for the test execution and to maintain a link with the local marine environment. Significant mortality rates were not observed during the trials due to the utilisation of the pumps. No filter was used at the end of the inlet pipe during the test execution.

### 4.4.2 Ultraviolet light and ultrasound treatments

The same basic test arrangements were used in both test phases, but some details were modified for the second test phase based on the experience gained during the first test phase. The aggregate where UV and US devices (see chapter 4.2 for technical specifications) were mounted was modified by changing the piping arrangements in order to minimise the source of error caused by the dead-end pipes, valves and bends. The duration of the test runs was longer than in the laboratory scale test trials, typically 1 h with each combination of parameters. Two different US transducers (2 kW and 4 kW) were included in the test programme during the second series of tests in August–October 2003 (Fig. 4).

*Figure 4. The 4 kW US and power control unit during the onshore test trials.*

The technical information of the 4 kW US processor is shown in Table 6. The US devices used were designed and constructed by Acomarin Engineering Ltd, Naantali, Finland.

*Table 6. The technical specification of a UIP4000 Ultrasonic Processor.*

| | |
|---|---|
| Power supply | 400V~3Phase, 48–63 Hz |
| Fuse | 3x25 A |
| Effective power | 4000 W |
| Efficiency | > 85% |
| Power control range | 50–100% continuous control |
| Operating frequency | 19 kHz |
| Frequency control range | ±1 kHz |
| Operational safety | Steady state proof, even within air |
| Safety classification / degree of protection | generator: I, grounded; transducer: IP 65 |
| R.F.I. suppression | complies to EN 55011 and EN 50082-2 |
| Operational temperature | 5–40 °C |
| Environment humidity | 10–90% relative humidity, non-condensing |
| Weight | ca. 45 kg |

The 4 kW processor generates longitudinal mechanical oscillations of 19 kHz. The cascade sonotrode mounted to the electroacoustic transducer is made of titanium alloy. Designed as an $\lambda/2$-oscillator it boosts the longitudinal oscillation and radiates the sonic energy with increased density via its front face into the medium to be processed.

In addition to the individual techniques, combinations of US and UV and UV and hydrogen peroxide ($H_2O_2$) were also tested. Various flow rates, i.e. 200, 400, 520, 800 and 1,600 l/h, for UV and US were included in the test programme. The concentrations of $H_2O_2$ were 13 mg/l and 30 mg/l.

### 4.4.3 Ozone Treatment

Instead of the flow-through arrangement utilised previously in the laboratory test trials, the contact time was extended by introducing ozone into two contact tanks of different size, 60 l and 360 l. The aim was to monitor the ozone dosage per water volume versus contact time. During the previous laboratory test trials, it was noticed that with the flow-through arrangement, the contact times were too short in order to achieve a contact time effective enough. Therefore, various ozone dosages and contact times were studied and also long-term test runs (24 h) were carried out.

Ozone gas was fed into the bottom of the tank with a plastic pipe from the ozone generator, and a diffuser was installed at the end of pipe in order to generate smaller bubbles. The contact tanks were stored indoors in order to keep them warm enough during the night. The contact tanks were equipped with a mixer. The ozone dosages per water volume were constant during each test run.

### 4.4.4 Analysis

The treatment efficiency was studied on four groups of mesozooplankton, i.e., copepods, copepod larvae (nauplii), water fleas (cladocerans) and rotifers, which are the main mesozooplankton groups in the study area (Fig. 5). In addition, the larvae of barnacles (*Balanus improvisus*) and mussels (bivalves) were occasionally present in the samples and were included in the analysis. The effects on phytoplankton and bacteria were not studied in the Tvärminne trials. A wider generality of the results in respect to changing seasons and species was achieved by conducting the trials during two separate periods. Since species composition fluctuated a lot during the test phases, the water samples for the zooplankton assemblage were taken every second day, on average.

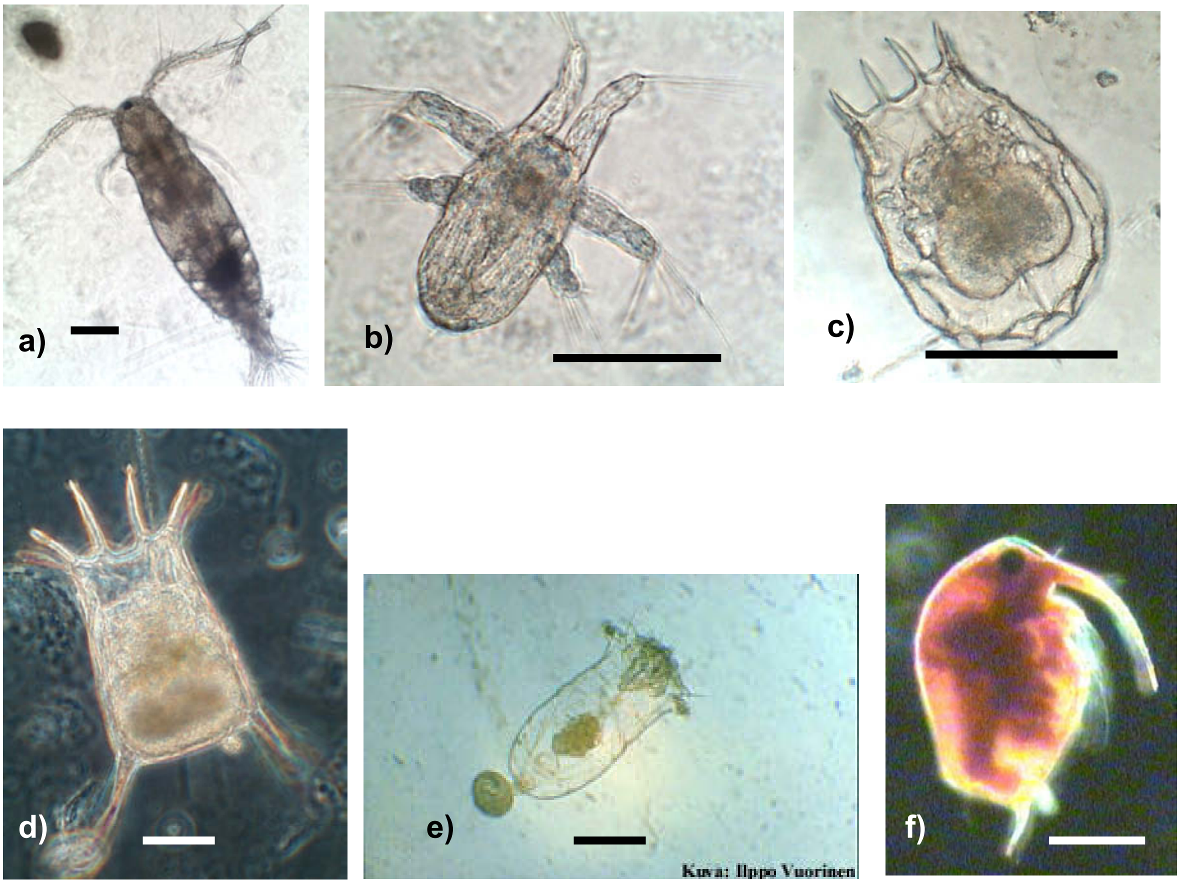


*Figure 5. a) Acartia bifilosa male b) A. bifilosa nauplius c) Keratella cruciformis var. eichwaldivar. eichwaldi d) K. quadrata var. platei e) Synchaeta baltica f) Bosmina longispina maritima. Scale bar indicates 100 µm. Photos a)–d) by Sari Lehtinen, e) Ilppo Vuorinen, f) Satu Viitasalo.*

The water samples for the biological analysis were taken before and after the treatment, sieved through a 100 µm sieve and studied after a recovery time of 2–5 h with a stereo microscope. Three replicates were included in the analysis for UV, US and ozone and two replicates for the combination of UV and hydrogen peroxide. In each replicate trial, only mesozooplankton groups with a minimum density of 1 ind/l before treatment were included in the analysis. The statistical analyses were carried out using parametric Student's *t*-test and an analysis of variance (ANOVA) or non-parametric Mann-Whitney U-test and Krustall-Wallis test, depending on the distribution of the data.

### 4.4.5 Results

The results, with considerable reliability for UV treatment, were a 94–99% kill rates for copepods, 78–100% for copepods nauplii and 98–100% for rotifers. For the US technology, the mortality rates achieved were 94–99% for copepods, 86–99% for copepod nauplii, 95–98% for cladocerans, 80% for rotifers and 97% for barnacle nauplii. For the combination of US and UV, the mortality rates were between 97–100% and the combination of UV and hydrogen peroxide achieved mortality rates of 94–100%.

The results, with considerable reliability for ozone treatment, with ozone dosage of 17 mg/L were 96–100% for copepods, 98–100% for copepod nauplii and 99–100% for rotifers. When ozone dosage was 7 mg/l, the results were 95–100% for copepods, 96–100% for copepod nauplii, 97–100% for rotifers and 99–100% for barnacle nauplii. The volume of the contact tank was 60 l for the ozone dosage of 17 mg/l and 360 l for a dosage of 7 mg/l. The ozone dosages were kept constant throughout the trials.

The onshore test trials confirmed that all devices were working as they were designed and also most of the sources of error that occurred during the laboratory test trials could be reduced. The results were relatively reliable due to the adequate number of replicates and provided a basis for the up-scaling of the UV, US and ozone treatment processes.

### 4.4.6 Discussions and conclusions

The effect of different treatments varied for one species group to another. For all groups studied, however, high reduction rates were observed with some treatments. The most effective treatment, with regards to all organism groups, appears to be the combination of US and UV. In addition, UV combined with hydrogen peroxide seemed to be effective, although our data is deficient in respect to cladocerans and barnacle nauplii, which were not present in the study area at the time of the experiments. However, we must bear in mind that only a limited number of different treatment combinations was tested and some of the potential combinations based on the laboratory test trials had to be excluded.

We must also emphasise that only moderate flow rates were used. In addition, in some cases, an insufficient number of replicates make further conclusions difficult. Fortunately, high mortality rates were achieved in many cases to draw a general conclusion on the killing power of different treatments. Thus, we suggest that a combination of the treatments tested would be effective in eliminating mesozooplankton from ballast waters.

Compared to the results attained from the laboratory test trials conducted in WP3, the results confirmed that the equipment was working as designed. The decision that onshore test trials would be conducted instead of full-scale onboard trials seems to be justified since most of the error sources occurred during the laboratory test phase can be avoided and the results achieved were more reliable and logical. The results also provided a basis for the upscaling of UV, US and ozone treatment processes.

## 4.5 The results from the onshore test trials vs. IMO Ballast Water Performance Standard

In our experiments, the effect of all treatments was studied on organisms $\geq$ 100 µm, which generally is the lower range of the mesozooplankton fraction in the Baltic Sea. The IMO standard implicates that ships are allowed to discharge organisms of this size in a quantity of no more than 0.01/l.

In the onshore experiments, the densities of viable organisms after the treatment decreased as the treatment efficacy increased (Table 7). This variation is mainly caused by a variation in the initial densities. However, since we did not use any pre-treatment (filter) before the treatments in the inlet pipe, the initial mesozooplankton densities were considerably high. Thus, the average final density of viable organisms was below 0.01 ind./l only in 24 h ozone treatment and UV+$H_2O_2$ treatments. To achieve the level of organism elimination required by IMO, it might be necessary to combine pre-treatment filtering with some of our treatments.

*Table 7. The average density (and range) of viable organisms after the different treatments. C.P. = counter pressure. In bold, the treatments which conform to IMO standards.*

| **Treatment** | **Parameters** | **Viable organisms** (ind, per litre) |
|---|---|---|
| UV | 200 l/h | 0.32 (0.23–0.40) |
| | 400 l/h | 1.05 (0.90–1.20) |
| | 520 l/h | 2.61 (1.78–3.43) |
| | 800 l/h | 1.52 (1.27–1.77) |
| US 2 kW | 200 l/h, 25% | 2.39 (1.13–4.73) |
| | 200 l/h, 50% | 1.61 (0.77–2.83) |
| | 200 l/h, 75% | 1.21 (0.23–3.25) |
| | 200 l/h, 100% | 1.57 (0.23–3.25) |
| | 400 l/h, 50% | 2.38 (0.47–5.33) |
| | 400 l/h, 100% | 1.05 (0.27–1.48) |
| | 520 l/h, 50% | 6.00 (3.17–10.97) |
| | 520 l/h, 100% | 3.04 (1.23–4.00) |
| | 800 l/h, 100% | 2.67 (0.77–3.97) |
| | 800 l/h, 100%, C,P, | 6.60 (4.03–11.67) |
| US 4 kW | 800 l/h | 1.25 (0.05–3.60) |
| | 800 l/h, C,P, | 0.11 (0.07–0.15) |
| | 1600 l/h | 1.05 (0.28–2.50) |
| | 1600 l/h, C,P, | 1.27 |
| $O_3$ (6 h) | 17 mg/l, after 4 h | 0.73 (0.00–1.10) |
| | 17 mg/l, after 5 h | 0.20 (0.00–0.30) |
| | 17 mg/l, after 6 h | 0.67 (0.00–2.00) |
| $O_3$ (24 h) | 7 mg/l, after 8 h | 0.46 (0.00–1.20) |
| | **7 mg/l, after 24 h** | **0.00** |
| UV+US | US 50% | 0.35 (0.18–0.53) |
| | US 100% | 0.24 (0.13–0.32) |
| UV+$H_2O_2$ | UV (800 l/h) (S2) | 1.52 (1.27–1.77) |
| | **UV+$H_2O_2$ 15 mg/l (S3)** | **0.00** |
| | UV+$H_2O_2$ 30 mg/l (S4) | 0.02 (0.00–0.03) |
| | UV 48 h (R1) | 1.18 (0.47–1.90) |
| $H_2O_2$ | 15 mg/l (R3) | 0.18 (0.13–0.23) |
| | 30 mg/l (R4) | 0.08 (0.03–0.13) |
| $H_2O_2$ +UV | $H_2O_2$ 15 mg/l (S6) | 1.10 (0.60–1.60) |
| | **$H_2O_2$ 15 mg/l + 48 h (S7)** | **0.00** |
| | $H_2O_2$ 30 mg/l + (S9) | 1.10 (0.90–1.30) |
| | **$H_2O_2$ 30 mg/l + 48 h (S10)** | **0.00** |

The total density of zooplankton during the studies performed in Finland with UV, US, US+UV, UV + $H_2O_2$ and ozone, ranged from 30,000 to 150,000 organisms/$m^3$, dominated by copepods and copepods nauplii. Thus, a 99% kill rate corresponds to 300–1,500 viable organisms/$m^3$ after treatment. It should also be noted that a maximum of 60 litres of water was examined after treatment. Thus, even in those cases where 100% mortality was observed, the required $\leq 10$ viable organisms/$m^3$ after treatment level was not necessarily confirmed due to the relatively small sampling volume.

## 4.6 Upscaling of the ultraviolet light, ultrasound and ozone technologies

### 4.6.1 General

This chapter describes the ambition to upscale the treatment methods used in the onshore test trials. The concept of ballast water circulation and contact tank approach will be introduced. The cost related issues have been estimated based on various literature sources and the valuable work conducted earlier in the Martob-project. In addition to literature data, the experimental data and expertise of various companies and their personnel regarding the UV, US and ozone technologies have also been taken into consideration.

### 4.6.2 Ballast water circulation

If the ballast water is required to be treated during ballasting or deballasting with flow rates as high as around 5,000 $m^3$/h, the required capital costs for US and UV units would be extremely high. Therefore, the possibility for ballast water circulation would enable a cost-effective design and use of US and UV treatment options. The circulation of the ballast water from the ballast water tank to the treatment process and back to the tank during the voyage enables smaller US and UV (and other treatment processes based on the flow-through principle) disinfection units. The potential benefits would be

- less floor space required for one unit
- more flexible installations due to smaller treatment units
- lower power requirements
- lower investment and operational costs
- better utilisation rate and payback time for the investment.

The ballast water circulation will cause modifications to the ballast water pipelines and changes to the ballast water management practices in existing vessels. However, the circulation is not feasible on short voyages due to the limited time available for treatment and may cause problems to the stability of a ship on rough seas like in ballast water exchange. Also, the structure of ballast tanks makes it difficult for ballast water to flow freely during circulation and therefore some of the ballast water might not be exposed to the treatment. In addition, the circulation will blend sediment to the ballast water and increase the turbidity of the water.

### 4.6.3 Contact tank approach

A treatment option based on ozone disinfection (or other options based on a long contact time) will expose all of the ballast water tanks to potentially harmful impacts. Therefore, all of the ballast tanks must be equipped with a pipeline network for ozone injection and also with adequate alarm and corrosion monitoring devices.

Rather, two ballast tanks would serve as contact tanks for ozone and ballast water would be circulated from the ballast tank to the contact tank and back to the ballast tank. The potential advantages that could be achieved are a reduced need for additional piping and control and safety monitor systems, and reduced corrosion risks in other ballast tanks.

This alternative ballast water circulation and contact tank approach requires a more profound study in order to define their feasibility in onboard installations.

### 4.6.4 Ultraviolet light technology

***General***

UV radiation can be divided into three sub-groups depending on the wave length: UV-A (315–400 nm), UV-B (280–315 nm) and UV-C (200–280 nm), see Figure 6. The shorter wave lengths (< 280 nm) are generally considered to be the most effective against bacteria and viruses (SWRCB, 2002).

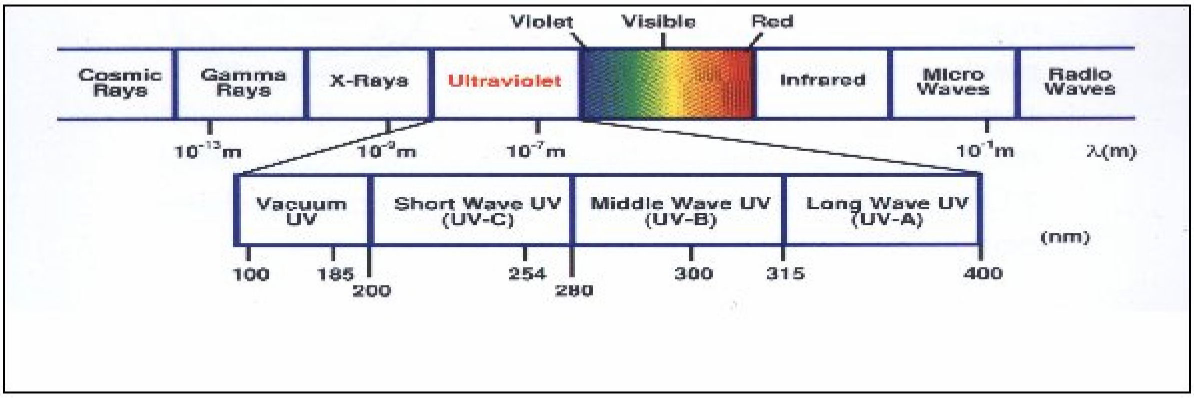


*Figure 6. UV spectrum (Buchholz et al., 1998).*

Commercially available UV lamps (Table 8) are usually of two types: conventional low-pressure (LP) mercury arc lamps that emit monochromatic UV light at UV-C range, and the higher intensity medium pressure (MP) mercury arc lamp that emit UV polychromatic light at all UV wave lengths, but are concentrated at selected peaks within the germicidal wavelength region.

*Table 8. Characteristics of typical low and medium pressure and pulse UV-lamps (EPRI, 1999).*

| **Characteristic** | **Low pressure** | **Medium pressure** | **Pulse UV** |
|---|---|---|---|
| Wavelength | Monochromatic, 85–90% at 254 nm | Polychromatic, 185–1,400 nm | Polychromatic, 185–800 nm |
| Emission | Continuous-wave | Continuous-wave | 30 pulses / sec. |
| Mercury vapour pressure | $10^{-3}$–$10^{-2}$ torr | $10^{2}$–$10^{4}$ torr | N/A |
| Operating temperature | 40–60°C | 500–800°C | 15,000°C |
| Arc length | 40–75 cm | 5–40 cm | 15 cm |
| Lifetime | 8,000–10,000 h | 2,000–5,000 h | > 9,000 h at 30 pulses / sec. |
| Relative light intensity | Low | Medium | High |

UV systems are usually constructed of stainless steel to help prevent corrosion. The radiation lamps are enclosed in protective quartz sleeves. Lamps are submerged in a pipeline, open channel or tube and water introduced to the radiation source. Lamps are usually set in a linear configuration, but they can also be twisted into loops or a spiral configuration to increase the dosage given (intensity) along the linear axis. The assembly conditions, e.g., the size available during retrofitting work on an old ship can be the primary reason for the applied design configuration.

The design dosage, e.g., the certain UV energy requirement for a specific amount of ballast water at a given time, should be maintained during ballasting or deballasting. If the ballast water is very turbid, colourful or contains a lot of inorganic material, the lethal dosage of UV energy must be higher compared to the design figures based on laboratory tests with clear water.

The required maintenance work of full-scale systems consists typically of cleaning the quartz cover of the lamps, replacing lamps after their radiation dosage has been fallen too low or in case of breakdown. If the system configuration contains a set of modules, maintenance work includes the overall checking of the system functions. If any primary treatment system is included in the system, the inspection of this device includes overall system checking, too. Ship personnel should be trained to keep the device in good operational condition, and help to minimise the extra service required in addition to a fixed internal service provided by the service company.

The UV lamp itself and the production rate of UV radiation is one important item to be developed. Usually, the source of UV radiation is constant and produced by state-of-the-art intensive direct current (DC) arcs (e.g., xenon or mercury vapour lamps). An arc temperature of 10,000 K is required to produce adequate quantities of UV photons. DC arcs, however, have two limitations: 1) the electrodes must be adequately cooled to prevent meltdown, and 2) the nature of DC arcs is a highly constricted plasma arc. This will limit the number of UV photons available. Moreover, the main body of the energy in DC arcs is produced in areas near to the electrodes where the potential gradients are the largest. It should be remembered that the 1 kW UV system only produces around 60 W UV output while in the 200–300 nm range. Thus, it might be an advantageous solution to replace the DC arc with another source of UV radiation. One possible solution might be a high-frequency electrodeless arc operating around 40 kW giving a considerable amount of UV for the full-scale application. There are some laboratory-based studies available on the use of high-frequency electrodeless applications, but their use for UV production should be verified. More ideas on this possible application are shown in Laiho and Sprouse (2003).

### *General requirements for UV device*

Based on the results and conclusion presented in Gloster-Herbert (2002), a UV treatment system designed for 90% transmittance should be able to deliver the following performance:

- reduce bacteria by 90%
- reduce the MS-2 coliphage virus by > 90%

- reduce phytoplankton growth potential (chlorophyll *a* concentrations) by > 50%, but without 100% mortality, some phytoplankton survives with the capability to reproduce, though at slower rates. Holding the phytoplankton in dark tanks seems to increase the mortality rates.
- reduce the concentration of live zooplankton relative to the control, especially if treated during ballasting and deballasting. Zooplankton is weakened by the first treatment, continues to die off in the BW tank and suffers the greatest kill or removal rate on discharge. More die off after the discharge due to latent damage.
- with combined cyclonic separation + UV and treatment during ballasting and deballasting, 90% reduction in live zooplankton density should expected (based on results from *Princess Regal* experiments).

### ***Safety***

UV treatment is a safe and robust technology already that has been used for years in many applications onshore. Waterworks and wastewater treatment works use UV-based disinfection system. More and even new applications can be found in the industry, particularly in pharmacy and food factories. As a proven technology, land-based applications are safe when provided with reliable control procedures.

Onboard applications, however, are not so common at least on a large-scale. Water disinfection treatment systems have been installed onboard ships, but large-scale UV solutions are almost all still at the demonstration stage. Some safety concerns should be directed to the use of mercury-containing lamps: ships may induce vibrations, slamming forces, etc., which should be taken into account in the design phase. Some materials are also not resistant to large dosages of UV light causing a risk of degradation and failure of the system.

Another possible environmental concern is the release of genetically mutated organisms to the aquatic environment due to their survival after treatment with UV radiation that could cause damage to their DNA. However, the possibility of such organisms thriving in the environment is limited since it is unlikely that the genetic mutation would give the organism competitive advantage in the receiving ecosystem. This assumption, however, should be further investigated in order to evaluate the environmental risk associated with the UV treatment of ballast water (Oemcke, 1999).

### ***Biological effectiveness***

The amount of damage caused by UV radiation is related to the intensity and the exposure time when the target organisms are exposed to the germicidal wavelength range. The UV dose can therefore be expressed as units of intensity of UV light in mW/cm$^2$ (or in J/m$^2$) and the exposure time in seconds. Typical UV doses for drinking water disinfection purposes (90% inactivation) are presented in Appendix 1. Table 9 shows the percentile reduction of different bacteria and viruses when irradiated with a dose of 20 mW/cm$^2$/sec.

*Table 9. Percentile reduction of different bacteria and viruses irradiated with a 20 mW/cm2/sec dose (originally, Carins, 2001 in Comparison of UV disinfection technologies using low intensity monochromatic and high intensity polychromatic UV lamps) (SWRCB, 2002).*

| **Organisms** | **Inactivation** [%] | **Organisms** | **Inactivation** [%] |
|---|---|---|---|
| *Bacillus antracis* | 99,9964 | *Shigella dysenteriae* | 99,9999 |
| *Clostridium tetani* | 97,8456 | *Streptococcus faecalis* | 99,9972 |
| *Corynebacterium diphthera* | 99,9999 | *Vibrio cholerae* | 99,9162 |
| *Echerichia coli* | 99,9999 | *Influenza virus* | 99,9997 |
| *Legionela pneumophila* | 99,9999 | *Poliovirus* | 99,7846 |
| *Mycobacterium tuberculosis* | 99,9536 | *Rotavirus* | 98,3014 |
| *Pseudomonas aeruginosa* | 99,9769 | *Saccharomyces cerevisiae* | 99,8179 |
| *Salmonella paratyphi* | 99,9999 | | |

Data from the literature suggest that a UV dose of around 60 mWs/cm$^2$ is effective for the removal of bacteria, most viruses and many protists and a dose of 120 mWs/cm$^2$ for almost all micro-organisms except highly resistant cysts and viruses (Oemcke, 1999). In laboratory tests, it has been demonstrated that UV irradiation can be effective for the inactivation of the dinoflagellate *Amphidinium sp.* and vegetative cells of *Gymnodinium catenatum*. However, cysts of *G. catenatum* were not inactivated (Rigby & Taylor, 2001).

Jelmert (1999) has reported on the effectiveness of UV irradiation in two small semi-scale laboratory test trials (including a hydrocyclone as pre-treatment). The first of these used a flow rate of 55 m$^3$/h and an applied UV-dose of 92 mWs/cm$^2$. Two days after the combined hydrocyclone/UV treatment, no *Artemia* nauplii were found, and 100% of the *Isochrysis* and 59% of the remaining *Pavlova* were rendered immobilised. Apart from the extremely UV-resistant *Artemia*–cysts, the tested equipment removed model zooplangton, two species of marine alga, and a community of marine bacteria to a higher percentage than practical trials with ballast water exchange have accomplished.

The second pilot study operating at a flow rate 70 m$^3$/h, used a prototype UV unit built by Enviro Tech A/S of Norway and contained 9 low pressure Heraus lamps with a nominal output of 200 W. Doses (in the centre of the chamber) in the range of

96–115 mWs/cm$^2$ were utilised in the tests. Nauplii narva of *Artemia* showed a morality of 99.5% and the number of hatching cysts was 26% lower than the numbers before the unit. A mortality of the dinoflagellate *Prorocentrum minimum* and the green alga *Tetraselmis* sp. of 84.7% and 87.6% respectively was achieved with the UV treatment. Two marine bacteria cultures were reduced corresponding to –2.3 log and –1.9 log elimination.

The length of the exposure time at any predetermined dose also helps to determine the effectiveness of the treatment. There are studies available on the regrowth of organisms in ballast tanks during the voyage. Thus, it is recommended that UV treatment should be conducted on both ballasting and deballasting modes. Another recommendation will be the design of the UV system, which will treat the ballast water during the voyage. This usually requires extra ballast pipelines and valves for old ships to ensure the continuous treatment of all ballast tanks.

The onboard test results from the cruise ship *Regal Princess* (Glosten-Herbert, 2002) revealed that UV was proven to be effective against zooplankton, phytoplankton, bacteria and viruses. The tests also indicated that there is a direct relationship between UV transmittance and percentile inactivation of bacteria and viruses and chlorophyll *a* (Table 10).

*Table 10. The correlation between UV transmittance and inactivation rate.*

| **UV transmittance** | **30–45%** | **90–95%** |
|---|---|---|
| Mean inactivation for bacteria | 25 | 90 |
| Mean inactivation for coliphage MS-2 virus | 50 | 95 |
| Reduction of chlorophyll a concentrations | 32 | 57 |

The studies conducted by Waite *et al.* (2003) concluded that UV treatment will be effective at significantly reducing bacterial populations, and that pretreatment with screens or hydrocyclones will not be required in order to enhance the removal efficiencies of a UV system. However, the effectiveness of UV treatment was short-lived, as bacterial regrowth occurred after the samples were held for 18 h. One possible explanation for this is that bacteria are capable of repairing genetic damage induced by UV treatment and this phenomenon may have also occurred in the study. Another possible explanation is that 100% mortality did not actually occur, and the remaining cells (a few, yet intact) were sufficient to increase the population to higher than ambient levels over an 18 h period.

It appears that the use of UV treatment for destroying phytoplankton in ballast water would not be an efficient or predictable process, and probably would not be successful in producing ballast water free of phytoplankton. However, it should also be noted that chlorophyll *a* is effectively a monitor of biomass and may not be a sensitive measure of inactivation of photosynthetic activity due to UV treatment. It is known that even if a vegetative cell is inactivated, it takes some time (hours to days) before the chlorophyll present in the cell is reduced or disappears altogether. Sutherland (2001) conducted longer-term (16 d) incubation studies and found that the starting concentration, growth rate, and relative abundance of *Chaetoceros gracilis* were reduced in UV-treated samples.

Obviously, the issue of regrowth is significant and must be addressed if UV treatment is to be considered as a technology for reducing micro organism abundance in ballast water. It should also be noted that in other applications (e.g., drinking water treatment), typical water treatment technologies require that treatment efficacy must be substantial and far in excess of that required to reduce natural populations of microorganisms by only 2 to 3 orders of magnitude. For example, if water is to be treated to remove bacterial populations in the range of $10^3$ organisms/ml, then treatment to facilitate at least 6 logs reduction is required in order for the process to be considered reliable and viable. Thus, if UV treatment is to be used as a treatment technology, the dose required will need to be in excess of that utilised in the experiment (> 60 mWs/ $cm^2$) to guarantee the reliable and predictable removal of microorganisms. Clearly, the regrowth issue observed in the study will mean that the required UV dose would have to be excessively high to ensure that all organisms are permanently inactivated (Waite *et al.*, 2003).

### ***Environmental acceptability***

The environmental concerns, if any, are related to the possible break-down of the lamps, and the release of mercury. UV light also affects the DNA chains of the organisms, and a risk of mutated organisms is present. This possibility, however, has been considered low.

### ***Status of technology***

As discussed earlier, UV technology is proven technology with many onshore applications. Some of the larger existing devices can be mounted onboard ships for ballast water treatment. One of the latest ballast water treatment systems based on UV has been installed on the cruise ship *Coral Princess* in co-operation by Berson UV Techniek and Hyde Marine (Fig. 7).

*Figure 7. Cruise ship Coral Princess, which is equipped with a combination of filter and UV disinfection as a ballast water treatment method (Berson, 2004).*

The treatment system consists of an Arkal Galaxy automatic back flush filter of 50 µm as the primary treatment and a Berson InLine® UV disinfection unit as the secondary treatment. Automatic wipers keep the quartz sleeves clean and the treatment process, including pumps and valves, is controlled by a master Programmable Logic Controller. The ballast water is treated during ballasting and deballasting with a flow rate of 250 $m^3$/h. Berson InLine® systems use high intensity medium pressure UV technology, which enables the delivery of a higher UV dose with fewer and smaller lamps compared to low pressure installations. The equipment requires a small floor area and can be installed at any angle, which is beneficial in onboard installations with confined spaces. The maintenance work required from the ship crew is limited to the replacement of the UV lamps once a year and occasional preventative maintenance work (Berson, 2004).

UV disinfection appears to have considerable promise for practical, successful secondary treatment, since Glosten-Herbert (2002):

- UV has potential to be effective against all target organisms. It may be possible to increase irradiation intensities to address turbid water conditions. For varying turbidity and transmission levels, the optional automatic control of bulb intensity or ballast water flow rate could be provided.
- UV has a long history in the marine industry and demonstrated low maintenance requirements.
- New development in UV unit design with multiple lamps in cross-flow configurations shows potential advantages.

- The basic technology is readily available for both low and high flow rates. Even for high flow rates (3,000 $m^3/h$), the physical size is reasonable (around 4 m long, 2 m in diameter).
- UV enables treatment during both ballasting and deballasting.
- UV creates only a small pressure drop and requires simply piping connections.
- UV is capable of automatic operation with electronic monitoring and alarms.
- UV light does not change the physical characteristics of the treated water and is environmentally friendly with no known toxic by-products, residuals or lasting effects.

***Cost data***

The installation and lifecycle costs for filter and cyclon as a primary treatment and UV as a secondary treatment have been estimated for the oil tanker *Polar Endeavour* in the reference Glosten-Herbert (2002). The general data of the tanker is presented in Table 11.

*Table 11. The general data of the oil tanker Polar Endeavour.*

| | |
|---|---|
| Vessel name | M/S Polar Endeavour |
| Vessel type | 125,000 dwt crude oil carried |
| Year delivered | 2001 (new building) |
| Owner/Operator | Polar Tankers, Inc. |
| Length overall | 272.69 m |
| Beam | 46.20 m |
| Depth | 25.30 m |
| Draft | 16.31 m |
| Deadweight | 127,005 MT |
| Ballast capacity | 60,700 $m^3$ (55,000 $m^3$ used for heavy ballast conditions) |
| Number of ballast tanks | 6 pairs of main tanks + 1 forepeak tank + 4 aft. tanks |
| Ballast pumping capacity | 2 at 2,860 $m^3/h$, main pumps; 2 at 1,000 $m^3/h$, aft pumps |

The installation and lifecycle cost data are presented in Tables 12 and 13.

*Table 12. Installed cost data of Polar Endeavour.*

| **Item** | **Material cost** [$] | **Labour cost** [$] | **Material Mark-up** [$] | **Contingency** [$] | **Total** [$] |
|---|---|---|---|---|---|
| Main ballast system cyclonic separators | 321,300 | 83,300 | 48,200 | 48,600 | 501,400 |
| Main ballast system UV light Treatment units | 427,000 | 181,503 | 64,100 | 73,000 | 745,600 |
| Aft Ballast system cyclonic separators and UV units | 473,900 | 135,190 | 71,100 | 73,100 | 1,506,293 |
| Chemical treatment | 38,000 | 22,450 | 5,700 | 7,300 | 73,500 |

*Table 13. Lifecycle cost data of Polar Endeavour.*

| **Item** | **Installation cost** [$] | **Lifecycle (LC) cost** [$] | **Present value of LC cost** [$] | **Uniform equivalent annual cost (AAC)** [$] | **Tonnes of ballast water pumped / year** | **Cost / tonne** [$] |
|---|---|---|---|---|---|---|
| Main ballast treatment – CS & UV<br>- CS only<br>- UV only | 1,247,000<br>501,000<br>746,000 | 2,444,000<br>729,000<br>1,716,000 | 1,614,000<br>573,000<br>1,041,000 | 143,000<br>51,000<br>92,000 | 1,435,200<br>1,435,200<br>1,435,200 | 0.10<br>0.04<br>0.06 |
| Aft ballast treatment – CS & UV | 753,000 | 918,000 | 803,000 | 71,000 | 1,435.200 | 0.05 |
| Sum of main + aft CS & UV | 2,000,000 | 3,362,000 | 2,417,000 | 214,000 | 1,435,200 | 0.15 |
| Chemical treatment @ $0.20 / ton | 74,000 | 11,119,000 | 3,879,000 | 345,000 | 1,435,200 | 0.24 |
| Chemical treatment @ $0.10 / ton | 74,000 | 5,731,000 | 2,014,000 | 179,000 | 1,435,200 | 0.12 |

According to the installation cost data, chemical treatment appears to be a more attractive treatment option compared to the combination of cyclon separation and UV when considering only the economical aspects. When comparing the lifecycle costs between chemical treatment and cyclon+UV combination, the cost per tonne of treated ballast water seems to be less propitious for chemical treatment.

### 4.6.5 Ultrasound technology

***General***

US devices generate high frequency energy that causes the exposed liquid to vibrate producing physical and chemical impacts on the organisms in the treated water. The basic form of the impact is the formation of cavitation, which can be defined as the rapid formation and collapse of microscopic gas bubbles in liquid as the molecules in the liquid absorb ultrasonic energy. The implosion of microscopic gas bubbles in turn ruptures the cell membranes and causes collisions with other organisms. Thus, when treating ballast water with suspended sediments or other inorganic or organic matter, killing efficiency will be better when compared to the results from water with less suspended material. This will differ from the efficiency of both UV or ozone treatments, where a large load of organic or inorganic material, turbidity, etc., requires more energy than defined on the basis of laboratory tests with clear water. If a filtering device is installed before the US device, however, this filtering may have a mixed effect on the treatment process: filtering will reduce the amount of organisms to be treated with US, but the lack of organisms will need more energy from the US due to the lack of collisions and friction with submerged particles.

***Safety***

US transducers are usually constructed of steel, titanium, aluminium or ceramic material. Some transducers are constructed of combinations such as aluminium stacked ceramic discs (SWRCB, 2002). US technology is also a proven technology, and some small-scale US devices are in operative use. US is often combined with primary filtering systems developed for filtering, cleaning or decreasing purposes. The construction materials make the systems rather robust and corrosion free. Some concern might be present on the possibility of the insufficient cooling system of the device: the device generates high temperatures while in operation; thus, in connection with a cooling system failure, the system should be switched off automatically. The US system also develops noise that can irritate humans and animals. If a large US system is assembled onboard, noise reduction and/or hearing protection should be designed in a proper manner. A ship, as an assembly environment, is not an easy task due to the steel famed structure where impulses can be transmitted over long distances and even be strengthened by resonation.

Some applications are also connected with pressure cells to maintain certain pressure levels in the treatment process. A pressurised system may cause a potential for hazards during the service or cleaning work if not properly switched off. In systems with complex pipelining and several valves, the controls must be designed to direct the flows in the designed direction. Manual valve systems should be simple and secured in a manner to prevent the closure of the main valves causing a reduction or the ineffectiveness of the system.

### *Biological effectiveness*

US can affect viruses and bacteria effectively (Bucholz *et al.*, 1998). According to SWRCB (2002), large systems are available that could be effective in treating ballast water and large volumes of water. These treatment systems, however, are mainly developed for industrial purposes and onboard solutions are scarce. Devices with a capacity of 100 gpm (gallons per minute), equivalent to 23 $m^3$/h, have shown around a 7 log reduction for the Polio Virus (< 5 µm) and a 6–7 log reduction for the bacteria *Cryptosporidium parvum*. With Nematode Heliminth ova, *Ascaris* (8–10 µm) and mollusk zebra mussel veligers (70 µm), 100% mortality was achieved. The same mortality rate with zebra mussel has been demonstrated in 600 gpm flow systems (Buchholz *et al.*, 1998).

Inactivation rates of 100% have been achieved in larger organisms and a 6–7 log reduction in bacteria and viruses. With 20 s exposure in an experimental continuous flow system, 93–98.6% inactivation of *Cryptosporidium* ocyst and a 4 log reduction at 10 s exposure in a laboratory batch reactor has been achieved. Inactivation rates have also been reported for *Cryptosporidium parvum* (7 log), viable helminth eggs (4.2 log), polio virus (8 log), *Salmonella* sp. (9 log) and *Echerichia coli* (9 log) (Oemcke, 1999; Buchholz *et al.*, 1998).

The log number represents the number of 9's in the percentage reduction. For example, a 2 log reduction means that 99% of the organisms originally present in the water have been inactivated. A 3 log reduction means that 99.9% have been inactivated, etc.

The capacity of the US system is also dependant on the power delivered. High intensity US devices require less exposure time for mortality to occur thus allowing higher flow rates to be treated. High power US supply systems can be used for ballasting and deballasting, while less effective systems may have their applicability range in ballast tank treatment.

### *Cost data*

Only a limited number of references with cost data of large-scale ultrasound applications were available when preparing this publication. The operation of a US unit is, in principle, 24/7/365 mode (24 hours a day, seven days a week, all year round). The price estimation for a US treatment unit is 10,000 €/kW excluding installation, training and maintenance costs. Maintenance will be required after 5,000 h of use. Based on the results achieved from the onshore test trials, it was estimated that 1 kW would be required to treat 1 $m^3$ of ballast water/h. Constant pressure (around 1–1.5 bar) is required for process optimisation. The most powerful US unit manufactured by Hielscher GmbH is 16 kW with a space requirement of 1–2 $m^3$ (Hielscher, 2003).

### 4.6.6 Ozone technology

***General***

Ozone treatment systems are based on the combination of high power electric current and oxygen supply systems: a high voltage electric current flow between electrodes and oxygen is discharged between the electrodes. Electrodes are separated by a dialectric gap that contains the discharge chamber through which oxygen flows. Oxygen molecules are broken down in the electric field and the attaching free oxygen atoms thus form ozone. After generation, the ozone is directed towards the connection chamber where the treated water is to be disinfected. Because the produced ozone will break down rapidly, the ozone generators must be situated on-site.

An essential feature is also the contact time required, thus the deballasting or ballasting modes for larger ballast water amounts might be too expensive in full-scale applications. An optimum ozone application may be the supply configuration, where one or several ballast water tanks are equipped with ozone injection equipment, and these tanks are used as contact chambers. The ballast water should then be treated by pumping the water into these contact tanks from each tank, in order to achieve a long enough contact time. It appears that the ozone treatment process also requires preliminary treatment (filter or cyclone) to reduce the fine particles to enter the treatment process and the sediment formation to the ballast water tanks. Oemcke (1998) suggests that pre-filtering at 10 to 20 µm would probably be necessary to remove particles larger than bacteria, viruses and smaller organisms.

Treatment during ballasting would ensure that all ballast water pumped into the ballast tanks would be exposed to ozone at the beginning of the voyage. If a long contact time is not required for the target organisms, disinfection would be ensured. In cases where the target organisms require longer contact times, treatment during ballasting would not be efficient enough and therefore treatment during voyage would be a solution for enabling longer contact times.

Organic carbon tends to be associated with sediments, which settle at the bottom of the ballast tanks during voyage. It is not likely that ozone treatment will be efficient enough in the sediment. Sediment contains organisms that are more difficult to kill such as viral clumps and bacteria colonising surfaces. This region may produce ammonia as the result of the biological activity during the voyage. Ammonia will react with disinfection residuals producing bromamines, which are weaker disinfectants. These effects reduce the efficiency of long contact times. The sizes of treatment plants for in-transit treatment have been determined in Table 14.

*Table 14. The sizes of treatment plants for in-transit ozone treatment (Oemcke & van Leeuwen, 1998).*

| **Organisms** | **C,t** [mg,min/L] | **Treatment time** [h] [1] | **$M_0$** [kg/h] | **$M_d$** [kg/h] | **$M_T$** [kg/h] | **$C_{peak}$** [mg/L] |
|---|---|---|---|---|---|---|
| Bacteria, virus, | 100 | 24 (12/12) | 0.084 | 13.7 | 13.75 | 0.11 |
| amoebae | 100 | 48 (24/24) | 0.031 | 6.8 | 6.86 | 0.05 |
| | 100 | 96 (48/48) | 0.014 | 3.4 | 3.34 | 0.03 |
| *Amphidinium* sp, | 1,000 | 24 (12/12) | 0.84 | 13.7 | 14.51 | 1.14 |
| | 1,000 | 48 (24/24) | 0.31 | 6.8 | 7.14 | 0.57 |
| | 1,000 | 96 (48/48) | 0.14 | 3.4 | 3.56 | 0.30 |
| *Bacillus subtilis* spores | 17,000 | 24 (12/12) | 14.23 | 13.7 | 27.9 | 19.3 |
| | 17,000 | 48 (24/24) | 5.31 | 6.8 | 12.1 | 9.3 |
| | 17,000 | 96 (48/48) | 2.37 | 3.4 | 5.8 | 4.6 |
| *Gymnodinium* | 42,000 | 24 (12/12) | 35.16 | 13.7 | 48.8 | 47.8 |
| *catenatum* cysts | 42,000 | 48 (24/24) | 13.13 | 6.8 | 20.0 | 22.6 |
| | 42,000 | 96 (48/48) | 5.84 | 3.4 | 9.3 | 11.6 |

$M_o$ = the mass flow of ozone from ozone generation for disinfection.
$M_d$ = the mass flow from the ozone generator to meet ozone demand.
$M_T$ = the size of the ozone generator for shipboard treatment.

The peak oxidant concentration varied from 0.03 to 47.8 mg/L depending on the organism group and contact time. The ozone dosages used in the onshore test trials were 7 and 17 mg/L.

The technical data of two commercially available ozone generator plants from two different manufacturers are indicated in Table 15.

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[1] 24 h treatment is divided into 12 h of ozonation, 12 h of contact time hence 24 (12/12) etc.

*Table 15. The technical data of two commercially available ozone generators.*

| **Manufacturer** | **Type** | **Max. ozone production** [g/h] | **Oxygen requirement** [$m^3$/h NTP] | **Cooling water requirement** [$m^3$/h] | **Power supply at 100% ozone production** [kW] | **Dimensions L x D x H** [mm] | **Weight** [kg] |
|---|---|---|---|---|---|---|---|
| ProMinent Dosiertechnik GmbH, Germany | BONa 9D | 720 | – | 0.9 | 35 | 3,400 x 2,200 x 600 | 2,000 |
| Wedeco AG, Germany | GSO 60 | 1,000 | 10 | 1.50 | 7.5 | 2,400 x 1,000 x 500 | 360 |

### *Safety*

Ozone is very reactive and corrosive gas. Thus, system configuration must be constructed using corrosion resistant materials. Ozone treatment can cause an increased corrosion in ballast tanks. However, if the concept of special treatment chambers is to be used, the risk of corrosion decreases and the treatment tanks will be coated with resistant materials.

Even if the contact time and ozone injection have been designed in a proper way, some ozone gas may be spread into the air volume of the ballast tanks. This effect was noticed during the laboratory and onshore test trials. In low concentrations, ozone causes a typical smell that can cause headache or nausea in human people. The excess gases of the treatment chambers must be filtered or treated before releasing them into the outer atmosphere. However, the experiment carried out on S/T *Tonsina* did not include any filtering for excess ozone, thus the issue needs to be studied. UV light may also increase the ozone reactivity by forming aggressive compounds.

Ozone acts as a primary irritant, affecting mainly the eyes, upper respiratory tract and the lungs. Ozone can be detected in the air by its distinctive tangy odour at a concentrations of about 0.02–0.05 ppm. However, olfactory fatigue occurs quickly and odour is therefore not a reliable detection of ozone concentrations in the air and therefore modern ozone generators are manufactured in accordance with the relevant safety requirements. Many people exposed to airborne ozone rapidly develop a headache, which often disappears after a few minutes in fresh air. A reduction in lung functioning due to scar tissue forming in the lung may occur with long-term exposure to ozone at concentrations above 0.2 ppm, or a single high exposure.

According to Andersen *et al.* (2001), the permissible exposure level (PEL) or time weighted concentration for ozone to which workers may be exposed is an average of 0.1 ppm over 8 hours and 5 days a week. The short-term exposure limit is an average of 0.3 ppm over 15 minutes. A concentration of 10 ppm in the air is generally accepted as immediately dangerous to life or health.

When setting the threshold limit for ozone, the vital issues are the effects of ozone towards the respiratory ducts and lungs. The health protection threshold limit for 8 hours according to the EY Directive 92/72/EEC is 0.055 ppm (EY, 1992). The detrimental effects of ozone may occur if the concentration in the air exceeds 0.05 ppm in exposure over eight hours and 0.2 ppm in exposure over 15 minutes (FIOH, 2001).

By the Decree on Concentrations Known to be Hazardous (109/2005), the Ministry of Social Affairs and Health in Finland has confirmed a list of concentrations of impurities in workplace air known to be hazardous (i.e. HTP values). The HTP values for ozone has been defined as 0.05 ppm (0.1 mg/m$^3$) in exposure over eight hours and 0.2 ppm (0.4 mg/m$^3$) in exposure over 15 minutes.

In human health risk assessment, EPA assigns a health risk to every hourly average concentration above 0.04 ppm. The Occupational Safety and Health Administration (OSHA) in the U.S.A has determined the maximum ozone concentration levels in the atmosphere of work places to 0.1 ppm in exposure over eight hours and 0.05 ppm over a 24 h exposure. U.S.A EPA believes that natural background levels of ozone range from 0.03 to 0.05 ppm.

### ***Biological effectiveness***

Ozone levels of 0.4 ppm have been reported to control most vertebrate species, unicellular, and some benthic organisms. More resistant organisms (cysts) can be eliminated at 10.0 ppm. Preliminary results onboard S/T *Tonsina* showed that Ozonization killed more than 99.9% of the bacteria after 5 h of Ozonization, and over 90% of the zooplankton after 10 h.

The experiments with *Bacillus subtilis* showed that a dose of 11 mg/l with a contact time of 24 hours were required to achieve a 4 log disinfection at a pH of 7. It was estimated that 4 log reductions could be achieved at 6 hours with a dose of 14 mg/l and at 2 hours with a 16 mg/l of ozone dose. At a pH of 8 it was concluded that more than a 24 mg/l ozone dose would be required for disinfection within 24 hours and more than 27 mg/l for 2 hours. The experiments with *Amphidinium* sp. suggested that at least an ozone dose of 14 mg/l would be needed to achieve 4 log disinfection within 6 hours (Oemcke & van Leeuwen, 1998).

The required C.t -values for *Amphidinium* sp. were between 200–1,040 mg.min/l for a 4 log reduction. The required C.t -values for disinfection of *Bacillus subtilis* were between 1,300–17,000 mg.min/l depending on the pH-value and log reduction. Ozone is not effective against *Gymnodinium catenatum* hypnocysts based on the data from experiments with *Amphidinium* sp. and *B. subtilis* (Oemcke *et al.*, 1998). In the tests reported by Andersen *et al.* (2001), the C.t-values for the tested organisms varied from 40 to 2,500 mg.min/l. The C.t.-values for *Amphidinium* were lower (40–100 mg.min/l) than those reported by (Oemcke & van Leeuwen, 1998), due to the possible differences in used cultures.

### *Environmental acceptability*

Ozonisation is proven technology that has been used for years in the food industry, waste water purification, process industry and in many applications for disinfecting water. No harmful residuals are reported that should be treated or removed. Ozonisation also increases the amount of dissolved oxygen, which is a benefit in some industrial applications.

### *Experiments onboard S/T Tonsina*

BP Alaska and Nutech O3, Inc. undertook the development and testing of ozone gas as a potential treatment method against non-indigenous species in ballast water. A full-scale prototype Ozonisation plant was installed onboard the BP-affiliate vessel *S/T Tonsina* (Alaska Tanker Company). The specific objectives of the study were to

- determine the disinfection effectiveness of a full-scale ozone system in comparison with ballast water exchange efficiency
- determine the acceptability of discharging treated water using whole effluent toxicity testing, and to determine the latent toxicity of the subsequent ballast water discharge
- obtain operational experience with the prototype ozone system in order to implement further system improvements.

The S/T *Tonsina* is an 869 ft (264 m), double-hull oil tanker on which a prototype Ozonisation system has been installed and connected to the ship’s 12 segregated ballast water tanks, each of which has a capacity of approximately 850,000 gallons (3,217 $m^3$). Three ozone experiments with various ozone loading rates (0.59, 0.86 and 1.35 mg/l/h) were carried out. Two ballast water exchange experiments were conducted using ballast tanks that were filled at the same time using the same sea water as that used in the ozone experiments to obtain a comparison between the two options. Grab samples and net tow samples were collected for water chemistry, and microbial and plankton community composition. Samples were collected immediately prior to the ozone experiments, then again prior to and following an open water ballast exchange event using standard S/T *Tonsina* protocols.

Results from the first two exchange experiments suggested that the average removal of marine organisms using ballast water exchange on the S/T *Tonsina* was 64%, which is less efficient than ballast water exchange efficiencies sometimes measured on other vessels. The direct comparison of ballast water exchange and ozone treatment on the same vessel is critical in evaluating the ozone treatment's effectiveness. Moreover, the results underscore the variation the can exist by ship type, and suggest the level of "kill" needed for ozone treatment to surpass ballast water exchange onboard the S/T *Tonsina* may be lower than that for other vessels.

The results indicated that

- 99.9% of the culturable bacteria were killed
- in separate experiments, no bacterial re-growth was observed after 30 days storage in the dark in the laboratory
- up to 99% of the zooplankton were killed or near death using the ozone process
- between 92–100% of the phytoplankton were killed using the ozone process (except for diatoms, for which the results were inconclusive)
- sheepshead minnows appeared somewhat more resistant to ozone treatment, but in the latter two tests, when both dead and near death organisms percentages were combined, 98 and 100% mortality was achieved
- mysid shrimps were effectively removed in one experiment where 78% were killed or near death
- the benthic organisms studied (shore crabs, amphipods) were not effectively killed or rendered moribund by the ozonization process
- these results were consistent with experiments conducted using known numbers and species of marine organisms suspended in ballast water tanks in mesh cages.

In addition, the laboratory toxicity studies provided a realistic indication of ozone toxicity against various species.

A major concern following the treatment of ballast waters with any biocide is the discharge of potentially toxic chemicals to the environment. For ozonated seawater, bromine is the residual oxidant most likely to exist for reasonable periods of time in concentrations of potential concern to marine organisms. The toxicity of ballast water after Ozonisation was studied utilising whole effluent toxicity (WET) tests and latent toxicity tests. The results of the WET tests using ozone-treated ballast water, with the mysid shrimp *Americamysis bahia* and the topsmelt *Atherinops affinis*, indicated that ozonisation by-products were stable enough to cause toxicity (30–80% ozonated ballast water causing acute mortality) in ballast waters even 1–2 days after ozonisation. However, no chemical measurements were conducted in these tests to quantify concentrations of ozone-produced oxidants.

The latent toxicity tests indicated that residual oxidants did not disappear from ozonated waters held in the dark for 24 or 48 h in a sealed container at 12 ºC. All organisms died when exposed to 50, 75, or 100% ozonated water that was stored either for 0, 24, or 48 h. It appears that sufficient amounts of bromine oxidants built up in the ozonated water over 1.5 h to have induced both immediate and, to an even greater extent, delayed mortality after transferring organisms to clean water (up to 48 h later).

The presence of bromine thus may cause both immediate and delayed toxicity to marine organisms even after relatively short periods of ozonisation. Preliminary experiments suggested, however, that this residual bromine may be easily removed using commonly available reducing agents such as sodium thiosulfate, and thus could remove toxicity from ozonated ballast waters prior to discharge. Bromine is also likely to be quickly destroyed (i.e., chemically reduced) upon discharge into marine surface waters, and so may be of only limited environmental or regulatory concern for ballast water discharge. Additional study is warranted, however, to verify this conclusion.

The studies carried out onboard the S/T *Tonsina* suggested that ozonisation has the potential for being an effective and safe technology for the removal of non-indigenous species from ballast water. Some of the primary conclusions of the study included the following:

- Using this prototype system, 5–10 h of ballast water ozonisation resulted in 71–99% removal of most marine phytoplankton, zooplankton, and bacteria depending on the amount of ozone gas delivered to individual ballast water tanks over time. Benthic organisms (e.g., crabs, amphipods), however, appeared to be relatively resistant to ozone treatment. It is possible, however, that these experiments could have underestimated the overall system's effectiveness because of the longer-term residual toxicity of bromine, which is likely the most important and toxic oxidant produced by ozone in seawater. Additional study under field conditions is warranted to verify this conclusion.
- This organism removal efficiency was greater than that achieved (64% on average) using empty-refill ballast water exchange on the same vessel. Other vessels may achieve greater ballast water exchange efficiency, but studies are few and highly variable.

- Both field and laboratory experiments suggested that significant organism mortality can be achieved once concentrations of ozone-produced oxidants reach 1–3 mg/l (as chlorine equivalents), or when oxidation-reduction potential reaches levels of 700–800 mV. Once further validated, such toxicity thresholds could be used to help develop control targets for aiding the routine operation of ozone systems.
- Preliminary results suggested that bromine was the ozone-produced oxidant that was most likely responsible for organism mortality. Furthermore, bromine may persist at toxic concentrations in ballast waters 1–2 days following ozonisation depending on the storage conditions and exposure to sunlight. However, bromine may easily be eliminated (i.e., chemically reduced) prior to, or quickly following, ballast water discharge. Additional study will be required to further evaluate these conclusions.

While these results suggest that the ozonisation of ballast water may be a useful treatment technology for the prevention of the introduction of non-indigenous species, uncertainties remain in our scientific understanding of system efficacy. Additional studies are planed to address some of the following issues and uncertainties:

- It will be important to better quantify the spatial and temporal variability of ozone effectiveness within and between different ballast water tanks.
- The length of time bromine residuals persist following ozonisation under field conditions will need to be verified.
- The toxicity of bromine residuals to marine organisms will need to be evaluated further in order to determine whether this residual toxicity can be used to increase overall organism removal efficiency over longer periods of time.
- Results from the present study can be used to refine system operations to maximise organism removal efficiency, either via the enhanced delivery of ozone gas, use of bromine residuals, enhanced mixing of these oxidants, or a combination of all three.
- Given the current regulatory focus on ballast water exchange as a benchmark technology for comparison to alternative treatments, we will to continue comparisons of ozone treatment to ballast water exchange organism removal efficiencies on this same vessel to improve statistical confidence in our conclusions.
- To ensure environmental and regulatory acceptance of this treatment system, it will be critical to further evaluate the removal/destruction of bromine residuals prior to ballast water discharge (e.g., using chemical reducing agents). It will also be important to evaluate the extent to which bromine concentrations will

naturally attenuate following discharge to surface waters (e.g., mixing with natural water, photochemical decomposition, etc.) (Cooper *et al.*, 2002).

### 4.6.7 Cost estimations for full-scale applications

*General*

Since no full-scale installation and experiments with UV, US and ozone treatment options were carried out during the project, the cost evaluation was prepared utilising same principles and cost data for fuel as in Ellis and van der Woerd (2004). The objective of the cost estimation is to provide only a rough estimation of the costs utilising the results from onshore trials and cost data available. The basic energy data and conversion factors for electricity production have been indicated in Tables 16 and 17.

*Table 16. Basic energy data.*

| **Basic energy data** | | **Unit** |
|---|---|---|
| kWh to MJ | 3.6 | MJ/kWh |
| Conversion rate diesel to electricity | 30% | |
| Conversion rate diesel to steam | 66% | |
| Energy content diesel (MJ/kg) | 42.5 | MJ/kg |
| Price diesel (Euro/kg) | 0.40 | €/kg |

*Table 17. Conversion factors for electricity production.*

| **Electricity production** | | **Unit** |
|---|---|---|
| energy requirement | 100 | kWh |
| kWh to MJ (electricity) | 360 | MJ (electricity) |
| MJ (electricity) to MJ (diesel) | 1,200 | MJ (diesel) |
| MJ to kg (diesel) | 28.24 | kg (diesel) |
| Energy costs (diesel) | 11.29 | € (28.24 kg) |
| | | |
| Energy costs electricity | 0.113 | €/kWh |

As a result, the cost for energy (electricity) is 0.113 €/kWh based on the data presented in Ellis and van der Woerd (2004).

Cost evaluations have been carried out for two different ship types, *Tempera* oil tanker and *Don Quijote* pure car and truck carrier. *Tempera* oil tanker (Table 18), owned by Neste Shipping, is a double acting 1 AS ice class crude oil carrier with double-hull and segregated ballast water tanks. Double skin cofferdams are provided for all bunker tanks. The pump room has a double bottom. The layout of the ballast water and oil cargo tanks is presented in Figure 8.

*Table 18. The main particulars of the Tempera Oil Tanker (Neste Oil, 2005).*

| Vessel name | Tempera |
|---|---|
| Built | 2002 |
| Owner | Neste Shipping, Finland |
| Length O.A. | 252.0 m |
| Length B.P. | 237.59 m |
| Breadth moulded | 44.0 m |
| Depth moulded | 22.5 m |
| Draught on summer freeboard | 15.3 m |
| Corresponding deadweight | 106,034 dwt |
| Air draught in ballast condition | 44.11 m |
| T.P.C | 95.1 m |
| Distance keel/top antenna | 53.1 m |
| Ballast water pump, electric driven | 2,500 $m^3$/h x 35 m T.H, 1 set |
| Ballast water pump, electric driven | 3,000 $m^3$/h x 70 m T.H, 1 set |
| Ballast water volume | 46,922.4 $m^3$ |
| Number of BW tanks | 12 |

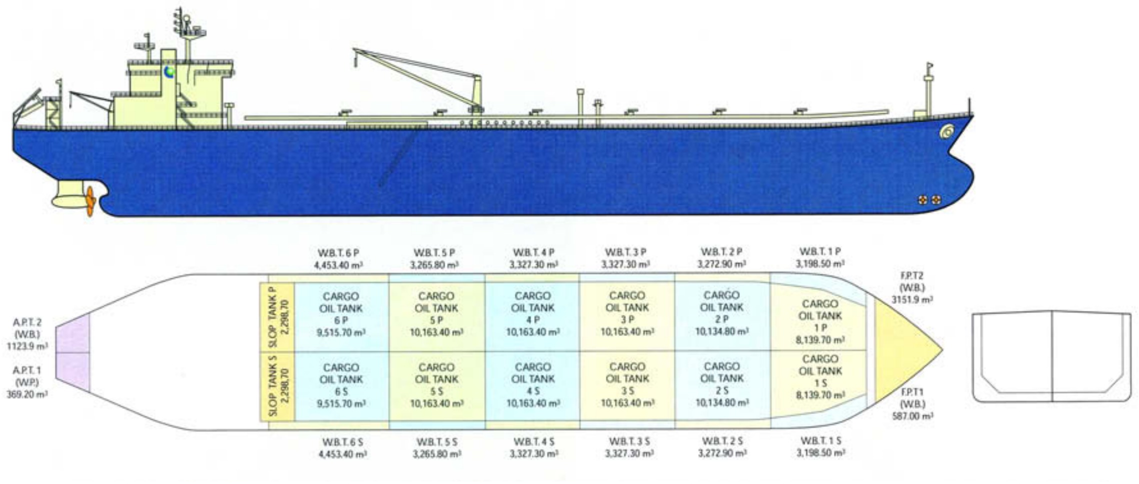

*Figure 8. The layout of the ballast water and cargo oil tanks on Tempera (Neste Shipping, 2005).*

*M/V Don Quijote* (gross tonnage 56,893 GT, deadweight at max. draft 22,615 MT, net tonnage 23,693 NT) is owned by the Swedish shipping company Wallenius Lines AB (Fig. 9). It has a capacity of 5,873 cars or a combination of 2,949 cars and 488 trucks on 13 car decks. The overall length is 199.10 m, the beam (moulded) 32.26 m, and the height to upper-deck is 33.48 m. Maximum speed is 20.5 knots. The ballast water volume is 8,076 $m^3$ and number of BW tanks is 17. The ballast water pumps have a total capacity of 500 $m^3$/h.

*Figure 9. M/V Don Quijote, 14,800 dwt pure car and truck carrier (Wallenius Lines, 2005).*

When estimating the effect of the ballast water treatment to the costs of maritime transport, a daily running costs of 26,000 € for 109,000 dwt oil tanker and 17,000 € for the pure car and truck carrier has been utilised. The circulation of ballast water is possible in both vessels, based on information from ship crew and the ship's owner. However, the concept of ballast water circulation and contact tank approach requires a more detailed feasibility study.

***Cost evaluation for two ultraviolet light installations***

The estimated cost evaluation data is presented in Table 19 for two different UV installations with the hypothesis that ballast water circulation during the voyage is possible. The hypothetical duration of the voyage is 5 days and the ballast water volumes to be treated are 46,900 $m^3$ in the 106,000 dwt oil tanker (*Tempera*) and 8,076 $m^3$ in the 14,800 dwt pure car and truck carrier (*Don Quijote*). The cost calculations are based on the estimated depreciation period of 10 years, estimated number of voyages 50 per year and an interest rate of 8%.

Berson InLine 3000 embodies eight B2035 ultraviolet lamps with 1.5 kW each. The power supply for each lamp is 0.15 kW and for the control unit 0.3 kW. The required power supply for the system is 13.5 kW. For the PCTC vessel the Berson InLine 1500 or equivalent with four B2035 lamps and power consumption of 6.9 kW appears to be suitable. The disinfection units deliver an ultraviolet dose of 65 $mJ/cm^2$ at flow rates of 500 $m^3/h$ and 70 $m^3/h$ at the end of lamp life.

*Table 19. Estimated parameters and costs for two different UV installations on a new ship.*

| | Oil tanker (106,000 dwt) | Pure car and truck carrier, PCTC (6,000 units, 14,800 dwt) |
|---|---|---|
| Ballast water volume [m$^3$] | 46,900 | 8,076 |
| Number of ballast tanks | 12 | 17 |
| Time scale for treatment during one voyage [h] | 120 | 120 |
| Capacity of ballast water pumps [m$^3$/h] | 5,500 | 500 |
| Required treatment capacity [m$^3$/h] | 400 | 70 |
| Estimated power consumption of additional pumps for the required treatment capacity [kW] | 50 | 15 |
| Estimated capacity of disinfection units (Berson InLine 3000 or equivalent) [m$^3$/h] | 500 | 500 |
| Required number of UV units (Berson InLine 3000 or equivalent) for the oil tanker | 3 | |
| Required number of UV units (Berson InLine 1500 or equivalent) for the PCTC | | 2 |
| Energy consumption for UV units[2] [kWh] | 2,430,000 | 828,000 |
| Energy consumption for additional pumps [kWh] | 3,000,000 | 900,000 |
| Weight (one UV unit 157 kg wet + 450 kg power control module) [kg] | 1,821 | |
| Weight (one UV unit 157 kg wet + 250 kg power control module) [kg] | | 814 |
| Required floor space, height min. 2.5 m [m$^2$] | 6 | 4 |
| Annual capital costs at 8% interest [€]: | 34,723 | 18,181 |
| – *investment of UV disinfection units* | *200,000* | *100,000* |
| – *installations* | *20,000* | *15,000* |
| – *additional pumps for BW circulation* | *10,000* | *5,000* |
| – *commissioning and testing* | *3,000* | *2,000* |
| *Total capital costs [€]* | *233,000* | *122,000* |
| Annual operational costs [€]: | 64,200 | 32,270 |
| – *materials* | *20,000* | *15,000* |
| – *fuel for disinfection units* | *275,000* | *200,000* |
| – *fuel for extra pumps due to treatment* [3] | *339,000* | *101,700* |
| – *labour* | *8,000* | *6,000* |
| *Total operational costs [€]* | *642,000* | *322,700* |
| Annual maintenance costs [€]: | 6,000 | 4,000 |
| – *spare parts* | *40,000* | *30,000* |
| – *labour* | *20,000* | *10,000* |
| *Total maintenance costs [€]* | *60,000* | *40,000* |
| Annual training and management costs [€]: | 1,000 | 800 |
| – *training* | *5,000* | *4,000* |
| – *management* | *2,000* | *2,000* |
| – *certification* | *2,000* | *1,000* |
| – *health and safety manuals* | *1,000* | *1,000* |
| *Total training and maintenance costs [€]* | *10,000* | *8,000* |
| Total annual costs [€] | 105,923 | 44,611 |
| Total volume of BW to be treated annually [4] [m$^3$] | 2,345,000 | 403,800 |

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[2] Energy consumption for one unit is 13.5 kW or 6.9 kW, number of operating hours in 10 years is 60,000.

[3] Estimated cost for fuel consumption based on the required treatment capacity: 50 kW, 60,000 operational hours.

[4] 50 voyages per year, BW volume 46,900 or 8,076 m$^3$ for one voyage.

*Table 19. Continues...*

| | | |
|---|---|---|
| Estimated cost for treated ballast water excluding retrofitting costs for existing vessels and the cost of primary treatment [€ / $m^3$] | 0.045 | 0.11 |
| Estimated cost per voyage [€] | 2,118 | 892 |
| Rate of the vessel for one voyage [€] | 130,000 | 85,000 |
| Proportion of the costs for one voyage [%] | 1.6 | 1.0 |

Turbid particle-rich waters reduce disinfection efficiency and therefore the UV treatment process requires primary treatment. In order to reduce turbidity, particles down to 40–50 µm must be removed or the design of the treatment system must account for the ambient turbidity likely to be encountered. The total amount of suspended solids should be less that 20 mg/l. Alternatively, ballasting could be conducted in areas with low turbidity when possible. When the number of UV disinfection units was defined, extra capacity was prepared due to the probability of maintenance work and malfunction.

The pre-treatment unit will obviously increase the total costs, estimated capital costs could be around 200,000 € for filter or 500,000 for hydrocyclon (SWRC, 2002). The operational costs for a cyclon separator are estimated as USD 0.04 in Glosten-Herbert (2002). Maintenance of the UV units is required after 8,000 h of operation.

### Cost evaluation for two ultrasound installations

The estimated cost evaluation data for two different US installations with the hypothesis that ballast water circulation during the voyage is possible, is presented in Table 20. The hypothetical duration of the voyage is 5 days and the ballast water volumes to be treated are 46,900 $m^3$ in the 106,000 dwt oil tanker and 8,076 $m^3$ in the 14,800 dwt car carrier. The cost calculations are based on the estimated depreciation period of 10 years, estimated number of voyages 50 per year and 8% interest rate. The US power requirement is estimated based on results and experience gained from the onshore test trials.

*Table 20. Estimated parameters and costs for two different ultrasound installations on a new ship.*

| | Oil tanker (106,000 dwt) | Pure car and truck carrier, PCTC (6,000 units, 14,800 dwt) |
|---|---|---|
| Ballast water volume [m$^3$] | 46,900 | 8,076 |
| Number of ballast tanks | 12 | 17 |
| Time scale for treatment during one voyage [h] | 120 | 120 |
| Capacity of ballast water pumps [m$^3$/h] | 5,500 | 500 |
| Required treatment capacity [m$^3$/h] | 400 | 70 |
| Estimated power consumption of additional pumps for the required treatment capacity [kW] | 50 | 15 |
| Required power for US units [kW] | 400 | 70 |
| Required number of 16 kW US units (Hielcher or equivalent) | 25 | 5 |
| Energy consumption for US units in 10 years [kWh] | 24,000,000 | 4,800,000 |
| Energy consumption for additional pumps [kWh] | 3,000,000 | 900,000 |
| Weight (one US unit 150 kg) [kg] | 3,750 | 750 |
| Required floor space, height min. 3 m [m$^2$] | 40 | 8 |
| Capital costs per year at 8% interest [€]: | 602,084 | 106,407 |
| – *investment of US disinfection units* | *4,000,000* | *700,000* |
| – *installations* | *25,000* | *7,000* |
| – *additional pumps for BW circulation* | *10,000* | *5,000* |
| – *commissioning and testing* | *5,000* | *2,000* |
| *Total capital costs [€]* | *4,040,000* | *714,000* |
| Annual operational costs [€]: | 309,600 | 65,310 |
| – *materials* | *30,000* | *6,000* |
| – *fuel for disinfection units* | *2,712,000* | *542,400* |
| – *extra fuel for extra pumps due to treatment* | *339,000* | *101,700* |
| – *labour* | *15,000* | *3,000* |
| *Total operational costs [€]* | *3,096,000* | *653,100* |
| Annual maintenance costs [€]: | 7,500 | 1,700 |
| – *spare parts* | *70,000* | *14,000* |
| – *labour* | *15,000* | *3,000* |
| *Total maintenance costs [€]* | *75,000* | *17,000* |
| Annual training and management costs [€]: | 600 | 320 |
| – *training* | *2,000* | *1,000* |
| – *management* | *1,000* | *700* |
| – *certification* | *2,000* | *1,000* |
| – *health and safety manuals* | *1,000* | *500* |
| *Total training and management costs [€]* | *6,000* | *3,200* |
| Total annual costs [€] | 919,784 | 173,737 |
| Total volume of BW to be treated annually | 2,345,000 | 4,038,000 |
| Estimated cost for treated ballast water excluding retrofitting costs for existing vessels [€ / m$^3$] | 0.39 | 0.43 |
| Estimated cost per voyage [€] | 18,396 | 3,475 |
| Rate of the vessel for one voyage [€] | 130,000 | 85,000 |
| Proportion of the costs for one voyage [%] | 14.2 | 4.1 |

Due to the strong cavitation, the sonotrodes are subject to wear. This can even result in cracks and therefore the sonotrode have to be checked visually every 5,000 h of operation and be replaced if required.

### *Cost evaluation for two ozone treatment installations*

In Table 21, estimated parameters and costs for two different ozone installations with the hypothesis that the contact tanks approach could be utilised are presented. The hypothetical duration of the voyage is 5 days and the ballast water volumes to be treated are 46,900 $m^3$ (106,000 dwt oil tanker) and 8,076 $m^3$ (14,800 dwt pure car and truck carrier). The depreciation period for the vessel is estimated for 10 years and estimated number of voyages 50 per year. Based on the experience gained from the onshore test trials an ozone dosage of 17 mg/l could be adapted.

*Table 21. Estimated parameters and costs for two different ozone installations on a new ship.*

| | Oil tanker (106,000 dwt) | Pure car and truck carrier, PCTC (6,000 units, 14,800 dwt) |
|---|---|---|
| Ballast water volume to be treated [$m^3$] | 46,900 | 8,076 |
| Number of ballast tanks | 12 | 17 |
| Number of contact tanks | 2 | 2 |
| Total volume of contact tanks [$m^3$] | 6,000 | 1,000 |
| Capacity of ballast water pumps [$m^3/h$] | 5,500 | 500 |
| Power consumption of BW pumps [kW] | 550 | 200 |
| Time scale for one voyage [h] | 120 | 120 |
| Time scale for treatment (= contact time) [h] | 15 [5] | 15 [6] |
| Operational time for BW pumps during treatment [h] | 4,250 [7] | 2,000 [8] |
| Required ozone dosage based on onshore trials [mg/l] | 17 | 17 |
| Required ozone dosage (for 6,000 and 1,000 $m^3$) [kg] | 102 | 17 |
| Number of ozone generators with an ozone production rate of 0.720 kg / h for one unit (ProMinent BONa 9D or equivalent) | 10 | 2 |
| Energy consumption for ozone generators [9] [kWh] | 21,000,000 | 4,200,000 |
| Energy consumption for BW pumps due to treatment [kWh] | 2,337,500 | 400,000 |
| Weight (one generator 2,000 kg) | 20,000 kg | 4,000 kg |
| Required floor space (height min. 3.5 m) [$m^2$] | 30 | 6 |
| Capital costs per year at 8% interest [€]: | 171,829 | 34,574 |
| – *investment of ozone generators and required* accessories | *950,000* | *190,000* |
| – *installation, incl. extra piping and safety equipment* | *200,000* | *40,000* |
| – *commissioning and testing* | *3,000* | *2,000* |
| *Total capital costs [€]* | *1,153,000* | *232,000* |
| Annual operational costs [€]: | 276,714 | 57,480 |
| – *materials* | *50,000* | *10,000* |
| – *fuel for disinfection units* | *2,373,000* | *474,600* |
| – *extra fuel for BW pumps due to treatment* | *264,137* | *45,200* |
| – *corrosion monitoring* | *30,000* | *15,000* |
| – *labour* | *50,000* | *30,000* |
| Total operational costs [€] | *2,767,137* | *574,800* |
| Annual maintenance costs [€]: | 12,000 | 3,000 |
| – *spare parts* | *60,000* | *15,000* |
| – *labour* | *60,000* | *15,000* |
| *Total maintenance costs [€]* | *120,000* | *30,000* |

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[5] Total volume to be treated 46,900 $m^3$, volume of two contact tanks 6,000 $m^3$, 8 times volume of contact tanks to be treated, duration of voyage 120 h, time scale for treatment of 6,000 $m^3$ would be 15 h.

[6] Total volume to be treated 8,076 $m^3$, volume of two contact tanks 1,000 $m^3$, 8 times volume of contact tanks to be treated, duration of voyage 120 h, time scale for treatment of 1,000 $m^3$ would be 15 h.

[7] 8.5 h (5,500 $m^3/h$, 6,000 $m^3$) per voyage, 10 years, 50 voyages per year.

[8] 4 h (2,000 $m^3/h$, 1,000 $m^3$) per voyage, 10 years, 50 voyages per year.

[9] Energy consumption for one unit is 35 kW, operational hours are (15 x 8 x 50 x 10) 60,000.

*Table 21. Continues...*

| | | |
|---|---|---|
| Training and management costs [€]:<br>– *safety training*<br>– *management, incl. certification and health and safety issues*<br>*Total training and management costs [€]* | 1,000<br>*6,000*<br>*4,000*<br>*10,000* | 500<br>*3,000*<br>*2,000*<br>*5,000* |
| Total annual costs [€] | 461,543 | 95,554 |
| Total volume of BW to be treated annually[10] [m$^3$] | 2,345,000 | 403,800 |
| Estimated cost for treated ballast water excluding primary treatment and retrofitting costs for existing vessels [€/ m$^3$] | 0.20 | 0.24 |
| Estimated cost per voyage [€] | 9,231 | 1,911 |
| Rate of the vessel for one voyage [€] | 130,000 | 85,000 |
| Proportion of the costs for one voyage [%] | 7.1 | 2.2 |

The contact tank approach requires modifications to ballast water pipelines, pumps and ballast water management practices. If the ozone is generated from pure oxygen instead of ambient air, extra costs will be caused by oxygen generators and associated equipment. The estimated operational cost for a cyclon separator is 0.04 €/m$^3$ (Glosten-Herbert, 2002).

Ozonisation as proven technology is safe and robust also for large amount of waters. Industrial applications are large-scale devices and require significant amounts of cooling water. The lack of cooling water onboard ships is not a problem, but the installation and the design of the treatment chambers and adequate pumping lines are problematic for older ships.

### 4.6.8 Discussions

The continuous use of ballast water pumps will increase maintenance costs and risk of malfunction and therefore additional pumping capacity might be required. In the cost estimations in Tables 19 and 20, it is estimated that two additional pumps for each treatment capacity, i.e. 50 kW pump for 400 m$^3$/h and 15 kW pump for 70 m$^3$/h would be required.

UV treatment seems to be the most cost-effective treatment method when comparing the calculations in Tables 19, 20 and 21. The fuel consumption for US disinfection units appears to be significant. The combination of US and UV could reduce the energy requirements for the treatment and also improve the efficiency compared to the single technologies based on the results achieved on the onshore test trials. The relative high estimated costs for US treatment could be reduced by developing the process conditions and the transducer technology since the technology does not have applications especially designed for ballast water treatment at the moment.

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[10] 50 voyages per year, BW volume 46,900 or 8,076 m$^3$ for one voyage.

Compared to the cost evaluation conducted in other studies, the costs estimated for one cubic metre of treated ballast water seem to be at the same level for UV and ozone (Table 22). The cost for US treatment estimated in Ellis and van der Woerd (2004) seems to be lower than the cost estimated in this publication. It should be kept in mind that different source and background information has been available for each study and therefore reasonable comparison is difficult. Also, the costs of primary treatment and retrofitting are not included in this study.

*Table 22. Cost data from various references.*

| Treatment option | Cost per $m^3$ | Reference |
|---|---|---|
| Ultraviolet light | 0.11 €<br>$0.06 (UV only)<br>$0.10 (cyclon separator + UV) | Ellis & van der Woerd, 2004.<br>Glosten-Herbert, 2002. |
| Ultrasound | 0.28 € | Ellis & van der Woerd, 2004. |
| Ozone | 0.22 € | Ellis & van der Woerd, 2004. |

The cost per $m^3$ treated ballast water for various treatment options has been estimated in Ellis and van der Woerd (2004; Fig. 10). The treatment options included in the figure are thermal treatment, biological oxygen removal, ultraviolet light (UV), ultrasound (US), ozone, the oxicide method and BenRad AOT (advanced oxidation technology).

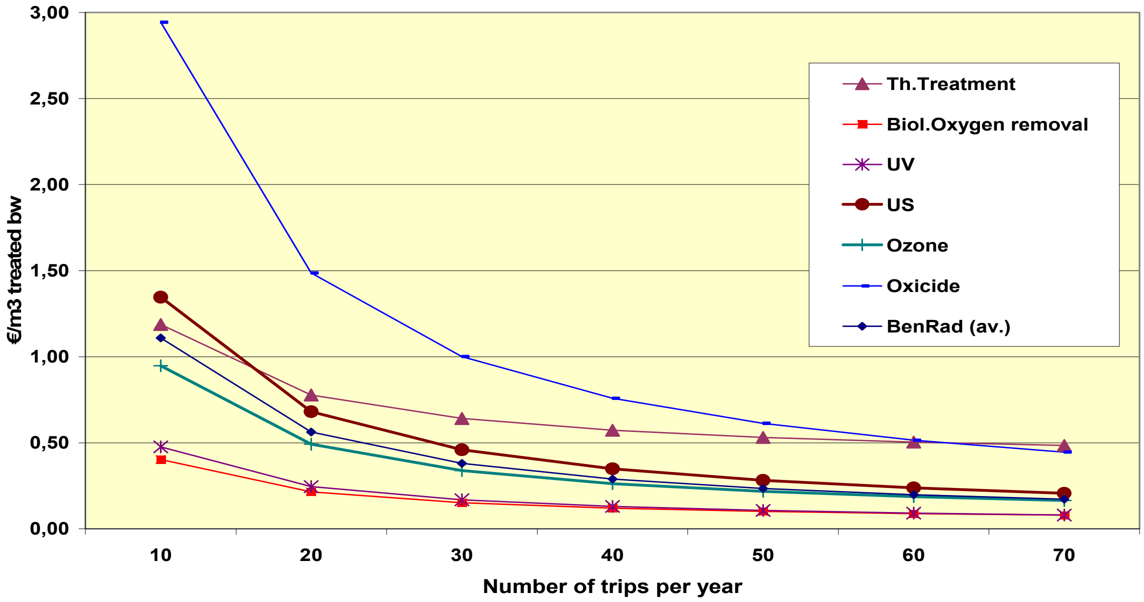

*Figure 10. Cost per $m^3$ of treated ballast water for a different number of trips per year for various treatment options (Ellis & van der Woerd, 2004).*

The costs estimated in Ellis and van der Woerd (2004) varied a lot when the number of trips per year was small. When the numbers of trips were higher, the differences between the treatment technologies were distinctively smaller.

In Figure 11, the estimated proportions of the treatment costs for both *Don Quijote* and *Tempera* are presented.

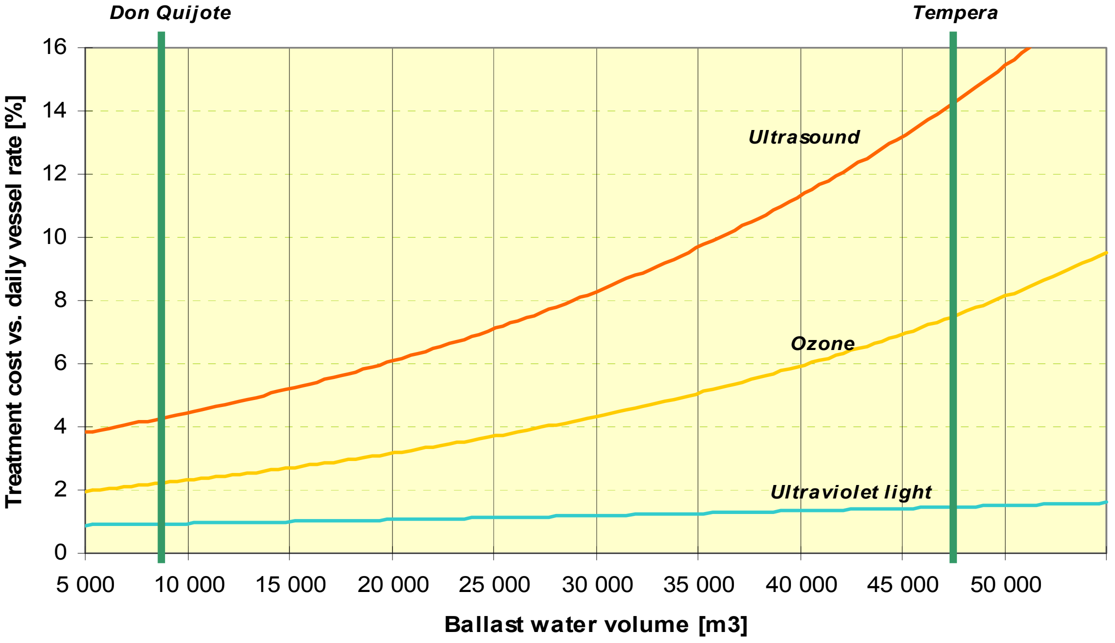

*Figure 11. The estimated proportions of the treatment cost for the14,800 dwt PCTC (Don Quijote) and the 106,000 dwt oil tanker (Tempera).*

When estimating the effect of the ballast water treatment on the cost of marine transport, the proportion of the treatment cost for one voyage (i.e. estimated treatment cost per voyage vs. running costs of vessel for one voyage) varies between 1–4% for *Don Quijote* and between 1.5–14% for *Tempera*.

The total annual costs due to the treatment based on the reference period (10 years) are presented in Table 23 and in Figure 12. The cost data has been presented in detail in Tables 19, 20 and 21.

*Table 23. The total annual costs due to the treatment based on the reference time of 10 years.*

| **Treatment** | **106,000 dwt Oil Tanker (*Tempera*)** (BW capacity 46,900 m$^3$) | **14,800 dwt PCTC (*Don Quijote*)** (BW capacity 8,076 m$^3$) |
|---|---|---|
| Ultraviolet light | 105,923 € (0.045 € / m$^3$) | 44,611 € (0.11 € / m$^3$) |
| Ultrasound | 919,784 € (0.39 € / m$^3$) | 173,737 € (0.43 € / m$^3$) |
| Ozone | 461,543 € (0.20 € / m$^3$) | 95,554 € (0.24 € / m$^3$) |

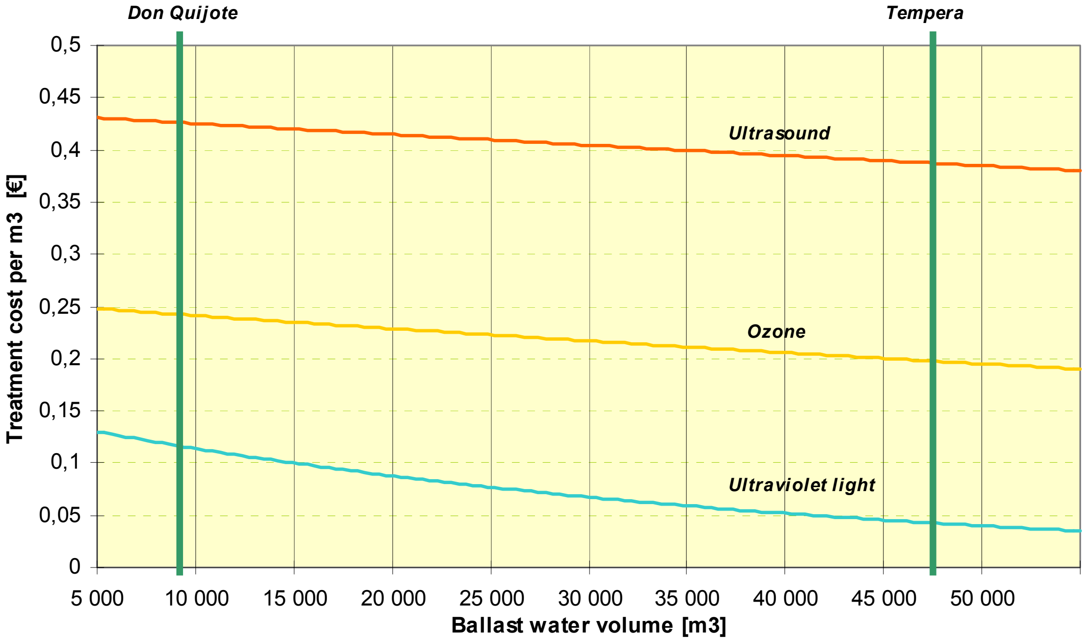

*Figure 12. The estimated cost per m$^3$ for UV, US and ozone treatments for the 14,800 dwt PCTC (Don Quijote) and the 106,000 dwt oil tanker (Tempera).*

The total annual costs for UV treatment were 0.045 €/m$^3$ in the case of *Tempera* and 0.11 €/m$^3$ in the case of *Don Quojote*. The estimated costs for US were 0.39 €/m$^3$ and 0.43 €/m$^3$ and for ozone 0.20 €/m$^3$ and 0.24 €/m$^3$, respectively.

When considering the cost aspects, it is essential that all of the costs and economic benefits are identified in the calculations, and consistent assumptions be utilised. When considering any treatment option, the following cost parameters should be included (Gloster-Herbert, 2002):

- initial equipment purchase, including taxes, shipping, vendor mark-up, etc.
- full installation costs:

    - indicating where work will be done, labour rates and currencies
    - including related system modifications for equipment installation (piping, valves, control units, electrical installations)
    - including dry-docking and tank cleaning (if required) and scheduled disruption
    - including upgrades of related equipment if necessary to maintain flow rates or volumes (ballast pumps, etc)

- operational costs:

    - regular maintenance (labour and spare parts)
    - additional crew labour for new procedures
    - additional power consumption of new equipment and existing equipment running longer
    - increased maintenance of pumps and related systems operating longer or under greater load

- savings from ballast exchange no longer carried out and changes in port fees and reporting requirements
- savings from reduced sediment formation in tanks and the associated cleaning costs
- savings/costs from changes in available cargo deadweight due to the treatment equipment weight and/or reduced tank sediments
- disruptions in ship schedules due to longer ballasting times
- engineering and contingencies.

For operational cost analysis, the following issues should be clearly identified:

- ship or system life
- discount rate
- inflation rate
- one time and recurring costs
- present value of cash flows, and present value or initial invest
- average annual cost of all cash flows.

When examining the cost estimations in Tables 19, 20 and 21, and Figures 10, 11 and 12, it must be kept in mind that the figures are merely estimations and must therefore be taken as such. Also, the additional costs caused by primary treatment and retrofitting are excluded. The required energy levels and disinfection dosages depend on water properties (among other things pH, salinity, turbidity, organism type and concentrations), ballast water volumes to be treated and also on shipping patterns (route, time scale for treatment). Rigby and Taylor (2001) have estimated the costs for various treatment systems (filtration, heating, chemical treatment) as compared to ballast water exchange. In all cases, they estimated that ship-board treatment would be at least 10 times more expensive than ballast water exchange and could be significantly higher. The only way to find out the actual costs for full-scale installation and operations of various ballast water treatment options is to install and operate the treatment processes onboard a vessel and evaluate the costs, i.e., how much it will cost to treat ballast water in a way that it meets IMO requirements. After that, a meaningful comparison of different treatment options can be made.

## 4.7 Ballast Water quality and Sediment consideration

When considering the total concept of the onboard treatment process, one should distinguish the functionalities of primary and secondary treatment options. Various investigations have shown that there exists a need for both primary and secondary treatment methods. Thus, the combined method, e.g., hurdle techniques, should be used to cope with both the removal of small biota and organisms and larger debris, minerals, etc. The Martob-project was mainly based on the testing of various treatment options without any considerations on the effects of particle load or other kind of turbidity on efficiency. Some treatment techniques, however, were tested in series to find out the combined effect of two different treatment solutions. Filters or cyclons as primary treatment options were not included in the Martob-project.

Thus, when up-scaling the test results to the full-scale environment, some general requirements for the treatment devices should be considered. Too turbid water may decrease the efficiency of UV-based solutions, thus if the primary system is based on UV, the need for a pre-treatment facility is evident. The UV chambers should also be protected against material that can break or spoil the surface of the radiation sources. The objectives of the pre-treatment devices can then be listed as follows (Parsons, 2003):

- protect the primary treatment (Parsons uses the definition of primary instead of pre-treatment, and secondary treatment instead of primary treatment), such as UV devices from damage by large objects
- improve the effectiveness of the treatment system by removing large biota that are more difficult to kill allowing the primary treatment system to be optimised to affect biota that cannot be treated any other way
- improve water turbidity if that will interfere with the primary treatment method, for example, UV

- remove non-biological material that may decrease primary treatment, cause added consumption of chemical-based treatment and decrease the ballast water tank sedimentation.

Three different pre-treatment methods were tested at full-scale having the discharge rate around 340 $m^3$/h. The treatment devices were screen filtration, hydrocyclone and disk filtration (Parsons & Harkins, 2002). These results were later up-scaled to the ballast water discharge rate in Parsons (2003). The author theoretically studied the required pumping capacity, backwash frequency required by the filter, net flow rate and made a trade-off study based on the multi-criterion optimisation. The analyses showed that the disk filter system was preferred as a pre-treatment system, the screen filter was judged to be second, and the hydrocyclone was the least effective option for meeting the overall goal of an effective treatment choice. The analyses also showed the up-scaling for hydrocyclone and screen would not cause problems due to the size of the unit, but the disk filters of the type evaluated in the project are only available to about half the size at the present time.

Both disk- and filter-type mechanical separation systems were able to remove around 90% above their respective ratings (Table 24). The figures represent more or less the removal efficiency of the macrozooplankton (SWRC, 2002). For the microzooplankton and phytoplankton, 70–80% removal effectiveness was achieved. Studies conducted at the Lake Superior (*M/V Algonorth*) showed, that filtration with automatic back-flush screen filter was feasible with existing technology down to approximately 50 µm.

Hydrocyclone had a much lower performance (10–54% depending on the test). Hydrocyclone cannot remove particles or biota that is almost neutrally buoyant so that it can drift freely in the water column. It can be used to protect the main treatment device, but its efficiency to remove light particles or even the larger biota is restricted. More profound discussion on this subject is presented in (Parsons, 2003) and the attached references.

*Table 24. Pre-treatment evaluation, ranking based on the parametrization of (SWRC, 2002).*

| **Parameter/device** | **Filtering** | **Disk filter** | **Hydrocyclone** |
|---|---|---|---|
| Safety | safe, installation after ballast pump | safe, installation after ballast pump | safe, installation after ballast pump |
| Biological effectiveness | 95% removal up to 50 µm; 70–80% microzooplankton, phytoplankton | 95% removal up to 50 µm; 70–80% microzooplankton, phytoplanton | 50% removal; protect the primary (secondary device) restricted removal capacity |
| Environmental acceptability | usually needs a secondary treatment system; disposal should be carried out when ballasting | usually needs a secondary treatment system; disposal should be carried out when ballasting | usually needs a secondary treatment system; disposal should be carried out when ballasting |
| Status of technology | several applications tested, device capacities in the order of 2000 $m^3/h$ | several applications tested, device capacities should be enlarged, with back-wash systems | several applications tested, some application in operative use, sizes in the order of few hundred tons/hour. |
| Cost | capital cost, 40,000–100,000$; larger devices more expensive | – | combined with UV, 120,000–140,000 $; larger devices 500,000 $ |

Another important design factor for pre-treatment devices is sludge removal. If the sludge collected by the pre-treatment system cannot removed from the ship during harbour operations, problems may arise due to the need for the extra storage space and possible permission required for large amounts of material to be disposed.

# 5. Discussions and recommendations

***Full-scale equipment – onshore test trials***

One possible option for full-scale testing and the evaluation of various treatment methods could be the installation of devices in containers. In container installations, different treatment processes would be designed for the same flow rates (e.g. around 500–1,000 $m^3$/h for flow through treatment processes) and water volumes (around 500 $m^3$ tank for treatment options based on contact time) for evaluation. Each treatment process would be placed in one or several containers depending on the space requirements, and the containers could be placed in different ports for onshore test trials. Another option could be the installation of the containers onto a barge vessel with sufficient facilities in a manner how the test trials with filters and hydrocyclons onboard MV *Algonorth* in the US (SVRCB, 2002) have been conducted. These arrangements would enable various marine environments to be included in the test programme and would provide a basis for comparison of the technologies against IMO standards. Also, combinations of various treatment options would be possible.

If a full-scale treatment process could be verified with onshore test trials utilising full-scale flow rates and ballast water volumes, it would provide the basis for the design of full-scale treatment process to be installed onboard. The test arrangements at various ports would decrease the difficulties occurred during the onboard installations and sea trials. The installations onboard a vessel could be addressed in other tasks since the installation will depend entirely on the specific ship type, treatment option and shipping pattern. The IMO Convention’s Regulation D-4, Prototype Ballast Water Treatment Technologies, might offer some possibilities for onboard testing.

Primary treatment options (filtration, cyclones, screens, etc.) and combinations of various technologies should be included in the test programme since the literature studies and test trials have clearly indicated that many treatment processes require some type of primary treatment to improve the efficiency of the secondary treatment.

The process conditions for UV and US technologies should be studied for optimisation: type of UV source, cleaning of UV lamps, wavelength and pre-treatment options to improve efficiency in turbid waters, counter pressure, US amplitude, sonotrode type and pressure level. A more thoughtful study of ozone treatment is required to establish the potential of the technology at full-scale onboard ballast water treatment in terms of biological efficiency, operational aspects and environmental acceptance. Investigations into the cost of retrofitting and new building of ballast water treatment systems should be carried out. The feasibility of ballast water circulation and contact tank approach requires a more profound study.

### *The development of analysis methods*

It is stated in the International Convention for the Control and Management of Ships' Ballast and Sediments that the time required for analysing the samples shall not be used as a basis for unduly delaying the operation, movement or departure of the ship (IMO, 2004). At the moment, sampling and analysing of ballast water samples is very laborious and time consuming. Therefore, it is essential that new methods for assessing the viability of organisms are developed in order to enable rapid, accurate and undisputable results of onboard analysing. Normally, the laboratory facilities required for analysing are not available near harbour areas or onboard vessels and therefore ships' crew should be able to carry out the sampling.

# 6. Conclusions

The onshore trials with UV, US and ozone treatment options demonstrated that all of the technologies have potential for ballast water treatment. Each technology proved its efficiency against the target organisms in the brackish Baltic Sea water. Although a great amount of work was conducted during the laboratory and onshore trials, there are still many issues that should be addressed in order to define the feasibility of the technologies against non-indigenous species in ships' ballast water in full-scale applications onboard vessels.

Equipment installations onboard a vessel is a complicated task because the ballast pumps, pipelines and valves are located in or near the pump room, which is one of the most crowned and densely packed areas on the vessel. The floor space required for treatment equipment is relatively large. In addition, the installation of electric equipment requires careful planning and design, and the equipment must meet the relevant safety certificates.

The real-life conditions onboard a ship set different requirements to the treatment systems compared to those in onshore applications. Vibrations, a ship's motion, accelerations, salty water atmosphere, flow rates and pressure drops must be taken into account when designing devices robust enough for onboard installations. Also, the characteristics of ballast water (pH, salinity, suspended solids, rubbish, etc.) differ from typical industrial process waters onshore and may cause problems if not addressed in system design. The duration of the voyage is an important parameter when estimating the feasibility of various treatment options: the shorter the time for treatment, the higher dose of disinfectant or energy will be required and higher capital and operational costs will be evident.

The long-awaited guidelines for test and performance specifications adopted in the IMO MEPC 53 meeting in July 2005 standardise the testing procedures of various existing and forthcoming BWM technologies and provides the technology developers and manufacturers with a uniform approach to the challenge.

According to the Business Times Magazine (Singapore, May 14, 2004), the adoption of stricter rules for ballast water treatment are expected to spawn an SGD 10 billion market for treatment technologies in the next 10 years. In many presentations held at the 2nd International Conference & Exhibition on Ballast Water Management in May 2004 in Singapore, the evident need for full-scale experiments on various treatment options was disclosed. The additional cost to shipping due to the ballast water treatment is likely to be brought down in the future due to the development of treatment technologies.

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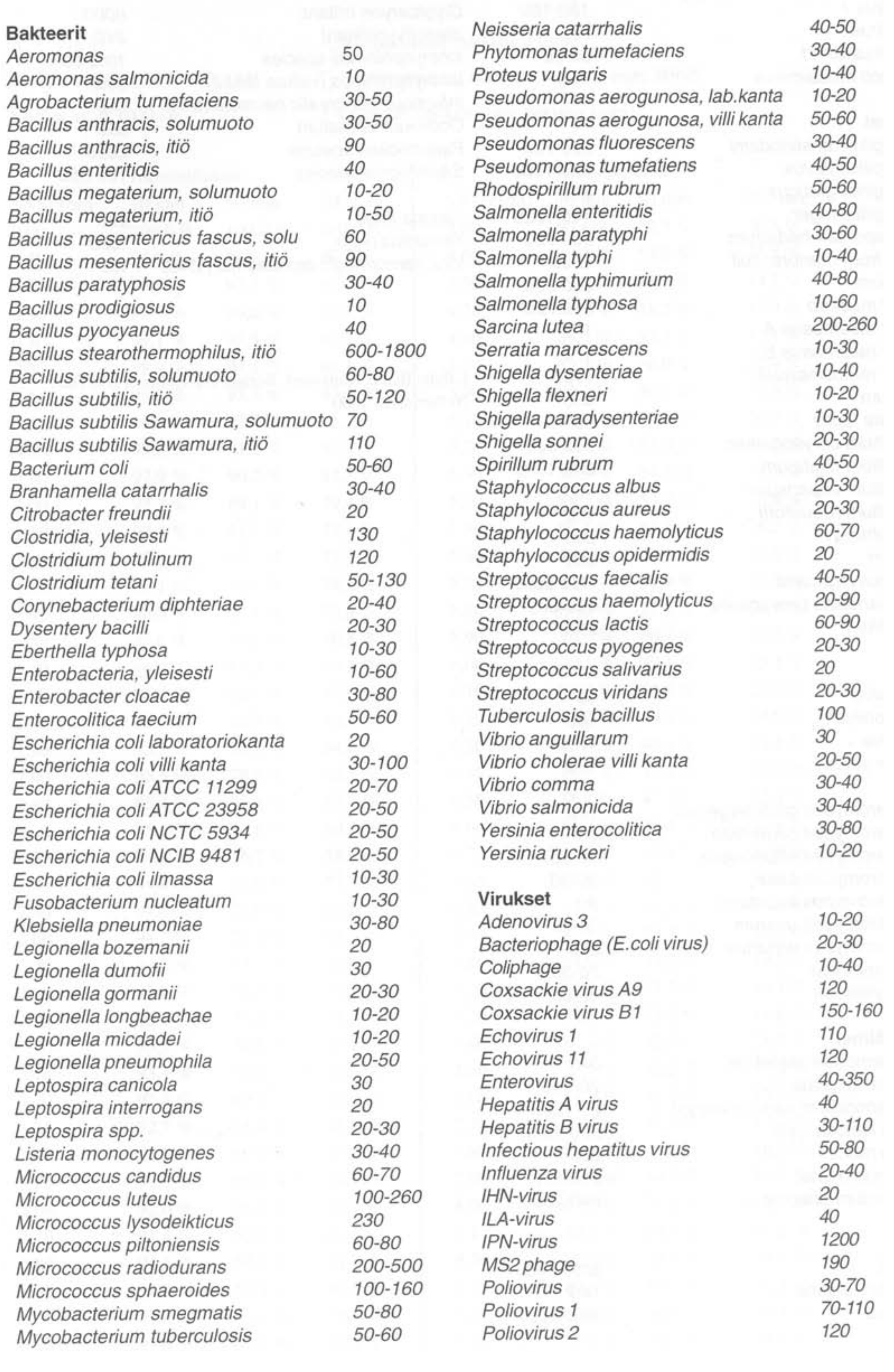
# Appendix 1: Required UV-dosages [J/m2] for 90% inactivation against microbes (Vesi- ja viemärilaitosyhdistys, 2003)

### Required UV-dosages [J/m$^2$] for 90% inactivation against microbes

(Vesi- ja viemärilaitosyhdistys, 2003)



| | |
|---|---|
| **Bakteerit** | |
| *Aeromonas* | 50 |
| *Aeromonas salmonicida* | 10 |
| *Agrobacterium tumefaciens* | 30-50 |
| *Bacillus anthracis, solumuoto* | 30-50 |
| *Bacillus anthracis, itiö* | 90 |
| *Bacillus enteritidis* | 40 |
| *Bacillus megaterium, solumuoto* | 10-20 |
| *Bacillus megaterium, itiö* | 10-50 |
| *Bacillus mesentericus fascus, solu* | 60 |
| *Bacillus mesentericus fascus, itiö* | 90 |
| *Bacillus paratyphosis* | 30-40 |
| *Bacillus prodigiosus* | 10 |
| *Bacillus pyocyaneus* | 40 |
| *Bacillus stearothermophilus, itiö* | 600-1800 |
| *Bacillus subtilis, solumuoto* | 60-80 |
| *Bacillus subtilis, itiö* | 50-120 |
| *Bacillus subtilis Sawamura, solumuoto* | 70 |
| *Bacillus subtilis Sawamura, itiö* | 110 |
| *Bacterium coli* | 50-60 |
| *Branhamella catarrhalis* | 30-40 |
| *Citrobacter freundii* | 20 |
| *Clostridia, yleisesti* | 130 |
| *Clostridium botulinum* | 120 |
| *Clostridium tetani* | 50-130 |
| *Corynebacterium diphteriae* | 20-40 |
| *Dysentery bacilli* | 20-30 |
| *Eberthella typhosa* | 10-30 |
| *Enterobacteria, yleisesti* | 10-60 |
| *Enterobacter cloacae* | 30-80 |
| *Enterocolitica faecium* | 50-60 |
| *Escherichia coli laboratoriokanta* | 20 |
| *Escherichia coli villi kanta* | 30-100 |
| *Escherichia coli ATCC 11299* | 20-70 |
| *Escherichia coli ATCC 23958* | 20-50 |
| *Escherichia coli NCTC 5934* | 20-50 |
| *Escherichia coli NCIB 9481* | 20-50 |
| *Escherichia coli ilmassa* | 10-30 |
| *Fusobacterium nucleatum* | 10-30 |
| *Klebsiella pneumoniae* | 30-80 |
| *Legionella bozemanii* | 20 |
| *Legionella dumofii* | 30 |
| *Legionella gormanii* | 20-30 |
| *Legionella longbeachae* | 10-20 |
| *Legionella micdadei* | 10-20 |
| *Legionella pneumophila* | 20-50 |
| *Leptospira canicola* | 30 |
| *Leptospira interrogans* | 20 |
| *Leptospira spp.* | 20-30 |
| *Listeria monocytogenes* | 30-40 |
| *Micrococcus candidus* | 60-70 |
| *Micrococcus luteus* | 100-260 |
| *Micrococcus lysodeikticus* | 230 |
| *Micrococcus piltoniensis* | 60-80 |
| *Micrococcus radiodurans* | 200-500 |
| *Micrococcus sphaeroides* | 100-160 |
| *Mycobacterium smegmatis* | 50-80 |
| *Mycobacterium tuberculosis* | 50-60 |
| *Neisseria catarrhalis* | 40-50 |
| *Phytomonas tumefaciens* | 30-40 |
| *Proteus vulgaris* | 10-40 |
| *Pseudomonas aerogunosa, lab.kanta* | 10-20 |
| *Pseudomonas aerogunosa, villi kanta* | 50-60 |
| *Pseudomonas fluorescens* | 30-40 |
| *Pseudomonas tumefatiens* | 40-50 |
| *Rhodospirillum rubrum* | 50-60 |
| *Salmonella enteritidis* | 40-80 |
| *Salmonella paratyphi* | 30-60 |
| *Salmonella typhi* | 10-40 |
| *Salmonella typhimurium* | 40-80 |
| *Salmonella typhosa* | 10-60 |
| *Sarcina lutea* | 200-260 |
| *Serratia marcescens* | 10-30 |
| *Shigella dysenteriae* | 10-40 |
| *Shigella flexneri* | 10-20 |
| *Shigella paradysenteriae* | 10-30 |
| *Shigella sonnei* | 20-30 |
| *Spirillum rubrum* | 40-50 |
| *Staphylococcus albus* | 20-30 |
| *Staphylococcus aureus* | 20-30 |
| *Staphylococcus haemolyticus* | 60-70 |
| *Staphylococcus opidermidis* | 20 |
| *Streptococcus faecalis* | 40-50 |
| *Streptococcus haemolyticus* | 20-90 |
| *Streptococcus lactis* | 60-90 |
| *Streptococcus pyogenes* | 20-30 |
| *Streptococcus salivarius* | 20 |
| *Streptococcus viridans* | 20-30 |
| *Tuberculosis bacillus* | 100 |
| *Vibrio anguillarum* | 30 |
| *Vibrio cholerae villi kanta* | 20-50 |
| *Vibrio comma* | 30-40 |
| *Vibrio salmonicida* | 30-40 |
| *Yersinia enterocolitica* | 30-80 |
| *Yersinia ruckeri* | 10-20 |
| **Virukset** | |
| *Adenovirus 3* | 10-20 |
| *Bacteriophage (E.coli virus)* | 20-30 |
| *Coliphage* | 10-40 |
| *Coxsackie virus A9* | 120 |
| *Coxsackie virus B1* | 150-160 |
| *Echovirus 1* | 110 |
| *Echovirus 11* | 120 |
| *Enterovirus* | 40-350 |
| *Hepatitis A virus* | 40 |
| *Hepatitis B virus* | 30-110 |
| *Infectious hepatitus virus* | 50-80 |
| *Influenza virus* | 20-40 |
| *IHN-virus* | 20 |
| *ILA-virus* | 40 |
| *IPN-virus* | 1200 |
| *MS2 phage* | 190 |
| *Poliovirus* | 30-70 |
| *Poliovirus 1* | 70-110 |
| *Poliovirus 2* | 120 |

## Required UV-dosages [J/m$^2$] for 90% inactivation against microbes

(Vesi- ja viemärilaitosyhdistys, 2003)

| | |
|---|---|
| *Poliovirus 3* | *100* |
| *Staphylococcus aureus phage A994* | *100* |
| *Reovirus 1* | *150-160* |
| *Rotavirus* | *60* |
| *Rotavirus SA11* | *60-90* |
| *Tabacco mosaicvirus* | *750* |

**Homeet**

| | |
|---|---|
| *Aspergillus amstelodami* | *660-700* |
| *Aspergillus flavus* | *400-1000* |
| *Aspergillus glaucus* | *440* |
| *Aspergillus niger* | *440-1320* |
| *Cladosporium herbarum* | *300-700* |
| *Fungi from manure, soil* | *1200* |
| *Fusarium* | *250-350* |
| *Mucor mucedo* | *500-700* |
| *Mucor racemosus A* | *170* |
| *Mucor racemosus B* | *170* |
| *Mucor ramosissimus* | *170* |
| *Olpidium* | *350* |
| *Oospara lactis* | *50* |
| *Penicillium chrysogenum* | *300-500* |
| *Penicillium digitatum* | *290-1000* |
| *Penicillium expansum* | *130* |
| *Penicillium roqueforti* | *130* |
| *Phytophtora* | *350* |
| *Pythium* | *350* |
| *Rhizopus nigricans* | *1100-2000* |
| *Scopulariopsis brevucaulis* | *300-800* |
| *Verticillium* | *350* |

**Hiivat**

| | |
|---|---|
| *Kuivahiiva* | *40* |
| *Panimohiiva* | *100* |
| *Palahiiva* | *40-50* |
| *Gunger yeast* | *190* |
| *Pichia* | *350* |
| *Saccharomyces carlsbergensis* | *100* |
| *Saccharomyces cerevisiae* | *60* |
| *Saccharomyces ellipsoideus* | *40-60* |
| *Saccharomyces sake* | *80-90* |
| *Saccharomyces turpidans* | *90* |
| *Saccharomyces uvarum* | *30-40* |
| *Saccharomyces willianus* | *340* |
| *Torula spaerica* | *20-30* |
| *Hiivat, yleisesti* | *40-60* |

**Alkueläimet**

| | |
|---|---|
| *Acanthamoeba castellinii* | *340* |
| *Chorella vulgarus* | *70-140* |
| *Cryptosporidium parvum oocyst* | *20-1200* |
| *Giardia lamblia cyst* | *630-1000* |
| *Giardia muris* | *820* |
| *Nematode munat* | *310-510* |
| *Paramecium species* | *640-2000* |

**Levät**

| | |
|---|---|
| *Sinilevä* | *3000-6000* |
| *Chlorella vulgaris* | *140* |
| *Viherlevä* | *3000-6000* |

**Kalankäsittelylaitosten mikrobit**

| | |
|---|---|
| *Chilodonella cyprini* | *10000* |
| *Cryptcaryon irritans* | *8000* |
| *Sieni (tyypillinen)* | *240* |
| *Ichthyophthirius species* | *1000-3360* |
| *Ichthyophthirius (valkea läikkä)* | *400* |
| *Infectious pancreatic necrosis (IPN)* | *600* |
| *Oodinium ocellatum* | *350* |
| *Paramecium species* | *2000* |
| *Saprolegnia species* | *100-350* |

| | |
|---|---|
| *Sarcina lutea* | *270* |
| *Trichodina nigra* | *1590* |
| *Viral hemorrhagic sepricaemia (VHS)* | *100* |

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Title

# Experiments with ultraviolet light, ultrasound and ozone technologies for onboard ballast water treatment

Abstract

The introduction of invasive marine species into new environments through ships' ballast water, attached to ships' hulls and via other vectors has been identified as one of the four greatest threats to the world's oceans. Different treatment methods have been proposed for onboard ballast water treatment options to reduce this effect, among those also ultraviolet light (UV), ultrasound (US) and ozone (O3) treatments. The literature survey that was carried out during the first phase of the project indicated that all of the methods have potential for ballast water treatment and numerous reports were available presenting the research activities carried out around the world. The technology that has been studied most widely appears to be UV, whereas US seems to have very limited application in terms of ballast water treatment. In addition to single technologies, the combinations of US + UV and UV + hydrogen peroxide ($H_2O_2$) were also tested as part of the hurdle experiments.

During the first phase, the methods were tested under laboratory both in Finland and the UK. After an evaluation of the laboratory test results, onshore trails were carried out in Tvärminne, Finland, in order to confirm the proper operation of the devices and to obtain information about the efficiency of the treatment options against the organisms in the Baltic Sea marine environment. The effects on phytoplankton and bacteria were not studied.

The results from the laboratory trials were partly confusing due to the various scale effects related to the test system and thus the results were difficult to explain. The results from Tvärminne onshore trials, with considerable reliability for UV, varied between 78–100%, for US treatment between 80–99% and for ozone treatment 95–100% depending on the organism group, flow rate and ozone dosages. The combination of US and UV achieved mortality rates of between 97–100% and the combination of UV + $H_2O_2$ between 94–100%. Even in those cases where 100% mortality was observed, the requirements for the maximum allowable number of viable organisms per water volume set by IMO were not necessarily confirmed due to the relatively small sampling volume. It must also be emphasised that only moderate (200–1,600 l/h) flow rates were used. During the trials in the UK, a possible modification of ballast water properties and contents by the treatments was also identified. Ozone treatment causes a significant increase in Redox potential with possible consequences on metal corrosion, coatings and gaskets. However, these effects can be minimised by careful material selection.

Costs evaluations were carried out in order to provide rough estimations of treatment costs for each treatment option on two different case study ships. It appears that the costs for treated ballast water varies between 0.045–0.11 €/$m^3$ for UV treatment, for US 0.39–0.43 €/$m^3$ and for ozone 0.20–0.24 €/$m^3$. The effect on the shipping costs due to the treatment varies between 1–14% per voyage for these case study ships. These values represent the cost evaluation for a full-scale application based on the current level of treatment technology available. It is more likely that treatment costs would lower due to technology development. It must be kept in mind that different source and background information has been available for each study and therefore reasonable comparison between the methods is difficult.

In most of the cases, the treatment processes are not predictable due to the different water properties and operational aspects. Therefore, further studies and full-scale trials are required in order to optimise the process conditions for each treatment technology. One option for the testing and evaluation of various treatment methods could be container installations, where treatment processes would be designed for full-scale flow rates and water volumes. This option would also enable different marine environments to be included in the test programme. In addition to the secondary treatment options, primary treatment options, i.e., filters and cyclons, should also be included since many secondary treatment options require primary treatment in order to perform efficiently. In addition to the treatment technologies, the sampling and analysing methods also need to be developed in order to ensure reliable results and easy-to-use samplers for the ship's crew.

The long-awaited guidelines for test and performance specifications adopted in the IMO MEPC 53 meeting in July 2005 standardised the testing procedures and provides technology developers and manufacturers with a uniform approach to the challenge.

Keywords
ballast water, water treatment, ultraviolet light, ultrasound, ozone, hurdle technology, alien species, non-indigenous species, IMO, NIS

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