An Evaluation of Vessel Quieting Design, Technology and Maintenance Options

The Enhancing Cetacean Habitat and Observation (ECHO) Program commissioned a study to identify technical ways to make vessels quieter. This summary document was prepared to describe why the study was conducted, its key findings and conclusions, and how the results are used by the ECHO Program and the Vancouver Fraser Port Authority to help manage the impact of shipping activities on at-risk whales throughout the southern coast of British Columbia.

What questions was the study trying to answer?

Endangered Southern Resident Killer Whales (SRKW) and other at-risk whale species frequent the Salish Sea, which also hosts commercial and recreational vessel activities. Noise from vessel traffic combines to increase ambient underwater noise levels and can interfere with the ability of animals to hunt their prey and communicate with one another.

The ECHO Program commissioned a study to answer the following questions:

- What makes ships quieter? More specifically, what kinds of technology, maintenance and design options exist to make ships quieter?
- What options and criteria can be used to encourage quieter vessels and help reduce underwater noise in the Port of Vancouver?

Underwater noise can interfere with marine mammals ability to find food and communicate

Through its EcoAction Program, the Vancouver Fraser Port Authority currently offers discounted harbour dues and recognition to vessels that meet certain environmental performance criteria. The findings of this study were used to inform how to incorporate underwater noise performance criteria into the EcoAction Program, which could result in additional incentives for vessel operators.

Who conducted the study?

Hemmera Envirochem Inc. (Hemmera) was selected to undertake this study based on their team's proposed approach, experience and understanding of underwater noise and its effects on marine mammals.

What methods were used?

Hemmera conducted a literature review and solicited the input of experts to identify and evaluate various quieting vessel design, technology and maintenance options. Subject matter experts and shareholders were engaged through a workshop and as reviewers.

Several factors were considered in the option identification and evaluation process including cost, feasibility of implementation, availability, effectiveness etc. The most important factors for the EcoAction Program were 1) noise reduction effectiveness and 2) whether the option can be verified by EcoAction Program staff.

What were the key findings and conclusions?

The study identified and evaluated 30 design, technology and maintenance options to reduce vessel noise. The options fell into the following broad categories:

1. Regular propeller polishing and repair;
2. Regular hull cleaning;
3. Hull coating (e.g. decoupling coating, coatings that reduce fouling);
4. Propeller design modified to reduce cavitation and improve wake flow (e.g. high skew, air injection);
5. Alternate propulsion (e.g. water or jet pump);
6. Use of quieter engines (e.g. diesel-electric, electric drive);
7. Reduced on-board engine and machinery noise (location, mounting and insulation of components); and
8. Changes to hull form.

Quantitative information on noise reduction effectiveness for the different options and for determining which option is most effective at reducing underwater noise was found to be lacking. The effectiveness of each option could therefore not be directly compared and the evaluation, instead focused solely on scientific evidence of noise reduction.

This study identified a range of options, based on the eight categories above, that could be considered to receive incentives through the EcoAction Program and provided a framework for their use as criteria.

Ship classification societies are non-government organizations that are responsible for establishing, maintaining and inspecting to technical standards for the construction and operation of vessels. This study also identified three ship classification societies which have developed standards for vessel-generated underwater noise, to allow a vessel to be recognized as a quieter ship. These include:

- Bureau Veritas (Underwater Radiated Noise (URN) notation);
- DNV GL (SILENT E notation); and
- RINA (DOLPHIN notation).

Green Marine, a marine environmental certification program, will be introducing performance criteria for underwater noise that could also be used in the future to identify and recognize quiet vessels.

How are the results being used to help reduce underwater noise and its effects on at-risk whales?

The Vancouver Fraser Port Authority reviewed the report's conclusions and made changes to the EcoAction Program after conducting financial modelling and external stakeholder consultation, and issuing a public notification of changes to the program.

Quiet notations from ship classification societies Bureau Veritas, DNV-GL and RINA are eligible for a gold level (highest) discount in harbour dues. Three propeller technologies shown to reduce propeller-generated noise: Propeller Boss Cap Fins (PBCF), Schneekluth duct and Becker Mewis duct are eligible for a bronze level discount.

The EcoAction discounts are effective as of January 1, 2017. More information can be found at www.portvancouver.com/ecoaction.

Vessel Quieting Design, Technology, and Maintenance Options for Potential Inclusion in EcoAction Program
Enhancing Cetacean Habitat and Observation Program

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File: 302-045.03
April 2016

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Attn: Orla Robinson, Program Manager, and Krista Trounce, Project Manager, ECHO (Enhancing Cetacean Habitat and Observation) Program

Dear Orla and Krista,

Re: Vessel Quieting Design, Technology, and Maintenance Options Report

Thank you for your review and comments on the draft report. Hemmera Envirochem Inc. is pleased to provide you with the enclosed final report.

We have appreciated the opportunity to work with you on this project and trust that this report meets your requirements. Please feel free to contact the undersigned by phone or email regarding any questions or further information that you may require.

Regards,
Hemmera Envirochem Inc.

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EXECUTIVE SUMMARY

As part of the Enhancing Cetacean Habitat and Observation (ECHO) Program managed by the Vancouver Fraser Port Authority (VFPA), Hemmera was contracted to research and evaluate vessel quieting design, technology, and maintenance options and provide recommendations for vessel noise reduction criteria for inclusion in VFPA's EcoAction Program. The EcoAction Program offers discounted harbour dues to vessels that meet certain environmental performance criteria.

Vessel quieting designs, technology, and maintenance options were compiled through a literature review and discussions with experts. Options and sub-options identified fell into eight categories: 1) regular propeller cleaning and repair, 2) regular cleaning of the hull, 3) hull coating, 4) propeller and devices designed, selected or modified to reduce cavitation and improve wake flow, 5) alternative forms of propulsion to conventional propeller, 6) use of quieter engines, 7) reduction of on-board engine and machinery noise, and 8) hull form design or modification. Information was also collected on noise reduction effectiveness, cost, availability of technology, feasibility of implementation, whether the information is verifiable by VFPA, and other co-benefits or environmental impacts. Each of the options or sub-options identified (30 in total) was then rated based on factors of most importance to the EcoAction Program criteria development: noise reduction effectiveness and verifiability.

Only regular propeller cleaning/repair received the maximum score (six out of six) based on the rating criteria selected. Seven options scored five out of six on the basis of some evidence of effectiveness at reducing underwater noise and relative ease of verifiability: 1) regular cleaning of the hull, 2) decoupling coating, 3) Propeller Boss Cap Fins (PBCF), 4) Schneekluth duct, 5) Mewis duct, 6) air injection and bubble curtains, and 7) a type of vessel that uses LNG-fueled, gas and steam turbine powered (COGAS) and electrically driven technology. Elastic mountings and structural reinforcements used to reduce on-board engine or machinery noise had high ratings for noise reduction effectiveness but were deemed harder to verify and therefore scored four out of six. On the basis of these ratings, the top ten of the 30 options rated was carried forward for consideration in the development of EcoAction criteria. In addition, three ship classification societies with quiet notations and one environmental certification program, Green Marine, were also carried forward for consideration in the EcoAction criteria as they provide recognition of vessels that have overall quieter underwater noise levels and are in line with similar criteria included for air emission in the EcoAction Program.

Similar to the current EcoAction criteria for air emissions, underwater noise criteria could fall into three categories of noise reduction measures: 1) Vessel and Engine Technology, 2) Maintenance, and 3) Ship Classification Societies and Environmental Programs. Participants could qualify for the EcoAction Program if they satisfy one underwater noise reduction measure. Award levels could be structured similarly to the existing levels of bronze, silver and gold. Two methods were suggested for defining criteria based on: 1) evidence of noise reduction effectiveness, and 2) on additional considerations of relative potential underwater noise reduction benefits based on expert opinion. Using additional information under the second method, VFPA could consider incentivising certain propeller designs (e.g., high skew and new blade section propellers) that have documented improved propulsion efficiency (and theoretical or ideally proven reductions in vibration/cavitation noise) over conventional propellers.

In conclusion, this study serves as a basis for further developing the EcoAction criteria for underwater noise. Further research may be needed to determine the relationship between increased efficiency and underwater noise for the different options. As more evidence becomes available, the EcoAction Program could include additional options. This study provides general information on potential measures related to vessel designs, technologies and maintenance, and recommends two frameworks for the EcoAction Program criteria which can serve as a first step in the development of appropriate criteria.

This Work was performed in accordance with Purchase Order OF 14355 000 between Hemmera Envirochem Inc. (“Hemmera”) and Vancouver Fraser Port Authority (VFPA) (“Client”), dated October 15, 2015 (“Contract”). This Report has been prepared by Hemmera for sole benefit and use by VFPA. In performing this Work, Hemmera has relied in good faith on information provided by others, and has assumed that the information provided by those individuals is both complete and accurate. This Work was performed to current industry standard practice for similar environmental work, within the relevant jurisdiction and same locale. The findings presented herein should be considered within the context of the scope of work and project terms of reference; further, the findings are time sensitive and are considered valid only at the time the Report was produced. The conclusions and recommendations contained in this Report are based upon the applicable guidelines, regulations, and legislation existing at the time the Report was produced; any changes in the regulatory regime may alter the conclusions and/or recommendations.

This Executive Summary is not intended to be a “stand-alone” document, but a summary of findings as described in the following Report. It is intended to be used in conjunction with the scope of services and limitations described therein.

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Table A1 Information Compiled on Vessel Quieting Design, Technologies and Maintenance by Category

Table A2 Evaluation Matrix for Vessel Quieting Methods Using Underwater Noise and Verifiability as Rating Criteria

1.0 BACKGROUND

As part of the ECHO Program, VFPA contracted Hemmera to complete a review of vessel quieting design, technology, and maintenance options and to provide supporting information and recommendations for the development of vessel noise reduction criteria for VFPA's EcoAction Program.

Underwater noise from vessels can potentially affect marine life in different ways. Marine mammals, in particular, use sound to navigate, communicate, and locate prey. Underwater noise can mask important sounds or cause behavioural effects to marine mammals and could potentially affect an individual's ability to forage, mate, rest, or socialise. Underwater noise was identified as one of the key potential threats to resident killer whales in British Columbia (BC) in the Fisheries and Oceans Canada federal Recovery Strategy (DFO 2008). Southern resident killer whales (SRKW) are endangered and their designated critical habitat overlaps with VFPA's navigational jurisdiction.

Vessel traffic is predicted to increase through SRKW critical habitat into the future and increases in underwater noise from shipping could potentially affect marine life. VFPA, through its ECHO and EcoAction programs, is working collaboratively with regional partners and the shipping industry to reduce potential effects to marine mammals from current and future commercial shipping activities.

1.1 ENHANCING CETACEAN HABITAT AND OBSERVATION (ECHO) PROGRAM

The Enhancing Cetacean Habitat and Observation (ECHO) Program is a VFPA-led collaborative initiative aimed at better understanding and managing the impact of shipping activities on at-risk whales throughout the southern coast of BC[1]. One of the key focus areas of the ECHO Program is underwater noise from shipping activities and finding ways to reduce it.

1.2 ECOACTION PROGRAM

The EcoAction Program offers discounted harbour dues to vessels for a variety of fuel, technology and environmental management options[2]. Vessels may qualify for gold, silver, or bronze levels for air emission reduction measures in the categories of Cleaner Fuels, Vessel and Engine Technologies, Environmental Programs, and Ship Classification Societies. The addition of an underwater noise component to the Program may complement VFPA's current environmental initiatives and assist with meeting the ECHO Program's objectives. Under this new EcoAction Program component, VFPA could provide incentives to vessels berthing at Port of Vancouver terminals that have taken measures to reduce their underwater noise.

1 http://www.portmetrovancouver.com/environment/water-land-wildlife/marine-mammals/
2 http://www.portmetrovancouver.com/wp-content/uploads/2015/03/EcoAction-Brochure.pdf

1.3 STUDY OBJECTIVES

The objectives of this report are to:

1. Identify vessel design, technology, and maintenance options that reduce vessel underwater noise; and
2. Provide information and recommendations to support VFPA in the development of vessel quieting criteria to be incorporated into the EcoAction Program.

2.0 METHODOLOGY

Vessel quieting design, technology, and maintenance options were compiled through a literature review and additional discussions with experts. Operational measures that can reduce underwater noise, such as vessel speed reduction, were beyond the scope of this report and were therefore not included. The process used for compiling and evaluating the options for inclusion into the EcoAction Program is described in the following sections.

2.1 LITERATURE REVIEW

An extensive review of available literature on vessel quieting design, technology, and maintenance options was conducted. Sources of information included consultant technical reports, government technical reports, primary peer-reviewed literature, underwater noise performance criteria developed by other programs and organisations, pamphlets, and other scientific literature. The list of options identified was compiled based on their potential or demonstrated underwater noise reduction benefits and relevance for developing suitable EcoAction Program criteria.

Key literature reviewed and used in identifying and evaluating potential options included:

- Guidelines for Regulation on Underwater Noise From Commercial Shipping (AQUO 2015):
- A Review of Practical Methods for Reducing Underwater Noise Pollution from Large Commercial Vessels (Leaper and Renilson 2012);
- Overview of Regulations and Mitigation Measures: Understanding Anthropogenic Noise (Nolet 2015); and
- Reducing Underwater Noise Pollution from Large Commercial Vessels (Renilson Marine Consulting Pty Ltd. 2009).

To assist with the evaluation of the various options for potential use in the EcoAction criteria, information was compiled into six categories (**Table A1: Appendix A**):

- Evidence of noise reduction effectiveness;
- Cost;
- Availability of technology or service;
- Feasibility of implementation;
- Information is verifiable by VFPA; and
- Other co-benefits or environmental impacts to consider.

2.2 ADDITIONAL INPUT SOLICITED

A workshop was held with VFPA ECHO and EcoAction staff to review initial findings and further define information of relevance for developing EcoAction criteria. To supplement the literature review, targeted technical experts (e.g., naval architects, classification societies and members from the shipping industry) were also consulted on possible options and information available to help fill data gaps identified during the literature review. Input was primarily solicited through meetings or a combination of questionnaires and follow-up discussions. The names of people who were consulted on various topics (outside ECHO Program staff) and provided input to this study are provided in **Table 1**.

Table 1 Summary of Input Received on Vessel Quieting Options

Name	Affiliation	Topics of Input	Date Consulted
Jeff Pelton, BMS	Marine Operations Specialist Operations and Security, VFPA	• Process for soliciting input • Cost of vessel quieting options • Other potential vessel quieting options	November 24, 2015
Christine Rigby	EcoAction Program staff, VFPA	Relevant information to inform development of EcoAction criteria	November 26, 2015
James Hoffele	EcoAction Program staff, VFPA	Relevant information to inform development of EcoAction criteria	November 26, 2015
Chris McKesson, Ph.D., P.E., P.Eng.	Instructor – Naval Architecture, Department of Mechanical Engineering, Faculty of Applied Science, The University of British Columbia	• Cost, feasibility, verifiability, and potential co-benefits of vessel quieting options • Expert opinion on underwater noise reduction potential of the different options	January 8 and14, 2016
Andra Papuc, BASc, P.Eng	Project Manager and Naval Architect, Robert Allan Ltd.	• Cost, feasibility, verifiability, and potential co-benefits of vessel quieting options • Other potential vessel quieting options	February 5, 2016
Stephen Brown	President, Chamber of Shipping of British Columbia	• Feedback from Ship Classification Societies (e.g., Lloyd's Register) • Other potential vessel quieting options	January 29, 2016

2.3 EVALUATING VESSEL QUIETING OPTIONS

Based on ratings developed for selected categories of information collected (see **Table A2**: **Appendix A),** each option was rated and ranked by Hemmera with input from VFPA staff and experts. For more details on evaluating vessel quieting options, see **Section 4.0**.

2.4 QUIET SHIP RECOGNITION THROUGH OTHER PROGRAMS

Also relevant to developing the EcoAction program criteria are other programs and organisations (e.g., classification societies) that recognise quieter vessels, irrespective of the means taken to produce a lower underwater radiated noise (URN). A preliminary search and review of such programs and classification societies was carried out as part of this study. A list and the descriptions of those identified are included in this report as they relate to potential EcoAction criteria.

2.5 DEVELOPING ECOACTION CRITERIA

Top ranking vessel quieting options were further considered on the basis of their potential underwater noise reduction benefit and relevance for inclusion as EcoAction criteria. More details on this iterative process are provided in **Sections 4.0** to **6.0**.

3.0 VESSEL QUIETING OPTIONS IDENTIFIED

Following a combination of literature review and additional discussions with experts, a long list of potential vessel quieting options (including vessel quieting design, technology, and maintenance options) were identified which fall into eight broad categories:

1. Regular propeller cleaning and repair;
2. Regular cleaning of the hull;
3. Hull coating;
4. Propeller and devices designed, selected or modified to reduce cavitation and improve wake flow;
5. Alternative forms of propulsion to conventional propeller;
6. Use of quieter engines;
7. Reduction of on-board engine and machinery noise; and
8. Hull form design or modification.

A total of 32 options were identified and each is described in **Table 2**.

Table 2 Vessel Quieting Options and Descriptions

#	Vessel Quieting Methods	Description of Technology and Potential Underwater Noise Reduction Mechanisms
1	**Regular propeller cleaning/repair**	Propeller cleaning and repairs done in dry dock or underwater using divers. This can reduce propeller cavitation and also reduce turbulence which increases efficiency.
2	**Regular cleaning of the hull**	Hull cleaning done in dry dock or underwater using divers. This can reduce turbulence and therefore related noise.
3	**Hull coating**	
a	Decoupling coating	A layer of material, generally consisting of visco-elastic tiles, typically a few centimetres thick and containing air cavities, which reduces the radiation efficiency of the hull and thus reduces transmission of underwater noise from the hull into the water.
b	Anti-fouling paints	Coatings and other methods generally used to prevent fouling of the hull. Reduced fouling improves water flow and reduce turbulence related noise.
c	Non-stick coating	
d	Biocides	
e	Differential electrical charge	
f	Prickly coating	
4	**Propeller and devices designed, selected or modified to reduce cavitation and improve wake flow (descriptions adapted from ACCOBAMS (2013))**	
a	High skew propellers	This propeller has the combined effect of causing the blade to pass through the varying wake field (particularly near the top of the cycle) in a more gradual manner, improving the cavitation pattern on the blades.
b	Contracted and loaded tip propellers (CLT)	These propellers are designed with an end plate which reduces the tip vortices, thereby enabling the radial load distribution to be more heavily loaded at the tip than with conventional propellers. Therefore, optimum propeller diameter is smaller, and cavitation may be reduced.

#	Vessel Quieting Methods	Description of Technology and Potential Underwater Noise Reduction Mechanisms
c	Kappel propellers	The tips of this propeller are smoothly curved towards the suction side of the blades. This reduces cavitation.
d	New blade section propellers (NBS)	A high propulsive performance and compact propeller. The diameter is approximately 5% smaller, and the weight is approximately 20%lower, than conventional propellers. This might provide higher efficiency and reduce cavitation.
e	Propeller Boss Cap Fins (PBCF)	Small fins attached to the propeller hub and designed to reduce the magnitude of the hub vortices, thereby recovering the lost rotational energy, and reducing cavitation.
f	Propeller Cap Turbine	This propeller comprises a number of hydrofoil shaped blades integrally cast into the hub cap. Energy from the rotating fluid coming from the propeller hub is recovered, resulting in energy savings but link to underwater noise reduction is unconfirmed..
g	Twisted rudder	The propeller is designed to account for the swirling flow from the propeller. This may increase propeller efficiency but link to underwater noise reduction is unconfirmed.
k	Rudder fins	The propeller is designed to recover some of the rotational energy. This may increase propeller efficiency but link to underwater noise reduction is unconfirmed.
l	Costa Propulsion Bulb (CPB)	The propeller is integrated hydrodynamically with the rudder by fitting a bulb to the rudder in line with the propeller shaft. This is claimed to reduce underwater noise.
m	Schneekluth duct	Designed to improve the flow to the upper part of the propeller, which causes the formation of cavitation at the blade tips to be less pronounced, resulting in lower pressure pulse levels. This may increase efficiency of propellers and reduce cavitation by improving wake inflow.
n	Mewis duct	These ducts aim to improve flow into the propeller but few details are available. This may improve the wake, increase the propeller efficiency, and reduce cavitation/vibration.
o	Simplified compensative nozzle	This design improves the flow into the propeller. The improved efficiency is achieved by re-shaping the nozzle (more vertical or cylindrical shape, as opposed to circular) to improve uniformity of wake flow into the propeller. This may increase propeller efficiency and reduce propeller noise.
p	Grothues spoilers	These spoilers consist of a small series of curved fins attached to the hull just ahead of the propeller. They straighten the flow into the propeller, thereby improving the propeller efficiency and potentially reduce propeller noise.
q	Pre-swirl stators/vortex generators	Vortex generators are added appendages used to improve the wake flow which can reduce propeller vibration and cavitation.
r	Air injection to propeller and bubble curtains	A bubble curtain is a system that produces bubbles in a deliberate arrangement and the bubbles act as a barrier or a curtain, breaking or reducing the propagation of sound from the propeller or the hull. Air injection can be used to minimise cavitation erosion in propeller ducts.
5	**Alternative forms of propulsion to conventional propeller**	
a	Water or pump jet	A system that creates a jet of water for propulsion. This type of propulsion could potentially reduce noise or create a noise at different frequencies relative to conventional propellers and requires further research
b	Podded drivers	Propellers placed in pods that can be rotated to any horizontal angle (azimuth), making a rudder unnecessary. This type of propulsion could potentially reduce noise relative to conventional propellers and requires further research

#	Vessel Quieting Methods	Description of Technology and Potential Underwater Noise Reduction Mechanisms
c	Twin propeller arrangement	Propellers placed in pods that can be rotated to any horizontal angle (azimuth), making a rudder unnecessary. This type of propulsion could potentially reduce noise relative to conventional propellers and requires further research
6	**Use of quieter engines**	
a	Steam/gas turbines	Steam or gas turbine systems.
b	Diesel-electric	Diesel-electric systems. These are quieter than conventional 2-stroke diesel engines.
c	LNG-fueled, gas and steam turbine powered (COGAS), and electrically driven	This combination of technologies is used in a type of vessel to drive the engine and could lead to engine noise reductions relative to conventional engines
7	**Reduction of on-board engine and machinery noise**	
a	Elastic mountings	Flexible mounts that connect two parts and are used for vibration isolation to reduce noise.
b	Structural reinforcements	Structural reinforcements of the main engine foundations. These reinforcements reduce onboard vibration transmission to the hull.
8	**Hull form design or modification**	A well designed hull form will require less power for a given speed, which is likely to result in less noise. Such hull will also likely provide a more uniform inflow to the propeller, thereby increasing the propeller's efficiency, and reducing noise and vibration caused by the uneven wake flow. This will further reduce the underwater noise

The large number of types of propellers and associated devices identified reflects the known relationship between propeller cavitation and underwater noise, the recognition that propeller cavitation is the largest source of URN in vessels (Ross 2005), and the incidental efforts by the maritime industry to improve vessel efficiency. Compiled information on the selected categories (i.e., noise reduction effectiveness, cost, availability of technology, feasibility of implementation, whether the information is verifiable by VFPA, and other co-benefits or environmental impacts, as well as technical references) is included in **Table A1** for each of the options.

4.0 EVALUATION OF VESSEL QUIETING OPTIONS

Each option was evaluated for potential use in EcoAction criteria based on information deemed most important by EcoAction Program staff, i.e., noise reduction effectiveness and whether the information is verifiable by VFPA. Qualitative ratings definitions were developed for these two criteria as described below.

4.1 NOISE REDUCTION EFFECTIVENESS

Relatively little evidence currently exists directly linking vessel design, technology, or maintenance options to a measured reduction in underwater noise (see **Table A1** for more information on evidence of noise reduction effectiveness). Improved efficiency and/or reduced cavitation claims by developers and manufacturers are often not confirmed by independent research. Also, the relationships between efficiency, cavitation and noise is not clear, and noise reduction benefits of alternative technologies is still speculative in most cases (ACCOBAMS, 2013). For vessel designs focused on reducing URN, there is generally a trade-off between efficiency and underwater noise reduction (AQUO 2015). Also, several factors influence total URN from a vessel, and studies often do not control for all factors to determine the effect of a particular option on URN. As a result, it was not possible to develop a rating scheme to compare the absolute or relative noise reduction levels provided by the various options. Noise reduction effectiveness was rated as follows based on potential or evidence of measured noise reduction in the literature:

- Low (1) = potential theoretical underwater noise reduction;
- Medium (2) = at least one study suggesting underwater noise reduction; or
- High (3) = measurable underwater noise reduction.

4.2 VERIFIABILITY

To meet the verifiability requirements under the EcoAction Program, documentation has to be submitted by the ship owner or agent. Documents proving that certain options have been implemented may be easy to produce, whereas others may not be documented or verifiable simply using documentation. To assist with determining whether an option could be verified by VFPA staff, the following ratings were developed:

- Easy (3) = documentation should be available to show that option has been implemented on vessel (e.g., vessel specifications, maintenance records, information is part of notation from classification society);
- Moderate (2) = documentation may be available but its form may need to be confirmed; or
- Hard or impractical (1) = no documentation available, inspection likely required to confirm presence or proper installation, or verification is impractical.

4.3 EVALUATION

The evaluation of vessel quieting options consisted of assigning ratings based on information compiled from the literature review and additional validation or information based on input from experts and the definitions described in **Sections 4.1** and **4.2**. A total score was calculated as a general guide for identifying options that merit further consideration. These scores, although based on best available information, remain subjective. Additional options with lower rankings may warrant further consideration as evidence of noise reduction effectiveness or verifiability becomes available in the future, or if consideration of additional factors increases their value. A table showing the ratings by category and scores for each option is included in **Table A2** in **Appendix A**.

In summary, the results indicate that:

- A total of 30 options[3] were evaluated;
- Total scores ranged from 2 to 6;
- Only regular propeller cleaning/repair scored 6 out of 6;
- Seven more options had a score of 5 out of 6 indicating that there was at least some evidence suggesting effectiveness at reducing underwater noise and easy verifiability of the implementation of the measure:
  - Regular cleaning of the hull;
  - Decoupling coating;
  - Propeller Boss Cap Fins (PBCF);
  - Schneekluth duct;
  - Mewis duct;
  - LNG-fueled, gas and steam turbine powered (COGAS), and electrically driven; and
  - Air injection to propeller and bubble curtains.
- 16 options, including several propeller and engine types, scored 4 out of 6. Some of these options related to engine and machinery noise reductions (elastic mountings and structural reinforcements) had high evidence of noise reduction effectiveness, but were deemed harder to verify, at least in terms of providing documentation showing that the measures are effective and maintained overtime. Most others had low evidence of noise reduction effectiveness but could be easily verified; and
- Six options had scores of 3 or less including various hull coatings and changes to hull form.

3 Alternative forms of propulsion were combined in the evaluation due to limited information available on each form of propulsion

Based on this information, options can be divided into four main groups:

1. Proven effectiveness of underwater noise reduction and easy to verify (scores of 5+);
2. Proven effectiveness of underwater noise reduction and moderate to hard to verify (score of 4);
3. Low evidence of underwater noise reduction effectiveness, but easy to verify (score of 4); and
4. Lower compatibility for inclusion in EcoAction criteria at present (score of 3 or less).

Options in group 1 (eight options) are considered to be the best options to carry forward for consideration in the development of EcoAction criteria given the ranking criteria used. Options in group 2 (two options) are also considered as good potential options to include as part of the EcoAction Program given their proven effectiveness at reducing underwater noise levels, for a total of 10 options carried forward. Additional options could also be considered for inclusion on a case-by-case basis if considering additional factors as discussed in **Section 6.0**.

5.0 QUIET SHIP RECOGNITION THROUGH OTHER PROGRAMS

The following ship classification societies have developed notations for quieter vessels based on different standards of measured URN (see **Table 3** for more details):

- Registro Italiano Navale;
- Bureau Veritas; and
- DNV GL.

Table 3 Ship Classification Societies Underwater Noise Notations

Ship Classification Society	Notation	Available (Yes/No)	Reference
Registro Italiano Navale (RINA)	DOLPHIN	No	RINA (2014)
Bureau Veritas	Underwater Radiated Noise (URN)	Yes	Bureau Veritas (2014)
DNV GL	SILENT E	Yes	DNV GL (2015)

These notations are all voluntary and relatively new and few vessels are anticipated to initially have these notations. More classification societies are anticipated to develop similar notations. Information provided in communications suggests that the URN levels selected would apply to vessels that have a measured URN below average and that may have implemented measures to achieve this URN. In addition, performance criteria for underwater noise are being developed by Green Marine, an environmental certification program for the North American marine industry. These criteria may not be available prior to the launch of the EcoAction underwater noise criteria.

Similar to existing EcoAction criteria, ships with quiet notations or meeting underwater noise performance objectives of environmental certification programs, such as Green Marine, could potentially receive incentives under the underwater noise component of the EcoAction program. Therefore, these additional options were also considered further in recommendations for developing EcoAction criteria.

6.0 DEVELOPING ECOACTION CRITERIA

The information and ranking exercise provided in **Table A2** and this report identified the following for further consideration as part of the EcoAction Program's underwater noise component:

- Ten vessel design, technology or maintenance options;
- Three classification society quiet notations; and
- One Environmental Program with an underwater noise component (in development).

At the most basic level, the EcoAction Program could potentially use these as criteria and provide some level of incentive to vessels with any of the 14 above options upon submission of suitable documentation of these measures being implemented.

Similar to the structure of existing EcoAction criteria for air emissions, underwater noise criteria could fall into three categories of noise reduction measures:

1. Vessel and Engine Technology:
    a. Decoupling coating;
    b. Propeller Boss Cap Fins (PBCF);
    c. Schneekluth duct;
    d. Mewis duct;
    e. LNG-fueled, gas and steam turbine powered (COGAS), and electrically driven ships;
    f. Air injection to propeller and bubble curtains;
    g. Elastic mountings; and
    h. Structural reinforcement
2. Maintenance:
    a. Regular propeller cleaning/repair; and
    b. Regular cleaning of the hull
3. Ship classification societies and Environmental Program:
    a. RINA - DOLPHIN notation
    b. Bureau Veritas – URN notation
    c. DNV GL – Silent E notation
    d. Green Marine (Level X for underwater noise performance indicator)

Participants could qualify if they satisfy one noise reduction measure. Award levels could be structured similar to the existing levels of bronze, silver and gold, with the possibility of adding a discretionary level. The actual level of incentive associated with the above options will depend on several factors but generally, a greater level of incentive could be given to measures that have the most noise reduction benefits. Because quantitative information to determine the relative noise reduction benefits of the various options is not currently available, two methods could be used to inform decisions of award level:

1. Evidence of noise reduction effectiveness; or
2. Additional information on relative potential underwater noise reduction benefits (based on increased efficiency and reduced cavitation).

The proposed EcoAction award levels for each option with consideration of potential criteria details and associated measures for verification are presented in **Table 4** for methods 1 and 2.

Table 4 Award Levels Based on Evidence of Underwater Noise Reduction Effectiveness, Potential Criteria Details and Proposed Measures for Verification Using Method 1) Evidence of Noise Reduction Effectiveness, and Method 2) Additional Information on Relative Potential Underwater Noise Reduction Benefits

Category of Noise Reduction Measure	Vessel Quieting Option – Method 1	Additional Vessel Quieting Option – Method 2	Criteria Details and Proposed Measure to Verify	Proposed EcoAction Award Level – Method 1	Proposed EcoAction Award Level – Method 2
Vessel and Engine Technology	Decoupling coating		Presence documented in vessel specifications or other paperwork.	Bronze	Bronze
	Propeller Boss Cap Fins (PBCF)		Presence documented in vessel specifications or other paperwork.	Bronze	Bronze
	Schneekluth duct		Presence documented in vessel specifications or other paperwork.	Bronze	Bronze
	Mewis duct		Presence documented in vessel specifications or other paperwork.	Bronze	Bronze
	LNG-fueled, gas and steam turbine powered (COGAS), and electrically driven ships		Presence documented in vessel specifications or other paperwork.	Bronze	**Gold**
	Air injection to propeller and bubble curtains		Presence documented in vessel specifications or other paperwork.	Bronze	**Gold**
	Elastic mountings		Presence documented in vessel specifications or other paperwork. Ideally this measure would come with a plan to ensure that the mountings installed are maintained and continue to perform as originally intended.	Silver	Silver
	Structural reinforcements		Presence documented in vessel specifications or other paperwork.	Silver	Silver
		Propeller designs	Presence documented in vessel specifications or other paperwork. Initially, the following two types could be considered: • High skew propeller • New blade section propeller		Potentially tiered up to Gold

Category of Noise Reduction Measure	Vessel Quieting Option – Method 1	Additional Vessel Quieting Option – Method 2	Criteria Details and Proposed Measure to Verify	Proposed EcoAction Award Level – Method 1	Proposed EcoAction Award Level – Method 2
Maintenance	Regular cleaning of the hull		Evidence of a vessel-specific hull cleaning management plan to keep fouling to a minimum and maintenance records[4]	Bronze	Potentially Bronze to Gold
	Regular propeller cleaning/repair		Evidence of a vessel-specific propeller cleaning and repair management plan to keep fouling and damage to a minimum and maintenance records[5]	Silver	Potentially Bronze to Gold
Ship classification societies and Environmental Program	RINA - DOLPHIN notation		Evidence of having obtained the notation	Bronze	Bronze
	DNV GL – Silent E notation		Evidence of having obtained the notation	Bronze	Bronze
	Bureau Veritas – URN notation		Evidence of having obtained the notation	Bronze	Bronze
	Green Marine		Evidence of having met a certain minimum level for underwater noise (to be determined). Note that this may not be available in the first year of the EcoAction Program's underwater noise component.	Bronze	Bronze

4 Consideration of cleaning method used (in-water or dry dock) may be warranted as some in-water measures can have negative effects on the environment.

Reviewing the literature on propulsion/fuel efficiency of various options was not part of the scope of this review. However, information on relative potential for underwater noise reduction benefits was provided by a naval architect (Chris McKessen, pers. comm.), primarily on the basis of increased fuel/propulsion efficiency of the various options and theoretical linkage to underwater noise reduction. Because the greatest source of underwater noise on a vessel is cavitation from the propeller (Ross 2005), and that several propeller designs have demonstrated improved fuel efficiency (assumed to also result in noise reductions), including more efficient propeller designs as an option in the the EcoAction Program initially or in the future may be warranted. For this option, criteria for eligibility could include installation of one of various propeller types. On this basis, two propeller types that were judged to have demonstrated increased fuel efficiencies and likely noise reductions (Chris McKessen, pers. comm.) relative to conventional propellers were added to the criteria previously considered (in bold in **Table 4**).

Proposed award levels were modified for two Vessel and Engine Technology options as indicated in bold in **Table 4** based on their relative effectiveness at reducing engine noise, the second largest source of noise of a ship. In addition, instead of a single award level for certain options that might present more variability, a tiered award level could be used to reflect different potential noise reduction benefits or efforts deployed by vessel operators. This approach could apply to propeller types and hull/propeller cleaning and maintenance management plans (reflected in **Table 4** for method 2). Additional research would be required to fully develop the criteria for the different levels.

7.0 CONCLUSIONS AND NEXT STEPS

This section describes the key findings and conclusions of this report, data gaps, considerations for further developing the EcoAction Program underwater noise criteria, and proposed next steps.

In summary, this study provides a basis for identifying options to consider under the EcoAction Program's underwater noise component and a proposed framework for their use. The 14 options carried forward for further consideration fall in three categories: Vessel and Engine Technology, Maintenance, and Ship classification societies and Environmental Programs. Proposed awards could be structured similarly to current EcoAction Program criteria for air emissions with participants qualifying if they can demonstrate that they meet any of the noise reduction measures identified. Award levels could retain the bronze, silver and gold levels already used in the EcoAction Program. Two different schemes for award levels were proposed as a starting point for further development. One proposed scheme is based on results of our analysis while the other incorporates additional input received from a naval architect. Both options can be further considered and brought forward as a starting point for the engagement process required to develop the final criteria.

This study was limited by availability of information on noise reduction effectiveness. The current focus seems to be on reducing overall noise footprint (URN) using multiple options rather than quantifying potential benefits of single options due to challenges with conducting controlled studies (before and after modifications). Further research may be needed to link improved efficiency with reductions in underwater noise. Underwater noise levels measured by the ECHO Program's Strait of Georgia Underwater Listening Station could be helpful in providing further evidence of noise reduction benefits of different options. As further research is conducted, we anticipate that evidence of underwater noise reduction for the options included in this study will increase (as well as the understanding of the linkage between fuel efficiency, cavitation/vibration and underwater noise). The EcoAction Program could include additional options such as certain propeller types as information becomes available. The standards for qualifying under the Programs are also likely to evolve over time as more guidelines and regulations are developed in a way similar to the development of air emission guidelines.

This study provides general information on potential measures related to vessel design, technologies and maintenance, and recommendations for a framework for developing the EcoAction Program criteria. Next steps for developing the criteria could include deciding on the method for further developing the criteria, soliciting input from the shipping industry, conducting any additional research required to finalise the criteria, and formalising them under the EcoAction Program.

This study did not consider any operational measures, such as reductions in vessel speed. These measures can provide notable underwater noise reduction benefits. VFPA is currently looking into quantifying these potential benefits. As indicated by VFPA, operational measures could also be included in the EcoAction Program at a later stage. A similar approach to the one used in this report could be taken for evaluating these operational options.

8.0 REFERENCES

ACCOBAMS. 2013. Anthropogenic Noise and Marine Mammals. Review of the effort in addressing the impact of anthropogenic underwater noise in the ACCOBAMS and ASCOBANS areas. ACCOBAMS-MOP5/2013/Doc22.

Anderson, P., S.V. Andersen, L. Bodger, J. Friesch, and J.J. Kappel. 2000. Cavitation considerations in the design of Kappel propellers. Proceedings of NCT'50. International Conference on Propeller Cavitation, 3-5 April 2000, University of Newcastle, UK.

Aono, T. S. Iwamoto, and M. Takai. 2001. Advantages of New Blade Section Propeller. Sumitomo Heavy Industries Technical Review. No. 168. http://www.shi.co.jp/ejsite/no168/07.html

AQUO (Achieve Quieter Oceans). 2015. Guidelines for regulation on UW noise from commercial shipping. FP7- Grant Agreement No. 314394. SONIC Deliverable 5.4

Bohlander, J. 2009. Review of options for in-water cleaning of ships. Prepared for MAF Biosecurity New Zealand. Technical Paper No: 2009/42.

Breslin, J.P. and P. Andersen. 1994. Hydrodynamics of Ship Propellers. Cambridge Ocean Technology Series. ISBN 0 521 41360.

Bureau Veritas. 2014. Underwater Radiated Noise (URN). Rule Note NR 614 DT R00 E.

DFO (Fisheries and Oceans Canada). 2008. Recovery Strategy for the Northern and Southern Resident Killer Whales (*Orcinus orca*) in Canada. Species at Risk Act Recovery Strategy Series

DNV GL. 2015. Rules for classification. Ships. Part 6 Additional class notations. Chapter 7 Environmental protection and pollution control. http://www.dnvgl.com.

IMO (International Maritime Organization). 2014. Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life CIRC/MEPC/01/833.doc.

ITTC (International Towing Tank Conference). 1999. Final report of the Specialist Committee on Unconventional Propulsors. 22nd International Towing Tank Conference, Seoul and Shanghai.

Leaper, R.C. and M.R. Renilson. 2012. A review of practical methods for reducing underwater noise pollution from large commercial vessels. International Journal Maritime Engineering 154: Part A2.

Ligtelijn, J.T. 2007 Advantages of different propellers for minimising noise generation. Proceedings of the 3rd International Ship Noise and Vibration Conference, London, UK, September 2007.

Molland AF. And S.R. Turnock. 2007. Marine rudders and control surfaces, principles, data, design and applications. Butterworth-Heinemann. ISBN: 978-0-75-066944-3.

Mutton, R., M. Atlar, M. Downie, and C. Anderson. 2005. Drag prevention coatings for marine propellers, 2nd International Symposium on Seawater Drag Reduction, Busan, Korea, 23-26 May 2005.

Nolet, V. 2015. Overview of regulations and mitigation measures understanding anthropogenic noise. Document presented to Transport Canada.

Patience, G. 2000. The importance of cavitation from the manufacturers' point of view. Proceedings of NCT'50. International Conference on Propeller Cavitation, 3-5 April 2000, University of Newcastle, UK.

Renilson Marine Consulting Pty Ltd. 2009. Reducing Underwater Noise Pollution from Large Commercial Vessels. Commissioned by The International Fund for Animal Welfare.

RINA (Registro Italiano Navale). 2014 Rules for the Classification of Ships: Amendments to Part F: Additional Class Notations.

Ross, D., 2005. Ship sources of ambient noise, IEEE J. Oceanic. Eng. 30, 257-261.

Schultz, M.P., J.A. Bendick, E.R. Holm, and W.M. Hertel. 2011. Economic impact of biofouling on a naval surface ship. Biofouling 27: 87–98.

SISTEMAR. 2005. CLT: A proven propeller for efficient ships. Special Supplement to the Naval Architect, July/August 2005.

Würsig, G.M. and S.D. Adams. 2015. Power without pistons: GTT, CMA CGM and DNV GL present LNG-fuelled, turbine-powered mega box ship study. DNV GL Press Release. https://www.dnvgl.com/news/power-without-pistons-gtt-cma-cgm-and-dnv-gl-present-lng-fuelled-turbine-powered-mega-box-ship-study-45289.

9.0 CLOSURE

This Work was performed in accordance with Purchase Order OF 14355 000 between Hemmera Envirochem Inc. (“Hemmera”) and Vancouver Fraser Port Authority (VFPA) (“Client”), dated October 15, 2015 (“Contract”). This Report has been prepared by Hemmera for sole benefit and use by VFPA. In performing this Work, Hemmera has relied in good faith on information provided by others, and has assumed that the information provided by those individuals is both complete and accurate. This Work was performed to current industry standard practice for similar environmental work, within the relevant jurisdiction and same locale. The findings presented herein should be considered within the context of the scope of work and project terms of reference; further, the findings are time sensitive and are considered valid only at the time the Report was produced. The conclusions and recommendations contained in this Report are based upon the applicable guidelines, regulations, and legislation existing at the time the Report was produced; any changes in the regulatory regime may alter the conclusions and/or recommendations.

We sincerely appreciate the opportunity to have assisted you with this project and if there are any questions, please do not hesitate to contact the undersigned by phone at 604.669.0424.

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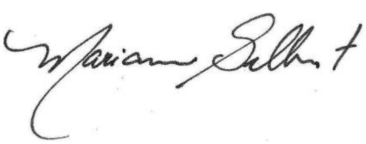

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APPENDIX A
Tables

Table A1 Information Compiled on Vessel Quieting Design, Technologies and Maintenance by Category

Information was not available for all options for all criteria but was searched for and compiled using a variety of sources including:

- Recent papers listed above and the literature cited within those papers;
- Keyword searches for each option on the internet;
- Provider websites and specifications for the technology options; and
- References or professional opinion provided by Naval Architects.

#	Vessel Quieting Methods	Noise Reduction Effectiveness	Availability of Technology or Services	Cost	Feasibility (of Implementation in Port of Vancouver	Measurable/Verifiable	Potential Co-benefits	Other Relevant Information
1	**Regular propeller cleaning/ polishing/repair**	• Cleaning reduces turbulence between hull and fluid around ship and therefore reduces losses of propulsive power caused by fouling (AQUO 2015) • Propeller polishing removes marine fouling and vastly reduces surface roughness, helping to reduce propeller cavitation (IMO Guidelines 2014) • Some reports that improving the surface of a propeller by using anti-fouling coatings can reduce the noise and can be effective for in excess of 36 months (Mutton et al. 2005 and Atlar et al. 2002 cited in Renilson Marine Consulting Pty Ltd. 2009).Measurements in a cavitation tunnel (with anti-fouling coating on the propeller) showed noticeable noise reductions at some loading conditions for some frequencies but not always, and when cavitation was more severe (i.e. in ballast), the effect was less noticeable (Mutton et al. 2006 cited in Renilson Marine Consulting Pty Ltd. 2009).	Yes	• Hull and propeller cleaning: Costs range from $26,200 to $34,200 for a full cleaning and $15,000 to $21,500 for an interim cleaning on naval surface ship (U.S.). Costs vary across ports (Schultz et al. 2011). • Exact cost of repairing propeller blades, in dry dock, will depend on the size of the propeller, and the level of damage, but is likely to be around US$20,000 (Renilson Marine Consulting Pty Ltd. 2009).	Services (divers, ship yards) available locally and elsewhere. Currently available underwater hull cleaning methods can introduce contaminants and invasive species.	Yes, Maintenance records	• reduced turbulence and therefore reduced losses of propulsive power (AQUO 2015) = more efficient • reduced propeller cavitation (IMO Guidelines 2014)	• It has been suggested that an inspection be conducted every six months (Patience, 2000 in Renilson Marine Consulting Pty Ltd. 2009). • Whale Shark Environmental Technologies has developed a machine that will clean and collect matter from ships' hulls before returning filtered water back into the sea. This technology may also work for propeller cleaning. A pilot study may be conducted by the ECHO Program to measure hull cleaning effectiveness on reducing underwater noise.

#	Vessel Quieting Methods	Noise Reduction Effectiveness	Availability of Technology or Services	Cost	Feasibility (of Implementation in Port of Vancouver	Measurable/Verifiable	Potential Co-benefits	Other Relevant Information
2	**Regular cleaning of the hull**	• Cleaning reduces turbulence between hull and fluid around ship and therefore reduces losses of propulsive power caused by fouling (AQUO 2015). Underwater noise reductions are mostly implied. • No studies identified that documented noise reduction effectiveness	Yes	• Hull and propeller cleaning: Costs range from $26,200 to $34,200 for a full cleaning and $15,000 to $21,500 for an interim cleaning on naval surface ship (U.S.). Costs vary across ports (Schultz et al. 2011).	• Services (divers, ship yards) available locally and elsewhere • Port environmental review/approved method required to do underwater hull cleaning in PMV jurisdiction	Yes, Maintenance records	Reduced turbulence (AQUO 2015) = more efficient	• Whale Shark Environmental Technologies has developed a machine that will clean and collect matter from ships' hulls before returning filtered water back into the sea. A pilot study may be conducted by the ECHO Program to measure hull cleaning effectiveness on reducing underwater noise. • U.S. NAVY ADVANCED HULL CLEANING SYSTEM (AHCS) SYSTEM: The U.S. Navy has developed a prototype multi-brush hull cleaning system that captures the debris generated from hull cleaning and transports it to the pier for processing in a mobile treatment trailer. Oceaneering, Inc of Hanover, Maryland, USA developed the system under contract from the Naval Sea Systems Command. See Bohlander 2009. • SEAWARD MARINE SERVICES MODIFIED SCAMP: in development, transport of the effluent materials in a hose to a barge for later treatment. See Bohlander 2009. • CleanROV system is an underwater ROV developed by CleanHull AS of Norway. It is remotely controlled from the surface and does not use divers and navigates by video and dead reckoning. It uses water jet cleaning, not brushes. They claim to capture the material generated by hull cleaning (http://www.cleanhull.no/). See Bohlander 2009.
3	**Hull coating**							
a	Decoupling coating	• Decoupling coating is used to reduce machinery noise. The efficiency of reduction in machinery noise is about 10 dB at medium frequencies and 20 dB at high frequencies (AQUO 2015). It is not as effective at lower frequencies (AQUO 2015).				Yes, Maintenance records		This may be effective in vessels where machinery noise dominates over propeller noise (AQUO 2015).
b	Anti-fouling paints	No studies identified that documented noise reduction effectiveness directly but several studies looking at relationship between efficiency and hull fouling.						
c	Non-stick coating							
d	Biocides							Potential leaching copper and zinc in environment when sitting in water
e	Differential electrical charge							
f	Prickly coating							

#	Vessel Quieting Methods	Noise Reduction Effectiveness	Availability of Technology or Services	Cost	Feasibility (of Implementation in Port of Vancouver	Measurable/Verifiable	Potential Co-benefits	Other Relevant Information
4	**Propeller and devices designed, selected or modified to reduce cavitation and improve wake flow**	**General comment on specialised propellers:** although claims of reducing cavitation/vibration are made, it is not clear exactly how much these will reduce underwater noise. Most of the emphasis of the concepts has been to increase efficiency, and to reduce noise and vibration propagating into the ship (not reducing underwater noise)		**General comment on specialised propellers**: typical cost is about 15 – 20% more than conventional ones due to additional design effort, additional model testing, and better casting and machining (Renilson Marine Consulting Pty Ltd. 2009).	Yes for options a to r	Yes for options a to r, Ship specifications		• Approximate conventional fixed pitch propeller costs for containerships: 2,000 TEU = $600,000 USD, 5,000 TEU = $1,300,000 USD, 8,000 TEU = $2,000,000 USD, 11,000 TEU = $2,400,000 (Renilson Marine Consulting Pty Ltd. 2009). • Approximate conventional fixed pitch propeller costs for tankers and bulk carriers: 30,000 tonnes = $300,000 USD, 70,000 tonnes = $400,000 USD, 110,000 tonnes = $650,000 USD, 200,000 tonnes = $1,300,000 USD, 300,000 tonnes = $1,600,000 USD (Renilson Marine Consulting Pty Ltd. 2009).
a	High skew propellers	• Together with reduced tip loading, very highly skewed propellers can have a significant influence on reducing propeller induced vibration (Breslin and Anderson, 1994 cited in Renilson Marine Consulting Pty Ltd. 2009). • commonly used in warships to reduce noise and vibration (Renilson Marine Consulting Pty Ltd. 2009). • Often, reduced cavitation claims are made by manufacturers but not verified. • No actual underwater noise reduction measurements found.	Yes. Owner: MAN/Diesel	The cost for a typical skewed propeller will be similar to that of a conventional propeller, although the costs for a very highly skewed propeller may be 10 – 15% greater (Renilson Marine Consulting Pty Ltd. 2009).			Improved cavitation pattern	
b	Contracted and loaded tip propellers (CLT)	These propellers are designed with an end plate which reduces the tip vortices, thereby enabling the radial load distribution to be more heavily loaded at the tip than with conventional propellers. In turn, this means that the optimum propeller diameter is smaller, and there is the possibility of reducing cavitation (De Jong, 1991 and SISTEMAR 2005 cited in Leaper and Renilson, 2012). No actual underwater noise reduction measurements found.but mentioned as part of designs tested in AQUO 2015 (results for noise were unclear and may require looking at supporting AQUO document).	Yes. Owner: SISTEMAR (Spanish).	According to SISTEMAR the cost of a typical CLT propeller is likely to be about 20% more than a conventional propeller. The cost of eight blades for Fortuny was about US$325,000 (in 2005) (in Renilson Marine Consulting Pty Ltd. 2009).			Reduced cavitation.	• SISTEMAR (2005) refers to comparative trials on two sister ships (164,000 dwt bulk carriers) where the ship fitted with the CLT propeller required 12% less power for the same speed (Renilson Marine Consulting Pty Ltd. 2009).
c	Kappel propellers	Andersen et al (2000) reported that a Kappel propeller can be used to reduce cavitation, and increase efficiency. MAN Diesel A/S Denmark suggests that this may not be the best approach to reducing underwater noise with recommendations for further studies (in Renilson Marine Consulting Pty Ltd. 2009).	Yes. Owner: MAN Diesel	No specific information found in recent reviews			• reduced cavitation, and increased efficiency.	

#	Vessel Quieting Methods	Noise Reduction Effectiveness	Availability of Technology or Services	Cost	Feasibility (of Implementation in Port of Vancouver	Measurable/Verifiable	Potential Co-benefits	Other Relevant Information
d	New blade section propellers (NBS)	The designers claim that design can provide higher efficiency and superior cavitation performance when compared to a conventional propeller due to an improved blade cross section. It also has a smaller diameter, permitting a lower ballast draught to satisfy propeller tip immersion (Sasaki and Patience, 2005 cited in Renilson Marine Consulting Pty Ltd. 2009). No actual underwater noise reduction measurements found.	Yes: developed by Sumitomo Heavy Industries Marine & Engineering Co.,Ltd	Similar cost to conventional propellers (Renilson Marine Consulting Pty Ltd. 2009).			Advantages include: 1) Reduction of fuel oil consumption and CO2 emission in navigation, 2) Reduction of hull vibration, 3) Increase of design flexibility and the value of the vessel and 4) Contribution to the cost and material resources saving. Aono et al. 2001 (http://www.shi.co.jp/ejsite/no168/07.html)	
e	Propeller Boss Cap Fins (PBCF)	• According to Mitsui O.S.K. Techno-Trade Ltd., experiments were conducted in a cavitation tunnel which showed that the PCBF caused a reduction in sound pressure level of 3 – 6 dB for frequencies exceeding 1,000 Hz (Renilson Marine Consulting Pty Ltd. 2009). • Benefits summarised by the International Towing Tank's specialist committee on unconventional propulsors (ITTC, 1999) cited in Renilson Marine Consulting Pty Ltd. 2009).	Yes. Owner: Mitsui O.S.K.Techno-Trade	• Ranging from $185,000 USD for container ships down to $40,000 USD for General Cargo ships (Table 5.1 in Renilson Marine Consulting Pty Ltd 2009).			Reduced cavitation.	Installation takes an estimate of 5 hours while dry docked, also possible to install without dry docking (Renilson Marine Consulting Pty Ltd 2009).
f	Propeller Cap Turbine	No studies identified that documented noise reduction effectiveness	Yes. Owner: Ship Propulsion Solutions, LLC				Energy from the rotating fluid coming from the propeller hub is recovered, resulting in energy savings.	
g	Twisted rudder	The propeller is designed to account for the swirling flow from the propeller or to recover some of the rotational energy. This may increase propeller efficiency but linkage to underwater noise reduction is unconfirmed.					The interaction between the propeller and the rudder has a significant impact on propulsive efficiency. Various concepts such as a twisted rudder and rudder fins have been developed to increase efficiency (Molland and Turnock (2007), cited in Renilson Marine Consulting Pty Ltd 2009).	
k	Rudder fins							
l	Costa Propulsion Bulb (CPB)	• It is claimed that this can reduce the hydro-acoustic radiated noise levels in practice by 5 dB(A) (Ligtelijn 2007). It is recommended that this be independently verified (in Renilson Marine Consulting Pty Ltd 2009)	Yes. Owner: Ship Propulsion Solutions, LLC					

#	Vessel Quieting Methods	Noise Reduction Effectiveness	Availability of Technology or Services	Cost	Feasibility (of Implementation in Port of Vancouver	Measurable/Verifiable	Potential Co-benefits	Other Relevant Information
m	Schneekluth duct	• increase efficiency of propellers and reduce cavitation by improving wake inflow (see references cited in Leaper and Renilson, 2012) • likely to be very beneficial in terms of reducing underwater noise for the noisiest ships (i.e. those with very non-uniform wake fields) (Renilson Marine Consulting Pty Ltd 2009). • Inconclusive: tests of wake improvement ducts on container ships show a slight decrease or increase in source level (AQUO 2105)	Yes. Owner: Schneekluth	Total cost of the duct and associated spoilers for a 2,500 TEU container ship is approximately US$120,000, with the installation cost (during a scheduled dry dock) being about US$20,000 (Renilson Marine Consulting Pty Ltd 2009). Possible fuel savings.			• increase efficiency	Wake improving devices may increase ship speed and therefore increase underwater noise as noise typically increases with speed (AQUO 2015)
n	Mewis duct	• Possibly improves the wake, increases the propeller efficiency, and reduces cavitation/vibration (Renilson Marine Consulting Pty Ltd 2009). • Inconclusive: tests of wake improvement ducts on container ships show a slight decrease or increase in source level (AQUO 2105) • No studies identified that documented actual noise reduction effectiveness	Yes. Owner: Becker Marine Systems				increases the propeller efficiency	Wake improving devices may increase ship speed therefore increasing underwater noise (AQUO 2015)
o	Simplified compensative nozzle	• No studies identified that documented actual noise reduction effectiveness	Yes. Owner: Ship Propulsion Solutions, LLC				Improves the flow into the propeller = improved efficiency	
p	Grothues spoilers	• No studies identified that documented noise reduction effectiveness including no information on the reduction in cavitation.	Yes. Owner: Schneekluth				straighten the flow into the propeller, thereby improving the propeller efficiency	
q	Pre-swirl stators/vortex generators	• a model test on a medium size tanker did not show much effect on the noise footprint but the arrangement and design was not optimized (AQUO 2015)					• Vortex generators are added appendages used to improve the wake flow which can reduce propeller vibration and cavitation (AQUO 2015).	Wake improving devices may increase ship speed therefore increasing underwater noise (AQUO 2015)
r	Air injection to propeller and bubble curtains	• A bubble curtain is a system that produces bubbles in a deliberate arrangement and the bubbles act as a barrier or a curtain, breaking or reducing the propagation of sound from the propeller or the hull. Air injection can be used to minimise cavitation erosion in propeller ducts. • expected decrease is several dB, up to 10 dB in medium frequency range. Measurements have been done on a cargo ship travelling at 14 knots; there was an estimated reduction of 3 to 6 dB depending on frequency range (AQUO 2015). • bubble curtain - limited use/examples in ships (AQUO 2015) • air injection - impacts on underwater noise have not been studied (AQUO 2015)	Yes				Likely none efficiency	Air injection may reduce propeller efficiency (AQUO 2015)

#	Vessel Quieting Methods	Noise Reduction Effectiveness	Availability of Technology or Services	Cost	Feasibility (of Implementation in Port of Vancouver	Measurable/Verifiable	Potential Co-benefits	Other Relevant Information
5	**Alternative form of propulsion to conventional propeller**	Water or pump jet, podded drivers, or a twin propeller arrangement. These types of propulsion systems could potentially reduce noise relative to conventional propellers and require further research. No studies identified that documented noise reduction effectiveness.				Yes, ship specifications		
6	**Use of quieter engines**	• Generally loudest to quietest (AQUO 2015): slow 2-stroke engine, medium 4-stroke engine, high 4-stroke, gas/steam, diesel-electric • Diesel- and steam-electric are quieter but not widely adopted (AQUO 2015).					decreased on-board noise	• Approx. 90% ships now built with 2-stroke diesel engines (AQUO 2015) • Diesel-electric are quieter but not widely adopted. Being investigated for fishery and cruise vessels but not feasible for majority of commercial ships because of high cost and use of clean fuels (AQUO 2015). • LNG-fueled, gas and steam turbine powered, and electrically driven vessels: potential to offer a more efficient, more flexible and greener box ship design than current 20,000 TEU two-stroke diesel engine driven ultra large container vessels. Würsig and Adams 2015 (https://www.dnvgl.com/news/power-without-pistons-gtt-cma-cgm-and-dnv-gl-present-lng-fuelled-turbine-powered-mega-box-ship-study-45289).
7	**Reduction of on-board engine and machinery noise**	• When properly designed, elastic mounting can lead to radiated noise level reduction of about 10 dB at medium frequencies and 20 dB at high frequencies for this noise component although the reduction overall might be lower (AQUO 2015). • Structural reinforcements of the main engine foundations can lead to reduction in underwater noise of 5 to 10 dB for frequencies over 100 Hz (AQUO 2015)		• elastic mounting high cost - limited to certain vessels (AQUO 2015) • adding structural reinforcements of the main engine to existing ships may be costly (AQUO 2015)			decreased on-board noise	• elastic mountings of 2-stroke engines currently not feasible (AQUO 2015)
8	**Changes to hull form**	• No studies found that show noise reduction effectiveness					• Improved wake field and efficiency, • may improve propeller efficiency as well	

Table A2 Evaluation Matrix for Vessel Quieting Methods Using Underwater Noise and Verifiability as Rating Criteria

#	Vessel Quieting Methods	Evidence of Noise Reduction Effectiveness	Noise Reduction Effectiveness SCORE	Verifiable	Verifiable SCORE	Total Score
1	**Regular propeller cleaning/repair**	High	3	Easy	3	**6**
2	**Regular cleaning of the hull**	Medium	2	Easy	3	**5**
3	**Hull coating**					
a	Decoupling coating	Medium	2	Easy	3	**5**
b	Anti-fouling paints	Low	1	Moderate	2	**3**
c	Non-stick coating	Low	1	Moderate	2	**3**
d	Biocides	Low	1	Moderate	2	**3**
e	Differential electrical charge	Low	1	Moderate	2	**3**
f	Prickly coating	Low	1	Moderate	2	**3**
4	**Propeller designed, selected or modified to reduce cavitation and improve wake flow**					
a	High skew propellers	Low	1	Easy	3	**4**
b	Contracted and loaded tip propellers (CLT)	Low	1	Easy	3	**4**
c	Kappel propellers	Low	1	Easy	3	**4**
d	New blade section propellers (NBS)	Low	1	Easy	3	**4**
e	Propeller Boss Cap Fins (PBCF)	Medium	2	Easy	3	**5**
f	Propeller Cap Turbine	Low	1	Easy	3	**4**
g	twisted rudder	Low	1	Easy	3	**4**
k	rudder fins	Low	1	Easy	3	**4**
l	Costa Propulsion Bulb (CPB)	Low	1	Easy	3	**4**
m	Schneekluth duct	Medium	2	Easy	3	**5**
n	Mewis duct	Medium	2	Easy	3	**5**
o	Simplified compensative nozzle	Low	1	Easy	3	**4**

#	Vessel Quieting Methods	Evidence of Noise Reduction Effectiveness	Noise Reduction Effectiveness SCORE	Verifiable	Verifiable SCORE	Total Score
p	Grothues spoilers	Low	1	Easy	3	**4**
q	Pre-swirl stators/vortex generators	Low	1	Easy	3	**4**
r	Air injection to propeller and bubble curtains	Medium	2	Easy	3	**5**
5	**Alternative form of propulsion to conventional propeller**	Low	1	Easy	3	**4**
6	**Use of quieter engines**					
a	Steam/gas turbines	Low	1	Easy	3	**4**
b	Diesel-electric	Low	1	Easy	3	**4**
c	LNG-fueled, gas and steam turbine powered (COGAS), and electrically driven	Medium	2	Easy	3	**5**
7	**Reduction of on-board engine and machinery noise**					
a	Elastic mountings	High	3	Hard	1	**4**
b	Structural reinforcements	High	3	Hard	1	**4**
8	**Changes to hull form**	Low	1	Hard	1	**2**