MARTOB

Onboard Treatment of Ballast Water (Technologies Development and Applications) and Application of Low-sulphur Marine Fuel

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2			
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CONTENTS

1 INTRODUCTION

1.1 MARTOB is a three-year project funded through the Transport and Energy Directorate of the European Commission (GROWTH Programme). The MARTOB project began in 2001 with the dual aims of

- developing methods for treating ballast water onboard ships
- developing recommendations of best practice for verification and monitoring of compliance of a sulphur cap for marine fuels.

Both aims are directed towards making shipping operations more environmentally friendly.

1.2 **Ballast Water Treatment:** The main objectives of this part of MARTOB were to investigate the various possible methods for controlling the transfer of non-indigenous organisms through ballast water and come up with a technologically and economically viable solution to the problem. This solution should be safe and not have any undue impact on ship operations and the environment.

1.3 A range of ballast water management guidelines and regulatory practices have been introduced by various countries in an attempt to minimise the risk of non-indigenous marine organisms being transported around the world in ballast water.

1.4 Data on ballast water discharges are not available for all of Europe. The amount of ballast water discharged is only an indication of the risk of future species introductions. This risk is not directly related to the quantity of ballast water released, but to the quality of the ballast water discharged (e.g. whether the origin and discharge areas have matching climate and salinity). Studies have shown that each vessel has the potential to introduce a non-native species. Ballast water discharges in waterways are excluded from this report. The total length of navigable canals, rivers and lakes regularly used for transportation in the EU-15 countries is 29,600 km. It is evident that the data are rather scattered and the type of data is very different from country to country. A uniform type of data enabling a proper comparison is lacking. However, according to information gathered approximately 180,000 ships visit European ports annually, discharging 105 million tonnes of ballast water from various origins, predominantly from Europe (mainly Baltic, North and Mediterranean Seas), Far East, Russia, North America, Middle East, South Africa, Indian Ocean, Black Sea and Australia. On the basis of current information a new species is introduced to a new region worldwide every 9 weeks.

1.5 A number of treatment techniques, namely Thermal Treatment, De-oxygenation, Ultraviolet, Ultrasound, Ozone, Oxicide, Advanced Oxidation Technology and combination techniques (Hurdle) have been investigated within MARTOB in detail. Large and/or full scale treatment systems of each of these techniques have been designed, simulated, manufactured and tested. In addition, other existing management techniques have been reviewed and analysed based on the available data.

1.6 The framework for evaluation developed within the MARTOB project, i.e. the test and sampling protocol and the standards for evaluation, will provide a common ground and a fair basis for comparison and evaluation of the different ballast water treatment options. The scope of the framework is focused on the assessment of biological effectiveness, environmental impact, safety, economic viability and onboard ship applicability of the ballast water treatment options. In addition to the standards for evaluation, the framework also includes a testing and sampling protocol. The framework was developed within the boundaries of existing and foreseen regulations, legislation and certification rules.

1.7 The MARTOB sampling and testing protocol provides standards for: (1) water quality, (2) species to be used for laboratory tests, (3) composition of a test mixture and (4) how to assess biological effectiveness of the different treatment methods. A test mixture called "MARTOB soup" has been proposed and prepared and all techniques (at the laboratory scale of operation) named in paragraph 5 have been tested and their biological effectiveness assessed.

1.8 MARTOB included an assessment of environmental impacts of ballast water treatment technologies tested within the project. Direct impacts to receiving waters could result from discharges of ballast water with altered quality, discharge of solids from physical separation methods used for pre-treatment, and discharge of living organisms that survive treatment. MARTOB considered indirect environmental effects of ballast water treatment to include energy consumption and associated emissions, materials used, and waste generated during operation or through disposal of worn out components and equipment.

1.9 Safety of the selected treatment methods was investigated and MARTOB considered the majority of possible concerns to be related to operational aspects. These include hazards related to operation of the equipment; hazards related to the storage, handling and/or generation of chemicals and residuals required for, or resulting from, the onboard treatment of ballast water; and risk of unintentional release onboard the vessel of treated ballast water containing residuals.

1.10 For onboard treatment of ballast water, an important problem is the corrosion of the hull structure, the piping system and the ballast water handling equipment. Therefore it was decided within MARTOB to investigate whether the installation and operation of selected treatment systems will significantly change the water properties in such a way that it could increase the corrosion risk of the ship structure and ballast water piping network.

1.11 Assessment of management technologies has not been limited to their biological effectiveness only, other criteria such as their compatibility with a particular ship and her route, overall cost, safety, crew, life cycle assessment, corrosion effects and many other factors have been considered here as ranking criteria with their individual weighting in the final assessment.

1.12 **Low Sulphur Fuel**: The main objectives of this part of MARTOB were to assess the financial, technical and operational effects of a sulphur cap on marine bunker fuel in European waters, and propose a verification scheme ensuring compliance with a sulphur cap from all players in the market.

1.13 And to help to facilitate the introduction of an important sulphur emission abatement measure without unintentional distortion of competition in the shipping market.

2 BACKGROUND

2.1 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 merchant fleet. Ninety percent of the EU's external trade and 40% of trade by volume between the member States are carried by sea. Thus any improvements that can lead to reduced environmental impacts from shipping are important for maintaining or improving the quality of the marine environment.

2.2 Ballast water has been recognised as one of the major vectors for the transfer of aquatic organisms across bio-geographical boundaries. Hundreds of non-indigenous species from different parts of the world have been introduced into European waters, particularly Northern Europe. 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. The introduction of alien species has also caused problems in other parts of the world, sometimes resulting in significant economic and environmental damage. Many of the measures introduced to date to help limit the introduction of alien species through ballast water include voluntary guidelines, most related to ballast water exchange. In some jurisdictions there are mandatory requirements.

2.3 Fuel quality studies are proposed based on national incentives and environmental analyses of impact from shipping where choice and present status of quality of marine bunker fuel has become an important issue. The difference in measures applied for shipping for reduction of sulphur emissions compared to other transportation modes and incentives implemented by the European Community is likely to draw increased attention in the future.

2.4 MARTOB's main objectives were:

.1 To investigate methodologies and technologies for preventing the introduction of non-indigenous species through ships' ballast water.

.2 To develop design tools and treatment equipment to be used in the further development of ballast water treatment techniques.

.3 To assess the effectiveness, safety, and environmental and economic aspects of current and newly developed methods.

.4 To develop cost-effective (capital and operating), safe, environmentally friendly onboard ballast water treatment methods, which have a minimum impact on ship operations.

.5 To produce guidelines for crew training and criteria for selecting appropriate ballast water management method.

.6 To assess the financial, technical and operational effects of a sulphur cap on marine bunker fuel in European waters, and propose a verification scheme ensuring compliance with a sulphur cap from all players in the market.

.7 To help to facilitate the introduction of an important sulphur emission abatement measure without unintentional distortion of competition in the shipping market.

It was envisaged that MARTOB would result in detailed recommendations for ballast water management solutions, which will be useful to IMO, ICES, IOC and other maritime organisations, marine environment agencies and regulatory bodies.

2.5 The main work components carried out as part of the MARTOB project were as follows:

- Collection and assessment of data and information on ballast water management methods and existing relevant legislation, and a review and update of alien species introductions in European waters

- Development of selected methods for onboard treatment of ballast water through lab-scale testing and in-depth analysis

- Large and full-scale testing of selected ballast water treatment methods

- Assessment of the financial, technical and operational effects of a sulphur cap on marine bunker fuel in European waters.

2.6 The first phase of the project related to ballast water management was completed in early 2002. This included collection of information on ballast water management methods that are currently used, that have been tested onboard ships, or that are in an advanced stage of development. In addition to collecting information on biological effectiveness, information was collected on the safety of methods, environmental effects, and costs. Information was also collected on existing and proposed regulations, to give an indication of future directions for ballast water management requirements. In the second phase, laboratory scale tests of the selected treatment technologies and their assessment were conducted. This phase was completed in January 2003. During the third and final phase of MARTOB, full/large scale prototypes of ballast water treatment systems were designed, optimised and manufactured. Some of them were installed and tested onboard a vessel and others were tested at shore facilities.

3 REGULATIONS AND FUTURE INDICATIONS

3.1 Ballast water regulations and guidelines in local, regional or international forms have been around for last 3 decades. There are a number of different options a country (or group of countries such as EU) might adopt to protect their ports and waters from invasion of non-indigenous species. These range from taking administrative action but not adopting any domestic legislation to adopting a comprehensive legislative regime. This decision depends on each country and its assessment of its trade, environment and administrative concerns, particularly in connection with the discharge related regime.

3.2 Existing Guidelines recommended by IMO and GloBallast for reporting, recording, training, port surveys, precautionary practices and continuing scientific research is an approach to ensure better informed and internationally harmonised risk assessments. GloBallast suggests that states should avoid establishing any particular method of ballast water management in legislation, rather this should be part of the ship specific Ballast Water Management Plan. Implementation of a flag-state responsibility before full implementation of the Convention is suggested to have relatively little extra cost with possibly no conflict with the Convention.

3.3 Now that the Convention is in place, it can be foreseen that states, either in a unilateral approach or by seeking partners in the geographical or political neighbourhood, will attempt to direct their existing regional regulations or develop new legislations in accordance with the Convention. Globallast also outlines the following options (or a combination of them):

- New regulations under, or amendments to, existing ship source pollution prevention legislation. A State may choose to adopt legislation as either a new regulation under or as an amendment to existing ship source pollution prevention legislation (usually the law implementing MARPOL 73/78 in the State) and administrative systems. It could be implemented on a phased-in basis with mandatory reporting and use of voluntary ballast water exchange or other treatment methods and research oriented inspections to start with.

- Take administrative action without legislation. A country may choose not to embark on any formal legislative action until the international convention is open for signature or even in force. However, it may still implement many aspects of the Guidelines by carrying out port baseline surveys and requesting ships, on a voluntary basis, to submit ballast water reports and samples. In addition marine environment training institutions in the country can be encouraged to include ballast water management issues in their curriculum. Flag States and Classification Societies can also work with industry associations to encourage ships to develop and implement ballast water management plans.

- Adopt comprehensive environmental/ biodiversity protection legislation. A country may also choose to adopt legislation that addresses the issue comprehensively within the larger framework of biodiversity or environmental protection under biodiversity/security/or other border control-quarantine legislation. Such an approach has some advantages in that it may generate new administrative arrangements and will allow for comprehensive implementation of rules pertaining to both the unintentional import and export of harmful aquatic organisms and pathogens, exchange or other operations based treatment, mandate coasting trade and all flag-ships to comply and will provide for appropriate ecological and scientifically appropriate procedures for identifying zones or areas for safe ballasting operations and other contingency arrangements.

4 ALIENS IN EUROPEAN WATERS

4.1 The data on aliens in European waters are rather scattered and the type of data is very different from country to country. A uniform type of data enabling a proper comparison is lacking. However, according to information collected approximately 180,000 ships visit European ports annually discharging 105 million tonnes of ballast water from various origins, predominantly from Europe (mainly Baltic, North and Mediterranean Seas), Far East, Russia, North America, Middle East, South Africa, Indian Ocean, Black Sea and Australia. It should be noted that the amount of ballast water discharged is only an indication for the risk of future species introductions. This risk depends not only on the quantity, but also to the quality of the ballast water discharged (e.g. whether the origin and discharge areas have matching climate and salinity). Studies have shown that each vessel has the potential to introduce a non-native species.

4.2 On the basis of current information a new species is introduced to a new region worldwide every nine weeks. However, recent indications are that this may be higher with approximately one new exotic species introduced every three weeks over the period 1998-2000 in European waters. The unintentional transport of living organisms and their spread worldwide as Non-Indigenous Species (NIS) is an environmental problem that is currently one of the most widely spread and important problems in the maritime world, but also the least discussed until the mid-1990s. The European coastal ecosystems are under growing environmental pressures, one of them being NIS introduced by various vectors. In some isolated areas, particularly on oceanic islands, the current rates of invasion may be more than 1 million times their natural levels. This trend also applies to the semi-enclosed and enclosed seas of for example Europe, even if no comparable estimates are available. (Bright, C., “Life Out of Bounds: Bioinvasion in a Borderless World”)

4.3 Although there are still knowledge gaps (note geographic ones, e.g. the Iberian Peninsula), there is a good wealth of knowledge on bio-invaders from North, Baltic Irish Seas, European coasts of the Mediterranean Sea, all around UK, Norway and many more. These are well presented in the book edited by E. Leppäkoski, S. Gollasch & S. Olenin in 2002: *Aquatic Invasive Species of Europe - Distribution, Impacts and Management*. It is known, from data collected in other areas, such as for the zebra mussel (*Dreissena polymorpha*) in the Great Lakes in the USA, that there can be great economic as well as environmental problems involved in the introduction of just one new species. It has also been pointed out by different experts that just because an area has not been much affected by invasions in the past, there is no guarantee that it will remain unaffected in the future - only with sufficient research will it be possible to establish some sort of pattern and to find ways of preventing further introductions.

5 CURRENT TREATMENT METHODS

5.1 The scope of this part of the project was to review the ballast water treatment methods that had been assessed onboard vessels or at large scale shore based pilot installations and also to summarise the methods that were undergoing the first stages of development. The review did not include those methods being tested in MARTOB i.e. Thermal Treatment, De-Oxygenation, Ultraviolet, Ultrasound, Ozone, Oxicide and Advanced Oxidation Techniques.

5.2 The information for the review was collected via literature searches and by contacting researchers directly to obtain more detailed and up to date results. The review gave a brief outline of ballast water treatment, legislation and the current status of ballast water research. Methods that had been tested at pilot or full scale were discussed in more detail particularly with regard to the biological effectiveness, operational and safety aspects.

5.3 At the time the review was written there were no ballast water treatment standards in existence and different criteria had been used to assess the biological efficiency of the treatment methods and it was therefore difficult to make an accurate comparison between the results of the studies. Now the IMO standard has been finalised it will be easier to assess whether particular treatment methods are effective.

5.4 None of the available methods discussed in the review would, at that time, be effective at removing some organisms of concern e.g. dinoflagellate cysts. It was likely that many treatments would work more effectively in combination i.e. a pre-treatment followed by a secondary treatment.

6 SAMPLING AND TEST PROTOCOL

6.1 In the MARTOB project it was necessary to compare the performance of various ballast water treatment techniques and a standard test protocol was therefore required. However, the standards under discussion at IMO were unlikely to be finalised in time to be utilised by the MARTOB project and it was therefore necessary to develop a test protocol specifically for this project. The developed protocol was to some extent based on the draft IMO standards but as these were under development other suggested protocols were also taken into account.

6.2 The sampling and test protocol provided standards for:

- water quality,
- species to be used for laboratory tests,
- composition of test mixture and
- methods to assess biological effectiveness of the different treatment methods.

6.3 Five species were selected for testing purposes: the larvae of a benthic polychaete (*Nereis virens*), the harpacticoid copepod (*Tisbe battagliai*.), the calanoid copepod (*Acartia tonsa*.), and the phytoplankon *Thalassiosira pseudonana*.(diatom) and *Alexandrium tamarense* (dinoflagellate).

6.4 The standard protocol also outlined the density of the species to in the test mixture with the premise that densities should reflect the top end of the natural range for each taxa.

6.5 In order to assess the biological effectiveness of each ballast water treatment method, the number of organisms living after treatment was determined. The zooplankton specimens were fixed and stained in a manner that allowed living and recently dead material to be easily distinguished. This allowed the efficiency, expressed as % kill, of each technique for each group of organisms to be reported. For the phytoplankton, levels of chlorophyll *a* were measured and direct cell counts were carried out to determine whether the treatment had different effects on each species.

7 TECHNIQUES TESTED WITHIN MARTOB PROJECT

7.1 **High Temperature Thermal Treatment** (HTTT): This method uses heat to incapacitate and kill organisms in ballast water. The water is heated to a high temperature (55-80°C) for a short period (up to a few seconds). Low temperature treatment (35-45°C) requires a long time (hours-days) and will not be effective against bacteria and some of the hardier organisms, but will be cheaper to implement as it uses waste heat onboard the ship. High temperature treatment is more expensive as in most cases it needs a dedicated heating system, but is much more effective at killing the organisms and requires a much shorter exposure time. High temperature-short time treatment is an established preservation method in the food industry.

7.2 **De-Oxygenation Treatment**(DEOX). By adding nutrients to the ballast water (approx. 1 litre per 10 m^3) naturally occurring bacteria in the water will quickly multiply and deplete the oxygen in the water. This is a simple, non-mechanical method, but it will not have any effect on organisms that can grow anaerobically such as many bacteria, or on resting stages such as spores and cysts. The time it takes to obtain anoxic conditions depends upon the water temperature and varies from less than one day at >20ºC to more than three days at <5ºC. Once anoxia has been obtained, it must be maintained for 3-5 days in order to obtain a high mortality. Deoxygenation of ballast water can also be done mechanically by gas sparging or low pressure extraction, or chemically by adding reducing chemicals. Mechanical and chemical methods have only briefly been locked upon, mainly due to their higher costs and/or possible negative impact on the environment, but they do have the advantage of generating anoxia rapidly regardless of the temperature. With respect to biological efficiacy they are expected to be fairly similar to the DEOX treatment.

7.3 **Ultraviolet Treatment**(UV): Ultraviolet lamps are used to irradiate the organisms in the ballast water. The ballast water passes through a chamber where it receives an UV dose of 140-560 mJ/cm^2 depending on the flow rate. The UV radiation will break the chemical bonds in DNA in the organisms. This can lead to problems should the organisms survive, as they may carry mutations. There is a requirement for pre-treatment of the ballast water, as the performance of the system decreases with increasing turbidity of the water. UV is a well established and proven disinfectant in the drinking- and wastewater treatment sector, as well as for surface and air disinfection.

7.4 **Ultrasound Treatment**: (US). Ultrasound is generated by a transducer that converts mechanical or electrical energy into high frequency vibration. The ballast water passes through a chamber where it receives US energy (19-20 kHz) of 0.4-2.3 Wh/L depending on the flow rate and the output of the US device. The cavitations generated by the US vibrations can disrupt the cells of organisms. US has been shown to be effective towards bacteria, plankton and other larger organisms However, it may have an adverse effect on ship/tank coatings and ship structure and therefore need to be tested. US treatment has been successfully used in water treatment and the food industry to control microorganisms.

7.5 **Ozone Treatment**: Ozone is unstable and must be produced on the site, and the Ozonation system produces ozone that is added directly to the ballast water. The organisms in the water are subjected to a concentration of 7-17 mg/L for 1-24 hours. Ozone oxidises organic compounds including essential cell components and thereby kill the organisms. It has been used in onshore applications such as swimming pools, disinfection of drinking water, and control of microbial contamination in various areas. In these applications it has proven to be very effective and a more powerful biocide than chlorine, which has traditionally been used. Ozone is toxic and will have to be handled with care, but because it is unstable and rapidly degrade to harmless compounds, it does not represent a problem after discharge of the ballast water. Due to the oxidising properties, there is a concern that ozone may increase corrosion in tanks and pipes.

7.6 **Oxicide Treatment**: The Oxicide method is an electrochemical method that generates hydrogen peroxide (H_2O_2) in the ballast water to a concentration of approx. 15 mg/L. The organisms are subjected to this concentration for 24-48 hours during the voyage. H_2O_2 oxidises organic compounds including essential cell components and thereby kill the organisms. It decomposes in water and will therefore not cause any problems to the environment. H_2O_2 is an irritant and has to be handled with care. An advantage of the Oxicide process is that H_2O_2 is produced on site, eliminating the need to handle and store large volumes of the chemical onboard. Due to the oxidising properties, there is a concern that H_2O_2 may increase corrosion in tanks and pipes.

7.7 **Advanced Oxidation Technology** (AOT): In the AOT process it is primarily hydroxyl radicals that kill the organisms. The process consists of a combination of ozone, UV and catalysts. Ozonolytic, photolytic and photocatalytic redox processes operate simultaneously within a titanium reactor, and this generates large amounts of radicals, mainly hydroxyl radicals. The reactor can be operated with or without prefiltering of the

7.8 **Hurdle Technology**: Hurdle technology is the combination of two or more treatment methods. This increases the effectiveness of the treatment and if chosen properly, can also eliminate some of the disadvantages of the separate treatment methods.

8. BIOLOGICAL EFFECTIVENESS OF TESTED TECHNIQUES

The biological effectiveness of the developed treatment methods were tested both in laboratory scale in Newcastle in June 2002 and in large/full scale onboard a ship or on shore during the summer of 2003.

8.1 The overall aim of the laboratory test trials was to evaluate the efficiency of the different technologies at removing or killing organisms i.e. the biological effectiveness of the treatment. For reasons of logistics and consistency it was decided to bring all the prototype treatment technologies to one location at the University of Newcastle in the UK. In these trials standard seawater, with a known density of each of the organisms (see section 6) in order to assess the efficacy of the treatments. Over one hundred different tests were carried out during the course of the trials.

8.2 The outcome of the trials was that three of the technologies were considered to be at a stage where they could be scaled up for shipboard application. These were high temperature thermal treatment(HTTT), de-oxygenation (DEOX) and advanced oxidation technology (AOT). The other technologies tested were undergoing further development and were tested in large scale shore based test facilities.

8.3 Overall, the lab scale trials provided valuable information in terms of the logistics of setting up such tests, especially, as this was the first time many different technologies have been tested simultaneously. Much experience was gained regarding the setting up of such tests and the successes and problems encountered during the trials can now be used to improve on any future lab-scale trials.

8.4 In the high temperature (HT) trials water was treated at 40-65ºC. For two of the three tested species of zooplankton, *T. battagliai* and *N. virens*, HT treatment at 60 or 65 ºC yielded a mortality of more than 95%, while for *A. tonsa* the highest mortality was 89%. Treatment at 45ºC or below resulted in significantly lower kill rates. With respect to phytoplankton, treatment at 50ºC and above led to a significantly larger reduction in chlorophyll a level than treatment at lower temperatures. The cell counts indicated a reduction in the total number of cells as a function of the treatment, but no clear correlation with the treatment temperature could be found. Only two analyses of the effect of HT on bacteria were performed. Treatment at 40ºC had no significant effect on the concentration of viable bacteria, while treatment at 55ºC reduced the viability with almost three orders of magnitude.

8.5 The Oxicide treatment (H_2O_2) was very effective towards *N. virens* achieving a total mortality in all cases. The viability of *A. tonsa* was reduced with more than 95% in all but one case (kill rate 93%). *T. battagliai*, however, was more resistant and the viability was frequently reduced with less than 60%, and only in one experiment was 96% mortality achieved. No significant reduction in chlorophyll a was obtained, and the phytoplankton cell counts were difficult to interpret. No bacterial analyses were performed.

8.6 During the trials with ultrasound (US), ultraviolet radiation (UV) and ozone a large number of treatment conditions were tested, and this makes it difficult to draw general conclusions. However, both US and UV separately had limited effect on the viability of the zooplankton species with mortalities mostly below 30%. Ozone alone had a somewhat higher effect towards *N. virens*, with a mortality of up to 78%, but for the other two species the mortality was below 30%. When US + UV was combined with filtration (125 µm), the removal/kill rate was almost 100%, but it is likely that much of this effect can be ascribed to the filter. Ozone reduced the concentration of chlorophyll *a* with from 60 to almost 100% depending on the treatment process, while UV reduced the concentration 10-

50% and the US treatment ranged from no effect to around 60 % reduction. The combination of US + UV reduced the concentration of chlorophyll *a* with from 20 to 60 %. The effect of the treatments upon the cell counts was more variable, particularly for the diatom (*T. pseudonana*), but the concentration of the dinoflagellate (*A. tamarense*) was mostly reduced by the treatments, for all treatments with up to 80%, although there were also experiments showing no effect. A single test of the efficiency of UV towards bacteria was performed, and the concentration of viable bacteria was reduced with more than six orders of magnitude. The effect of US and ozone towards bacteria was not examined.

8.7 Biological deoxygenation of the water had a high efficacy (above 95 % mortality) after four days of anoxia (five days after the start of the treatment) for *A. tonsa*, while the mortality was 97.1 % and 100 % for *T. battagliai* and *N. virens*, respectively, after 6 days of anoxia. T. battagliai was the least sensitive of the three species of zooplankton tested, while *A. tonsa* also showed a relatively high mortality also in the untreated controls. Deoxygenation did not seem to have any significant effect on the tested phytoplankton species within the timeframe of the study.

8.8 The Advanced Oxidation Technology (AOT) treatment (OH-radicals) killed or removed more than 98% of the zooplankton when combined with pre-filtering of the water (100µm). However, without the filter the kill rate never reached more than 80%, and was frequently below 50%. The concentration phytoplankton cells generally decreased after treatment (up to 95 % reduction for the dinoflagellate and 69 % for the diatom), but there was no clear correlation between the reduction and the degree of treatment. A single test of the efficiency of AOT towards bacteria was performed. In this test the concentration of viable bacteria was reduced with almost five orders of magnitude.

8.9 From the results of hurdle technologies, the treatment that worked best was HT +DEOX, which had 100% efficiency for all three zooplankton species. Care must be taken as we cannot assure that with replicates this would still be so. Comparing the efficiency of UV+H_2O_2 with and without filter (150µm), the results showed that the filter did affect the survival/removal of the organisms (mainly at low H_2O_2 concentration), as the percentage in organisms removal increased for *A. tonsa* (principally), *T. battagliai* and *N. virens* when the filter was used.

8.10 Overall, the results showed that some of the treatments produced a consistent decline in chlorophyll a levels, which indicates that there was a treatment effect. However, the more variable cell count data needs to be taken into account as well. It is possible that some of the cell count data may have included counts of cells that looked normal and undamaged but had actually been killed. It had been intended to use a flow cytometer to count and assess viability of the cells but this was not possible owing to circumstances beyond our control. The counts were therefore carried out on preserved samples where it is more difficult to assess whether a cell was alive before preservation.

8.11 In conclusion, much was learnt from these shore based tests, which had never been carried out on such a large scale before. If future tests are to be carried out it would be necessary to have a well planned experimental design that included replication and controls and also the methods for counting and assessing viability of the phytoplankton would need to be refined.

8.12 The ship trials were performed in May-June 2004 onboard the pure car-truck carrier *Don Quijote* owned by the Swedish company Wallenius Wilhelmsen Lines (WW). In the trials water was pumped from the ballast tanks to the heat treatment unit and the sampling point on deck via the ship's fire pump system. It was later discovered that this pumping killed a substantial fraction of the zooplankton in the water, and this complicated the evaluation of the results. In both trials the zooplankton fauna was dominated (>98 %) by copepods and nauplii. The original plan was that also the advanced oxidation process should be tested onboard *Don Quijote*, but this could not be done due to last minute technical problems. The results of the treatments were as follows:

- The ballast water for the high temperature (HT) thermal treatment was pumped into the ballast tanks outside the coast of Egypt, and contained around 1000 zooplankton per m^3. The HT treatment in combination with the killing effect of the fire pump, reduced the concentration of viable organisms to less than 10 per m^3 (the new IMO limit) in about 40% of the trials, the remaining ranged up to around 150 viable organisms per m^3. There was no clear effect of increasing the treatment temperature from 55 to 80ºC. Due to the killing effect of the fire pump, it was difficult to quantify the effect of the HT treatment. However the result from the control samples suggests that the HT treatment alone would have killed at least 90% of the zooplankton in the ballast water.

  The concentration of phytoplankton in the ballast water was too low to yield any meaningful results with respect to treatment effects.

  The ballast water contained around $1 \cdot 10^4$ growth units of viable bacteria per ml. The HT treatment reduced the concentration with approximately 95%, but there was no significant increase in the mortality when the treatment temperature was increased from 55ºC and up to 80ºC.

- The ballast water for the deoxygenation (DEOX) was pumped into the ballast tanks in the English Channel. Both in the control tanks and the treated tanks, the total concentration of zooplankton, i.e. both live and dead, decreased during the trial from a starting level of around 2500 organisms per m^3. The decrease was fastest in the treated tanks and after 5 and 7 days the average total concentration was significantly lower in treated than in untreated water; 25-50 organisms/m^3 in treated versus 400-430 organisms/m^3 in untreated water The average concentration of viable organisms in the water samples from the treated tanks was only 1-3 per m^3, while the samples from the untreated tanks contained 10-150 viable organisms per m^3. The DEOX treatment in combination with the killing effect of the fire pump therefore achieved the new IMO standard, but it is not possible to determine if this standard would have been achieved without the fire pump.

  The ballast water contained only around 1000 phytoplankton (dinoflagellates + diatoms) cells per litre from start, and the effect of the DEOX treatment is unclear. The cell counts showed that there were fewer cells in the treated tanks on the last day of treatment compared to the controls, indicating an effect of the treatment. However, the concentration of chlorophyll *a* was higher in the treated tanks than in the control, which would seem to indicate that although the cells were present in lower numbers those that were present contained more chlorophyll.

In the case of the onboard ship trials the results are:

- For high temperature thermal treatment, or more correctly the HT + fire pump treatment, increasing the treatment temperature above 60ºC did not improve the effectiveness. There was an increase in nauplius mortality over time, i.e. the longer they had been in the tank the more effective the treatment. Due to the killing effect of the fire pump, it is difficult to quantify the effect of the HT treatment. However the result from the organisms in the control samples suggests that the HT treatment alone would have killed at least 90% of the zooplankton in the ballast water. In combination with the fire pump the HT treatment only achieved the new IMO standard of less than 10 viable organisms per m3 only in about 40% of the trials.

- Both in the control tanks and the treated tanks in the Deoxygenation trial, the total concentration of zooplankton, i.e. both live and dead, decreased during the trial. The decrease was fastest in the treated tanks and after 5 and 7 days the average total concentration was significantly lower in treated than in untreated water; 25-50 organisms/m3 in treated versus 400-430 organisms/m3 in untreated water The average concentration of viable organisms in the water samples from the treated tanks was only 1-3 per m3, while the samples from the untreated tanks contained 10-150 viable organisms per m3. The DEOX treatment in combination with the killing effect of the fire pump therefore achieved the new IMO standard, but it is not possible to determine if this standard would have been achieved without the fire pump.

8.13 The large scale shore-based trials were performed at Tvärminne on the south cost of Finland (UV, US, ozone and H_2O_2) and at Den Helder on the cost of Netherland (Oxicide). The results are summarized as follows:

- At Tvärminne the concentration of zooplankton (organisms >50 μm) ranged from 30 to 150 thousand organisms per cubic metre during the study, mainly dominated by copepods and copepod nauplii. Depending on the group of organisms and various technical parameters such as flow rate and dosage, the killing rates for the UV treatment ranged from 78-100 %, for US treatment 80-99 % and for ozone treatment 95-100 %. The combination of US and UV achieved mortality rates between 97-100 % and the combination of UV + H_2O_2 between 94-100 %. It should be noted that, due to relatively small sample volumes, an observed mortality of 100 % indicated less than 20-100 viable organisms per cubic metre, i.e. the new IMO requirement was not necessarily achieved. The high pre-treatment concentration of zooplankton should, however, be taken into account here. It must also be emphasized that only flow rates of 200l/h to1,600 l/h were used. In most of the cases the treatment processes were not predictable (although more predictable than onboard trials) 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.

  No studies of the effects of the treatments on phytoplankton or bacteria were performed at Tvärminne.

- During the onshore studies at Den Helder there were too few organisms in the water to yield meaningful biological results. However, the onshore pilot experiments with seawater showed the applicability of the Oxicide system for *in situ* production of H_2O_2. The biocidal effect on zoo- and phytoplankton had been shown earlier in small-scale experiments, and verified by literature reports. A dosage of 15 mg/l proved to be very effective against a variety of organisms, although some organisms required substantial higher dosages for >95 % removal. Combined methods (hurdle techniques

8.14 In the case of combined treatment (Hurdle) technologies:

- For thermal treatment and de-oxygenation savings in energy consumption, while maintaining an acceptable treatment time is possible. Problems with corrosion and structural stress need to be addressed carefully.

- For thermal treatment with hydrogen peroxide no benefit as compared to only hydrogen peroxide treatment is identified. Possibly applying thermal treatment may reduce the treatment time for the hydrogen peroxide process, but at increased costs. Also corrosion and structural stresses need to be addressed.

- Ultraviolet combined with hydrogen peroxide appears to be more effective with possible savings on the amount of hydrogen peroxide used.

- Ultraviolet in combination with Ultrasound is more effective, saving energy while achieving a higher biological effectiveness.

- For all options, additional experimental work is required at full scale to obtain quantitative data and be able to optimize the working conditions for all of the techniques. Also a combination with mechanical filter techniques requires full scale experiments, as this appeared to be beneficial from the laboratory tests.

9 Environmental Impacts, Risk and Safety, and Economic Aspects of Treatment Methods

9.1 The first phase of the study investigated the risk and safety issues, environmental impacts, and economic aspects of existing ballast water management methods and techniques that are currently in use or that have been tested at a reasonable scale. This was carried out to establish a reference point for the further development of onboard ballast water treatment systems within the MARTOB project. Subsequent work included the evaluation of economic aspects, environmental impacts, and risk and safety effects of ballast water treatment methods tested at laboratory scale, and at full/large scale within MARTOB. The evaluation was based on information obtained during the MARTOB testing phase and from system designers for a case study ship.

9.2 Risk and safety issues:

- Ballast water management methods were assessed in terms of primary safety issues and hazard types. Generally, the methods that had the most serious hazards identified included sequential exchange of ballast water and chemical biocide methods where there is a need to handle, transport, store, or generate toxic/hazardous or corrosive chemicals. Physical removal of sediments and organisms by filtration or hydrocyclones has very minor safety concerns – the handling and disposal of sediments from heavily contaminated or polluted areas may be a concern.

- For most of the treatment methods tested within MARTOB, including thermal treatment, UV and US the hazard would be confined to the equipment location. For the biological de-oxygenation method there is the potential for the generation of toxic hydrogen sulphide gas to be produced in the ballast tanks if the water remains in the tank for extended periods beyond the recommended 7-day treatment time. In this case the hazard would encompass a much larger area of the ship. Ozone treatment requires the ozone (which is hazardous) to be piped into the ballast tanks, hazards could exist along the length of the piping and in areas of the tank if the gas accumulates in air spaces within the tanks. The potential of ballast water and vapours leaking out of the tanks and into adjacent areas of the ship could also be a concern. For the Oxicide method, there will be some hydrogen peroxide residual in the ballast water when it is returned to the tanks after treatment.

- With all methods, the risks can be reduced through appropriate training and safety procedures. Also applicable to all methods, is the potential that stress and fatigue resulting from additional workload on the crew may contribute to unsafe conditions.

9.3 Environmental aspects:

- The categories of environmental aspects investigated in the review included total energy use, direct emissions from use of energy, discharge of chemicals, and discharge of nutrients or solid organic material. The main comparable factor for indirect environmental impact that was identified was the fuel consumption per m^3 of treated ballast water. Direct environmental impacts include discharge of water with altered quality, including residuals of treatment chemicals or organic matter in the form of dead organisms, which may be a concern in eutrophic waters.

- Some negative environmental impact is inevitable, and this is mainly a result of energy use, although discharge of ballast water with altered quality has the potential to have impacts on sensitive waterbodies. The large positive environmental impact is of course the prevention of the introduction of non-indigenous species. In terms of consequences resulting from fuel combustion, such as air emissions contributing to climate change and acidification, the negative impact resulting from energy use for the treatment systems is much less than the impact of energy use for the entire ship. Many ships use more than 100,000 kg of marine diesel every day or 500,000 kg per 5-day trip, which is 100 times more than the most energy consuming system..

9.4 Economic aspects:

- The various cost data for different types of ballast water treatment options and different vessel types were extracted from previous studies and reports. Cost data for the methods that are still in an experimental phase show great differences in the cost data provided by several sources. A reason for this is that those costs are often based on rough estimates and often comprise incomplete data. Economic comparison of the treatment methods, based on the cost data collected for this review, is not appropriate as the cost calculations or estimations are all based on different background data and standards. Many differences could be identified such as, differences in ship types, amount of ballast water treated, biological efficacy required, time horizon and discount rate used for depreciation, maintenance cycle included in the assessment, and trade pattern. These findings emphasize the need to develop a standard or framework for evaluation and comparison of different ballast water treatment techniques.

- In order to compare the cost of the treatment methods studied in MARTOB, the calculations were based on a case study ship (approx. 15 000 tonnes deadweight) with a need to treat 2000 cubic metres per voyage and 50 trips per year. The estimated treatment costs, including capital costs (8 % interest rate, 10 year depreciation), per cubic metre ranged from € 0.10 for DEOX and € 0.11 for UV, to € 0.53 for HT and € 0.61 for Oxicide. The cost for the US, ozone, and AOT treatments were all in the range € 0.21-0.28.

- Sensitivity analysis of the calculated results shows that the operational costs per m^3 treated ballast water hardly change if the number of trips or the amount of cubic metres ballast water to be treated per trip varies greatly. The total costs per treated cubic metre ballast water declines as the number of trips increases due to spread evenly the same capital costs over an increased number of cubic metres per year.

10 CONCLUSIONS AND RECOMMENDATIONS FOR "ONBOARD TREATMENT OF BALLAST WATER"

10.1 Enforceability of the Convention:

- In MARTOB's experience, it takes almost 30 minutes to filter 1000 litres of seawater through 50µm sieves and 90 litres of seawater through 10µm filters under ideal conditions, i.e. use of a suitable pump, piping and valves, easy location for sampling and access to equipments, well designed and tailored filtering facilities, low to moderate concentration of plankton in ballast water, i.e. no bloom, and four trained and experienced staff. It was also concluded that:
  i. To produce defendable data and analysis, sampling must be done at least three times at every attempt,
  ii. To get a good representative of a tank we have to take samples from three different locations (or depths) inside the tank,
  iii. To get a possible representative of the ships ballast tanks we have to at least examine 3 tanks

  For a ship, this will result in sampling and filtering of 27000 litres of seawater which will take a minimum of 13.5 hours of non-stop sampling. Biological analysis of sampled sea-water will take considerably longer, particularly in the case of smaller plankton. All these procedures will definitely cause unavoidable delay to ship operation and is in contradiction to Article 12. For certain ship types (e.g. tankers which are heavily ballasted) with a turn-around time of less than 12 hours this problem is rather paramount,

- Samples taken from ballast tanks via man-holes or sounding-pipes and samples taken at discharge point could lead to different results; particularly if the ballast water treatment is conducted during discharge. Since the regulation clearly refers to ballast "discharge", presence of viable species in the tanks may not necessarily lead to their discharge. According to our experience, plankton and other species may seek shelter in the sediments, hide behind bulkheads and stiffeners or get killed during the process of pumping.

  a. In MARTOB's large-scale study we found a very large variation in the concentration of zooplankton per cubic metre in samples taken from the same ballast tank on the same day. A factor of 3-4 between the highest and lowest concentration in three successive samples was not uncommon, and the difference was occasionally considerably higher. This large variability in zooplankton concentration reflects an inhomogeneous distribution of the zooplankton in the ballast tanks),

  b. Internal design and structure of ballast tanks varies depending on ship structure and type which can also change between two sister ships. This may have a significant impact on the concentration and survival of the zooplankton and therefore the sampling results.

  c. Ships may need to conduct full/partial ballasting and de-ballasting at any location when required. Ballast water in tanks may be a combination of waters from different origins. In our experience, ballasting whilst the ship is moving could also increase diversity in species types and concentration.

- According to Regulation D2, ships can discharge up to 10 viable organisms per cubic meter greater than or equal to 50µm in minimum dimension. A ship with 50,000 cubic meters of ballast water may thus be permitted to discharge up to 500,000 viable organisms in a complete de-ballasting operation. Based on non-homogenous distribution of species in ballast water tanks, as described above, one may argue that even after sampling of 27000 litres of discharged water and finding more than 270 viable organisms (less than 500,000), it cannot be solidly concluded that this ship will discharge more than 500,000 viable organisms by the end of her de-ballasting and consequently may not be considered to be in breach of the regulation. Therefore, it would be difficult to design a sampling programme that would ensure that a vessel was achieving the treatment standard. Statistical and legal advice would be required.

- One of the areas which the MARTOB project highlighted is the urgent need for the development of methods to assess the viability of organisms, particularly phytoplankton. There are no standard methods currently available and the methods that are available would require much more research and development before they could be used on a large scale.

10.2 Recommendations on Regulations:

- To increase the level of enforceability of regulations, MARTOB strongly suggests that an approved procedure for "Treatment System Type Approval" must be put in place. IMO has accepted that there is a need for an internationally agreed type-approval system, by which the efficacy of any treatment system can be judged. Type approval will need involvement by coastal states as well as flag states. There will be an absolute need for coastal states to accept the output from type approved equipment or systems. MARTOB assumes that a type-approval process will be agreed, and that the ability of a system to meet the performance standard in Regulation D-2 will be confirmed and certified. This procedure must define:
  i. A representative test mixture of organisms (e.g. MARTOB soup)
  ii. Test and analysis protocols (MARTOB has carried out the first steps of developing protocols but acknowledge that changes would be required depending on what it was used for),
  iii. A set of required operational parameters for an individual (or combined) treatment system, that if complied with, it can be assumed that Regulation D2 had been implemented.

  Once a system has been tested and verified, coast authorities, similar to their inspections for ballast water management documents, may seek evidence of active operation of such equipment or system which could be digitally logged or monitored during operation,

- MARTOB recommends that port reception facilities must also be capable of receiving and treating Ballast Waters from these ships that have not been able to follow Ballast Water management procedure (Regulation A-3) or have been identified as potential risk according to Article 10 Paragraph 3. Similarly, such facilities shall operate without causing undue delay to ships,
- Many ships in European waters will not have to carry out BW exchange, because of the 200nm/200m or 50nm/200m restriction. Therefore, until the treatment standard comes into force for all vessels, they will not be required to treat their ballast water. MARTOB's concern is: what happens if the water is deemed to be high risk and how it will be treated for such vessels.

10.3 Recommendations to biologists:

- There must be a clear distinction between "sampling for research purposes" and "sampling for monitoring and compliance with Regulations".

- When testing an equipment, season, sea depth and location for ballast water intake investigations must be chosen with extreme care and consideration of plankton communities to avoid having no animals to treat,

- Sampling points must be convenient to set up filtering facilities and could be used for all weather and sea conditions,

- Make sure that sea-water is directly supplied from the intended tank and the residual water in the connecting pipes is removed.

10.4 Recommendations to technology developers:

- Internal design of ballast water tanks in new ship designs, although difficult to implement, must consider minimising the number of places where organisms could shelter and provide ease of flow and full discharge of ballast water and sludge removal,

- Design of ballast water treatment technologies should provide facilities for easy sampling before and after treatment for both prototypes and full-scale systems,

- Ballast water transfer pumps (at full size and laboratory scale) play an important role in killing organisms. If they are not a part of the treatment, sampling ports should be designed in such away to disregard pumps' effects,

- Treatment systems must take piping runs and valves into account very carefully, in both laboratory and real scale applications,

- All tests, either in laboratory or onboard ships, must have at least three replicates,

- There is a need to get beyond bench testing or laboratory work or even full-scale sea trials merely to determine effectiveness. MARTOB suggest the following:
  - i. a proven and reliable effectiveness in a design that can be built into a ship;
  - ii. a consistency of performance at a known flow rate matching the needs of the industry;
  - iii. plans for lengthy shipboard trials to be undertaken where the performance can be monitored and analysed,
  - iv. series production by an already-chosen manufacturer ready to begin and
  - v. a capability ready to prove to port and flag state officers through type-approval

- A system need not necessarily be cheap. The ability of a ship to fulfil its contractual obligations, especially in the bulk cargo trades that are so competitive, will depend upon its freedom to discharge any ballast water. Above all, the ship-owner will demand reliability and consistency. A treatment system that provides both and costs twice as the one that has been pared to the bone or which demands extensive man-hours to operate may be seen as preferable. An owner's choice of system will be helped, of course, by a manufacturer having a world-wide support network of engineers, able to help a ship in a remote loading port.

- The possibility of designing/using special internal treatment tanks for those ships/systems where on-line treatment may not be sufficient could be investigated.

10.5 Recommendations to European Commission:

- The Convention has difficult targets to achieve in terms of implementation; it may be many years before sufficient flag states ratify the convention to bring it into force through Article 18. Ship-owners may still have to deal with unilateral coastal state requirements that effectively implement it after 1 January 2009. It is simply unrealistic to expect a flag state to defend a ship's right to discharge unmanaged ballast water into a port of another state when that other state demands the ship should not. Therefore, enforceability of the Convention from technical, scientific and operational points of view must be reviewed and examined in more detail; in particular, its implementation, requirements and consequences at European ports must be investigated,

- Survey, assessment and certification of ballast water treatment systems must be standardised and recognised at an international level and in accordance with the regulation in the Convention. Scientific and technical results in MARTOB clearly shows that even based on the same data acquired, different interpretations (based on different statistical analysis) are quite possible, which can lead to significantly different conclusions,

- Biologically the term "viable" is vague and partly dependent upon the analytical method. The methods by which the viability is measured must therefore be defined, and such defined methods are currently lacking. In MARTOB's experience determination of the viability of zooplankton by staining techniques combined with microscopic examination, or by direct microscopic examination of live individuals, are very laborious and time consuming. Thus, there is a need for alternative, more rapid methods to avoid delays. For phytoplankton suitable methods for determination of viability in ballast water needs to be developed

- MARTOB has paved the way towards establishment of a unified approach for treatment systems' type approval; experiences learned, MARTOB soup and test protocols must be developed further and used in any future research,

- Even if ballast water treatment technologies have been type approved and can technically comply with the Convention, the real effectiveness of the regulation in protection of marine environment heavily relies on ships' crew to operate the systems correctly and efficiently. Practical, technical and operational training as well as ethical code of conduct are to be put in place for seafarers,

- Many technologies tested in MARTOB have shown that at laboratory and smaller scale, it could be possible to comply with the Convention. Nevertheless, up-scaling such systems to cope with large discharge rates of Ballast Water on heavily ballasted ships requires significant technological development. MARTOB suggests that additional research and development funds should be provided (through appropriate channels at national, continental and international levels) to enable technologists and scientists to proceed with further development,

- Enforceability of regulations must be examined in real operations. For a successful implementation and protection of European waters, port authorities in all EU states are required to go through appropriate training schemes.

11 CONCLUSIONS AND RECOMMENDATIONS FOR "APPLICATION OF LOW SULPHUR MARINE FUEL"

11.1 Several assessments have been made recently to try to quantify the marine bunkers consumption in Europe, BMT, Entec, Beicip-Franlab etc. The various studies do not provide consistent results, and this is to some extent due to different approach to the task, and how international/domestic sale and consumption have been considered. The most significant conclusion drawn from the comparison is that a significant uncertainty still exists with respect to the consumed volume of marine fuel oil in European waters. As a consequence of this it will be equally uncertain what effect new legislation will have on this market.

11.2 Based on sale figures collected in workshops arranged in connection with the MARTOB project, the sales in Europe of marine fuel oil have been estimated to be approximately 42.1 million tonnes (2001 figure). This figure does not include distillates, hence the figures found by Beicip-Franlab seems to be closest, but still somewhat low as this figure includes distillate sales.

11.3 Based on the MARTOB analysis is concluded that the fuel consumption within the SOxECA and by passenger vessels on regular services in EU waters is in the range 17 –19 MT by year 2007. The future low sulphur fuel demand will probably far exceed these figures. A quantity well above 20 MT is seen as a realistic demand in 2007.

11.4 Present European supply of low sulphur fuel oil with sulphur content below 1.5% (not including MDO/MGO) has been estimated to approximately 6.5 million tonnes, which the marine share represents less than 1 million tonnes annually. These figures are significantly smaller in magnitude than the estimated demand.

11.5 The provision of adequate quantities of segregated low sulphur bunker does not currently exist. In the short term part of the shipping operators might need to switch to distillates, and the distillate market redirect/increase to meet the increasing demand.

11.6 The options available to a refinery for increasing Low Sulphur Fuel Oil Supply to the bunker market are:

- Re-blending from the current HSFO market
- Switch to a lower sulphur crude diet
- Invest in Residue Desulphurisation (RDS)
- Redirect the low sulphur fuel oil destined for inland markets

11.7 A limited supply of lower sulphur content HFO could be available by re-blending current HSFO with MDO, or other components. This option presents a risk for producing unstable LSFO bunkers. Dilution of a thermally cracked residue with too high concentration of a paraffinic diluent ("cutter-stock") such as gas oil could result in an unstable fuel. It is consequently necessary to ensure that the aromaticity of any diluent is high enough to keep the asphaltenes dispersed. The addition of catalytically cracked cycle oils is one way of doing this, and so providing an adequate stability reserve.

11.8 If the tight supply should result in reduced stability for parts of the LSHFO products, the shipping industry will face more frequent operational problems, clogging of fuel separators and filters, fuel coagulation and heavy sludge formation. This also means increased chance for incompatibility with other fuel qualities during changeover operations.

11.9 Assuming properly done blending (right components from selected grades, and in correct order), the Beicip-Franlab report suggests that around 4 MT of 1.5% S bunkers could be available in North Europe and about 0.7 MT in the south, as indicated below.

11.10 It is difficult to predict what the future cost for low sulphur fuel will be, but sources considered by this work indicate additional cost of producing low sulphur fuel in the range 45-70 USD/t for 1.5 % sulphur to 65-95 USD/t for 0.5 % sulphur content. This study has not been able to contradict these projections.

11.11 The required use of low sulphur (1.5%) bunkers within EU territorial waters, with even tighter sulphur specifications (0.2%) within port areas will present a major challenge for the marine business in terms of segregation of fuels both in ship and shore tankage and delivery systems

11.12 Engine manufacturers recommend a preferred fuel viscosity at injection, and since the temperature of the fuel determines fuel viscosity, changing fuel type also mean changing injection temperature. Controlled conditions during changeover between two different fuel qualities are of vital importance to avoid too rapid and too large change in fuel oil temperature and, thereby. protect the fuel injection equipment on the engines. The high fuel oil injection pressure requires very narrow tolerances in the fuel injection equipment. An uneven thermal expansion of the equipment could cause seizure, e.g. of plunger and barrel.

11.13 Of engine tribology reasons the sulphur content of the fuel must be balanced with the Base Number of the engine lubricant. For engines operating on heavy residual fuel oil, a cylinder oil with a viscosity of SAE 50 and BN of about 70 is normally recommended. In most cases, the high BN cylinder lubricant will also be satisfactory during temporary operation on diesel oil/gas oil. In general, changing the cylinder oil type to correspond to the fuel used is considered relevant only in cases where operation on the respective fuel type is to exceed 10 hours.

11.14 For vessels operating all or most of the time inside a SOxECA, a monofuel operation on a selected low sulphur fuel quality will be the natural choice, with limited operational consequences. Regarding continuous operation on low sulphur fuel, the MARTOB project has assessed experience from two vessels with several years of operation on such products. Based on the cases, continuous operation on low sulphur qualities does not represent a significant technical/operational challenge, but fuel cost increase is higher than savings related to maintenance, operation etc.

11.15 Case studies from operation based on change between different fuel qualities (HS and LS), reveal that no firm general conclusion on best practice can be made with respect to amendment of operational procedures in such cases. The main reasons for this are that the trading pattern of the vessel, and the space available for fuel system modifications will heavily influence the operator’s decision.

11.16 Depending on the fuel system tank layout there will be different procedures to obtain correct sulphur values of the fuel entering the engine. If the vessel is equipped with single settling and service tanks, sufficient flushing time must be ensured. The time required for changing from a high sulphur fuel to one containing less than 1.5 % S could be very long – well above 100 hours.

11.17 The optimal solution from an operational point of view, considering both safety and extent of new operation procedures, is to have dual fuel storage and fuel pre-treatment systems for high and low sulphur fuel qualities. For ships in inter continental trade, change over from HSHFO to LSHFO is a viable option due to few visits each year to the SOxECA. Long hauls and few visits will provide sufficient time window to properly plan and execute change over from HSHFO to LSHFO, without significantly increasing the risk for stop of engines.

11.18 For ships with more frequent visits in the SOxECA, change over between HSHFO and LSHFO is not recommended unless the ship has two separate fuel pre-treatment systems, due to the complicated change over operational procedures and increased risk for stop of engines.

11.19 The study is not able to establish general cost estimates on the economic impact for any ship operating in a SOxECA. The economic impact, from a ship operator perspective, will vary between different trading patterns and ship designs etc. Ship owners are in general recommended to assess own need for low sulphur fuel operation and bunkering strategy, and to perform a fleet assessment of alternative options to comply with the new regulation. Included in a fleet assessment would be economical evaluation of impact of investment in equipment versus impact of revised operational procedures.

11.20 The proposed amendment to Dir. 1999/32 states that at berth use of fuel with a sulphur content above 0.2% will be prohibited. This will require vessels to carry gas oil, a quality not normally used onboard. Trans-ocean vessels might experience problems purchasing such low sulphur gas oil in international ports, hence it might be necessary to await entering European port. As some vessels are not allowed to carry out bunkering operations while loading or discharging, this will delay the loading operations. If the vessels have to change over to MGO at berth or in the harbour area (e.g. diesel electric power plants, auxiliary machinery) there are increased risks for black outs. A black out is of course much more critical if the vessel is under manoeuvring in restricted waters, hence change over to MGO should be limited to at berth condition.

11.21 Depending somewhat on fuel system layout, changeover operation between different fuel types or qualities always involve increased risk for engine stop, due to un-proper procedures, faulty operation, incompatibility between the actual fuels with heavy coagulation as consequence etc. Due to this, changeover operations should be avoided in restricted waters, and always be performed in open sea or at berth after manoeuvring is finished/started.

11.22 To allow the shipping operators adequate time and opportunity for adaptation to the new sulphur regulations, the maritime administrations should in due time prescribe the involved requirements to system arrangements and expected framework for control regime (routines for fuel sampling, logbook recordings etc.).

11.23 The practice to maintain documentary evidence of fuel oil quality standards laid down under regulation 18 of Annex VI of MARPOL 73/78 must be firmly adhered to so that a legally sound method can be documented for follow up of non-compliance vessels. Due to the possibilities of falsification of documentary evidence and samples, and also the cost and labour associated with undertaking a high percentage of investigation calls for additional verification procedures, these additional verification procedures should be designed to allow identification of possible non-compliance warranting a more detailed default investigation. Based on studies conducted in this work it was found that the AIS and remote sensing provide the most promising solution and it is recommended that further study should be conducted.

11.24 Three important areas of further work have been identified from the case studies:

- More work needs to be done to quantify the impact and ability for the refining industry to meet the changing demand in fuel qualities and to assess the overall cost impact on the business.

This should take account of work currently being undertaken by Concawe into the impact on the European oil industry resulting from the introduction of lower sulphur specifications for both inland and marine fuels.

- More experience feedback should be demonstrated on dual fuel operation to gain increased knowledge on potential safety and operational problems experienced with change over between HFO and LSHFO/MDO/MGO.

- Operational procedures should be carefully established for those who will operate on more than one fuel quality and with change over between different fuel qualities upon entering a SOxECA. Further work must be undertaken to clarify requirements for monitoring, documentation and verification of compliance defined as acceptable for any administration enforcing the new sulphur regulations.