MARTOB	**Design, Manufacture and Onboard Testing of the Thermal Treatment system** **Executive Summary**

The objectives of the work done were to design and manufacture a large scale test system, test the system onboard ship or shore side and to prove the effectiveness of the system against natural seawater.

The system used is a self-contained modular system comprising two heat exchangers; a preheater and a treatment heater, and the necessary control system and sampling pipework. All the components are mounted in a steel frame which is designed to facilitate the installation and removal of the system onboard a ship.

The first objective was achieved with the test system successfully designed and manufactured in-house at Newcastle University. The system was tested onboard the ship MV Don Quijote during a two week voyage between Alexandria, Egypt and Zeebrugge, Belgium.

The onboard testing phase was a success on the technical side, the system performed as designed. We were only limited by the ballast water supply, which was done through the fire hose and could only provide a maximum of about 9t/hr of ballast water to our system. The steam control system performed adequately when the steam supply was constant, but any perturbations in the steam supply led to oscillations in the treatment temperature as the control valve could not respond fast enough. This was further hampered by the fact that the valve did not have a variable feed rate and would often over-compensate.

When measured as live zooplankton after treatment, the HT treatment was very effective for all temperatures tested (55-80ºC) for both nauplii and adult copepods. Only in two cases for copepods and four cases for nauplii, was 95% inactivation not achieved, but only one of these situations (copepods in tank AP at 65^{o}C) had a significantly lower mortality than the rest. However, the high mortality in the control samples indicates that a significant fraction of the zooplankton was killed before they reached the heat treatment unit, most likely by the fire pump. This makes it difficult to determine how much of the killing effect that was due to the HT treatment. For copepods there was no significant difference between the mortality in the treated and the control samples, while for nauplii the mortality was significantly higher in the treated samples. Copepods may be up to forty times bigger than nauplii and therefore probably more sensitive to the fire pump. This may also explain that significantly higher mortality was found for copepods than nauplii.

Due to practical limitations all the different temperatures could not be tested on each sampling day and on water from each tank, but 60 and 65^{o}C were tested in all tanks on every sampling day. No significant differences in the killing rate were found between them throughout the study, hence between the tanks. These results indicate that increasing the temperature above 60^{o}C did not improve the treatment effectiveness.

The concentration of copepods and nauplii in the tanks did not change over time. Despite of this, the mortality of nauplii in the control samples increased significantly from the first day, indicating that there was an increment in mortality as a function of the time they had been in the ballast tank

Even though there was no significant difference in the mortality of copepods between treated samples and controls, the concentration of copepods, as well as of nauplii, were much lower in the treated water than in the control samples. The sudden increase in the temperature as the organisms entered the heat treatment unit must therefore have destroyed physically a large fraction of the organisms. This also indicates that if the organisms had not been killed by the fire pump before treatment, they would have been killed by the HT treatment, and that the mortality rates achieved after the combination of fire pump and HT treatment not are much higher than what could have been achieved by HT treatment alone.

Regarding the IMO standard the sum of live copepods and nauplii, hence organisms greater than 50 μm, was less than 100 per m^3 in all cases except in the sample from tank AP treated at 60ºC. The more strict option (max. 1 viable organism per m^3) was also achieved on two occasions, both on the last day of the trials, indicating an effect of time. The only tested temperature that yielded a significantly lower number of live organisms was 80ºC, however 65ºC also achieved the strictest IMO standard level occasionally. All the aforementioned indicate a high effectiveness of the HT treatment in this study.

The results from the phytoplankton analysis show no treatment effect in comparison to controls. However, the ballast water loaded into the tanks at the start of the trial had a very low concentration of phytoplankton owing to the time and location at which ballasting took place. Due to the low starting concentration it is difficult to assess the biological efficiency of the HT treatment. In order to make any reliable judgements it would be necessary to repeat the experiments with ballast water that contained a higher concentration of phytoplankton from the start.

Finally in the case of the bacteria, HT treatment reduced the bacterial concentration in the ballast water by approximately 95 %. Surprisingly, there was no significant increase in the killing rate with increasing treatment temperature. The killing of bacteria with heat is a well-known technology, and the killing rate always increases with increasing temperature under otherwise equal conditions. With the large temperature range tested in this study (55 to 80ºC) an effect of temperature should have been observed. A possible explanation is that the remaining 5 % consisted of bacterial endospores. Bacterial endospores are very heat resistant and require much higher temperatures than vegetative cells to be killed, usually more than 100ºC for several minutes. Possibly, almost all vegetative bacterial cells were killed already at the lowest treatment temperature (55ºC), while the remaining endospores were not affected within the temperature range tested. However, as the bacterial endospore concentration in the ballast water was not determined, no firm conclusions can be drawn.

The draft IMO ballast water performance standard proposes limits for some specified indicator bacteria in discharged ballast water. None of these indicator bacteria are spore formers and should therefore be relatively easy to kill by heating. The study indicate that the HT treatment would have reduced the viability of any of these bacterial species by at least 95 %, and possibly much more if the remaining viable bacteria in the ballast water after the heat treatment originated from bacterial endospores. Whether or not this is enough to achieve the IMO standard depend upon the starting concentration of the indicator bacteria. In most cases a reduction in the viability of the indicator bacteria with two orders of magnitude is likely to be sufficient, but in extreme cases a higher reduction in viability may be required.