**FINAL REPORT FOR THE AUSTRALIAN GOVERNMENT DEPARTMENT OF THE ENVIRONMENT AND HERITAGE**

# THE AUSTRALIAN PILOT PROJECT FOR THE TREATMENT OF SHIPS' BALLAST WATER

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Natural Heritage Trust

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## ACKNOWLEDGEMENTS

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## EXECUTIVE SUMMARY

**The issue of the translocation of marine organisms that become, or can become, pests is recognised by the Global Environment Facility as being one of the four greatest threats to the marine environment. The others are land-based marine pollution, over exploitation of living resources and physical destruction of habitat. Much of this translocation takes place via ships' ballast water and can lead to very high economic and environmental costs.**

**The International Maritime Organisation (IMO) has wrestled with the issue for many years and has recommended in the past that vessels exchange ballast in open waters to reduce the risk of organisms surviving the voyage. Individual countries, Australia included, have imposed mandatory ballast exchange unless it can be demonstrated that the ballast poses little risk of carrying organisms that could cause problems. There are many different regimes of regulation and this is of concern to shipping which would prefer consistent approaches to regulation world-wide. Added to this are safety concerns associated with ballast water exchange.**

**Clearly, it would be of considerable advantage if ships could be assured that the ballast that they were carrying was not going to cause environmental impacts. One way of achieving this is the development of suitable treatment systems that can reliably disinfect the water. The shipping and ports industries clearly need and want workable systems that will be approved by regulatory authorities.**

**This has been recognised by the IMO which has, over a period of years, developed the *International Convention for the Control and Management of Ships' Ballast Water and Sediments* which includes a set of standards for ballast water treatment which will be used as a basis for acceptance for ship-board ballast water treatment options. This Convention was finalised in February 2004.**

**For ballast water technologies to be accepted by the IMO, they will have to meet strict criteria relating to effectiveness and consequently each will require rigorous scientific testing.**

**To address this issue a consortium of Queensland Port Authorities (Mackay, Gladstone, Townsville and the Ports Corporation of Queensland), the CRC Reef Research Centre, James Cook University, Amiad International (a major filter manufacturer) and United Water International (a leading water treatment company) was established. All were committed to supporting the project if further funding could be found. The commitment by the partners was extremely helpful in the bid that was made to the Australian Government for funding. Funding from the National Heritage Trust made the project viable and further encouraged new partners to join.**

**In addition to the original Consortium partners, the following organisations have become participants:**

- **Queensland Department of Primary Industries;**
- **Pasminco Century Project;**
- **The Queensland Environmental Protection Agency;**
- **URS, an international environmental consulting company;**
- **Modular Solution Technologies, developers of sonic/shear based treatment systems; and**
- **The Great Barrier Reef Research Foundation, a non-profit agency charged with funding appropriate research and development to protect the marine environment.**

**The concept adopted was to build a pilot plant in a portable, twenty-foot long shipping container using largely established and scalable technologies. This has been done and the technologies used include filtration, ultra-violet light irradiation, chlorine dioxide injection and a high speed sonic/shear device. We consider that the best way to treat ballast water is as it is being loaded**

**aboard ship and that treatment will take place as the water flows through the various technologies. The plant mimics this approach and has been operating at James Cook University since June 2003.**

**Since then we have run extensive tests using a number of organisms, primarily the brine shrimp, *Artemia salina*, since this is a particularly useful surrogate for many of the organisms of concern carried in ballast water. It has a tough, encysted stage as well as a stage where it represents many planktonic organisms. It is also readily and cheaply cultured. We have also run tests on a rotifer, *Brachionus rotundiformes* and the phytoplankton *Nanochloropsis*. Organisms were collected from Townsville and Mourilyan ports and exposed to treatment.**

**A major part of the work that we have undertaken has been to develop robust and defensible sampling methods and protocols. This has not been undertaken to any appreciable extent by any other workers in the field of ballast water treatment. The consequence of this has been that other workers cannot, by and large, demonstrate whether treatments are, or just as importantly, are not, effective. The IMO standard is extremely stringent and it will be a major challenge to demonstrate system efficacy. We are addressing this issue as part of the overall project.**

**The major findings in relation to the effect of the treatments are:**

- **The primary pump can have a very significant effect on survival of hatched *Artemia* but virtually no effect on the encysted stage;**
- **Filtration using 50 micron screens is virtually 100% effective in removing *Artemia* cysts and nauplii (the newly hatched animal) and 85% effective for *Brachionus*;**
- **The sonic shear device was virtually 100% effective against nauplii and reduced hatching rates of cysts by 47%;**
- **The sonic shear device when combined with chlorine dioxide at approximately 3 parts per million reduced cyst hatching rates by nearly 70% after 11 hours and 99.9% after 40 hours;**
- **Ultra-violet treatment of nauplii significantly reduced survival after 15 hours, indicating a delayed effect, but actually increased the hatching rate of cysts; and**
- **Chlorine dioxide alone at approximately 3 parts per million reduced the hatching rate of cysts by 97% after 40 hours.**

**A preliminary, conceptual design of a shipboard system has been carried out as part of the project and this considers a number of the practicalities of operating a full-scale system. We do not believe that that there are insuperable difficulties associated with installation and operation of shipboard systems.**

**Given the size of the world shipping fleet and the new IMO Convention, there is considerable potential for commercial development of ballast treatment systems as well as for the maintenance, testing and verification of systems. These markets will run to many billions of dollars. The CRC and James Cook University will be establishing a commercial entity to further Australia's prospects of becoming a major player in these markets.**

**A summary of recommendations follows**

**It is recommended that Australian governments become more involved in resolving this issue. There are many opportunities for Australia to become involved in the testing and verification of systems and much of the work being planned or undertaken is on a bilateral or multilateral basis. With a relatively small resource investment Australia could become a part of what is likely to become a major industry.**

**As an incentive for shipowners and operators to be more inclined to install test systems on vessels, it is recommended that Australian governments consider something similar to the US**

**Shipboard Technical Evaluation Program. This program will facilitate the development of effective ballast water treatment technology, and will create more options for vessels seeking alternatives to ballast water exchange.**

**The use of filter technology has been shown to be able to significantly reduce risks of translocations of many organisms of concern. It is recommended that Australian governments consider ways in which filters could be brought into use in the immediate future even though the technology cannot meet the proposed IMO standard.**

**There will almost certainly be further deliberations regarding the proposed standard. The majority view of participants at the IMO/IMarEST Symposium on Ballast Water Treatment, held in July 2003, was that it was unlikely that the proposed standard could be met within the next 5 or even 10 years. This should not be seen as reason to not embrace risk reduction techniques that are more effective and safer than ballast exchange and available now. It is recommended that Australian representatives should be more forthright on this issue as opportunities arise.**

**The ABWTC project has explored many of the challenges associated with treatment systems and has probably raised as many questions as answers in the time available to it. The project has been very productive and made quantified studies of a range of available technologies. The project should continue for a further year to complete the pilot phase prior to scaling up appropriate technologies. Further funding is being sought to complete the pilot phase and continue into an adoption phase.**

**Given the technological challenges associated with treatment systems and the likelihood that ballast exchange will be the primary method of risk reduction for many years, it is recommended that Australia also further support research into ballast exchange efficiencies.**

# CONTENTS

# 1. INTRODUCTION

## 1.1 The ballast water problem

It is estimated that the world's shipping fleet transports ten billion tonnes of ballast water annually and ballast water is now recognised internationally as a major threat to coastal ecosystems. The translocation of exotic aquatic species in ships' ballast was first recorded by Medcof (1975). It is now recognised internationally as a potential vector for the intra- and trans-continental movement of marine species including toxic dinoflagellate algae (Hallegraeff & Bolch 1991), macroalgae (Ribera 1995), *Vibrio cholerae* (McCarthy & Khambaty 1994) and a range of zooplankton (Carlton 1995).

Translocation of coastal marine organisms around the world by commercial and recreational shipping has resulted in numerous cases where species have successfully colonised environments outside of their natural range. Ships may take on between several hundred to 100,000 tonnes of ballast water prior to or during voyages (Sutherland *et al* 2001) and this water can contain a diverse assemblage of nearshore marine species (Carlton 1995). The importance of ballast water as a vector appears to be increasing with time due to changing trading patterns such as new routes and decreasing voyage times (Oemcke 1999).

Marine species have been able to traverse huge global distances via international shipping. Gollasch *et al* (2000) noted that several planktonic species survived a voyage of 23 days from Singapore to Germany and harpacticoids (*Tisbe sp*.- a copepod crustacean) increased in abundance by 100 times *en route*. In some cases, introduced marine species establish by out-competing and displacing native species. They can become so abundant that they cause significant economic, ecological and health impacts. Unlike other major pollutants of the oceans like oil, sewage and garbage, once established, introduced marine pests are generally impossible to eradicate and can have serious and permanent consequences for the marine environment, sustainable development, biodiversity and public health. This sets the issue of introduced marine pests apart from the threats posed by other marine pollution issues.

In Australia, it is estimated that over 200 species have been introduced from overseas via ships' ballast water or hull fouling (Hewitt and Martin 2001) and, of these, several have had major impacts. There are likely to be many others yet to be discovered. Many of these introductions arrived inadvertently in ballast water carried by ships servicing the multi-billion annual Australian export trade.

Alien species that have been identified as pests include:

- the toxic dinoflagellate (*Gymnodinium catenatum*) that closed southern Tasmanian shellfisheries in 1986, 1987 and 1991 for up to 6 months;
- the Northern Pacific Seastar (*Asterias amurensis*) that has drastically reduced yields in the Tasmanian scallop industry;
- the Asian kelp (*Undaria pinnatifida*) is an aggressive, fast growing seaweed that has become established in the waters of southern Australia and New Zealand. It grows a shading canopy that threatens red algae, the food of abalone and sea urchins.
- the Giant Tube Worm (*Sabella spallanzanii*) has become established in many areas of southern Australia. It grows in dense beds on rocky reefs and man-made structures and can choke out native species. It is a filter feeder removing organisms from the base of the food chain, thus having the ability to have major effects on natural ecosystems; and
- introduced mussels in Cairns and Darwin have resulted in major expenditure in attempts to eradicate them before they could cause major damage.

There are many similarly disastrous examples from overseas and most infestations are untreatable once established.

## 1.2 Present management of the problem

The only control presently approved and recommended by the International Maritime Organisation (IMO) to prevent these introductions is to exchange ballast water at sea, even though this is not fully effective and can be dangerous for ships due to over stressing the hull. Some port states and individual ports are enforcing unilateral management regimes and different criteria, which pose difficulties for the shipping industry trying to comply with a complicated set of rules.

In the late 1980s, the classification by Australian Quarantine and Inspection Service of ships' ballast water as a "significant quarantine issue" has allowed Australia to address the problem. In 2001, Australia imposed mandatory risk-assessment for all incoming international ships with compulsory mid-ocean ballast water exchange for those ships deemed at risk. Mid-ocean ballast water exchange has certain limitations including the possibility of incomplete water exchange (and organism removal) and the difficulty of completely removing sediments (a possible reservoir for cyst stages (Hallegraeff and Bolch 1991). Further, the procedure is weather-dependant, poses safety threats under some circumstances and is not readily monitored for either compliance or effectiveness.

The shipping and ports industries clearly need and want workable systems that will be approved by regulatory authorities.

In February 2004, the International Marine Organisation (IMO), through their Marine Environment Protection Committee, developed new international guidelines and regulations to reduce the risk of marine bioinvasions. The *International Convention for the Control and Management of Ships' Ballast Water and Sediments* includes a set of standards for ballast water treatment which will be used as a basis for acceptance for ship-board ballast water treatment options (IMO 2004).

For developing ballast water technologies to be accepted by the IMO, these will have to meet strict criteria relating to effectiveness and consequently each will require rigorous scientific testing in the development stage. Relevant parts of the Convention regarding standards are reproduced below.

***Regulation D-1*** Ballast Water Exchange Standard

*1 Ships performing Ballast Water exchange in accordance with this regulation shall do so with an efficiency of at least 95 per cent volumetric exchange of Ballast Water.*

*2 For ships exchanging Ballast Water by the pumping-through method, pumping through three times the volume of each Ballast Water tank shall be considered to meet the standard described in paragraph 1. Pumping through less than three times the volume may be accepted provided the ship can demonstrate that at least 95 per cent volumetric exchange is met.*

***Regulation D-2*** Ballast Water Performance Standard

*1 Ships conducting Ballast Water Management in accordance with this regulation shall discharge less than 10 viable organisms per cubic metre greater than or equal to 50 micrometres in minimum dimension and less than 10 viable organisms per millilitre less than 50 micrometres in minimum dimension and greater than or equal to 10 micrometres in minimum dimension; and discharge of the indicator microbes shall not exceed the specified concentrations described in paragraph 2.*

*2 Indicator microbes, as a human health standard, shall include:*

*.1 Toxicogenic Vibrio cholerae (O1 and O139) with less than 1 colony forming unit (cfu) per 100 millilitres or less than 1 cfu per 1 gram (wet weight) zooplankton samples ;*

*.2 Escherichia coli less than 250 cfu per 100 millilitres;*

*.3 Intestinal Enterococci less than 100 cfu per 100 millilitres.*

***Regulation D-3*** Approval requirements for Ballast Water Management systems

*1 Except as specified in paragraph 2, Ballast Water Management systems used to comply with this Convention must be approved by the Administration taking into account Guidelines developed by the Organization.*

*2 Ballast Water Management systems which make use of Active Substances or preparations containing one or more Active Substances to comply with this Convention shall be approved by the Organization, based on a procedure developed by the Organization. This procedure shall describe the approval and withdrawal of approval of Active Substances and their proposed manner of application. At withdrawal of approval, the use of the relevant Active Substance or Substances shall be prohibited within 1 year after the date of such withdrawal.*

*3 Ballast Water Management systems used to comply with this Convention must be safe in terms of the ship, its equipment and the crew.*

***Regulation D-4*** Prototype Ballast Water Treatment Technologies

*1 For any ship that, prior to the date that the standard in regulation D-2 would otherwise become effective for it, participates in a programme approved by the Administration to test and evaluate promising Ballast Water treatment technologies, the standard in regulation D-2 shall not apply to that ship until five years from the date on which the ship would otherwise be required to comply with such standard.*

*2 For any ship that, after the date on which the standard in regulation D-2 has become effective for it, participates in a programme approved by the Administration, taking into account Guidelines developed by the Organization, to test and evaluate promising Ballast Water technologies with the potential to result in treatment technologies achieving a standard higher than that in regulation D-2, the standard in regulation D-2 shall cease to apply to that ship for five years from the date of installation of such technology.*

*3 In establishing and carrying out any programme to test and evaluate promising Ballast Water technologies, Parties shall:*

*.1 take into account Guidelines developed by the Organization, and*

*.2 allow participation only by the minimum number of ships necessary to effectively test such technologies.*

*4 Throughout the test and evaluation period, the treatment system must be operated consistently and as designed.*

The Convention will come into force twelve months after thirty States representing at least thirty-five per cent of world's merchant shipping tonnage have ratified it and be implemented according to Regulation B.3 (reproduced below). It is unknown when ratification is likely to take place but it is likely to be several years.

**Regulation B-3** Ballast Water Management for Ships

*1 A ship constructed before 2009:*

*.1 with a Ballast Water Capacity of between 1500 and 5000 cubic metres, inclusive, shall conduct Ballast Water Management that at least meets the standard described in regulation D-1 or regulation D-2 until 2014, after which time it shall at least meet the standard described in regulation D-2;*

*.2 with a Ballast Water Capacity of less than 1500 or greater than 5000 cubic metres shall conduct Ballast Water Management that at least meets the standard described in regulation D-1 or regulation D-2 until 2016, after which time it shall at least meet the standard described in regulation D-2.*

*2 A ship to which paragraph 1 applies shall comply with paragraph 1 not later than the first intermediate or renewal survey, whichever occurs first, after the anniversary date of delivery of the ship in the year of compliance with the standard applicable to the ship.*

*3 A ship constructed in or after 2009 with a Ballast Water Capacity of less than 5000 cubic metres shall conduct Ballast Water Management that at least meets the standard described in regulation D-2.*

*4 A ship constructed in or after 2009, but before 2012, with a Ballast Water Capacity of 5000 cubic metres or more shall conduct Ballast Water Management in accordance with paragraph 1.2.*

*5 A ship constructed in or after 2012 with a Ballast Water Capacity of 5000 cubic metres or more shall conduct Ballast Water Management that at least meets the standard described in regulation D-2.*

*6 The requirements of this regulation do not apply to ships that discharge Ballast Water to a reception facility designed taking into account the Guidelines developed by the Organization for such facilities.*

*7 Other methods of Ballast Water Management may also be accepted as alternatives to the requirements described in paragraphs 1 to 5, 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 the Committee.*

## 2. BACKGROUND TO THE PROJECT

As part of its environmental programme, EcoPorts, the Ports Corporation of Queensland (PCQ) recognised in the early 1990s that ballast water discharge had potentially serious economic and environmental effects. PCQ instituted a three-pronged approach to the issue. It commissioned port surveys of its major trading ports to establish baselines of plants and animals that were in the ports and whether there were any imported species and also if these were pests; in collaboration with other Queensland ports – Townsville, Mackay, Rockhampton, Cairns, and Bundaberg, commissioned a study to assess the risk of organisms being imported in ballast water based on environmental similarities between source and sink ports; and, along with the CRC Reef Research Centre, supported the fundamental research by Darren Oemcke at James Cook University which led to his Doctoral Thesis *Investigation of Options for the Treatment and Management of Ships' Ballast Water* (Oemcke, 1999 (1)). Among the recommendations that Oemcke made were that development of a pilot plant to test treatment methods at a scale large enough to represent 'real-world' conditions should be pursued.

The Australian Ballast Water Treatment Consortium (ABWTC) concept developed over a number of years, particularly since the conference, *The Ballast Water Problem – Where to from here*, which was

held in Brisbane in May, 1999 (Hillman, 1999). This conference was organised by the association of Australian Ports and Marine Authorities, the Ports Corporation of Queensland and Dames and Moore, and attracted about 100 participants. While recognising that there are a number of potential solutions to the ballast water problem, the participants agreed that one of the long-term objectives of ballast water management is to implement treatment solutions in an integrated and collaborative manner.

Initiated by the Ports Corporation of Queensland, a consortium of Queensland Port Authorities (Mackay, Gladstone, Townsville and the Ports Corporation of Queensland), the CRC Reef Research Centre, James Cook University, Amiad International (a major filter manufacturer) and United Water International (a leading water treatment company) was established. All were committed to supporting the project if further funding could be found. The commitment by the partners was extremely helpful in the bid that was made to the Australian Government for funding. This funding of $247,150 from the National Heritage Trust made the project viable and further encouraged new partners to join.

In addition to the original Consortium partners, the following organisations have become welcome participants:

- Queensland Department of Primary Industries;
- Pasminco Century Project;
- The Queensland Environmental Protection Agency;
- URS, an international environmental consulting company;
- Modular Solution Technologies, developers of sonic/shear based treatment systems; and
- The Great Barrier Reef Research Foundation, a non-profit agency charged with funding appropriate research and development to protect the marine environment.

A dedicated Project manager was appointed in 2002 and, as was planned, the project is based at the School of Engineering at James Cook University and administered through the CRC Reef Research Centre.

## 3. OBJECTIVES

As stated in the application for funding to the National Heritage Trust;

*The prime objective of the project is to formulate the design criteria for the successful development of an economical treatment plant capable of economically treating ships' ballast water in tropical, subtropical and temperate waters.*

*Other important objectives include:*

- *To provide greater understanding of the chemical, physical and biological properties of ballast water contamination in order to improve the capability of Australian ports and shipping management bodies to detect and more effectively respond to introduced marine pests;*

- *To conduct pilot plant testing of real port conditions that target the key introduced marine pest species that threaten Australia's temperate, sub-tropical and tropical waters. The tests would determine the best mix of filtration, hydrocyclones and UV treatment technology to achieve ballast treatment for these species; and*

- *To identify potential commercial applications and place Australia and Australian industry in a leading position in the development of an important new technology – ballast water treatment plants.*

## 3.1 Revised objectives

We revised some of the objectives during the course of the project. Primarily the changes related to the deployment of the pilot plant in ports, which was considered not to be a worthwhile objective.

The main reasons for this were:

1. ***The need to develop robust protocols for performance assessment.***

An early evaluation revealed that the lack of knowledge of highly variable concentrations of organisms in port waters would be extremely problematic in terms of determining treatment efficacy. Another problematic factor was the low concentrations of organisms which would result in low confidence in performance from a statistical point of view. This evaluation has been borne out by the findings of overseas researchers who have invested significant time and resources but not been able to demonstrate plant capability.

As statistical validity is essential for the success of this project we have taken the necessary time to ensure that our approaches to enumerating organisms are robust and repeatable.

2. ***The preferred use of surrogate organisms.***

The use of surrogate organisms allows the control of organism type, size and concentration. This, in turn, allows a full evaluation of the pilot plant capabilities under varied but known conditions, a situation not possible using raw port water.

3. ***Consistency with international protocols and standards.***

The proposed standard by the IMO is based upon the numbers of various organisms that remain in discharged ballast water. However, there is an underlying principle that this will be based upon a known concentration of organisms being input to the system. The protocols being developed overseas, with input from ABWTC, follow this principle. The low concentrations and variability of organisms in ports waters do not allow us to test to the accepted protocols.

4. ***Time constraints.***

We have only had the plant operational since May 2003 due to construction delays and component availability. This has meant that we have not been able to completely address the points made in '1' (above) in the time available. We still intend to take the pilot plant to ports once we are confident that results will be meaningful.

# 4. DESIGN AND DEVELOPMENT OF THE PILOT PLANT

We have designed and built the pilot plant in a 20 foot shipping container. This arrangement allows us to use the plant under pilot scale conditions and to move it to different ports for testing under various environmental conditions.

As described by Oemcke (1999 (2)), Oemcke and Hillman (2001), the pilot plant largely uses existing technologies; filtration, ultraviolet light and chlorine dioxide dosing, although we have incorporated a high velocity sonic/shear disintegrator (HVSD) that is currently under development.

We consider the best time to treat ballast water is during loading by the ship. This has the benefit of leaving filter backwash material at the port of origin and ensures all ballast water passes through the treatment system. Recognising that the quality of discharged ballast water is the essential criteria, the use of the system to treat water during discharge may be necessary to kill or inactivate organisms that may have recovered during the voyage. The pilot plant is therefore designed to treat water as it passes through the system. Design flow rate for the pilot plant is between 3 and 6 litres per second (up to 20 tonnes per hour). This balances our ability to sample the water effectively with the need to demonstrate pilot plant performance. It also investigates treatment at reasonable flow rates, which can be scaled up to meet required full-scale throughputs. A schematic of the pilot plant is at figure 1.

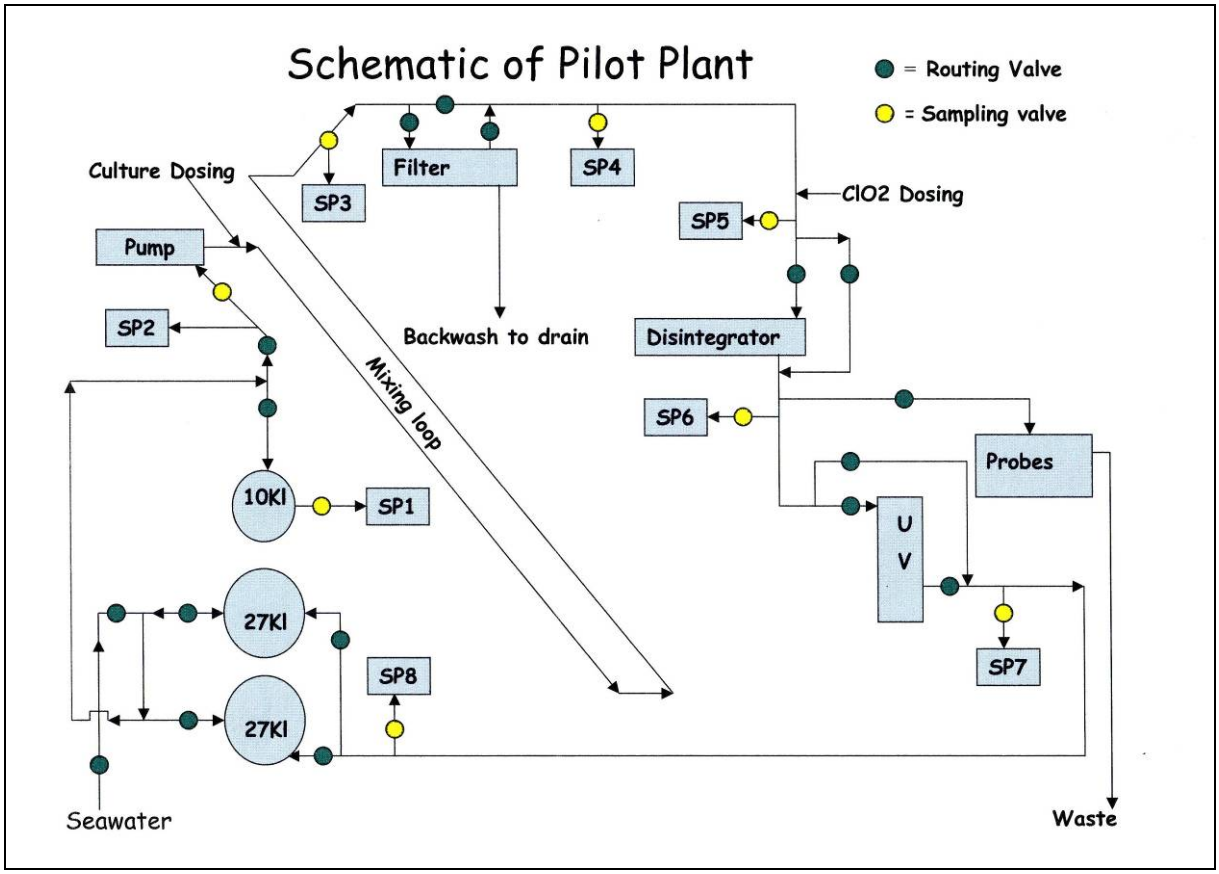



**Figure 1 Schematic of the pilot plant**

The pilot plant is presently installed at James Cook University's Marine Aquaculture Research Facilities Unit (MARFU). MARFU provides seawater, freshwater, aeration and laboratories for culturing a variety of marine organisms. The experimental set-up comprises three seawater holding tanks (two 27,000 litre and one 10,000 litre tank), all interconnected by 50mm PVC piping to the four ballast water treatment technologies installed within the shipping container (see figure 2). The water treatment systems are:

- A specially constructed automatic backwash screen filter (Amiad BW-4500) with interchangeable 25, 50 and 80 micrometre screens;
- A low pressure UV unit (Wedeco UVIFLO G100-P-170 with manual wiper and UV monitor capable of transmitting at a wavelength of 254 nanometers with an intensity of 42 mW.sec/cm$^2$ (the USEPA water treatment standard) at a flow rate of 20 tonnes per hour;
- A chlorine dioxide generator (Prominent$^R$ CDLa) with adjustable dosing rates of between 0.5 and 8.5 ppm when the flow rate of the pilot plant is set to 15 tonnes per hour; and
- A high-velocity sonic/shear disintegrator (HVSD) which generates shear and sonic stresses to either destroy organisms outright or make them more susceptible to synergistic treatments such as chlorine dioxide or UV.

Valves enable shunting of water between the experimental plant and any of the tanks as well as testing of single or multiple treatments. Test organisms can enter the pilot system in two ways. A concentrated culture can be mixed into seawater in the 10,000 litre tank and then pumped directly into the pilot plant. Alternatively, a 10-30 litre concentrated culture can be dosed directly into flowing water at a point in the PVC piping located after the water intake pump but before the treatments. For the latter method we utilised a Prominent$^R$ dosing pump (model Beta/4, 0708) that can be preset to pump from the 30 litre container at a constant rate. We used the maximum setting of 115 ml per minute (measured dose rate against pressure into the flowing water of the experimental system). In

March 2004 we also added an 18 metre loop of piping between the culture input point and the control sampling point to promote better mixing.

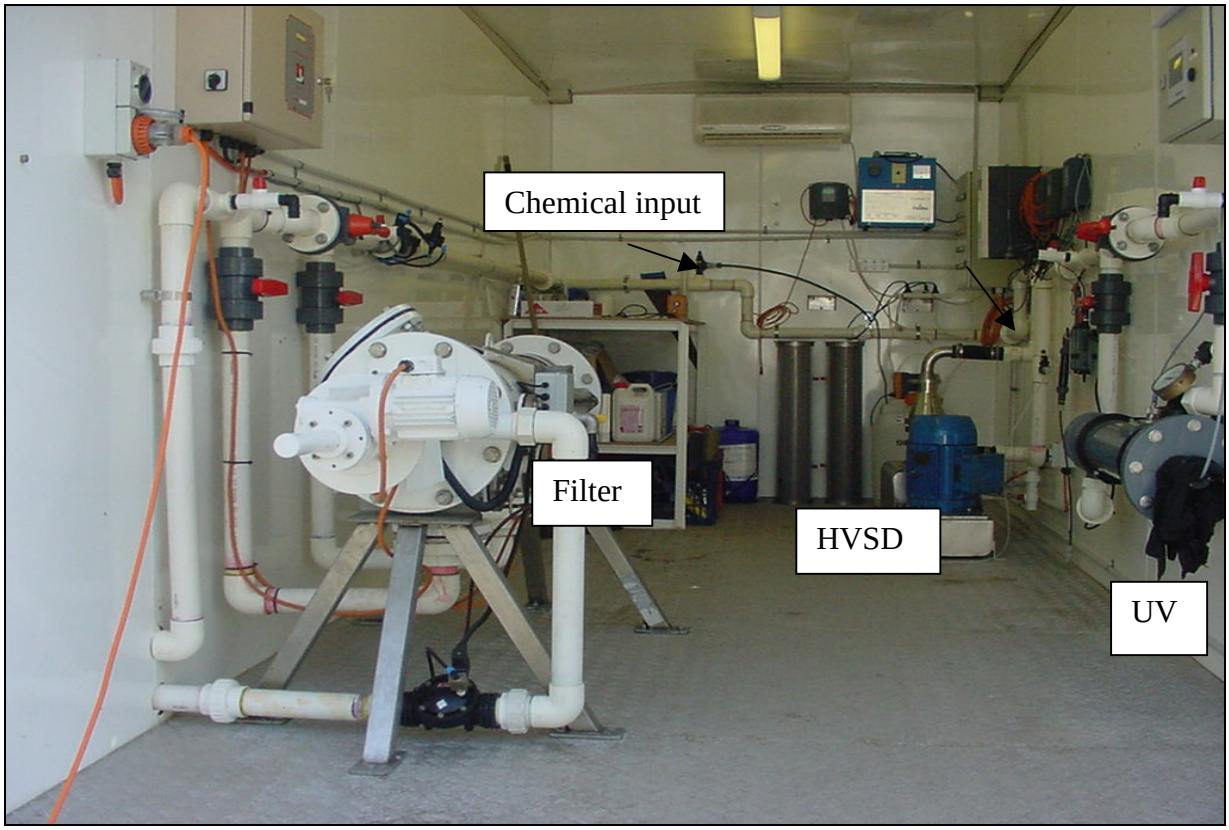



**Figure 2 Layout of pilot plant**

## 5. METHODS

### 5.1 Choice of treatment methods

There is a plethora of possible methods for treating ballast water. We primarily chose methods that we believed were readily available, had a history of success in water treatment and would be scalable and suitable for use aboard ships. We rejected treatment methods that we believed would not be cost effective, were environmentally questionable or were not suitable for use aboard ship. We further selected treatment methods that could be used while ballasting or deballasting since all ballast water would be exposed to the treatment process. This cannot be guaranteed using 'in tank' methods since there are issues associated with effective mixing and ballast tank 'dead spots'.

| SELECTED TREATMENT METHODS | POSITIVE ASPECTS | NEGATIVE ASPECTS |
|---|---|---|
| Ultra violet irradiation | Well established technology, used worldwide for purification, effective against pathogens, low maintenance, no residuals. | Effectiveness lowered by turbidity and colour. |
| Filtration | Well established technology, used worldwide for purification, will remove a large number of organisms of concern, will remove some sediment, almost certainly the front end to any system, low power consumption and maintenance. | Can't remove smaller organisms at the throughputs required aboard ship, unlikely to reduce turbidity to any great extent. |

| | | |
|---|---|---|
| Chlorine dioxide | Well established technology, very effective biocide, degrades in a matter of hours, complementary to other treatment methods, low corrosion potential. | Requires the mixing of potentially dangerous chemicals, some safety issues. |
| HVSD | At pilot scale has shown potential for destruction of many organisms. | Requires more development for higher flow rates, high power draw considerations. |
| | | |
| **TREATMENT METHODS UNDER CONSIDERATION** | **POSITIVE ASPECTS** | **NEGATIVE ASPECTS** |
| Hydrocyclones | Can remove much of the sediments, possibly effective in removing dinoflagellate cysts. | Will not remove most organisms since the specific gravity is very close to that of water. |
| Ultrasound and cavitation | Effective on many organisms. | Power draw considerations, scale up issues. |

| **REJECTED TREATMENT METHODS** | **POSITIVE ASPECTS** | **NEGATIVE ASPECTS** |
|---|---|---|
| Heat | Many organisms (including some cysts) are rendered ineffective by heat, source of heat is taken from waste from engine. | Heat budget may not allow ballast to be elevated to a suitable temperature, may not be effective in cold situations, ensuring all water is exposed is problematic, may be structural implications for the vessel. |
| Copper compounds | Reasonable biocide. | Large doses required, long breakdown period, environmental hazard. |
| Peraclean | Appears to be a satisfactory biocide. | Large doses required mean injection of very large chemical quantities. |
| Glutaraldehyde | None. | Very large doses required, toxicity and safety issues. |
| Chlorine | Established technology. | Not as effective as chlorine dioxide, larger doses required, residual THAs may be a problem, corrosive. |
| Ozone | Established technology, no chemicals or side effects. | Very fast reaction with bromide in seawater means effectiveness will be minimal. |
| Oxygen deprivation | Could remove many organisms of interest | May stimulate corrosive anaerobes. |

## 5.2 Description of methods used

Given the diversity of marine species present in ballast water, potential treatment systems should be tested on an adequate and appropriate range of species that are representative of the likely spectrum of invader types. Further, these should be trialed under environmental (eg. turbidity) and biological

(naturally occurring densities of organisms) conditions that are likely to be encountered at the time of routine ballast water loading. We are presently using surrogate organisms under controlled conditions before we move the pilot plant to ports to test it under natural (i.e. uncontrolled) conditions. The surrogate organisms used to date are *Artemia salina* (Salt Lake variety), the rotifer *Brachionus rotundiformis* and the phytoplankton, *Nanochloropsis*. We have also used naturally occurring estuarine zooplankton collected from raw port waters by means of plankton tows. A list of these organisms is located in appendix A.

*Artemia* nauplii were hatched at 28$^{o}$C under overhead lighting in one litre aerated containers. Unless otherwise stated, the tests reported here used newly hatched nauplii. *Artemia* cysts were soaked in seawater for 2 hours prior to experiments. *Artemia* were introduced from the 10,000 litre tank in early trials and by means of a dosing pump in later work. This was due to significant nauplii mortality caused by the main water delivery pump (for details see *Results* section, below).

*Brachionus rotundiformis* were cultured at MARFU and only introduced through the dosing pump.

Samples for these organisms were taken either in 10 litre plastic buckets or directly into 1 litre or 250 ml containers. 10-litre samples were concentrated by means of filtration through a 20-micron screen.

*Nanochloropsis oculata* was cultured in 1,000-litre outdoor containers before being transferred to the 10,000 litre tank. Both controls and treated samples were taken in 1 litre containers before being stored under either dark or light conditions. Cultures were maintained at 12:12 h light/dark cycle or completely in the dark at 24$^{o}$C in Contherm environmental growth chambers. Culture vessels were 250 ml Erlenmeyer flasks with cotton stoppers in medium f/2.

Plankton were collected from port water by means of a 65 micron plankton net. This was towed to sample between 40 and 100 cubic metres of water. Samples were placed in a 20 litre container for transport and treatment immediately to minimise mortality.

### 5.3 Experimental design and statistical aspects

An important and fundamental aspect in the testing phase is well-planned experimental design including appropriate laboratory and statistical analyses in order to provide sound estimates of treatment effectiveness.

When ballast water treatment system performance standards are implemented, the experimental procedure to verify these will become a critical factor. If we consider flow-through experimental testing systems (which simulate ballasting/deballasting conditions), the following aspects of experimental design should be carefully considered:

- selection of appropriate experimental design and use of suitable statistical analyses to express results;
- the experimental system should be simple, practical and designed to minimise sources of sampling bias and hence variability in results (eg. physically designed to minimise fluctuations in organism density in the throughput water);
- prior tests should be undertaken for selection of optimal sample volume and number of replicates to ensure statistically meaningful density estimates (i.e. narrow confidence intervals) and resulting ‘treatment effectiveness’ measures;
- optimal inoculant dosing technology (gentle pump/doser/feeder) to minimize damage to organisms prior to testing to avoid ‘weakening’ organisms prior to entering the treatment technology/ies; and
- selection of an optimal inoculation concentration balancing need for statistical precision and simulating in-situ plankton densities.

Presently, information on most of the developments in the area of ballast water treatment technology is only available as conference proceedings and on websites. In the course of a review, we noted that in many of these studies, while there was a strong focus on the technical aspects of the treatment system,

there was little detail regarding experimental sampling design or statistical analysis. In particular, justification of inoculant densities used, sample number (replicates) and sample volumes collected and the statistical rigour of results were lacking. We consider that addressing these points is essential given that any system put forward for commercial use will have to meet strict international standards and verification procedures in terms of effectiveness.

Prior to conducting experiments using the 10,000 litre tank as a source of *Artemia*-inoculated water, we undertook preliminary testing of the effectiveness of the aeration (25 mm pipes across the floor of the tank with high-flow aeration holes at 10 cm intervals) at mixing the inoculated *Artemia*. The inoculated water in the tank needs to be thoroughly mixed ensuring an uniform distribution of organisms so that a consistent concentration is passing through the system. To test this, we collected paired 250 ml samples from the tank (inoculated with 80 *Artemia* nauplii per litre) with a siphon hose at each of 5 locations within each of 3 depths (30 samples in total). The 5 locations at each depth were:

- the centre of the tank;
- close to the wall on the sunny side over aeration line;
- close to the wall on the sunny side between aeration lines;
- close to the wall on the shaded side over an aeration line; and
- close to the wall on the shaded side between aeration lines.

A single factor ANOVA (Zar 1999) was used to compare mean densities of *Artemia* at different locations in the tank (pooling data from different depths) with a null hypothesis that there was no difference in densities at different locations.

Another important statistical consideration, particularly in plankton sampling, is the theoretical distribution of the data. When summary statistics are used (eg. confidence intervals around a mean), a theoretical distribution is assumed (eg. normal, Poisson). Accordingly tests of distribution should be applied to several sets of sample data to determine which theoretical distribution is most appropriate and hence which tests to apply to obtain summary statistics. We tested for normal or Poisson theoretical distributions using Chi square tests of 'goodness of fit' to normal and Poisson distributions (Zar 1999) and a Chi square randomness test (Lund *et al* 1958).

In all experiments we collected replicate 'control' samples from a 20 mm diameter PVC tap located after the intake pump but before the treatments and replicate 'treated' samples from another (same diameter) tap after the treatment/s. Optimal sample number and volume were assessed based on data from a series of tests in which we deliberately used different sample volumes (250ml, 1 litre and 10 litre). To assess optimal sample number and volume we used the density data from control (untreated) samples from individual experimental runs to calculate the number of samples required to obtain a predefined confidence interval. We calculated the number of samples required to estimate *Artemia* density within a range of 20% (+/-10%) around the true mean with 95% confidence according to the method of Zar (1999).

For *Artemia*, *Brachionus* and zooplankton, effectiveness of a treatment was expressed in one or both of two ways. Per cent removal compares mean density of both viable and dead organisms in treated samples with those in control samples using equation 1. This was a useful measure in filtration tests were the treatment is designed to prevent all or most objects of a given size passing through. Per cent inactivation compares the mean density of live *Artemia* in treated samples with mean density of live organisms in control samples using equation 1, giving the per cent of organisms inactivated (dead) after treatment. Moribund (obviously injured and likely to die) organisms were counted as alive, so all our estimates of treatment effectiveness are conservative.

The general formula for effectiveness (as percentage) is:
Per cent removal or inactivation = 100*(1-(density in treated sample/density in control sample))…….Equation 1

# 6. RESULTS

## 6.1 Effectiveness of mixing in 10000 litre tank

A single-factor ANOVA (Zar 1999) was used to compare mean densities of *Artemia* nauplii of the 5 horizontal locations (pooling data from different depths) in the 10,000 litre source tank. The analysis showed that there was no significant difference between mean *Artemia* density in samples in the different regions within the tank (at the P = 0.05 level).

## 6.2 The effect of pumps on test organisms

In order to simulate the water-flow conditions of ballast water, a pump is required to draw seawater with associated organisms into the experimental system. In our preliminary experiments, we compared replicate samples of *Artemia*-inoculated water collected from the 10,000 litre tank just prior to pumping into the experimental system, with water samples collected just after passing through the pump. It was noted that there was a substantial mortality factor (from 74 to 93 % mortality) due to the pump alone (Table 1). This led to low numbers both in control and treated samples. The effect of this is to make small variations in numbers large with respect to the mean and leads to an end result that can neither demonstrate whether a treatment is effective or ineffective.

An alternative, more gentle system for introducing *Artemia* into the experimental system was subsequently installed in order to bypass the pump and reduce mortality. A Prominent (R) dosing pump injected constant preset volumes of *Artemia* from a concentrated 10-30 litre culture directly into the flowing water after the primary pump. It was found that when the dosing pump was set to maximum frequency and pulse duration (presumably exerting maximum force on *Artemia*), the mortality effect on *Artemia* was only 14-26% (Table 2), which was considerably lower than that associated with the intake pump. This method was adopted for subsequent tests since it minimized damage to test organisms prior to treatment.

**Table 1 Calculated mortality due to the intake pump obtained by comparing mean density (per litre) of live *Artemia* in the 10,000 litre tank prior to passing through the intake pump with mean density (per litre) of live *Artemia* collected just after the pump. Numbers of samples analysed to obtain a mean density are shown in brackets.**

| Sample volume | Mean density in 10K tank | Mean post-pump density | Per cent mortality |
|---|---|---|---|
| 250 ml | 74.4 (10) | 20 (20) | 73 |
| 250 ml | 52.8 (10) | 7 (8) | 87 |
| 1 litre | 77.0 (2) | 5.3 (6) | 93 |
| 10 litre | 47.8 (2) | 12.3 (3) | 74 |
| 10 litre | 56.9 (2) | 12.7 (5) | 78 |

**Table 2. Calculated mortality of *Artemia* nauplii in the flow-through water of the experimental system after injection by the Prominent(R) dosing pump. Per cent alive and dead *Artemia* were calculated for each sample and the mean taken. Number of samples analysed in each experiment are shown in brackets.**

| Sample volume | Mean percentage of live Artemia after dosing | Mean percentage of dead Artemia after dosing |
|---|---|---|
| 250 ml | 86 (7) | 14 |
| 1 litre | 80 (10) | 20 |
| 1 litre | 81 (5) | 19 |
| 1 litre | 74 (5) | 26 |

## 6.3 Sample volume and replicate number

Preliminary tests were undertaken to determine an optimal sample volume and replicate number. In order to achieve this we analysed control density data from 13 experiments using different sample volumes; the mean *Artemia* density in control samples across these experiments was 57 (+/- 29) *Artemia* per litre. We calculated the number of samples required to obtain 95% confidence that the mean of sample counts fell within a range of 20% (+/-10%) around the actual population mean density (Table 3). We found that 77, 37 and 14 replicates were required when using 250ml, 1 litre and 10 litre samples respectively to obtain the stated confidence in control density estimates.

**Table 3. Calculated number of samples required to get an estimate of the mean control (untreated) density that falls within 20% of the true mean (i.e. +/- 10%) for different sample volumes (using different experimental data sets).**

| Sample vol. | Life stage | Mean density (per litre) | No. control samples taken | No. required to be within 10% |
|---|---|---|---|---|
| 250 ml | nauplii | 18.4 | 10 | 135 |
| 250 ml | nauplii | 26 | 10 | 51 |
| 250 ml | nauplii | 33.2 | 20 | 46 |
| | | | Mean (250 ml) | 77 |
| | | | | |
| 1 litre | nauplii | 27 | 6 | 47 |
| 1 litre | cysts | 103 | 15 | 44 |
| 1 litre | cysts | 80.7 | 15 | 19 |
| | | | Mean (1 litre) | 37 |
| | | | | |
| 10 L | nauplii | 22.1 | 5 | 14 |
| 10 L | nauplii | 25 | 4 | 29 |
| 10 L | nauplii | 34.9 | 6 | 10 |
| 10 L | nauplii | 197.7 | 6 | 19 |
| 10L | cysts | 75.5 | 5 | 14 |
| 10 L | cysts | 110 | 6 | 4 |
| 10 L | cysts | 139.8 | 6 | 5 |
| | | | Mean (10 litre) | 14 |

## 6.4 Theoretical distribution of the data

Two statistical tests were applied to two data sets (*Artemia* counts within sets of 20-30 samples taken during two separate experiments) to elucidate the statistical distribution of data. In both cases it was found that the data conformed to a normal distribution and that the data did not conform to a Poisson distribution (Table 4).

**Table 4. Summary of tests to determine the theoretical statistical distribution for *Artemia* nauplii.**

| Experiment No. | No of samples | Volume of samples | Test applied | Distribution type |
|---|---|---|---|---|
| 1 | 30 | 1 litre | Chi square goodness of fit to normal | normal |
| 1 | 30 | 1 litre | Chi square randomness (Poisson) | Not a Poisson distribution |
| 2 | 20 | 250 ml | Chi square goodness of fit to normal | normal |
| 2 | 20 | 250 ml | Chi square randomness (Poisson) | Not a Poisson distribution |

## 6.5 Treatment Tests

### 6.5.1 FILTERS

#### 6.5.1.1 *Artemia*

In the first five experiments with filter screens, per cent removal was between 94 to 96% for *Artemia* nauplii (Table 5). Similar percentage removal values were recorded for all three screen sizes which suggested that there was a consistent by-pass within the filter unit. A technician located and repaired a small gap adjacent to the rubber filter seal and in a subsequent test the removal in samples was found to be 99.9% for *Artemia* nauplii using the 80 µm filter screen (Table 5). For *Artemia* cysts the removal rate was 95.9% before the repair and between 99.2 and 99.9% after repair (Table 6).

**Table 5. Effectiveness of filter screens on *Artemia* nauplii. Sample number refers to total number of control and treated samples.**

| Filter | Sample volume | Sample number | Mean control density (n per litre) | Per cent removal |
|---|---|---|---|---|
| Before repair to seal | | | | |
| 80 µm | 250 ml | 20 | 33.2 | 94% |
| 80 µm | 10 litre | 10 | 22.1 | 96% |
| 50 µm | 10 litre | 8 | 35.2 | 96% |
| 25 µm | 1 litre | 10 | 27 | 96% |
| | | | | |
| After repair to seal | | | | |
| 80 µm | 10 litre | 12 | 34.85 | 99.9% |

**Table 6. Effectiveness of filter screens with *Artemia* cysts. Sample number refers to total number of control and treated samples.**

| Filter | Sample volume | Sample number | Mean control density (n per litre) | Per cent removal |
|---|---|---|---|---|
| Before repair | | | | |
| 50 µm | 10 litre | 10 | 75.54 | 95.9% |
| | | | | |
| After repair | | | | |
| 25 µm | 10 litre | 12 | 139.8 | 99.7% |
| 25 µm | 10 litre | 12 | 63.3 | 99.7% |
| | | | | |
| 50 µm | 10 litre | 12 | 63.3 | 99.2% |
| 50 µm | 10 litre | 10 | 221.4 | 98.6% |
| 80 µm | 10 litre | 12 | 110 | 99.9% |
| | | | | |

#### 6.5.1.2 *Brachionus rotundiformis*

We used *Brachionus* as a further test of filtration capability. This is a smaller organism (approximately 80 micrometres minimum dimension) than *Artemia* and less rigid. We expected there to be an obvious relationship between filter screen specification and filtration effectiveness. This was shown to be correct; see table 7.

**Table 7. Effectiveness of filter screens with *Brachionus sp.*. Sample number refers to total number of control and treated samples.**

| Filter | Number of samples | Mean control density (per 10 litre) | Per cent removal |
|---|---|---|---|
| 50 µm | 10 | 174.3 | 85% |
| 80 µm | 16 | 175.0 | 35% |

6.5.2 HIGH VELOCITY SONIC/SHEAR DISINTEGRATOR (HVSD)
Two versions of the HVSD have been used. HVSD 1 refers to the early version that was used until March 2004. All other experiments used the later version and this is referred to as HVSD 2.

6.5.2.1 *Artemia* nauplii
The HVSD destroyed between 97.7 and 100% of *Artemia* nauplii. In most experiments no trace of organisms remained after treatment indicating near complete physical disintegration (Table 8).

**Table 8. Effectiveness of the high velocity sonic disintegrator for *Artemia* nauplii.**

| Treatment | Sample vol. | Sample number | Per cent removal | Per cent kill |
|---|---|---|---|---|
| HVSD 1 | 250 ml | 8 | 100% | 100% |
| HVSD 1 | 250 ml | 20 | 100% | 100% |
| HVSD 1 | 1 litre | 6 | 100% | 100% |
| HVSD 1 | 10 litre | 12 | 97.7% | 100% |

6.5.2.2 *Artemia* cysts
The HVSD1 alone significantly reduced cyst numbers by 21.6% (Table 9). When cysts were treated and then hatched out, live nauplii were 34.2% less in treated samples compared to controls. This result was not statistically significant (Table 9) but more replicates may give a significant result. The second version of the HVSD significantly reduced hatch out rates by 47 %. In two tests where cysts were treated with the HVSD and $ClO_2$ (at approximately 3 ppm), numbers of live nauplii hatched out were reduced by 69.4% (significant) and 54.7% (not significant) (Table 9). After 40 hours there were no live hatched organisms after treatment but there were also low numbers in controls (mean of 0.82 organisms per litre).

**Table 9. Effectiveness of the high speed shear device and chlorine dioxide for *Artemia* cysts after 11 hours (asterisk indicates statistically significant).**

| Treatment | Sample vol. | Sample number | Per cent removal of cysts prior to hatching | Per cent reduction in hatch out of live nauplii |
|---|---|---|---|---|
| HVSD 1 | 1 litre | 15 | 21.7* | 34.2 |
| HVSD 2 | 10 litre | 8 | n.a. | 47.0* |
| HVSD 1/ClO2 | 10 litre | 6 | n.a. | 69.4* |
| HVSD 1/ClO2 | 10 litre | 7 | n.a. | 54.7 |

6.5.3 ULTRA-VIOLET IRRADIATION
6.5.3.1 *Artemia* nauplii
Three experiments were conducted with newly hatched or 24 hr old *Artemia* nauplii (Figures 3 - 9). In all experiments the treated samples exhibited reduced survival compared to control samples. In two of the experiments, the comparative reduction in survival was significant. In all experiments, the reduction in survival was higher 15-28 hours after the treatment than at the 4-11 hour period, indicating that UV radiation had a delayed effect. All error bars represent the 95% confidence interval.

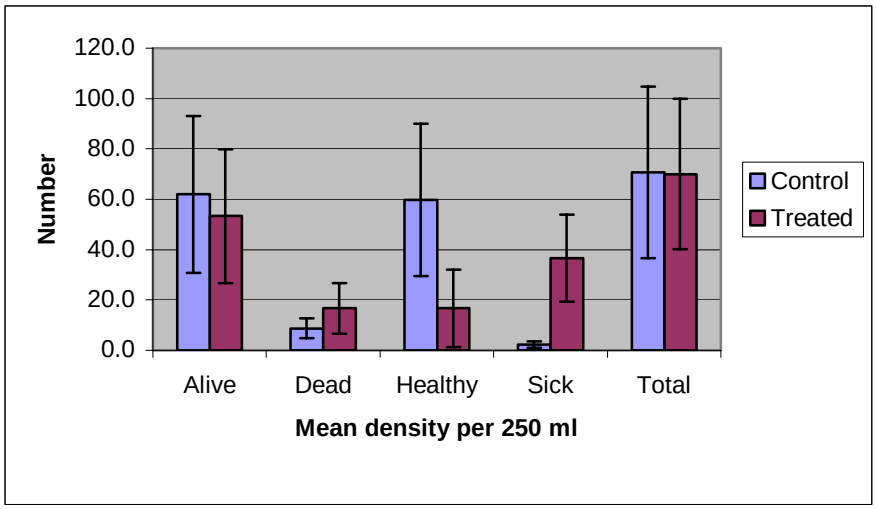



**Figure 3 First UV test – counted at 4 hours**

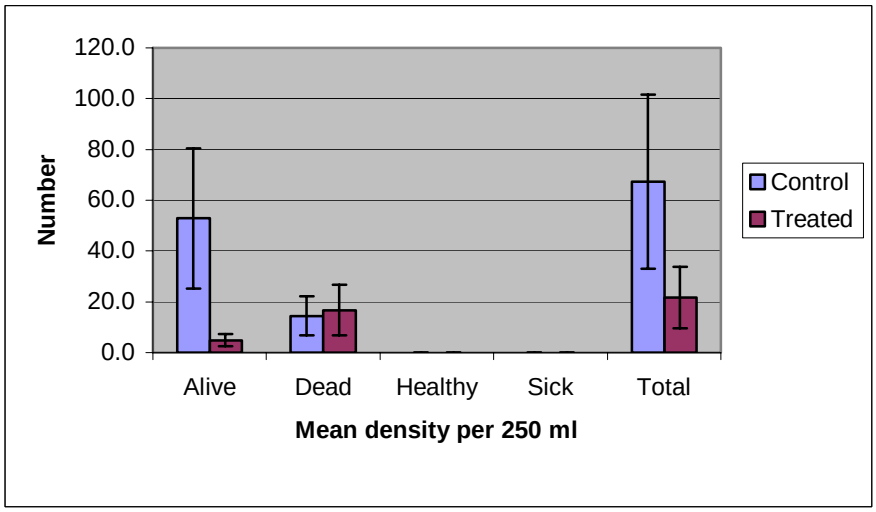



**Figure 4 First UV test – counted at 15 hours**

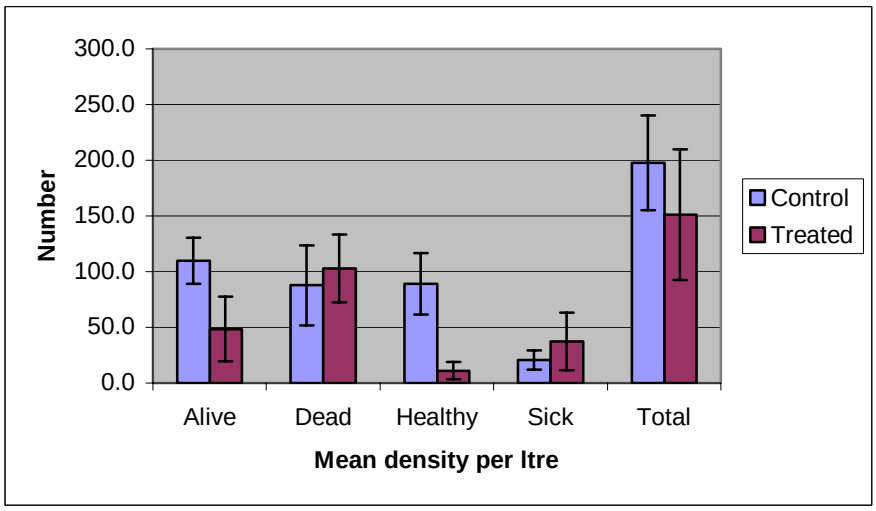



**Figure 5 Second UV test - counted at 11 hours**

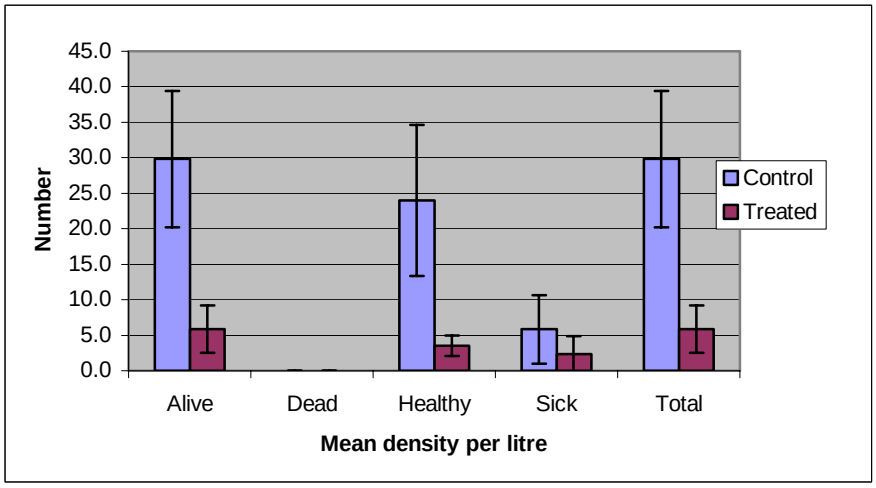



**Figure 6 Second UV test - counted at 28 hours**

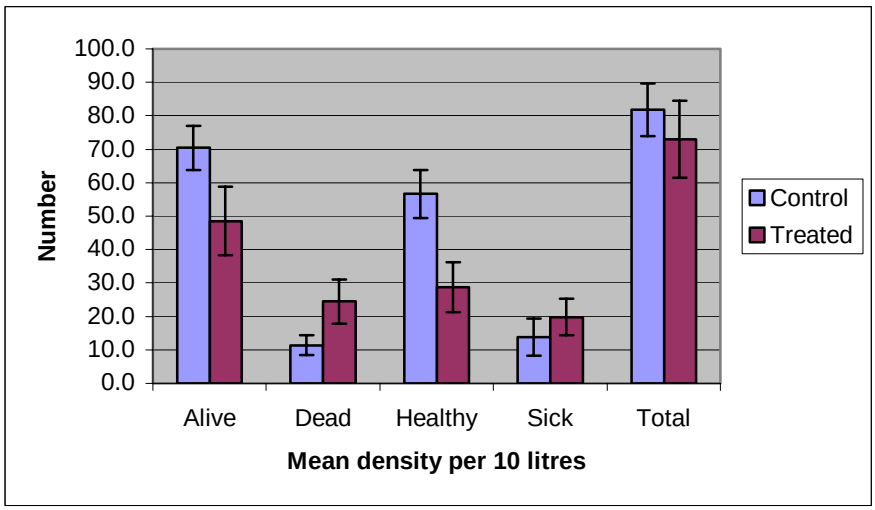



**Figure 7 Third UV test - counted at 11 hours**

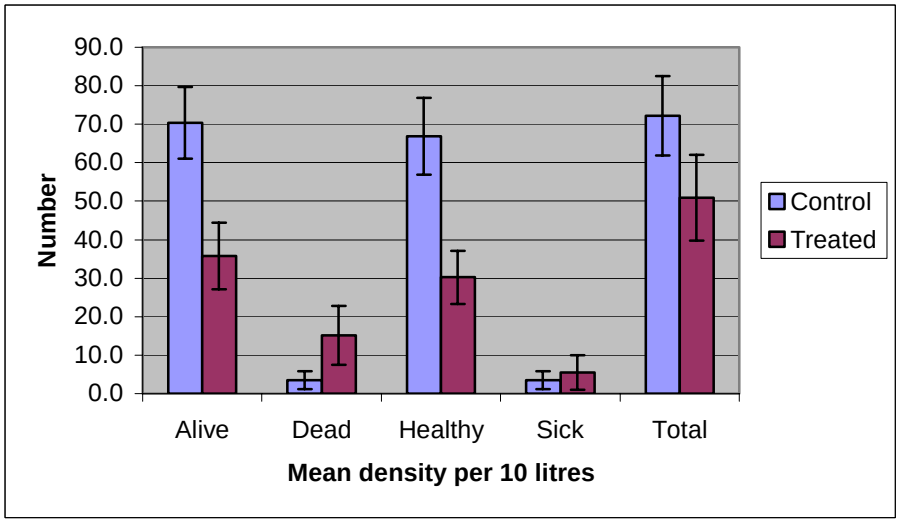



**Figure 8 Third UV test - counted at 24 hours**

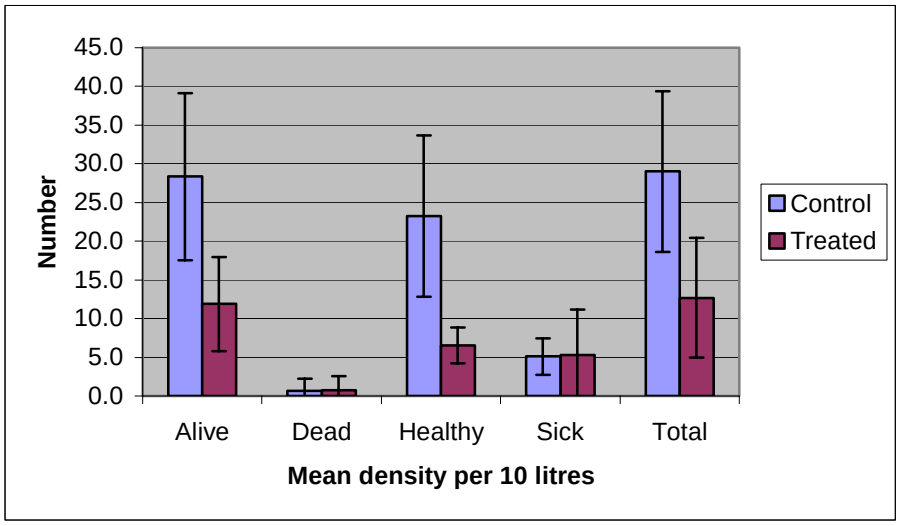



**Figure 9 Third UV test - counted at 48 hours**

6.5.3.2 *Nanochloropsis*
Initial work has been undertaken to determine effects on this phytoplankton of exposure to UV light. Results have yet to be properly analysed and cannot be reliably reported at this stage. However, good correlations between light attenuation and numbers of organisms have been found which will speed up analyses.

6.5.4 ULTRA-VIOLET IRRADIATION/HVSD
6.5.4.1 *Artemia* cysts
We exposed cysts to UV alone and to the HVSD followed by UV irradiation. UV irradiation alone increased hatching rates by more than 40% while the HVSD combined with UV also resulted in increased hatching rates (see figures 10 and 11) although not to such a large extent.

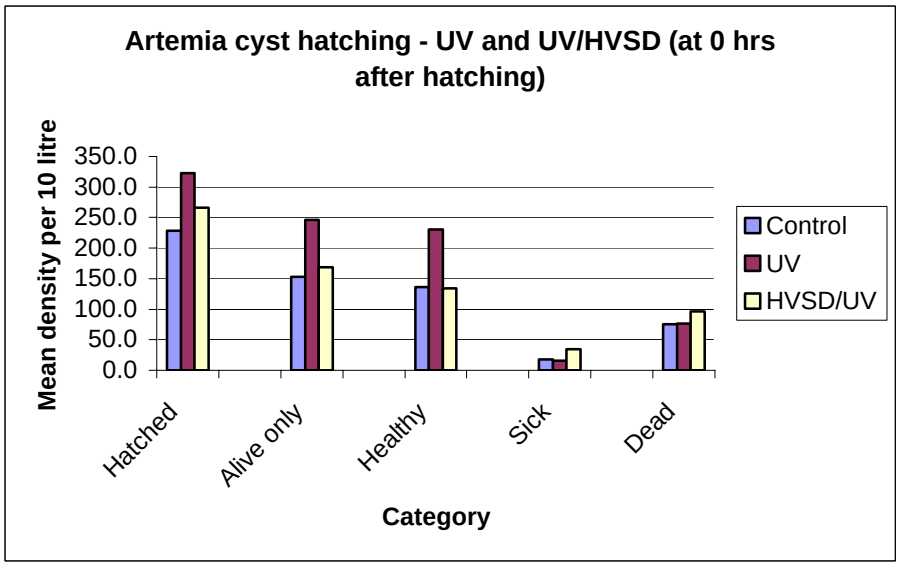



**Figure 10. Hatching rates of cysts following UV and UV/HVSD treatment**

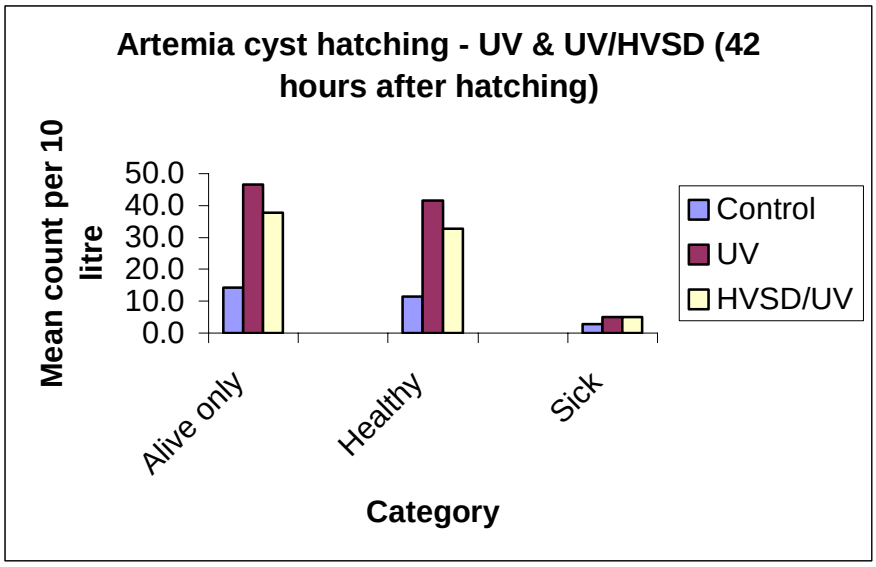



**Figure 11. Hatching rates of cysts following UV and UV/HVSD treatment**

6.5.5 ULTRA-VIOLET IRRADIATION/CHLORINE DIOXIDE

6.5.5.1 *Artemia* cysts

Chlorine dioxide alone and combined with UV irradiation gave the results represented in figures 12 and 13. 18 hours after treatment chlorine dioxide reduced hatch out rates and this was further reduced by the use of UV, although the results were not statistically significant (figure 12). Live hatch out rates at 42 hours were reduced by 97.5% with ClO2 alone and by 91.7 %with ClO2 and UV, although wide ranges around the mean of the controls did not allow a conclusive statistical result.

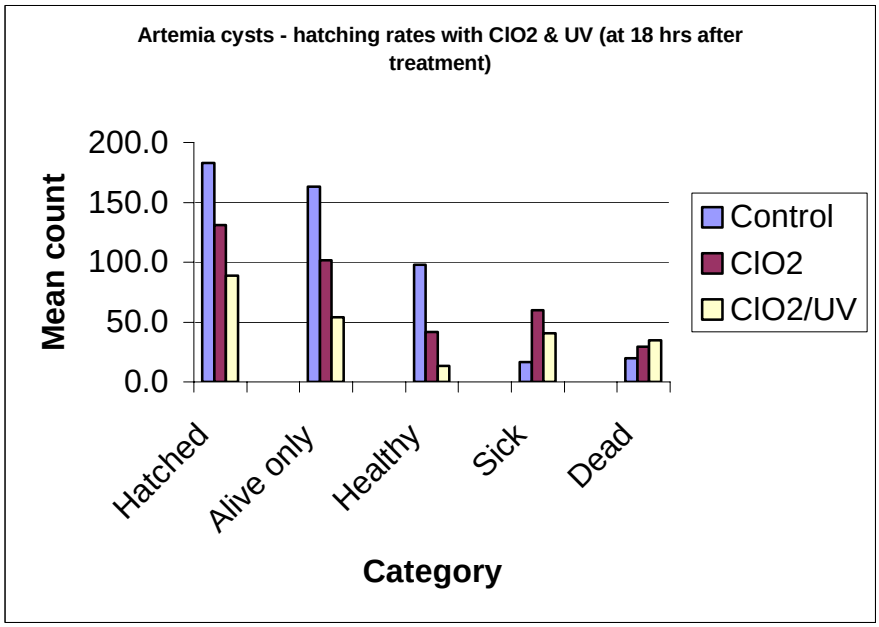



**Figure 12. Hatching rates of cysts following UV and ClO2 treatment (numbers per 10 litres)**

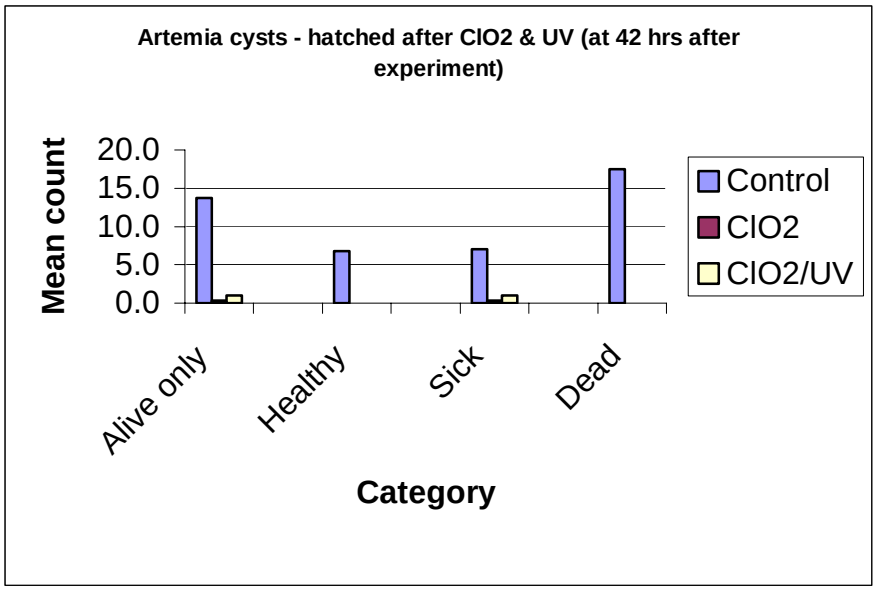



**Figure 13. Hatching rates of cysts following UV and ClO2 treatment (numbers per 10 litres)**

6.5.6 TESTS ON ORGANISMS COLLECTED FROM PORT WATERS

We exposed organisms collected from Mourilyan and Townsville ports to each of three individual treatments; UV, filtration and the HVSD. Results are summarised in tables 10, 11 and 12.

**Table 10. UV effects on zooplankton collected at ports 24 hours after exposure (asterix indicates a statistically significant difference between controls and treated)**

| | | |
|---|---|---|
| **Townsville Port 4-12-03** | Mean density per 10 litres | |
| Control | 24 | |
| Treated | 12.9 | |
| Per cent kill | **38%** | |
| | | |
| **Townsville Port 15-4-04** | | |
| Control | 31.7 | |
| Treated | 27.2 | |
| Per cent kill | **14.2%** | |
| | | |
| **Mourilyan Harbour 9-5-04** | | |
| Control | 11 | |
| Treated | 5.2 | |
| Per cent kill | ***52.7%** | |
| | | |
| | | |

**Table 11. Filtration effectiveness for zooplankton collected at ports (asterix indicates a statistically significant difference between controls and treated)**

| | | |
|---|---|---|
| **Townsville Port 15-4-04** | Mean density per 10 litres | |
| Control | 11.1 | |
| Treated | 0.7 | |
| Per cent removal | 94 | |
| | ***90.7** | |
| **Mourilyan Harbour 9-5-04** | | |
| Control | 6.5 | |
| Treated | 1 | |
| Per cent removal | ***81.6%** | |
| | | |
| | | |

**Table 12. HVSDII effectiveness for zooplankton collected at ports (asterix indicates a statistically significant difference between controls and treated)**

| **Townsville Port 15-4-04** | Mean density per 10 litres | |
|---|---|---|
| Control | 11.1 | |
| Treated | 0.2 | |
| Per cent kill | ***98.2%** | |
| | | |
| **Mourilyan Harbour 9-5-04** | | |
| Control | 3.5 | |
| Treated | 1.3 | |
| Per cent kill | ***61.9** | |

# 7. CONCEPTUAL DESIGN OF A SHIPBOARD SYSTEM

## 7.1 Why a shipboard system?

We believe that a shipboard system has a number of advantages:

- is totally controlled by the ship's master;
- is independent of any particular shipping route;
- can be accredited to a known level of risk reduction;
- sediment arising from filter backwash can be returned to the source port at the time of ballast loading;
- can reduce sediment load and need for tank cleaning;
- will increase safety since mid-water exchange of ballast water will be unnecessary; and
- ballast water can be treated again, if necessary, during ballast discharge, or *en route*.

## 7.2 Issues

There has been considerable comment with regard to the practicality of treating ballast water using ship-based systems. It is our view that many of these comments are overstated. A summary of some of the issues follows.

### 7.2.1 FLOW RATES

Much has been made of the difficulties associated with the flow rates required for vessels to treat ballast water. Often the stress has been on the relatively small number of large vessels (e.g. VLCCs/ULCCs) with ballast loading rates of 3,000 tonnes per hour or more. It is important to weigh this against the average bulk carrier dead weight tonnage being 35,750 tonnes and the average DWT of tankers being 38,000 tonnes (Lloyds Register 2002). This indicates that there are a very large number of vessels that will have loading rates that are more of the order of 500 tonnes per hour. We believe that a system designed to treat 1,000 tonnes per hour would be acceptable to a large proportion of the world shipping fleet and that larger systems could be specifically designed for the relatively small number of ships requiring greater loading rates.

As has been pointed out by Oemcke (1999(3)) small ships will release much less ballast water than large vessels and, therefore, a given kill rate will only need to be proportionally smaller to achieve approximately the same level of risk reduction. Furthermore, as suggested by Hilliard *et al* (1997) and Ruiz (2002), there is evidence that discharge frequency is at least as important as volume. Thus, there would be great advantages in risk reduction by incorporating treatment measures in the large number of smaller ships.

### 7.2.2 SPACE REQUIREMENTS

There are also issues associated with space limitations on vessels. While it is agreed that space on a vessel is at a premium, much of the required equipment can be attached to bulkheads (e.g. UV systems) or, where a footprint for equipment is genuinely not available then modifications to the vessel layout may be necessary such as the provision of false decks in engine and/or pump rooms.

An indicative size of a 1,000 tonne per hour filter is a footprint of approximately 4 by 3 metres and a height of less than 4 metres.

Off-the-shelf chlorine dioxide generators that can produce treatment for 1000 tonnes per hour at 3 parts per million have footprints of the order of 2 by 2 metres and heights of about 1.5 metres although the provision of precursor chemical storage tanks will be necessary. These are likely to be of the order of 10 to 20,000 litres capacity depending upon ship size and desired periods between recharging chemical storage vessels.

Ultra-violet units can be installed in parallel or in series as is necessary and can be attached to existing bulkheads if this is desirable in the particular application.

### 7.2.3 MAINTENANCE AND LABOUR OVERHEADS

It is important that any system does not impact on crew workloads to an extent greater than necessary. It is anticipated that filters would have an automatic backwash capability to minimise human intervention. UV units have bulb replacement intervals of around 10,000 hours of service and are also available with self-cleaning capabilities. Modern chlorine dioxide generators require little maintenance although it is acknowledged that the provision of chemical inputs will require some overhead both in terms of chemical management and safety.

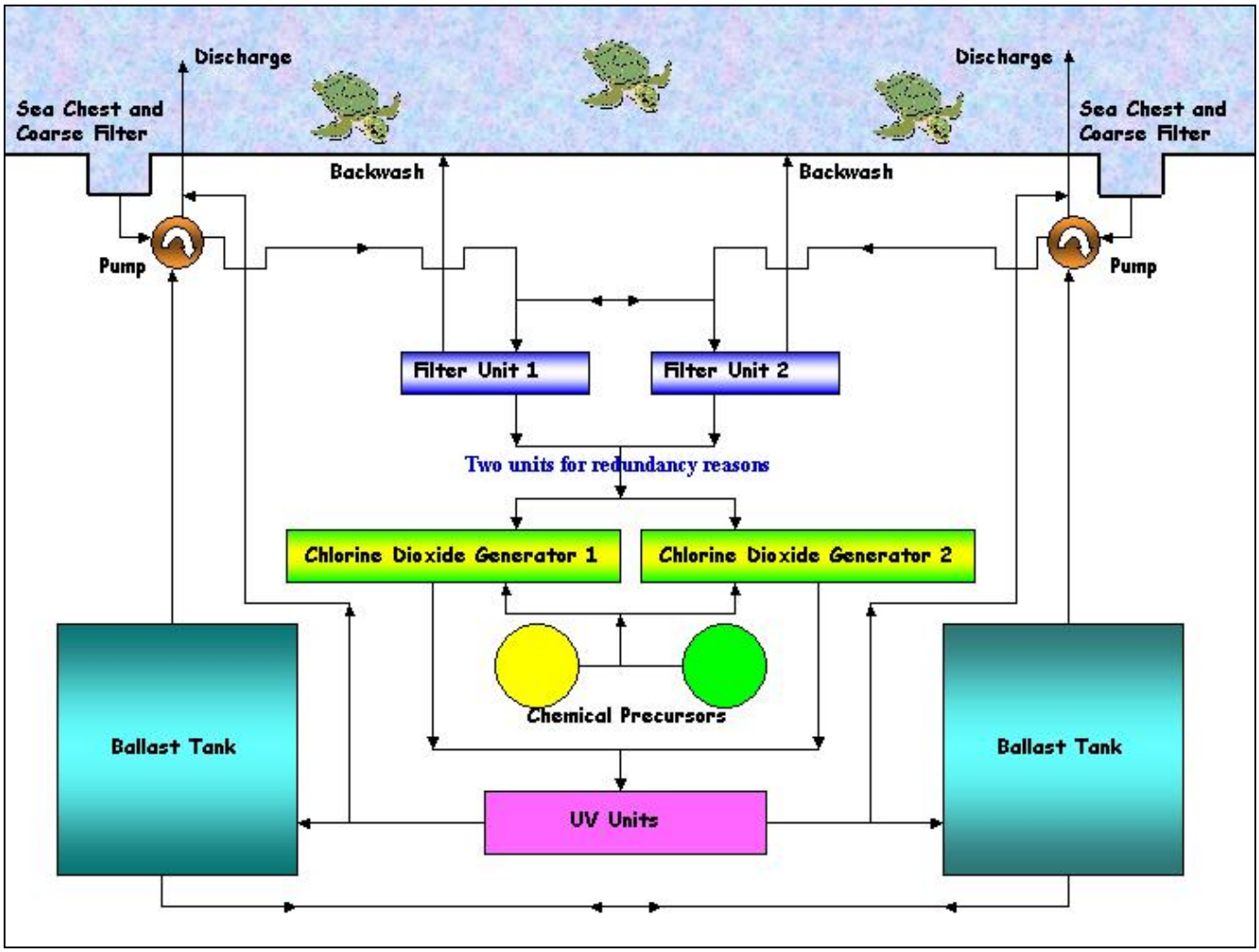
All systems can be equipped with alarm systems to indicate performance drops and shutdown mechanisms are available if operational parameters are exceeded. It is anticipated that systems control and monitoring would be located both on the bridge and adjacent to the equipment itself.

Safety considerations such as the use of electrical components and chemical handling and transfer systems will need to be assessed on a vessel-by-vessel basis. These considerations are likely to have an influence on the location of equipment.

### 7.3 Schematic of conceptual design

The following diagram shows the elements of a concept design for a ship-based system. As discussed at the most recent steering committee meeting, this will be further refined during the next twelve months in consultation with shipping industry representatives.

In summary, the system as portrayed assumes that the main ballast pumps are used both for ballasting and de-ballasting. It also allows for the treatment of ballast water during loading, while in-transit and while de-ballasting. Two filters and chlorine dioxide generators are assumed as necessary for redundancy purposes. Extra storage tanks may be required to accept filter backwash if the system is used during de-ballasting. The fact that the pumps are also used to transfer ballast between tanks is not shown for the sake of clarity, as is the simplification of only two ballast tanks. Routeing and sampling valves are also not shown in the schematic.




## 8. COMMERCIAL APPLICATIONS

The finalisation of the Ballast Water Convention by the International Maritime Organisation will mean that ships will have to meet the standards that are written into the Convention. This will inevitably lead to the need to develop treatment systems for the majority of the world's shipping fleet. This fit out of ships is a huge market running into billions of dollars for installation alone. There will also be markets for maintenance and testing and verification of systems.

As is detailed earlier in this report, most other workers in the field have not embraced robust testing and verification methods. This is likely to be a major strength of the work that is presented in this report in terms of marketability.

The CRC Reef Research and James Cook University are planning to set up a business entity as a vehicle for implementation aspects and will be seeking investment from interested partners. The business venture will also examine aspects of ballast water such as testing and verification of systems. It will also investigate organism identification using such things as protein typing and DNA analysis.

## 9. DISCUSSION

A major focus of our work has been the experimental design and the analysis of the effectiveness of flow-through ballast water testing systems. The IMO are currently developing guidelines for approval of ballast water treatment/technologies and are likely to implement strict 'effectiveness' criteria for potential ship-board treatment systems. Accordingly, experimental design and analysis is a critical factor in any testing program in order to provide scientifically sound estimates of treatment effectiveness.

An important consideration is the confidence intervals of control and treated sample density estimates, the width of which depend on collecting adequate sample volume and numbers of replicates. For our pilot-scale system we found that collecting 10 litre samples was the most practical option at the dosing concentrations we used, and we calculated that 14 samples need to be collected to obtain reasonably narrow confidence intervals (+/- 10%) around the mean control density. However, for practical reasons, we generally took less than this number of samples and were prepared to have larger confidence intervals as a trade-off against the time required for sorting and analysis.

In a number of reported ballast water treatment experiments, relatively low numbers of samples (often 3) have been collected at each sample point and there was has been no justification for this choice. Our results indicate that for reasonable precision in density estimates at the 'control' sample point/s, a higher number of samples are required even with relatively high organism concentrations (cf. natural zooplankton densities). Given that natural zooplankton densities are low, researchers testing treatments with natural seawater (eg. in ship-board trials) need to carefully consider the required sample volumes and replicates to overcome the expected high inter-sample variability. Sutherland *et al*. (2001) were unable to make conclusive statements as to treatment effectiveness for zooplankton in coastal seawater due to the low numbers of organisms in samples.

Flow-through systems from laboratory to shipboard-scale generally utilize a pump to draw water. We found that our intake pump had a significant mortality effect on incoming plankton and this introduces bias into experimental results. Pump damage to organisms may result in exaggerated treatment effectiveness that is due to the synergistic effects of the pump and treatment. In any ballast water treatment testing, pump mortality should be quantified and minimized and any control samples should be taken after the pump. There has been limited acknowledgement of pump effects in ballast water treatment research but it is likely to be a factor in most flow-through systems.

Ultimately, ballast water technologies have to be proven at flow-rates found in ship-board ballasting systems. Several high-flow rate tests of various ballast water treatment technologies have been undertaken. Filtration (Automatic Backwash Screen Filtration (ABSF) with screens of 20 to 100 micron) at high flow rates (340.8 $m^3$/hr) has been tested in the Great Lakes (Cangalosi *et al* 2001). Filtration effectiveness was 90-95% for zooplankton. Waite *et al* (2003) used a 342 $m^3$/hr flow-through system, incorporating hydrocyclones, a self -cleaning 50 µm ABSF and UV radiation at Biscayne Bay. The ABSF removed 90% of mollusc larvae and 60-95% of copepods. These authors found that UV was not effective for zooplankton. Cangalosi *et al* (2001) trialed cyclonic separation and UV in a 340.8 $m^3$/hr test system and obtained 56% reduction in zooplankton when intake water was treated and 86% when both intake and outgoing water was treated. Sutherland *et al* (2001) trialed a two-stage hydrocyclone-UV experimental system in a shipping container with flow of 312-350 $m^3$/hr. Zooplankton did appear to be reduced by the system but the very low densities in their samples prevented statistical conclusions regarding treatment effectiveness. This latter example highlights the inherent problems in ship-board testing on naturally occurring plankton and development of

appropriate experimental design to validate treatment effectiveness. The results of these high-flow studies are encouraging but improvement in effectiveness is still required if they are to meet the high standards of the IMO Convention.

Flow rate is a critical factor in assessing the effectiveness of ballast water treatments. Ultimately, any proposed treatment has to be proven at flow rates that simulate ballast uptake rates in ships which for most cargo ships is around 300-800 $m^3$/hr but can be as high as 3000 $m^3$/hr in VLCC/ULCC ships. Our experimental system was constructed at the pilot-scale with a flow of 15 – 20 $m^3$ per hr. However we are convinced that testing different organisms at low flow rates is still essential as a precursor to full-scale treatment tests. There are many variables to be considered when testing a treatment system and these have to be optimised during preliminary testing before working at full-scale where it is likely that opportunities to conduct tests and alter experimental design are limited. At smaller scales it is possible to run rapid, multiple tests and carefully control variables enabling fine-tuning of sampling and laboratory analytical and statistical methodologies. It is further expected that experimental and analytical methodologies will vary with different organisms. Methods refined at the pilot-scale for different groups can then be adapted to shipboard-scale tests.

We have experienced some difficulties associated with our sampling protocols and organic and chemical inputs to the system. This has resulted in greater variation in numbers of organisms in replicate samples than we would desire. Consequently, the results presented, while sound, cannot be used to form definitive conclusions at this stage. Our immediate effort in the next phase will be to devise a more constant input of organisms using an air pressure supply, control chlorine dioxide levels more closely, address the issue of consistent survival of controls post-experiment and ensure that the system allows for complete mixing. This should give much more reproducibility of results.

## 10. RECOMMENDATIONS

1. We have shown that are going to be many challenges associated with the treatment of ships' ballast water, not the least of which will be the categorical demonstration as whether a system does or does not achieve its stated aims. It is recommended that Australian governments become more involved in resolving this issue. There are many opportunities for Australia to become involved in testing and verification systems and much of the work being planned or undertaken is on a bilateral or multilateral basis. With a relatively small resource investment Australia could become a part of what is likely to become a major industry.
2. As an incentive for shipowners and operators to be more inclined to install test systems on vessels, it is recommended that Australian governments consider something similar to the US Shipboard Technical Evaluation Program. The U.S. Coast Guard has announced an innovative program that will allow vessel owners/operators to apply for acceptance of vessels, permitting them to install and test experimental ballast water treatment systems and relieving them of some of the regulations that are currently in place. This program will facilitate the development of effective ballast water treatment technology, and will create more options for vessels seeking alternatives to ballast water exchange. Details of the program are published in Coast Guard Navigation and Vessel Inspection Circular (NVIC) 01-04.
3. The use of filter technology has been shown to be able to significantly reduce risks of translocations of many organisms of concern. Many infestations could have been avoided with this one technology. Our work and the indications from international workers in the field indicate that most systems would require a filter as a front end to any other downstream treatment methods so it would not be a later burden on shipowners and operators insofar as they would not have purchased redundant equipment. It is recommended that the Australia government consider ways in which filters could be brought into use in the immediate future even though the technology cannot meet the proposed IMO standard.
4. There will almost certainly be further deliberations regarding the proposed standard. The majority view of participants at the IMO/IMarEST Symposium on Ballast Water Treatment, held in July2003, was that it was unlikely that the proposed standard could be met within the next 5 or even 10 years. This should not be seen as reason to not embrace risk reduction

techniques that are more effective and safer than ballast exchange and available now. It is recommended that Australian representatives should be more forthright on this issue as opportunities arise.

5. The ABWTC project has explored many of the challenges associated with treatment systems and has probably raised as many questions as answers in the time available to it. The project has been very productive and made quantified studies of a range of available technologies. The project should continue for a further year to complete the pilot phase prior to scaling up appropriate technologies. Further funding is being sought to complete the pilot phase and continue into an adoption phase.
6. Given the technological challenges associated with treatment systems and the likelihood that ballast exchange will be the primary method of risk reduction for many years, it is recommended that Australia also further support research into ballast exchange efficiencies.

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**APPENDICES**

## Appendix A

## Plankton caught with 65 micron net in Ross Creek Townsville 2003-4

| **ZOOPLANKTON** | | | |
|---|---|---|---|
| **Phylum** | **Group** | **Species** | **Abundance** |
| **Athropoda** (Crustacea) | Copepoda (S.O. Calanoida) | *Acartia sp.* | Rare = R |
| | | *Paracalanus sp.* | Present = P |
| | | *Tortanus barbatus* | Common = C |
| | | *Labidocera ?minuta* | R |
| | | | |
| | | *Temora ?discaudata* | P |
| | | *Eucalanus crassis* | R |
| | | Unidentified sp. 1 | P |
| | | | |
| | Copepoda (S.O. Harpacticoida) | *Macrosetella ?gracilis.* | P |
| | | *Oncaea sp.* | C |
| | | | |
| | Copepoda (S.O. Cyclopoida) | *Corycaeus catis* | P |
| | | | |
| | Branchiopoda | | P |
| | Cladocera | *Podon sp.* | R |
| | | | |
| | Cirripedia | Barnacle nauplius larvae | P |
| | | | |
| **Chaetognatha** | | *Sagitta sp.* | R |
| | | | |
| **Echinodermata** | | Echinoderm larvae | R |
| | | | |
| **Bryozoa** | | Bryozoa larvae | R |
| | | | |
| **Annelida** | | Polychaete larvae 1 | P |
| | | Polychaete larvae 2 | C |
| | | | |
| **Mollusca** | | Gastropod veligers | R |
| | | Bivalve veliger | C |
| | | | |
| **Cnidaria** | | Leptomedusae | R |
| | | ?Planula larvae | P |
| | | | |
| **Ciliata** | S.O. Tintinnoinea | Tintinid | P |
| | | | |
| **PHYTOPLANKTON** | | | |
| | **Diatom** | *Rhizosolenia sp.* | |

**Plankton caught with 65 micron net at Mourilyan Harbour**

| **ZOOPLANKTON** | | | |
|---|---|---|---|
| **Phylum** | **Group** | **Species** | **Abundance** |
| **Bryozoa** | | Bryozoa larvae | R |
| | | | |
| **Crustacea** | Copepoda (S.O. Calanoida) | *Tortanus barbatus* | C |
| | | *Paracalanus sp.* | P |
| | | *Centropages furcatus* | R |
| | | Copepod type 1. | R |
| | | | |
| | (Copepoda (S.O. Harpacticoida) | *Macrosetella ?gracilis* | A |
| | | *Oncaea sp.* | *C* |
| | | Harpacticoid type 1 | P |
| | | Harpacticoid type 2 | P |
| | | | |
| | Copepoda (S.O. Cyclopoida) | ***Corycaues sp.*** | R |
| | | | |
| | Cladocera | *Podon sp.* | R |
| | | | |
| **Mollusca** | Bivalva | Bivalve veliger | R |
| | Gastropoda | Gastropod veliger | R |
| | | | |
| **Polychaeta** | | Polychaete 1 | R |
| | | Polychaete 2 | R |
| | | | |
| **Coelenterata** | Siphonophore | ?*Dinophyses sp.* | R |
| | | | |
| | | | |
| **PHYTOPLANKTON** | | | |
| | | *Rhizosolenia sp.* | R |
| | | Diatom 1 | P |
| | | Diatom 2 | R |

**Appendix B**
**Steering Committee**

- Russell Reichelt – Cooperative Research Centre Reef Research and Chair of the Committee
- Warren Geeves – Australian Government Department of Environment and Heritage
- Bob Brunner – Ports Corporation of Queensland
- Darren Oemcke – Provisor
- Etai Dagan – Amiad
- Anthony Dickson – Modular Solution Technologies
- Rob Hilliard – URS Australia
- Teresa Hatch – Australian Shipowners Association
- Angela Gillham – Australian Shipowners Association
- Pauline Semple – Queensland Environmental Protection Agency
- Phil Schneider – James Cook University
- Steve Hillman – James Cook University
- John Hurst – AAPMA
- Kerry Neil – QDPI
- Edward Kleverlaan – DEH
- Keith Hayes – CSIRO
- Michael Drynan – AFFA
- Pohaye Tan - DOTARS

**APPENDIX C**
**PROGRESS AGAINST MILESTONES**

All agreed milestones have been met and these are tabulated below.

| Stage | Milestones |
|---|---|
| 1 | Project establishment - convene a steering committee/advisory group (proponents and other experts needed to complete the project) and develop a current work schedule, of tasks, responsibility and deliverables, based on the following tasks (for specific detail refer to proposal).<br>**Achievements**<br>A steering committee has been established and been consulted both formally and through correspondence. Membership is at appendix B.<br>Rolling work schedules have been developed as necessary. |
| 2 | 2.1. A portable treatment plant ballast water ('the plant') designed and developed.<br>**Achievements**<br>The plant has been designed, built and refined. |
| 3 | 3.1. The plant tested at James Cook University.<br>3.2. Development of sampling protocols using *Artemia.*<br>3.3. Results analysed and data compiled.<br>3.4. Report on results presented to Steering Committee.<br>3.5.Communication activities undertaken as per Communication Plan (Project Proposal Item 12 Attachment A) – [project launch].<br>**Achievements**<br>All of the above are detailed in this report. |
| 4 | 4.1. Initial testing conducted at JCU using *Artemia.*<br>4.2. Confirmation of sampling protocols.<br>4.3. Results analysed and data compiled.<br>4.4. Report on results presented to Steering Committee.<br>4.5 Communication activities undertaken as per Communication Plan (Project Proposal Item 12 Attachment A).<br>**Achievements**<br>All of the above are detailed in this report. |
| 5 | 5.1. Refine sampling protocols.<br>5.2. Further testing conducted at JCU using *Artemia* and algae.<br>5.3. Testing using *Brachionus* sp. (rotifers) and Harpacticoids (copepods).<br>5.4. Results analysed and data compiled.<br>5.5. Report on results presented to Steering Committee.<br>5.6. Communication activities undertaken as per Communication Plan (Project Proposal Item 12 Attachment A).<br>**Achievements** |

| | |
|---|---|
| | All of the above are detailed in this report. |

| | |
|---|---|
| 6 | 6.1. Investigate efficient sampling protocols for algae, *Nanochloropsis.*<br>6.2. Investigate effective analysis methods for determining treatment effects on *Nanochloropsis* by means of turbidity correlations with numbers and fluorescein di-acetate indicators for viability.<br>6.3. Carry out sampling from Townsville port waters for analysis at JCU.<br>6.4. Testing with algae.<br>6.5. Report on results presented to Steering Committee.<br>6.6. Communication activities undertaken as per Communication Plan (Project Proposal Item 12 Attachment A).<br>**Achievements**<br>All of the above are detailed in this report. |
| 7 | 7.1. Further sampling of Townsville and Mourilyan port waters for analysis at JCU.<br>7.2. Report on results presented to steering committee.<br>7.3. Collate test results stages 3-7.<br>7.4. Communication activities undertaken as per Communication Plan (Project Proposal Item 12 Attachment A).<br>**Achievements**<br>All of the above are detailed in this report. |
| 8 | 8.1. Consistent with project objectives - identify potential commercial applications for the ballast water treatment plant.<br>8.2. Communication activities undertaken as per Communication Plan (Project Proposal Item 12 Attachment A) – Results communicated to identified agencies and through identified media.<br>8.3. Submit Final Report.<br>**Achievements**<br>All of the above are detailed in this report. |

## APPENDIX D – PUBLICATIONS AND PAPERS

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