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SHIP OPERATIONS COOPERATIVE PROGRAM

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EXHAUST GAS CLEANING SYSTEMS SELECTION GUIDE

Prepared for
Ship Operations Cooperative Program (SOCP)

File No. 14136.01
9 July 2015
Rev. D

INNOVATIVE
MARINE
SOLUTIONS

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Corrections, suggestions for additional content, and installation experiences provided by web at http://www.socp.us or by email to programadmin@socp.us will be considered for future updates.

Revision History

Section	Rev	Description	Date	Approved
All	—	Initial release.	12 January 2011	KJR
Various	A	Administrative edits and added Non-OGV discussion item.	22 February 2011	KJR
All	B	Updated to reflect technology and installation developments since last guide release.	1 August 2012	KJR
Table 8	C	Table 7 was mistakenly repeated as Table 8. Inserted correct table.	1 December 2012	KJR
All	D	Updated to reflect technology, financial, and market developments since last release.	9 July 2015	KJR

Executive Summary

Since January 1st of 2015, ship operators trading in emissions control areas (ECAs) have been required to burn fuel with less than 0.1% sulfur content. This regulatory requirement, along with other international, federal, and regional requirements targeting sulfur, NO_x, and particulate emissions, require ship operators to thoroughly examine the compliance alternatives: burn higher-cost low-sulfur distillate fuel, burn low-cost no-sulfur natural gas, or use an Exhaust Gas Cleaning System (scrubber) so that they can continue to burn low-cost high-sulfur fuel oil. This Guide will assist members of the Ship Operations Cooperative Program (SOCP) in determining if a scrubber is a practical, lower-cost solution for all or a portion of their fleet to meet existing and future regulatory requirements.

The ship operator considering a scrubber faces a conflicting pair of recommendations. On the one hand, the fuel cost savings for those operating within an ECA can be so substantial that a scrubber may be a competitive necessity. On the other hand, installations are discouraged as technologies are still maturing; a significant burden is placed on ship arrangements and operations; and there remain environmental impact concerns.

The impact of a scrubber on ship arrangements, operations, and logistics is broad and pervasive. The machinery is large, affects key mechanical, electrical, and control systems, and, in the case of chemical based systems, requires logistics for bunkering and safe handling procedures. The ship operator installing a scrubber will need to return some of the significant fuel cost savings to overcome these challenges by investing in: a high level of engineering, installation, and commissioning support; ongoing technical support; initial and ongoing training; and possibly an increase in shipboard engineering staff.

A scrubber installation becomes compelling when a vessel burns more than 7,500 metric tons of fuel oil within an ECA annually. The breakeven point, where the fuel cost savings offsets the cost of installing and operating a scrubber, is typically reached when annual ECA fuel consumption reaches 4,000 metric tons. Fuel consumption above the amount provides the fuel cost savings. This metric is highly sensitive to the distillate fuel premium as compared to residual marine fuel oil and a company's internal discount rate. Considering the current distillate premium of $325 per metric ton and a 10% investment discount rate, a US West Coast containership burning 9,600 metric tons within an ECA annually can reduce annual operating expenses by approximately $2,600,000 – more than $7,000 per day. Should the distillate premium over residual increase to $425, the daily savings would increase to more than $9,500 per day. The operator should consider the competitive advantages of adopting the technology as well as the consequences of a competitor moving first.

A survey of eleven suppliers, see Appendix A, indicates that over 160 ships have been outfitted with scrubbers, many with multiple units, through March 2015. Since the last SOCP scrubber guide in 2012, there has been a significant shift away from open-loop technology towards hybrid scrubbers. This trend is significantly driven by wash water discharge concerns. In the case of open-loop scrubbers, seawater is taken into the ship, sprayed into the scrubbing tower, and then drained back to the sea. The US Environmental Protection Agency (EPA), for example, does not allow wash water discharges of less than pH 6.0 – which typical open-loop scrubbers cannot meet. The hybrid approach resolves this by temporarily switching to a closed-loop mode to retain that wash water and uses the addition of caustic chemical to maintain scrubbing efficiency.

Ship candidates that meet the following criteria are encouraged to analyze their specific applications and consider the installation of an exhaust gas cleaning system:

- The ship burns at least 7,500 metric tons of fuel oil annually within an ECA, for at least six years.
- A technical survey confirms that a scrubber can be integrated with ship arrangements, stability, and operations. For closed loop, hybrid, and dry chemical systems, supply chains are confirmed.

1. Regulatory Requirements

This section guides ship operators in identifying applicable air emissions requirements. Since January 1, 2015, any ship, existing or new, has been required to reduce sulfur oxide emissions to a fuel sulfur limit of 0.1% while operating in an emission control area (ECA), but other emissions requirements and applicability considerations must be examined as well. The geographic scope of these requirements is a patchwork that includes International Maritime Organization (IMO)-designated emissions control areas (ECAs), European Union (EU) designated port areas, US rules applicable to vessels with smaller engines, and a California State designated coastal zone.

Current ECAs include the Baltic Sea and North Sea ECA, the North American ECA, and the US Caribbean ECA. DNV GL suggests that Mexico and the Turkish Straits might be ECAs by 2018, and further ECAs could include Mediterranean, EU coastal waters, Singapore, Japan, and Hong Kong/Guangdong (Reference 104). Eventually, the ECA scope may include all coastal areas of the world.

The area outside of ECAs is subject to worldwide limits set by IMO. The current worldwide fuel sulfur limit of 3.5% is more generous than typical fuel quality, which averages 2.7% sulfur by weight. This limit changes, in practice, to a worldwide fuel sulfur limit of 0.5% in either 2020 or 2025, depending on a fuel availability review to be conducted in the interim.

IN-FORCE EMISSIONS CONTROL AREAS

- **BALTIC SEA (SO_X ONLY)**
- **NORTH SEA (SO_X ONLY)**
- **NORTH AMERICA (SO_X, NO_X, AND PM)**
- **UNITED STATES CARIBBEAN SEA (SO_X, NO_X, AND PM)**

POSSIBLE FUTURE ECAs

- **MEXICO**
- **TURKISH STRAIGHTS**
- **MEDITERRANEAN SEA**
- **EU COASTAL WATERS**
- **SINGAPORE**
- **JAPAN**
- **HONG KONG/GUANGDONG**

The following table summarizes the low sulfur phase-in dates specified in each of the presented regulations. The highlighted fuel limits, 0.5% sulfur and less, indicate distillate fuel grades.

Table 1 Low Sulfur Phase-In Dates

Sulfur Fuel Requirements	Operating Area				
Starting Year (January 1)	**Outside ECAs (%S in Fuel)**	**Inside ECAs (%S in Fuel)**	**EU Ports (%S in Fuel)**	**California Coastal (%S in Fuel)**	**US EPA Category 1 and 2 Vessels (%S in Fuel)**
2015	3.5	0.1	0.1	0.1	0.0015 (15 ppm)
2020 (2025) †	0.5	0.1	0.1	0.1	0.0015 (15 ppm)

† Implementation of Oceans Limits at 0.5% fuel sulfur subject to review in 2018

Existing ships are also required to achieve modest reductions in NO_x emissions—typically with on-engine modifications. New ships, especially starting with IMO Tier III requirements in 2016, will require advanced NO_x abatement technologies when operating in special NO_x ECAs. Section 2.2 outlines the challenges of integrating such advanced technologies with sulfur scrubbers.

The oceangoing vessel sulfur regulations were developed to reduce not only sulfur, but also particulate matter (PM). Emissions of PM, however, are not directly regulated or monitored.

Emission regulations are largely dependent on the vessel registry and operational area. The following section describes the requirements applicable to vessels based on their specific registry and operating area.

1.1 International Regulations and Emission Control Areas

Applicable Vessels

Ships operating on international voyages are generally subject to the agreements of the International Maritime Organization (IMO), including the *International Convention for the Prevention of Pollution from Ships* (MARPOL, Reference 0). *Regulations for the Prevention of Air Pollution from Ships* (Annex VI of Reference 47, henceforth referred to as simply “Annex VI”), which entered into force in 2005, includes: Regulation 12 Ozone Depleting Substances, Regulation 13 Nitrogen Oxides (NO_x), Regulation 14 Sulfur Oxides (SO_x) and Particulate Matter, and Regulation 15 Volatile Organic Compounds (VOCs). This guide discusses NO_x, SO_x, and particulate matter requirements.

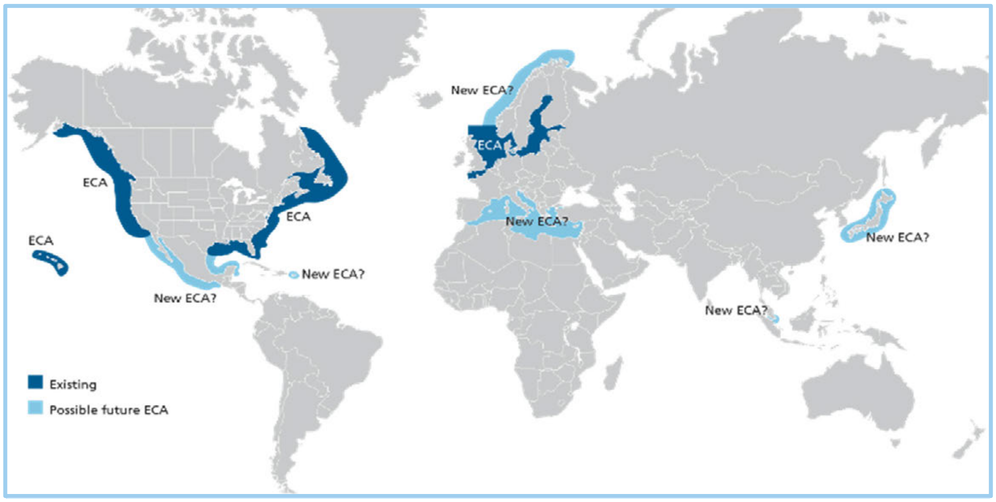


Figure 1 Current and possible future ECAs (source: DNV)

Flag State is a general term referring to the administration where a ship is registered. Flag States that are party to Annex VI are required to enforce the annex within the international *oceangoing* fleet that they administer. In some cases, such as the United States, the Flag State may have additional requirements.

Port State is a general term referring to an administration that controls a port or ports where ships registered by other administrations may call. Port States that are party to Annex VI have the right to board commercial ships arriving from international voyages to determine compliance with Annex VI. In general, the Port State will review required documentation and perform a visual inspection of any installed equipment.

Through Annex VI, the IMO also designates Emissions Control Areas (ECAs) with more stringent emissions requirements than in mid-ocean or non-ECA near-shore locations. Ships operating within ECAs are required to meet reduced emissions standards for SO_x and PM, NO_x, or both. Table 2 provides a list of ECAs that are currently in-force.

Table 2 In-Force Emissions Control Areas

Emissions Control Area	SO_x and PM (Effective Date)	NO_x (Effective Date)
Baltic Sea	19 May 2006	Not applicable.
North Sea	22 November 2007	Not applicable.
North America	1 August 2012	1 August 2012
US Caribbean Sea	1 January 2014	1 January 2014

Exemptions

There are numerous exemptions and exceptions from Annex VI. Ship operators considering such exemptions and exceptions should perform a detailed analysis of the Annex, and gain acceptance from their Flag State prior to implementing a strategy. In general, exemptions include vessels under 400 gross tons, diesel engines less than 130 kW output, technology research trials, emergency equipment, emergency situations, military and government vessels, and emissions from seabed mineral exploration. Additionally, there are exclusions based on geographical considerations such as transport on the US/Canada Great Lakes where regional agreements may be more appropriate.

An exemption until 2020 has been granted for existing vessels with steam propulsion boilers operating in the North American and US Caribbean ECAs.

Regulated Emissions

Sulfur and Particulate Matter (PM)

Annex VI provides a phased schedule for limiting sulfur emissions in ECAs and areas outside of ECAs (see Table 1). These requirements apply to *oceangoing* vessels over 400 gross tons operating in international trade.

Annex VI was developed with particulate matter control being a consideration. Specifically, Regulation 14 is titled “Sulfur Oxides (SO_x) and Particulate Matter.” However, there is no specific limit provided or monitoring required for particulate matter emissions. The annex intention is that the reduced sulfur in the fuel will result in a significant sulfur particulate load in the exhaust gas.

Nitrogen Oxides (NO_x)

IMO adopted a tiered system (see Figure 2) that has already required existing engines to make modest NO_x reductions and new engines since 2010 to achieve more significant reductions. Next year will find new engines having to be integrated with off-engine technologies to meet the vastly more restrictive Tier III requirements. The NO_x reductions are based on vessel build date, tonnage, length, and overall installed power, as well as individual engine power. It should be noted that the most stringent Tier III requirements are only applicable in NO_x ECAs.

Table 3 NO_x Emissions Applicability and Phase In (Annex VI and EPA Category 3)

Operational Area	Ship/Engine Particulars						Annex VI NO_x Requirement
	Build Date	**Gross Tons**	**LOA (m)**	**Total (kw)**	**Power (kw)**		
International	1/2000 – 12/2010	>400			>130		Tier I
International	Built after 12/2010	>400			>130		Tier II
NO_x ECA	Built after 12/2015	>400	>24	>750	>130		Tier III

IMO requires remanufactured engines installed on vessels built prior to 2000 to meet Tier I emissions levels, and for vessels built in 2000 or later to meet the current standard.

Table 4 IMO Major Conversion/Remanufactured Engine Tier Requirements

Registry	Operational Area	Ship/Engine Particulars				Requirement
		Build Date		**Gross Tons**	**Major Conversion/ Remanufacture Date**	
All	International	before	Jan. 2000	>400	Any	Annex VI Tier I
All	International	after	Dec. 1999	>400	Jan. 2000 to Dec. 2010	Annex VI Tier I
All	International	after	Dec. 1999	>400	after Dec. 2010	Annex VI Tier II
All	ECA	after	Dec. 1999	>400	after Dec. 2015	Annex VI Tier III

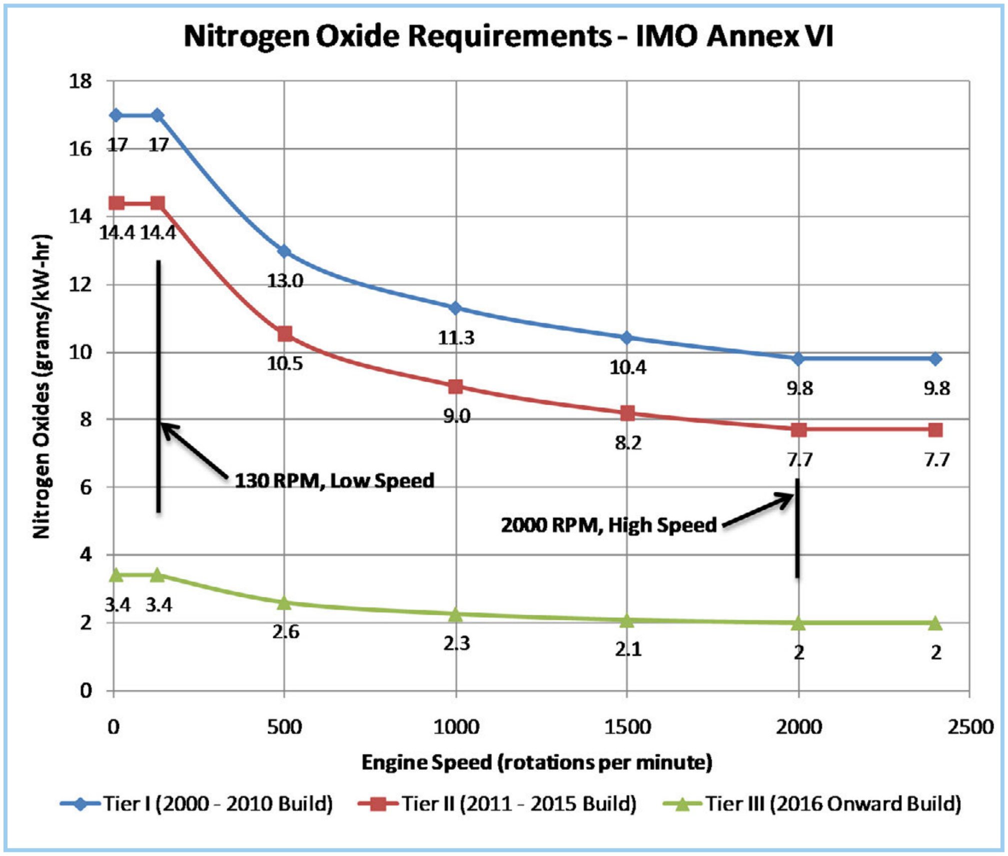


Figure 2 IMO Annex VI Tier NO_x Requirements

1.2 Federal Regulations — United States

Applicable Vessels

The *Act to Prevent Pollution from Ships* (Reference 114) is a US federal law that was last amended in 2008 to require the US Environmental Protection Agency (EPA) and US Coast Guard to implement Annex VI and enforce the provisions upon foreign vessels through port state control measures and upon US-registered domestic vessels. As a result, EPA developed domestic regulations that are aligned with Annex VI for oceangoing vessels. The EPA rule for this ship category, *Control of Emissions from New Marine Compression-Ignition Engines at or Above 30 Liters per Cylinder* (40 CFR Parts 80, 85, 86, et al, Reference 2) took effect in 2010.

These US domestic regulations are based on engine cylinder volumes rather than the international standard of engine speed. EPA refers to “Category 3” ships as those with at least one engine with cylinder displacements above 30 liters (see Table 5). The domestic rules also differ from Annex VI by requiring engine manufacturers to measure PM from engines operating on distillate fuel and adding limits on hydrocarbon and carbon monoxide emissions.

Table 5 EPA Engine Categories (40 CFR §142.1)

Engine Category	Maximum Engine Power	Displacement (D) [L/cyl]	Model Year
Category 1	kW <75	D <0.9	2009+
	75 ≤kW ≤3700	D <0.9	2012+
		0.9 ≤ D <1.2	2013+
		1.2 ≤ D <2.5	2014+
		2.5 ≤ D <3.5	2013+
		3.5 ≤ D <7.0	2012+
	kW >3700	D <7.0	2014+
Category 2	kW ≤3700	7.0 < D <15.0	2013+
	kW >3700	7.0 ≤ D <15.0	2014+
	All	15 ≤ D <30	2014+
Category 3	All	D ≥ 30	2011+

Exemptions

EPA has included two important exemptions for oceangoing vessels in §1042.650 of the rule:

- A vessel that employs Category 1 or 2 propulsion engines, rather than Category 3 propulsion engines, can apply for the “SOLAS exemption” provided that it operates for extensive periods outside of the United States. In other words, it can generally meet the IMO requirements rather than the EPA requirements. However, this EPA exemption requires documentation of compliance with the equivalent of Annex VI emissions and fuel usage.
- An oceangoing vessel that operates a Category 3 engine can certify its smaller Category 1 and 2 engines in accordance to Annex VI, rather than meeting the EPA Equipment Manufacturers Institute (EMI) certification for its Category 1 and 2 engines.

Regulated Emissions

Sulfur

The EPA has mandated that marine fuel for Category 1 and 2 engines be ULSD, or less than 15 ppm (0.0015%) sulfur. Category 3 vessels can still obtain higher sulfur fuels.

NO_x and Particulate Matter

<u>Oceangoing Vessels</u>

IMO and EPA NO_x abatement requirements have been largely synchronized for large oceangoing vessels (see Table 3 and Figure 2).

The EPA requires remanufactured engines over 600 kW to meet the tier requirements to which they were originally certified, and to reduce their particulate emissions by 25%—except for Tier 3 engines, which only need to maintain Tier 3 emissions. Additionally, EPA has set limits of 2.0 and 5.0 grams per kilowatt-hour for

HC and CO respectively. Time-phased exemptions for older ships also exist, specifically for engines manufactured prior to 1990.

Table 6 EPA Major Conversion/Remanufactured Engine Tier Requirements

Registry	Operational Area	Engine Particulars			Requirement
		EPA Tier	Power (kW)	Remanufacture Date	
US	Domestic	Tier 0	>600	before Jan. 2000	Tier 0+ (25% NO_x Reduction)
US	Domestic	Tier 1	>600	after Jan. 2000	Tier 1+ (25% NO_x Reduction)
US	Domestic	Tier 2	>600	after Jan. 2013	Tier 2+ (25% NO_x Reduction)
US	Domestic	Tier 3	>600	Any	Tier 3

<u>Domestic Operations</u>

The EPA has set forth a NO_x abatement implementation schedule for Category 1 and 2 engines. This schedule is dependent on engine power and bore size. It should be noted that these requirements might not apply to oceangoing vessels. Please refer to EPA regulations for details.

In general, Tier 1 requirements are similar to the IMO Annex VI Tier I requirements. Tier 2 and Tier 3 regulation incrementally reduce emissions with the intent that manufacturers can meet the requirements through modifications to piston rings, cylinder walls, timing, and fuel management. This is similar to the intent of IMO Annex VI Tier II requirements.

EPA Tier 4 emissions limits will require engines to use after-treatment devices, as the emissions limits are similar to the IMO Annex VI Tier III requirements. Specific EPA emission requirements including NO_x, HC, and PM limits can be found in 40 CFR Parts 9 and 85.

Table 7 EPA vessel emission requirements for domestic vessels (40 CFR §142.101)

			Ship/Engine Particulars			Emission Requirements		
EPA Tier	**EPA Engine Category**	**Power Density / Application**	**Displacement (D) [L/cyl]**	**Max Engine Power**	**Engine Model Year**	**PM [g/kW-hr]**	**NO_x [g/kW-hr]**	**HC [g/kW-hr]**
Tier 3	*Category 1 kW < 3700*	All	D < 0.9	kW < 19	2009+	0.40	7.5 (NO_x + HC)	
				19 ≤ kW < 75	2009-2013	0.30	7.5	
					2014+	0.30	4.7	
		Commercial engines with kW/L ≤ 35	D < 0.9	kW ≥ 75	2012+	0.14	5.4	
			0.9 ≤ D < 1.2	All	2013+	0.12	5.4	
			1.2 ≤ D < 2.5	kW < 600	2014-2017	0.11	5.6	
					2018+	0.10	5.6	
				kW ≥ 600	2014+	0.11	5.6	
			2.5 ≤ D < 3.5	kW < 600	2013-2017	0.11	5.6	
					2018+	0.10	5.6	
				kW ≥ 600	2013+	0.11	5.6	
			3.5 ≤ D < 7.0	kW < 600	2012-2017	0.11	5.8	
					2018+	0.10	5.8	
				kW ≥ 600	2012+	0.11	5.8	
		Commercial engines with kW/L > 35 and all recreational engines	D < 0.9	kW ≥ 75		0.15	5.8	
			0.9 ≤ D < 1.2	All	2013+	0.14	5.8	
			1.2 ≤ D < 2.5		2014+	0.12	5.8	
			2.5 ≤ D < 3.5		2013+	0.12	5.8	
			3.5 ≤ D < 7.0		2012+	0.11	5.8	
	Category 2 kW < 3700	All	7.0 ≤ D < 15.0	kW < 2000	2013+	0.14	6.2	
				2000 ≤ kW < 3700		0.14	7.8	
			15.0 ≤ D < 20.0	kW < 2000	2014+	0.34	7.0	
			20.0 ≤ D < 25.0			0.27	9.8	
			25.0 ≤ D < 30.0			0.27	11.0	
Tier 4	*Category 2 and Commercial Category 1 kW > 600*	All	All	600 ≤ kW < 1400	2017+	0.04	1.8	0.19
			All	1400 ≤ kW < 2000	2016+	0.04	1.8	0.19
			All	2000 ≤ kW < 3700	2014+	0.04	1.8	0.19
			D < 15.0	kW ≥ 3700	2014-2015	0.12	1.8	0.19
			15.0 ≤ D < 30.0			0.25	1.8	0.19
			All		2016+	0.06	1.8	0.19
Optional Tier 3	*Category 2*	All	All	kW ≥ 1400	2012-2014	0.14	7.8	
Optional Tier 4	*Category 2*	All	All	1400 ≤ kW < 3700	2015	0.04	1.8	0.19
				kW ≥ 3700		0.06	1.8	0.19

For specific exceptions and engine particulars not covered by this table, see 40CFR § 1042.101.

1.3 Regional Requirements

Ships are also subject to regional requirements depending on their operating location. Most regional requirements are driven by demands particular to the people living in those areas and, in some cases, topography that results in acute impact of air emissions on local population health. The Los Angeles basin is a primary example of regional requirements, where air quality is poor, population density is high, and the public is politically engaged on environmental issues.

Regional requirements are the most likely to change in a short timeframe. Such changes provide significant challenges to ship operators that are making air emissions abatement decisions. As such, the ship operator should understand the requirements of various port locations at which they are likely to call.

California Coastal Zone

The State of California requires the use of low-sulfur distillate marine fuel oil while operating within its 24 nautical mile coastal zone, including 24 nautical miles from the shoreline of each of the Channel and Farallon Islands. California oceangoing vessel requirements have, historically, been adjusted to align more closely with the North American ECA requirements; for example having matched the 1% sulfur requirement in August 2012. California did push ahead of IMO based ECA requirements by moving to 0.1% sulfur fuel one year earlier in 2014. It is the intent of California to sunset the state program once the North American ECA enforced equivalent emissions reductions, which occurred when the ECA fuel sulfur limit was lowered to 0.1% on January 1st, 2015. California Air Resources Board (CARB) is currently conducting a sunset review to assess if the federal regulations are achieving an equivalent emissions reduction and are being enforced within CARB Regulated California Waters. The review expected completion date of April 2015 is pending. For the time being, operators must meet both California and federal requirements.

European Union Ports

Ships calling in European Union (EU) ports that are located within the Baltic and North Sea ECA areas, such as Tallinn and Rotterdam, must comply with the current 0.1% sulfur limit at all times. In addition, the EU limits fuel sulfur content to 0.1% for ships at berth and inland waterways even outside of the ECA areas. In addition, the EU limits RoRo Passenger vessels operating within EU territorial seas to 1.5% sulfur. The EU also appears committed to implementing the 0.5% sulfur limit in 2020.

NO_x Abatement

There do not appear to be regional requirements for NO_x abatement that are applicable to oceangoing vessels.

1.4 Effluents

Similar to air emissions regulations, effluents are also governed by an overlapping set of international, federal, and regional rules and regulations. These requirements are relevant as the majority of the exhaust gas cleaning systems includes a wet component, and the resulting effluent. Section 4, Scrubber Compliance Requirements and Challenges, describes effluent requirements for scrubbers as well as no-discharge zones.

2. Compliance Options

Ship operators have several options for complying with the low-sulfur fuel requirements:

- **Fuel Switching**: Install secondary low-sulfur fuel storage capacity and piping systems. Convert combustion equipment for compatibility with both low- and high-sulfur fuel. The ship will then burn low-sulfur fuel when operating inside emission-regulated regions, and high-sulfur fuel when outside those regions.
- **Conversion to Distillate Only**: Convert all fuel storage tanks, fuel piping systems, and combustion equipment for compatibility with low-sulfur fuel. The ship will then only burn low-sulfur fuel oil.
- **Conversion to Natural Gas***:* Install natural gas storage tanks, convert piping and engines to handle natural gas, install natural gas bunkering stations, and complete hazard assessment and training requirements.
- **Exhaust Gas Cleaning System (scrubber)**: Install a scrubber to scrub sulfur oxides (SO_X) that result from burning high-sulfur fuel when operating inside emission-regulated regions.

In making the transition to exhaust gas cleaning systems, various ship operators have had success in obtaining exemptions to the low-sulfur fuel requirements from US EPA. These exemptions provide time for the operator to phase-in these new technologies over their vessels.

Table 8 Sulfur emissions compliance options

	Compliance Options			
	Fuel Oil Switching	**Conversion to Distillate Only**	**Conversion to Natural Gas**	**Exhaust Gas Cleaning System**
Emissions Control Area Operations	Burn Low-Sulfur Fuel	Burn Distillate	Burn Natural Gas	Burn High-Sulfur Fuel Scrubber ON
Non-Controlled Area Operations	Burn High-Sulfur Fuel	Burn Distillate	Burn Natural Gas	Burn High-Sulfur Fuel Scrubber OFF
Advantages	Low Cost Fuel in Non-Controlled Areas	Simplified Fuel and Waste Stream Operations	Low-Cost Fuel in All Areas, Clean Burning	Low-Cost Fuel in All Areas
Challenges	High-Cost Fuel in ECAs; Risks Inherent with Fuel Switching	High Fuel Cost	High Capital Cost, Complex Gas Handling Logistics and Equipment	Complex Operations, High Capital Cost, and Waste/Chemical Management

The term "distillate" is used in this report to refer to light, refined diesel fuel with a sulfur content of 0.5% or less. This fuel is called marine gas oil (MGO) in the industry, and is also known as ISO DMA. Although inclusive of some residual content marine diesel oil (MDO), or ISO DMB, is also considered "distillate," provided sulfur contents are below 0.5%.

The term "residual" is used to refer to the lesser-refined heavy fuel oils, which currently have sulfur contents on average of 2.7%. Industrial names for the residual marine fuel oil or heavy fuel oil (HFO) diesel grades are IFO180 and IFO380, corresponding to ISO grades RME25 and ISO RMG35 respectively.

A new grade of fuel oil, i.e. ExxonMobil HDME 50, is now offered that meets the low-sulfur requirements associated with distillate, and the higher flashpoint and lower volatility associated with residual fuel oils.

2.1 Fuel Oil Switching

Fuel switching to low-sulfur fuel oil distillates when entering port has been practiced for decades by vessels calling in California waters. More recently, fuel switching has been performed since 1 January 2015 for most oceangoing vessels entering the North American ECA. When the ship reaches a specified distance from an emissions control area (ECA), it initiates the process of switching from burning high-sulfur fuel oil to burning low-sulfur fuel oil. The duration of the switchover typically takes about two hours, depending on system component size and fuel burn rate.

Do new high-viscosity, low-sulfur fuels matter?

The refining industry has developed and released a new class of fuel oils that have less 0.1% sulfur, but maintain flash point and viscosity characteristics similar to residual fuel oil.

These fuels do matter, as they reduce safety hazards associated with switching over from heated residual fuel oils to distillates that are dangerous if heated. These designer fuels also resolve the lubricity issues with additives.

Don't expect a price break, however, as they cost as much as distillate. Also, stay tuned to potential lessons learned with these new products.

The switching to low-sulfur fuel, 0.1% sulfur within the ECA, is the most direct method to comply with the applicable regulations. In other words, the regulations are written as fuel requirements. The vessel operator is compliant through documenting the position and time of the fuel switching, and by maintaining received bunker delivery notes (BDNs) and corresponding samples for a minimum of three years.

The advantage of the fuel oil switching method is that it requires relatively minor modifications, and the vessel can continue to burn lower cost high-sulfur fuel when outside of ECAs for at least the next five years. The disadvantage is that the vessel must burn the higher cost low-sulfur fuel while within the ECA. Of course, the magnitude of the disadvantage is proportional to the amount of fuel burned within the ECA.

There are several challenges with fuel oil switching. The first is related to the BDNs and sampling. While seemingly simple to just get a receipt and take a sample, it has been easier said than done. Vessel operators have received off-specification bunkers, such as the "cappuccino" effect where air appears to have been added to the bunkers in an effort to increase the apparent volume of bunker loaded. More common has been BDNs reporting sulfur contents a bit lower than independent testing has shown. IMO's *MEPC Circular 508, Bunker Delivery Note and Fuel Oil Sampling* (Reference 106) provides a summary of requirements. Various class and association publications, such as BIMCO's *Bunkering Guide* (Reference 91), provide advice and best practices.

The API Technical Issues Workgroup's *Technical Considerations of Fuel Switching Practices* (Reference 0) and the ABS *Fuel Switching Advisory Notice* (Reference 0) both provide guidance on the below topics related to propulsion shutdown issues such as:

- Sticking/scuffing of fuel injection components due to thermal shock or reduced viscosity and lubricity, and the incompatibility of fuels being switched (causing complete fuel pump seizure).
- Mismatched crankcase or cylinder lubrication oil resulting in accelerated piston/liner wear.
- Liner lacquering resulting in difficulties maintaining oil film thickness.

These risks can be mitigated by a combination of the installation of special equipment and the modification of operational procedures. The extent and nature of conversion required for a vessel will be determined by the type of equipment installed on the vessel, and the arrangement of the affected systems. For vessels not already outfitted with special fuel switching equipment, modification costs will generally range from $15,000 to $80,000. This assumes that the vessel has the appropriate tank capacity to carry the two fuel types.

2.2 Conversion to Distillate

There are some vessels that have traditionally burned only higher-cost, low-sulfur distillate fuel oil. Reasons have typically been due to frequent speed changes or low load operations, or a focus on reliability and reduced maintenance. For vessels that operate significantly within an ECA, it might be an advantage to permanently switch over to only distillate fuel oil. This is similar to fuel oil switching, but without the switching back to lower-cost, high-sulfur fuel oil.

The advantage to this conversion is primarily simplicity. Distillate fuel oil does not require heating, requires significantly less purification as compared to residual fuel, and tends not to wear out diesel engine components as quickly. In addition, the risks associated with switching between fuel grades is eliminated. The primary disadvantage is that the vessel burns the high-cost, low-sulfur fuel at all times – even when outside of the ECA.

The conversion requires moderate modifications, primarily focused on removing or securing heavy fuel oil heating devices and processing equipment. A challenge is that more distillate fuel is required per volume measurement to get the same energy value. In some cases, this could mean that the vessel cannot make full speed without refitting some of the piping system.

2.3 Conversion to Natural Gas

A vessel operator has the option of converting the fuel system and engines to burn natural gas that has virtually no sulfur content. The current low cost of natural gas presents the ship operator with an advantage in that this low-sulfur solution is also similar to operating expenses as residual fuel oil. A further advantage, although not yet widely proven, is expected lower maintenance costs with natural gas engines as compared to those burning residual fuel oil.

There are two variations of a natural gas conversions: gas only and dual fuel. In the gas only, the engines are spark ignited and not capable of burning diesel fuel oil. The dual fuel engines are diesel pilot compression ignited, and typically can switch between diesel fuel oil and natural gas. The primary disadvantage of natural gas is the limitations in supply chain currently. There is significant effort to develop shore and barge based bunkering solutions, but only limited options available to date.

The primary challenge with natural gas is finding the room on an existing vessel for the gas storage tanks. These tanks typically require seven times the cubic footprint of vessel space, as compared to diesel fuel oil tanks. In addition, conversions can be very expensive depending on particulars. One current example of a conversion are the TOTE Orca Class Ro/Ro vessels. They are early candidates as they run exclusively within an ECA, have significant fuel consumption, a means of quickly moving tankage aboard, and have a fixed route that supports installing dedicated infrastructure.

2.4 Exhaust Gas Cleaning Systems

Exhaust gas cleaning systems (scrubbers) are devices designed to remove sulfur oxides (SO_x) to at or below regulatory emissions limits. Typically, the scrubber consists of a vessel where seawater or caustic soda contacts and removes the SO_x from the exhaust gas stream. The resulting wash water is then either held, or treated to acceptable discharge limits and pumped overboard. There is also a dry type scrubber where a solid caustic is used to absorb the SO_x from the exhaust gas.

As an alternative to utilizing low-sulfur fuel, the IMO, through Annex VI, and EPA, through its Category 3 engine final rule, both recognize scrubbers as acceptable emissions abatement methods, provided they achieve reductions in sulfur emissions at least as effective as that obtained by using low-sulfur fuel. The European Union (EU) port locations also permit the use of exhaust gas cleaning systems as a means of sulfur abatement while operating in ports or inland waterways. The California Coastal Zone does not specifically allow scrubbers as an alternative to burning low-sulfur distillate marine fuel oils; however, there is a Temporary Experimental or Research Exemption that provides for their use during development and testing of scrubber technology.

The advantages, disadvantages, and in particular compliance requirements is discussed in the following Section 3 – EGCS Compliance Requirements and Challenges.

New technologies are offering fresh views on how to scrub, including PM removal and use of seawater in closed loop circuits.

One of these makers, Clean Marine, uses seawater in its closed-loop configurations. This eliminates the need to consume fresh water. However, that comes at a price as it takes a lot more caustic soda to change the pH in seawater as compared to freshwater.

Saacke is removing the PM prior to its wet scrubber. As much of the sulfur from the fuel oil is in the sulfur based particulate, this can reduce scrubber water pH demand.

2.5 EPA Low-Sulfur Fuel Oil Exemptions

Several ship operators, including Royal Caribbean and Carnival, have obtained exemptions from the US EPA, as allowed under MARPOL Annex VI Regulation 3.2, from the low-sulfur fuel oil program in order to conduct scrubber trial program. EPA explains the RCCL exemption as follows: “Royal Caribbean’s research program has developed exhaust gas scrubber technology that has the potential to provide greater emission reductions than would be achieved using only ECA compliant low-sulfur fuel, and at a much lower cost.”

The Carnival exemption covers 32 ships that started fitting with scrubbers in 2014 and due to complete in 2016. The RCCL exemption covers 19 ships.

3. Life Cycle Case Studies

Five vessels were selected to support life cycle case studies, each selected to examine the impact of key characteristics. The life cycle cost analysis are located in Section 6 of this Guide, following descriptions of the scrubber technologies.

3.1 Transpacific Containership

This 4,000-TEU ship transits between Shanghai, China; Los Angeles, California; and Oakland, California in a round trip of 25 days at 23 knots. It operates a 36-megawatt propulsion plant at 30.2 megawatts to maintain speed. A combined 3,000-kilowatt ship's service plant typically runs at 1,200 kilowatts, increasing to 2,000 kilowatts while in port.

Annual fuel consumption is estimated at 34,900 metric tons total, of which 3,900 metric tons is consumed within the ECA. It is assumed that one scrubber will serve the one propulsion engine and second scrubber will serve the three ship's service engines. Operating, maintenance, and repair (OM&R) expenses are considered low as the system is infrequently operated.

Figure 3 Transit Route from transpacific containership

3.2 Containership US West Coast

This 2,000-TEU ship transits between Tacoma, Washington and Anchorage, Alaska in a round trip of 7 days at 20 knots. It operates a 16-megawatt propulsion plant at 14.7 megawatts to maintain speed. A combined 3,000-kilowatt ship's service plant typically runs at 800 kilowatts, increasing to 1,600 kilowatts while in port.

Annual fuel consumption is estimated at 19,000 metric tons total, of which 9,600 metric tons is consumed within an ECA. This assumes that the ship diverts course to outside of the ECA for 50% of its voyage to reduce distillate fuel consumption. Switching to a scrubber would eliminate the need for this course diversion. One scrubber will serve the one propulsion engine and second scrubber will serve the three ship's service engines. OM&R expenses are considered moderate as the system is operated approximately half time.

3.3 Tankship US West Coast

This 60,000-DWT product carrier transits between Anacortes, Washington and Long Beach, California in a round trip of 8 days at 14.5 knots. It operates a 10-megawatt propulsion plant at 9 megawatts to maintain speed. A combined 3,000-kilowatt ship's service plant typically runs at 350 kilowatts, increasing to 2,350 kilowatts while in port.

Annual fuel consumption is estimated at 10,800 metric tons, all of which are within the ECA. One scrubber will serve the one propulsion engine and second scrubber will serve the three ship's service engines.

3.4 Cruise Ship North America

Figure 4 Transit Routes for US West Coast Container and Tankers, with North American Cruise Ship

This 11,000-DWT and 2,200-passenger capacity cruise ship serves North America. The cruise ship transits between Seattle, Washington; various ports in Alaska; and Victoria, British Columbia in a round trip of one week with transits at just under 20 knots. It operates three 10.5-megawatt propulsion generators, typically at 24.7 megawatts. Ship's service is provided by two 7.5-megawatt ship's service generators typically operating at 9.0 megawatts.

Annual fuel consumption is estimated at 37,700 metric tons, all of which are within the ECA. One scrubber will serve the three propulsion generators, and a second scrubber will serve the two ship's service generators. Installation expenses are considered high due to the complexity of fitting a very large propulsion plant into relatively small machinery spaces.

3.5 Bulker US Great Lakes

This 80,900-DWT, self-unloading bulk carrier transports bulk cargo throughout the Great Lakes. The route detailed is an average length coal delivery route between Duluth, Minnesota and St. Clair, Michigan in a round trip of 5.5 days at 14 knots. It operates four 2.6-megawatt propulsion engines at a total of 9.72 megawatts to maintain speed. A combined 1,200 kW ship's service plant typically runs at 350 kW, increasing to 1,000 kW while in port. Great Lakes ships are normally laid up for less than three months a year while the lakes are frozen over.

Annual fuel consumption is estimated at 10,067 metric tons, all of which are within the ECA. Two scrubbers will serve the four propulsion engines, and a third scrubber will serve the two ship's service engines. Installation expenses are considered high due to the complexity of integrating a total of six engines into three scrubbers.

Figure 5 Great Lakes Bulk Carrier

4. Scrubber Compliance Requirements and Challenges

Exhaust gas cleaning systems (scrubbers) are devices designed to remove sulfur oxides (SO_x) to at or below regulatory emissions limits. Typically, the scrubber consists of a vessel where seawater or a caustic soda solution contacts and removes the SO_x from the exhaust gas stream. The resulting wash water is then either treated and recirculated, or treated to acceptable discharge limits and pumped overboard. One supplier offers a dry technology, in which dry calcium hydroxide granulates absorb the SO_x from the exhaust gas. A new entry to the market offers a membrane technology.

4.1 Meeting Emissions Requirements

Sulfur

The environmental regulations described in Section 1 require ship operators to burn low-sulfur fuel as a means of reducing sulfur-oxide emissions, or use an acceptable alternative. As discussed in Section 2, scrubbers are accepted by the IMO, EPA, California, and EU ports as an alternative. The international basis for this acceptance are the criteria provided in the IMO *2009 Guidelines for Exhaust Gas Cleaning Systems* that specifies the process for testing, certification, and verification. The Guidelines provide specific requirements for measuring of the sulfur content in the exhaust gas and monitoring wash water discharge quality, including pH changes and contaminant levels. The EPA's Vessel General Permit (VGP) provides the US federal basis, differing from the Guidelines in several important ways. The guidelines and the VGP continue to evolve as technology providers gain application experience and, as a result, administrations propose clarifications to IMO and EPA works towards its 2018 version of the VGP.

Figure 6 Selective Catalytic Converter, Clogged by Sulfates (Photo by MAN Diesel & Turbo)

Specific to sulfur compliance, the options are detailed in the Guidelines and termed Scheme A – Type Approval, and Scheme B – Continuous Emissions Monitoring (CEM). The Scheme A approach demands a significant testing and approval process resulting in a Type Approval. The Scheme B approach requires the use of sophisticated emissions monitoring equipment.

NO_x

Ship operators should consider requirements for the abatement of NO_x when selecting a suitable sulfur abatement strategy. In general, sulfur scrubbers are compatible with on-engine NO_x abatement strategies, such as engine tuning, that target currently enforced IMO Tier I/II and EPA Tier 1/2/3 emission limits. These on-engine strategies are typically compatible with sulfur scrubbers as their upstream location avoids concerns with pressure drops, temperature losses, and potential moisture content challenges.

However, most sulfur scrubbers are not compatible with NO_x abatement strategies, such as selective catalytic reduction (SCR), that target the IMO Tier III and EPA Tier 4 NO_x requirements that phase-in starting in 2016. Selective catalytic reductions work best with hot, dry, low-sulfur exhaust streams. A selective catalytic reduction located upstream of a sulfur scrubber might become clogged with sulfates. An SCR located downstream of a wet type scrubber would not be effective, as high exhaust temperatures are required to activate the SCR catalyst that reduces the nitrogen oxide emissions. In addition, the combined scrubber and SCR use would likely require fan use to avoid excessive backpressure on the engines.

The higher Tier III NO_x requirements are only required for new vessels and repowers starting in 2016, and only those operating in a NO_x ECA such as North America or the Caribbean. As such, NO_x requirements will not significantly affect the adoption of sulfur scrubbers until 2016 and only in the North American market. During this interval, it is possible that technologies such as exhaust gas recirculation that are compatible with scrubbers may be proven as reliable and capable of meeting emissions requirements. Further, such technologies as dry chemical scrubbers that are compatible with SCR technology may also prove reliable.

Particulate Matter

Sulfur regulations were initially developed as fuel standards, as the sulfur is not consumed in the combustion process, but rather passed into the air as sulfur oxides and sulfur based particulate matter. The scrubber alternative was accepted under the assumption that it would provide a similar level of emissions reductions. However, the sulfur-based fuel standard included an expectation that a significant reduction in particulate matter emissions would also occur. The expectation of particulate matter (PM) reduction is included in the Annex VI heading covering sulfur reductions, but there is no explicit PM reduction requirement. This creates uncertainty, as requirements for PM reductions could be included in future scrubber requirements.

Particulate matter are a small discrete masses of solid or liquid matter that remains individually dispersed in gas emissions (usually considered an atmospheric pollutant). In terms of air quality, PM can be smoke, soot, spores, dust, aerosols, fumes, and mists; some particulates are large enough to be seen, while others cannot be seen without the aid of a microscope. Two main standards exist for the measurement of particulate matter: PM_{10} and $PM_{2.5}$. Research into “ultrafine particulate,” which is less than 100 nanometers and its impact on health is ongoing.

PM_{10} are particles between 2.5 and 10 micrometers in diameter or coarse particles. They are generally the result of smoke, dirt, and dust from factories, farming, and roads; mold, spores, and pollen; and are made by crushing and grinding rocks and soil, then blown by the wind. These smaller particles particularly affect sensitive population groups such as children and people with respiratory diseases.

$PM_{2.5}$ are particles less than 2.5 micrometers in diameter, or fine particles. $PM_{2.5}$ is believed to pose the greater health risks than PM_{10}, as their small size (less than one-seventh the average width of a human hair) means that they can travel deeply into the respiratory tract and affect respiratory and cardiovascular health on a long-term basis. This pollutant is of most concern for people’s health when the levels in the air are high. $PM_{2.5}$ comes primarily from engine emissions, toxic organic compounds, smelting and processing heavy metals, and burning plants (References 0 and 0).

Though the EPA currently recognizes Regulation 4 of Annex VI that permits the use of scrubbers as an alternative means of emissions compliance, the organization is currently in a program that is evaluating the efficiency of PM_{10} and $PM_{2.5}$ reduction resulting from diesel combustion of low-sulfur fuels. It is possible that a

PM limit will be added to scrubber requirements. There is uncertainty as to the efficacy of scrubber in the removal of particulate matter, in particular $PM_{2.5}$.

At the same time, it is possible that scrubbers may reduce black carbon from marine exhaust emissions. Black carbon consists of ultra-fine particulate matter that can travel long distances and settle on the polar ice caps. Ice caps that are not covered by black carbon will reflect a high portion of the sun's radiation energy, a high albedo effect. In the case of ice caps covered with black carbon, more radiation is adsorbed which accelerates melting rates. IMO is currently considering the impact of black carbon from international shipping.

4.2 Sludge Residues

Scrubber systems typically generate sludge residues as a result of processing open and/or closed-loop wash water. The residue is the result of particulate captured in the scrubbing process, and being centrifuged, filtered, or settled out of the wash water stream. This is not applicable to the dry or membrane technologies.

The removal efficiency of open-loop scrubbers wash water processing plants tends to be low, as there is a tremendous amount of wash water passing through the system. For example, a 12 MW plant might see a flow rate of 600 cubic meters of wash water per hour that requires treatment. By comparison, that same plant operating in closed-loop might only process 2 cubic meters of "bleed off" wash water per hour. The greatly reduced closed-loop bleed off rate allows much greater processing efficiency. For example, open-loop processing might only produce 0.05 kg of sludge per MW-hr of engine operation, whereas closed loop might gain twenty-times this concentration (Wärtsilä March 2015 correspondence).

A notable exception is that some open-loop systems do not process the wash water, thereby producing no residue. This raises a significant question: What is different with these systems that they do not need to process the wash water, producing a sludge residue? What is likely is that these systems are not different, but simply that the great volume of wash water relative to contaminants in the exhaust gas results in acceptable concentrations for the IMO monitored parameters of turbidity and PAH (Polycyclic Aromatic Hydrocarbons). What is not as clear are the implications of various near-shore wash water criteria, discussed later in Section 4.4 – Wash Water.

Sludge residue is typically captured in totes for landing ashore or tanks for pumping ashore similar to sludge residue from fuel and lube purifiers. The content is typically 10% solids and the remainder liquid. The sludge typically contains trace heavy metals such as vanadium and nickel, as well as low concentrations hydrocarbons (Delft, March 2015). The IMO Guidelines prohibit the combustion of this sludge on board the ship or discharge overboard. It must be landed ashore. When landed ashore, it will not likely have adequate hydrocarbon concentration for use in fuel mixtures. It might also require special handling due to the metals concentration. Scrubber makers and ship operators indicate that sludge handing facilities are accepting scrubbers sludge residues. These transfers must be recorded in the Exhaust Gas Cleaning Record Book.

4.3 Wash Water pH Restrictions

This section identifies the regulatory requirements for scrubber effluent pH, or relative acidity of the wash water. These requirements are most relevant to open loop scrubbers, which continuously discharge overboard. Closed loop and hybrid scrubbers have the ability to run in zero discharge mode, able then to at least temporarily operate even in the most restrictive waters. Wash water restrictions, including the following no-discharge and monitoring sections, are not applicable to the dry or membrane technologies.

International Effluent Requirements

The international effluent requirements particular to scrubbers are provided in the IMO *2009 Guidelines for Exhaust Gas Cleaning Systems* (MEPC.184(59)). The Guidelines provide effluent limits for pH, PAH, nitrates, turbidity, and temperature.

Currently the Guidelines allow pH to meet a limit of 6.5 at a point 4 meters from the discharge pipe. This 4 meter distance means that an open-loop scrubber might actually be discharging wash water with a pH as low as 3.0 before being diluted in the receiving water. However, demonstrating the dilution at this off-ship distance is difficult and generally impractical as the ship would generally be underway if the scrubber was fitted to the propulsion engine.

The Marine Environmental Protection Committee (MEPC) sub-committee on Pollution Prevention and Response (PPR) took up the dilution discussion in January 2015. It was decided to allow modeling and calculation methods, along with titration curves and pH normalization to demonstrate expected dilutions to the required pH minimum of 6.5 at 4 meters from the discharge pipe.

U.S. Federal Effluent Requirements

Discharges into U.S. waters, within three (3) nautical miles of the coastline, must comply with the Environmental Protection Agency (EPA) Vessel General Permit (VGP), last updated in 2013. In addition to twenty-six (26) other discharges incidental to marine vessels, the EPA regulates exhaust gas scrubber wash water. The U.S. requirements closely mirror the international requirements in all but the critical pH property.

The EPA has taken a significantly different approach to pH dilution as compared to IMO/MEPC. EPA acknowledges dilution by accepting a significantly lower pH 6.0 at the discharge pipe, as compared to the IMO's pH 6.5. However, the EPA does not accept dilution trials or models at any distance from the discharge pipe. In practice, this makes the EPA limit extremely more restrictive.

The result is that the EPA pH requirement renders typical open-loop scrubbers impractical when operating inside of three nautical miles of US waters. This drives operators to consider closed-loop, hybrid scrubbers, and dry chemical scrubbers that can avoid effluent discharges within those restricted waters.

What is often misunderstood is that even though the North American ECA is set at 200 nautical miles from the coastline, the VGP applies within three (3) nautical miles of the US Coastline, including internal waterways and all US waters of the Great Lakes.

Wash water concerns remain, but the open and hybrid approaches have already solved the issue.

EPA's wash water criteria limits discharges within three miles of US Coastline to pH 6.0 at the point of discharge. This makes traditional open-loop scrubbers impractical at these near shore locations. However, equipment providers now employ solutions to this restriction:

- **Hybrid scrubbers switch to closed-loop modes, avoiding the discharge.**
- **Injection of caustic soda directly into the open-loop discharges, correcting the pH.**

U.S. States Effluent Requirements

Under the EPA VGP program, certain U.S. states have added additional requirements. In general, the states require discharges to meet local water quality standards in addition to the VGP numerical limits. The next section discusses no-discharge zones.

4.4 No Discharge Zones

There are long-standing no-discharge zones in marine sanctuaries. Traditionally, these are away from shipping lanes and harbors. A listing of US marine sanctuaries is provided in the below figure.

More recently, however, there is one no-discharge zone that affects ship operators. In the United States, the issuance of the 2013 Vessel General Permit allows states to add requirements to the federal rules. Specifically, Connecticut has banned scrubber wash water discharges from ships. While this impact may seem significant, it should be considered in light of the EPA pH restrictions. These pH restrictions effectively already limit discharges in US waters. As noted in the previous section, pH restrictions are most pertinent to open loop scrubbers, as hybrid and closed loop scrubbers have the ability to regulate pH before discharge.

The Clean Marine open loop with caustic soda addition is an exception to the open-loop pH challenge with the US EPA requirements. By injecting caustic into the seawater, this system is able to operate in open loop and meet this restriction. However, even Clean Marine is now also offering a hybrid solution that permits temporary no-discharge operations.

The Swedish Agency for Marine and Water Management appeared to consider banning wash water discharges in its territorial waters. This, however, was recently refuted: “Sweden has not included anything more stringent than the articles of the sulphur directive in our laws,” a source at the Swedish Transport Agency told Bunkerworld in November 2014. This discussion highlights continued concern over wash water.

In March 2015, CE Delft published a report on scrubbers that was commissioned by the German environmental organization NABU (Nature and Biodiversity Conservation Union). This report highlighted past research on wash water contaminants that (a) exceed local water quality requirements and (b) may jeopardize near coastal and inland sensitive areas that are already marginal or not attaining water quality targets. In particular, the report notes that the long-term effects of open loop scrubbers, specifically, demand rigorous investigation, including measurement and modeling of discharge water quality. It appears that the EU discussion on wash water discharges is not finished.

Table 9 No Discharge Zones Relative to Scrubbers

Location	Restriction Relevant to Scrubber Effluent
California	Water Quality Protection Areas – No discharge, except in those discharges that occur in transit associated with vessel traffic separation lanes. (see http://www.swrcb.ca.gov/water_issues/programs/ocean/asbs.shtml)
Connecticut	Discharge of wash water explicitly prohibited.
Hawaii	No discharge to natural freshwater lakes, saline lakes, and anchialine pools. No discharge to Inland Class I waters.
Marine Sanctuaries	The United States has a complex system of marine sanctuaries, marine protected areas, national park and wildlife refuge systems, wilderness areas, wild and scenic river systems, and outstanding national resource water. While these do not appear to prohibit wash water explicitly, it is recommended that discharges be avoided if possible.

4.5 Wash Water Monitoring and Sampling

As discussed above, there remain concerns with wash water discharges from open loop scrubbers. Both the EPA, through the Vessel General Permit (VGP), and 2009 IMO Guidelines require continuous wash water monitoring and periodic analytical sampling and analysis. The continuous wash water monitoring provides clear limits. However, the periodic analytical sampling and analysis requirements are less clear, specifically with regards to how IMO and California will utilize the collected data. The U.S. EPA will utilize the collected samples as follows:

- Samples will be analyzed for PAH, turbidity, nitrates, and pH.
- Dissolved and total metals will be collected for information only. There are published limitations relevant to point discharge permits. It is possible that if wash water exceeds these limits, they could become requirements in the future.
- PAH analytical sampling will be used to corroborate the continuous monitoring PAH limits.
- Nitrate and nitrite analytical sampling must demonstrate compliance with the limitations in the VGP.

In order to consider how wash water compares to US discharge limits, this Guide provides a “superset” of various possible wash water criteria below. The inputs for this “superset” are from the criteria published in separate documents by the US EPA and the CA Water Board. IMO guidelines do not provide acceptance criteria. The EPA has developed the National Recommended Water Quality Criteria (NRWQC) in accordance with the Clean Water Act. The NRWQC is broken into two guiding categories: The Aquatic Life Criteria Table and the Human Health Criteria Table.

VGP parameters identified in each of these tables were used as the EPA component of the super set criteria. The EPA Exhaust Gas Scrubber Washwater Effluent Guide was used as an additional resource to identify the relevant limits provided in the NRWQC. CA Water Board acceptance criteria for dissolved and total metals and pH are from the 2012 California Ocean Plan. The Ocean Plan criterion for PAH concentration is defined as a 30-day average, rather than a discreet time value, and has therefore not been considered in the super set. The Ocean Plan also does not mention criteria for nitrate or nitrite. These combined criteria are provided in Table 10. The acceptance criteria for parameters that are not mentioned in either regulatory document are classified as ‘not available’ (N/A). These parameters include the metal Vanadium; the PAHs acenaphtylene, benzo(ghi)perylene, napthalene, and phenanthrene; and nitrite.

Concerns with potential future restrictions on wash water might be addressed by adopting technology that does not require constant wash water discharge such as closed loop, hybrid, or dry chemical.

Table 10 Wash water Acceptance Criteria Super Set

Water Quality Parameter	Unit	IMO (no doc.)	Regulatory Body EPA[1] (NRWQC)	California[2] (Ocean Plan)	Acceptance Super Set
Dissolved & Total Metals					
Arsenic	ug/L	-	69	80	**69**
Cadmium	ug/L	-	40	10	**10**
Chromium	ug/L	-	1,100	20	**20**
Copper	ug/L	-	4.8	30	**4.8**
Lead	ug/L	-	210	20	**20**
Nickel	ug/L	-	74	50	**50**
Selenium	ug/L	-	290	150	**150**
Thallium	ug/L	-	0.47[4]	2	**0.47**
Vanadium	ug/L	-	-	-	**N/A[5]**
Zinc	ug/L	-	90	200	**90**
PAHs					
Acenaphthylene	ug/L	-	-	-	**N/A[5]**
Acenaphthene	ug/L	-	990[4]	-	**990**
Anthracene	ug/L	-	40,000[4]	-	**40,000**
Benz[a]anthracene	ug/L	-	0.018[4]	-	**0.018**
Benzo[ghi]perylene	ug/L	-	-	-	**N/A**
Benzo[a]pyrene	ug/L	-	0.018[4]	-	**0.018**
Benzo[b]fluoranthene +	ug/L	-	0.018[4]	-	**0.018**
Benzo[k]fluoranthene	ug/L	-	0.018[4]	-	**0.018**
Chrysene	ug/L	-	0.018[4]	-	**0.018**
Dibenz[a,h]anthracene	ug/L	-	0.018[4]	-	**0.018**
Fluoranthene	ug/L	-	130[4]	-	**130**
Fluorene	ug/L	-	1,100	-	**1,100**
Indeno[1,2,3,c,d]pyrene	ug/L	-	0.0038[4]	-	**0.0038**
Naphthalene	ug/L	-	-	-	**N/A[5]**
Phenanthrene	ug/L	-	-	-	**N/A[5]**
Pyrene	ug/L	-	830[4]	-	**830**
Nitrate-Nitrite					
Nitrate	ug/L	-	10,000[4]	-	**10,000**
Nitrite	ug/L	-	-	-	**N/A[5]**
pH	Units	-	6.5 - 8.5	6.0 - 9.0	**6.5 - 8.5**

[1] EPA limit expressed as Criterion Maximum Concentration (CMC)

[2] California Ocean Plan limit expressed as Instantaneous Maximum

[3] Ocean Plan limit for PAH expressed as 30-day Average; therefore not included in Super Set

[4] Limit sourced from NRWQC Human Health Criteria Table, consumption of Organism Only

[5] Criteria not identified from available resources

5. EGCS Technology Options

Exhaust gas cleaning system (scrubber) technologies are generally categorized as either *wet* or *dry* systems or a hybrid variation of the two options. There is essentially one option for the dry system whereas each wet variation has at least three variants. Each of the wet and dry options will be described in this section to provide a sense of their relative merits. More recently, a membrane technology has entered the market.

Appendix A of this Guide provides an extensive survey of the available scrubbers (summarized in Table 11). Please use this survey to perform comparisons between systems in terms of technology approach and physical plant integration. This section discusses the various technologies in general terms.

TYPES OF EXHAUST GAS SCRUBBERS

- “WET” SYSTEMS
    - OPEN LOOP SYSTEM
    - CLOSED LOOP SYSTEM
    - HYBRID SYSTEM
- “DRY” SYSTEMS
- MEMBRANE TECHNOLOGY

Table 11 Summary of manufacturer installations by scrubber type (as of March 2015)

Manufacturer	No. of Vessels with Scrubber Installations			
	Open	Closed	Hybrid	Dry/Membrane
Alfa Laval	6	4	19	
Clean Marine			4	
CR Ocean Engineering (CROE®)	2	1	5	
Ecospec		3		
Ecospray		24		
Envairtec GmbH				5
Ionada				1
Mitsubishi Heavy Industries, LTD.			1	
SAACKE	1			
Wärtsilä	25	12	37	
Yara	16			

5.1 Wet Systems

A wet scrubber system is one that uses either untreated seawater or treated freshwater as the scrubbing agent to remove SO_x and particulate matter from exhaust gas. The water undergoes some form of filtration and/or chemical treatment before being discharged overboard or recirculated to the system. Wet systems may be categorized as open loop, closed loop, or hybrid. Specific functional differences between the three variants are outlined below.

Open Loop System

An open loop system relies exclusively on ambient seawater for exhaust gas scrubbing. The term ‘open loop’ is used because 100% of the water drawn in from the sea is discharged after passing through the system. The process relies on the natural alkalinity of seawater to facilitate scrubbing of the sulfur oxides.

In this process, seawater is drawn from below the waterline and pumped to a scrubber located in the engine exhaust uptake. The volume of water required per MW of engine power varies between manufacturers. The scrubber is a passive device that puts the water in direct contact with the exhaust gas. Internal baffles divide the scrubber into several stages, each stage causing different interactions between the gas and water. Seawater is injected near the top through special nozzles and gravitates to the bottom passing through the various stages.

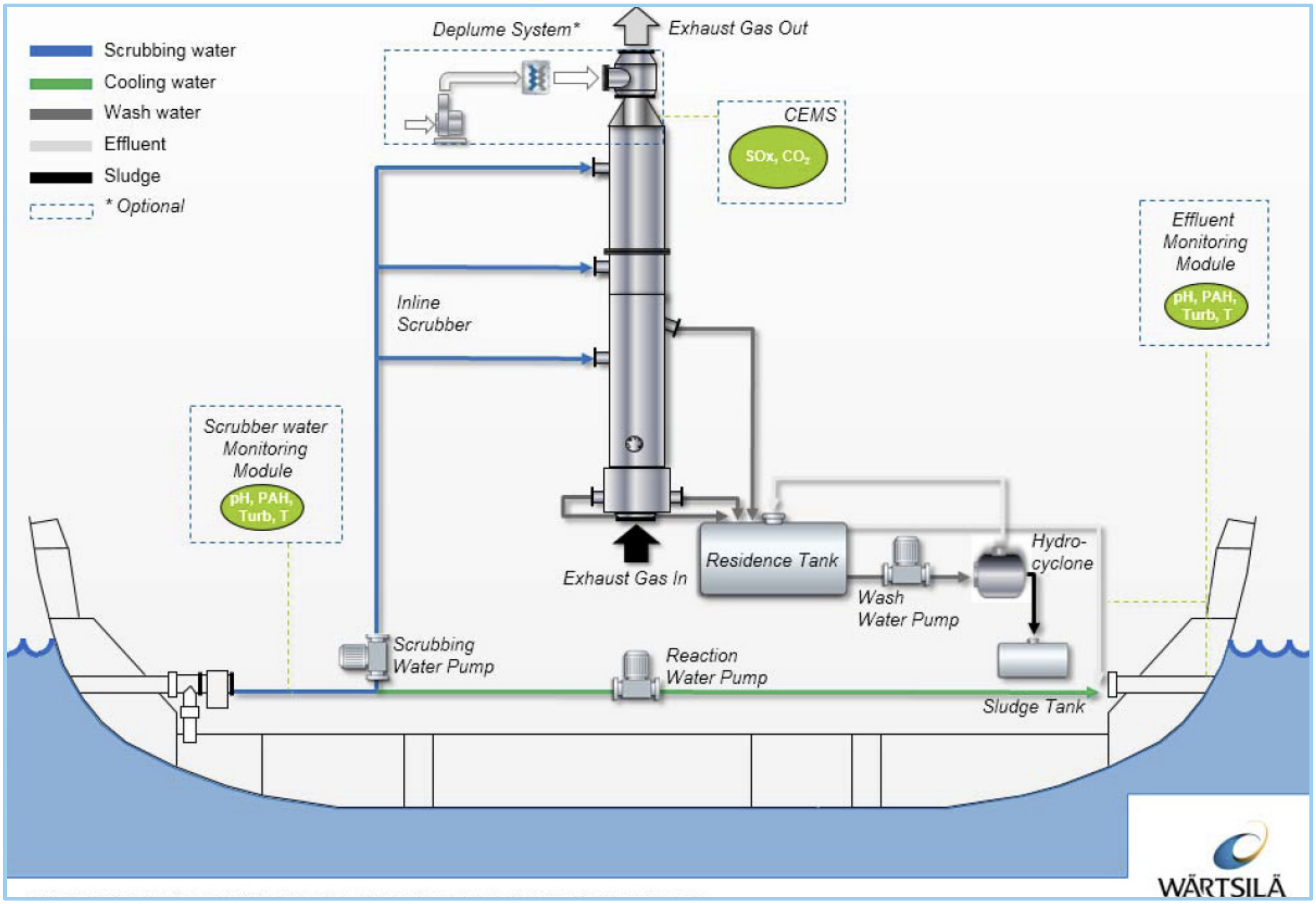


Figure 7 Open Loop System (Wärtsilä, 2014)

Upon leaving the scrubber, the water (now termed wash water) might be processed before discharge to the sea. Systems that process the wash water may use a combination of cyclonic separation, filtration, and/or settling. The wash water is either pumped or drained via gravity through this equipment and then overboard. If processed, the resulting material, mostly silt from the ambient seawater, is drained away as sludge while the great majority of the wash water is pumped or drained towards the overboard.

A secondary stream of seawater, which has bypassed the entire scrubbing process, is mixed typically in equal parts with the water leaving the scrubber. This mixing effectively dilutes the wash water bringing the pH to a level that is acceptable for overboard discharge in most areas.

Advantages of the open loop system include the following:

- The process requires no hazardous chemicals; seawater is the only scrubbing agent.
- The system has fewer components than other wet systems.

Disadvantages of the open loop system include the following:

- Operation in brackish or fresh water or in high water temperatures can inhibit scrubbing of SO_x.
- The discharge of effluent with acidic pH is restricted in US VGP waters, thereby requiring a switchover to low-sulfur fuel or use of an alternative scrubbing system.
- Operations in high silt areas may result in large accumulations of residues.

Skinny scrubbers are trendy, and they are not picking up PM.

Makers are offering narrow diameter scrubbers that offer the great advantage of taking the same footprint as the exhaust silencers that they typically replace. This approach, however, comes at the price of not removing as much particulate matter as the larger wide diameter scrubbers. This PM challenges gas monitoring equipment, and is exhausted out of the stack.

Closed Loop System

A closed loop system uses fresh water that is chemically treated to effect scrubbing. The term “closed loop” is used because most of the scrubbing agent is recirculated with only minimal water intake and effluent discharge. Chemical dosing is added at the rate needed to neutralize SO_x in the exhaust gas.

Fresh water that has been dosed with a sodium hydroxide (NaOH) solution, or other caustic solution, is pumped from a holding reservoir to the scrubber. The scrubber operates in the same manner as that used in open loop systems: putting exhaust in direct contact with the fluid. After scrubbing, the water is drained back to the reservoir. A seawater/freshwater heat exchanger extracts heat from the closed fresh water loop, the seawater being supplied by an independent SW pump.

As this process repeats, the chemical reaction between the sodium hydroxide and the SO_x depletes the reserves of NaOH in the solution. A dosing unit injects NaOH at the rate necessary to maintain a constant pH at the scrubber outlet. To purge the benign products of reaction (sulfates), a small flow of water is constantly drained from the reservoir. At the same time, make-up water from the ship’s fresh or potable water system is added to maintain the same volume in the reservoir. More recent scrubber versions use seawater for this make-up, and therefore reduce fresh water demand on the ship. The drained water is sent to a treatment unit for processing.

The treatment unit is typically a mechanized centrifugal separator similar to those employed in fuel oil and lube oil systems. The separator extracts the heavy particulates and oil residue, discharging clean water as effluent. The effluent is clean, or suitable for discharge overboard, and discharged in relatively small volumes (compared to open loop systems) and may be sent to a holding tank to avoid discharging while in port.

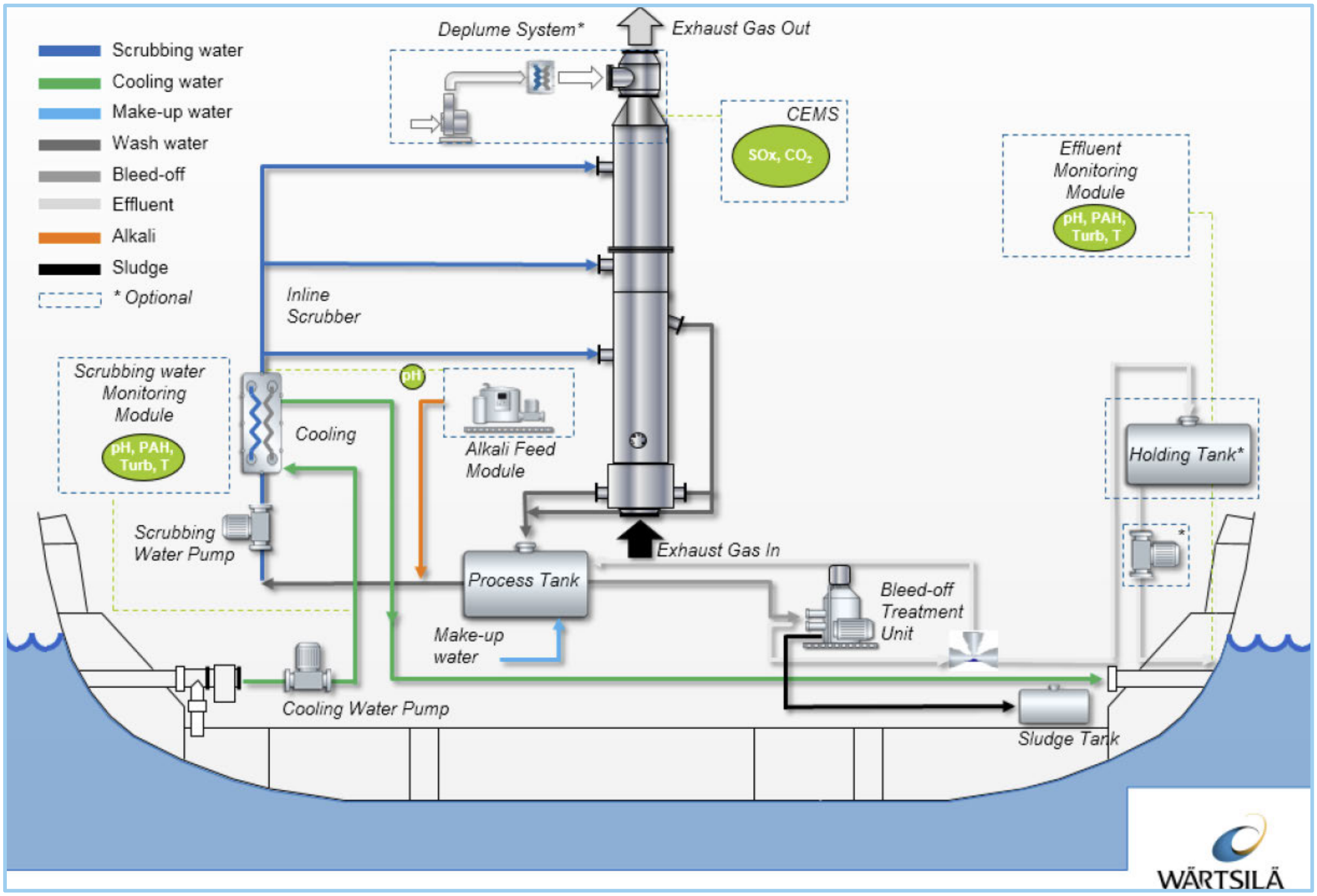


Figure 8 Closed Loop System (Wärtsilä, 2014)

Advantages of the closed loop system include the following:

- The system can operate in all regions regardless of seawater alkalinity or temperature.
- Effluent may be stored on board for whatever duration the tank volumes will permit until the vessel departs a no-discharge location and can then discharge the clean effluent overboard.
- The ancillary systems are generally smaller and less weight than other scrubber technologies.
- Low volumes of residuals generated. These residuals are waste products that regulations do not allow to be incinerated or dumped overboard, and must be landed ashore.

Disadvantages of the open loop system include the following:

- The system has more components than an open loop system.
- The system requires a constant supply of caustic chemicals requiring special handling, care, and cost.

Hybrid System

A hybrid system capitalizes on the advantages of the open and closed loop systems. The system largely resembles a closed loop system but incorporates additional components that allow it to operate as either an open or closed loop system. The intent is that the system can operate as an open loop system at sea to conserve chemical agent or operate as a closed loop system in port to avoid issues stemming from water quality or port discharge regulations.

The hybrid system has all of the same components that are present in the closed loop system, with the primary distinction being the presence of two wash water treatment devices. Because the open loop mode of operation requires 100% of the water to undergo separation, it is therefore necessary to have a secondary device large enough for the higher flow rate.

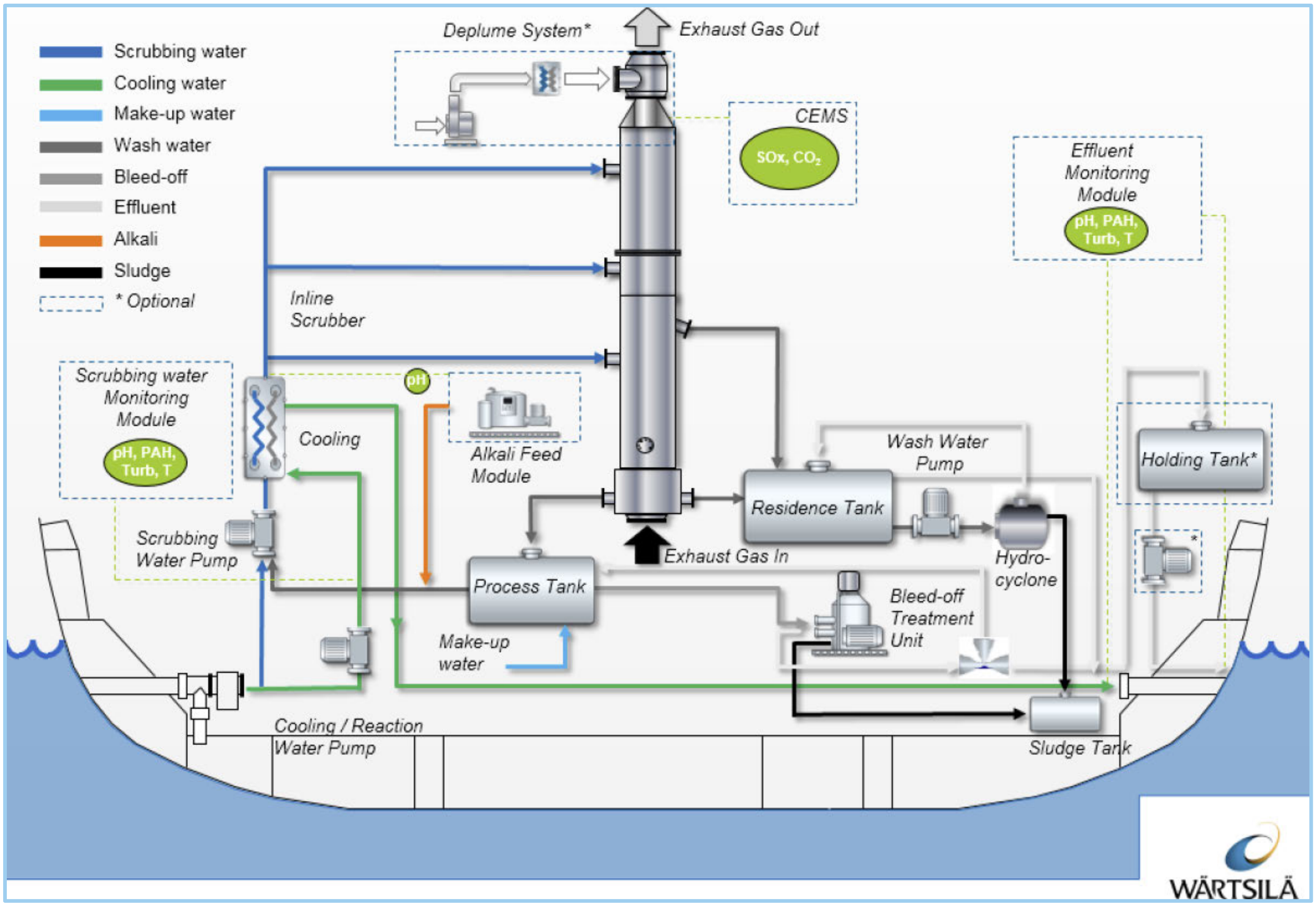


Figure 9 Hybrid System (Wärtsilä, 2014)

To change from the closed loop mode to the open loop mode requires a change in the functions of certain components:

- The seawater pump used to provide cooling water to the heat exchanger in closed loop mode becomes the supplier of dilution water in the open loop mode. The heat exchanger is bypassed in open loop mode.
- The pump used to circulate fresh water in closed loop mode becomes the source of seawater for the scrubber in open loop mode.

The change in modes requires a changeover from the small volume centrifuge to the large volume separator. Otherwise, system operation is the same as described in the above sections.

The same advantages and disadvantages described in Section 4.1.2 are applicable to this system. An additional disadvantage is that the system requires the most components of any wet option.

5.2 Dry Systems

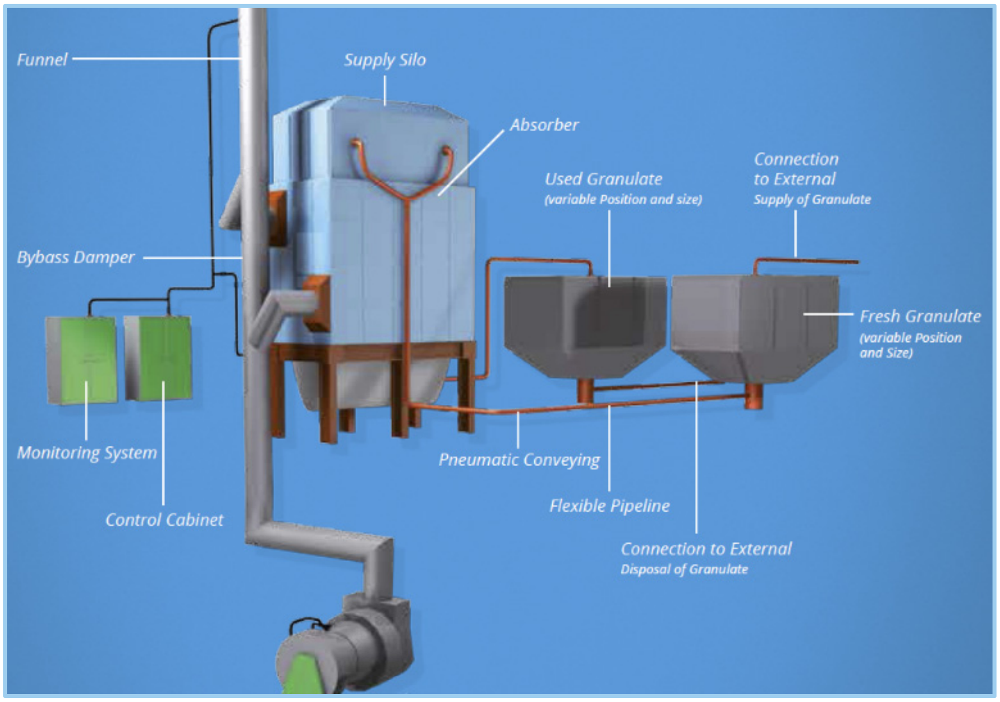


Figure 10 Dry System (Envairtec)

Dry exhaust gas cleaning systems are so described because they rely on dry bulk reactants for treatment of the exhaust gas. There is one dry system currently marketed, and its process utilizes calcium hydroxide in the form of spherical granulate. The granules are loaded on the ship and stored in bulk. When the system is in use, the granules are fed via belt or pneumatic conveyor to a dry reactor or "absorber" through which the engine exhaust passes. The SO_x reacts chemically with the granules to produce gypsum ($CaSO_4$) and water. The gypsum is removed from the bottom of the absorber by a pneumatic conveying system and captured for storage and subsequent offloading.

The gas travels from the absorber to an SCR reactor where NO_x is chemically removed from the gas with the injection of ammonia or urea. A large volume blower on the outlet of the SCR reactor may be required to pull the gas through the system, thereby reducing the backpressure at the engine exhaust outlet.

Advantages of the dry system include the following:

- The system does not produce any liquid effluent for overboard discharge, allowing it to operate indefinitely in no-discharge zones.
- Modifications are limited to the exhaust stack, reducing the complications associated with installing new sea chests and large pumping systems.
- The system is generally compatible with NO_x reducing technologies.

Disadvantages of the dry system include the following:

- The ship must have suitable storage and handling arrangements to accommodate the dry bulk reactants and products, as well as a reliable supply of materials.
- The system has significant weight and size, affecting cargo capacity and potentially stability.
- Increased costs from use of calcium hydroxide for SO_x abatement.

New to the market is a membrane technology with one supplier, ionada. The system circulates an "absorption solution" through porous membrane tubes in an exhaust housing. As the exhaust passes the membranes, the sulfur reacts with the solution and is reported to meet the sulfur reduction requirements. The clear advantage is a system where the washwater doesn't pick-up contaminants from the exhaust gas. It is not clear, however, if the system removes any particulate or how the membranes are kept clean from heavy fuel exhaust fouling.

6. Life Cycle Costs Analysis of EGCS

Exhaust gas cleaning systems (scrubbers) offer potential savings by allowing a ship to continue to burn low-cost, high-sulfur residual marine fuel oil when environmental regulations would otherwise require switching to a higher cost fuel. This fuel savings is most relevant within ECAs that require marine vessels to burn 0.1% sulfur distillate *or the equivalent* as of 1 January 2015.

FUEL COST SAVINGS

- **Nearly linear relationship between life cycle net savings and fuel consumed in an ECA.**
- **Initial investment in equipment, engineering, and installation have only a secondary impact on net savings.**

In general, such low-sulfur limits can only be achieved with high-cost distillate marine fuel oil. The cost savings is calculated by multiplying the amount of fuel consumed in an ECA to the distillate-residual fuel cost differential. This savings is then reduced by scrubber capital and operating expenses, including crew, maintenance and repair, consumed chemicals, and fuel use resulting from added machinery loads.

$$\begin{aligned}&\textit{Fuel Cost Savings}\\ &\quad = (\textit{ECA Fuel Consumption} \times \textit{Distillate Cost Differential})\\ &\quad - (\textit{Scrubber Capital and Operating Expenses})\end{aligned}$$

This analysis uses this fuel cost savings to estimate Net Savings (NS) of installing a scrubber as compared to the mutually exclusive option of switching to high-cost, low-sulfur distillate marine fuel oil. NS is calculated over the entire project life cycle (12 ½ years), assumed to start 1 January 2015. The life cycle analysis is based on a ten (10) year timeframe of operation (July 2017 - July 2027). In addition, annual operating savings are estimated to illustrate potential impacts on cash flow. The analysis is broken into the following parts:

- **Vessel/Route Comparisons**: Estimates the Net Savings and annual operating savings of five ship/route combinations using the same scrubbing technology.
- **Scrubber Technology Comparison**: Compares the Net Savings and annual operating savings of four different scrubbing technologies employed on a single ship/route combination.
- **Key Inputs, Assumptions, and Sensitivity**: Describes the key inputs and assumptions. Further, checks the sensitivity of the analysis to these inputs and assumptions.

It is envisioned that this analysis will provide adequate background for a ship operator to perform a customized analysis for their own ship or fleet. Such an analysis should also consider fuel switching capital and operating expenses associated with handling two fuel grades.

6.1 Vessel/Route Comparisons

The Net Savings and annual operating savings were analyzed for five vessel/route combinations. These combinations were selected to demonstrate the impact of power plant size and operating profile on life cycle costs. The vessel/route comparisons were performed with a single scrubbing technology, open loop.

The analysis is summarized in Table 12. A description of the vessel/route pairs and a discussion follow the table.

Table 12 Life Cycle Cost Analysis, Impact of Vessel Types and Trade Routes

Analysis: Impact of Vessel Types and Trade Routes *Amounts in Present Value.* *Totals and sub-totals rounded to 100,000.* *Savings compared to burning distillate in ECA.*		Open Loop Scrubber (All Cases)				
		Container ship Trans-Pacific	Container ship US West Coast	Tankship US West Coast	Bulker Great Lakes	Cruiseship North America
NET SAVINGS, LIFE CYCLE	***(1,000 USD)***	**2,000**	**12,800**	**14,500**	**11,000**	**60,500**
Operating Savings, Annual	(1,000 USD/yr)	1,000	2,600	2,800	2,600	10,500
Key Variables						
Plant (Prop. & Ship Service)	*(MW)*	39	19	13	12	47
Fuel burned inside ECA	*(%)*	11%	51%	100%	100%	100%
Initial Investment, One Time	***(1,000 USD)***	***4,500***	***3,600***	***3,300***	***5,200***	***5,000***
Equipment	*(1,000 USD)*	3,100	2,500	2,300	3,100	3,500
Engineer/Review/Training	*(% equip)*	9%	9%	9%	9%	9%
Installation	*(% equip)*	50%	50%	50%	75%	50%
Fuel Cost Savings, Life Cycle	***(1,000 USD)***	***7,000***	***17,200***	***19,400***	***18,000***	***67,400***
Fuel cost savings, annual	*(1,000 USD/yr)*	1,118	2,760	3,105	2,883	10,808
ECA residual/scrubber	*(m.tons/yr)*	3,982	9,829	11,057	10,268	38,489
Scrubber parasitic load	*(% fuel)*	2.0%	2.0%	2.0%	2.0%	2.0%
ECA distillate option	*(m.tons/yr)*	3,717	9,173	10,320	9,584	35,923
Distillate calorie correction	*(% fuel)*	-4.0%	-4.0%	-4.0%	-4.0%	-4.0%
Residual heat & process	*(% fuel)*	-0.8%	-0.8%	-0.8%	-0.8%	-0.8%
ECA residual baseline	*(m.tons/yr)*	3,904	9,636	10,840	10,067	37,734
Chemical Expenses, Life Cycle	***(1,000 USD)***	***0***	***0***	***0***	***0***	***0***
Chemical expenses, annual	*(1,000 USD/yr)*	0	0	0	0	0
Chemicals	*(% fuel cost)*	0.0%	0.0%	0.0%	0.0%	0.0%
OM&R Expenses, Life Cycle	***(1,000 USD)***	***500***	***800***	***1,600***	***1,800***	***1,900***
OM&R expenses, annual	*(1,000 USD/yr)*	76	140	272	304	320
Operating engineer	*(% position)*	15%	30%	60%	60%	60%
M&R of equipment	*(% equip cost)*	1.0%	2.0%	4.0%	4.0%	4.0%

Investment Terms			*Analysis based on NIST Handbook 135, published 1995*	
Base (Analysis) Date		1-Jan-15	Residual Cost April 2015 *(USD/m. ton)*	338
Construction Date		1-Jul-16	Distillate Premium *(USD/m.ton)*	325
Service Date		1-Jul-17	Rate of Inflation	3.0%
Service Period	*(years)*	10	Discount Rate	10.0%
Operating Engineer	*(1,000 USD/yr)*	300	Energy & Chemical Escalation	3.5%

All vessel/route pairs indicate positive Net Savings as compared to switching to distillate marine fuel oil when operating within an emission control area (ECA). Despite burning approximately 4000 metric tons per year of fuel in the ECA, the Trans-Pacific Container Ship realized only marginal net savings, therefore representing a rough ‘break-even’ point. In other words, with the assumed investment terms, a ship must burn greater than 4000 tons per year in an ECA to result in a positive net savings.

The potential NS and reduction in operating costs greatly depends on the combination of plant size and the percent of fuel burned within an ECA. More specifically, the cost savings is directly proportional to the fuel consumed within an ECA.

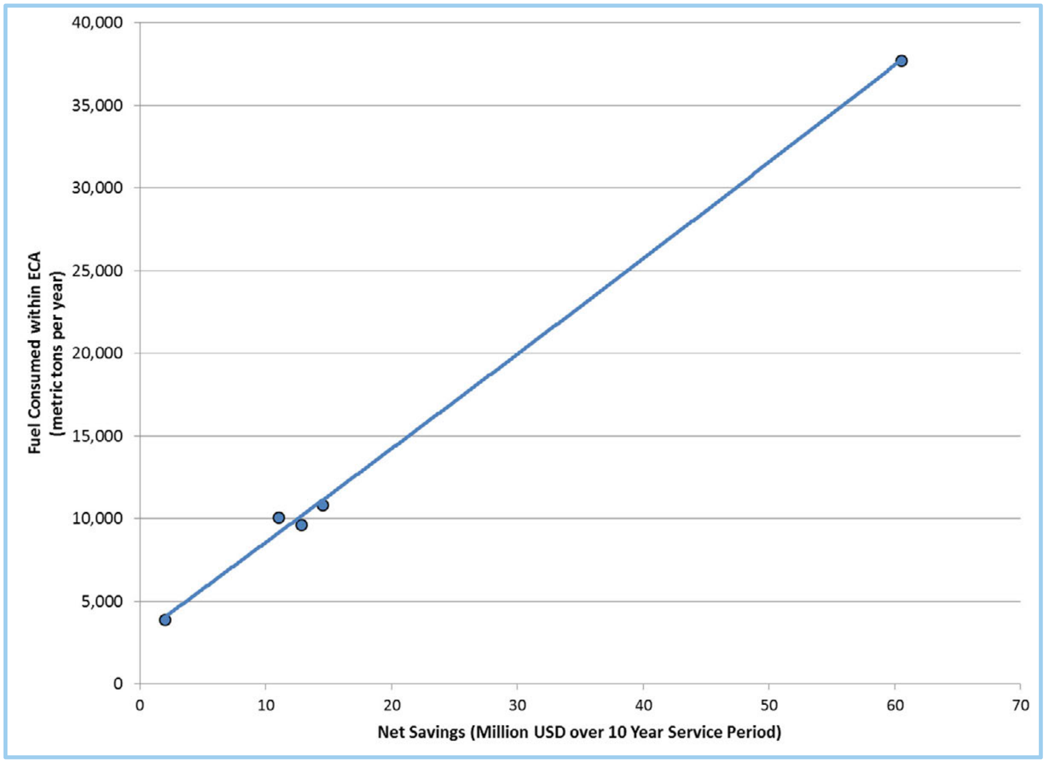


Figure 11 **ECA Fuel Consumption Impact on Net Savings**

With 2020 now only five years away, the 0.5% world sulfur limit turns the life cycle cost around 180 degrees. Will this create a new, even bigger scrubber market?

This analysis shows that the trans-Pacific containership does not show a compelling net savings. This is because it operates mostly outside of the ECA. However, once the world-wide 0.5% sulfur cap hits in 2020 or 2025, the exact opposite could be true. Don't be surprised to see a line of skinny, low efficiency open-loop scrubbers targeting only the 0.5% sulfur market soon.

Figure 11, above, shows a nearly linear relationship between life cycle Net Savings and ECA fuel consumption. This indicates that initial investment in equipment, engineering, and installation have only a secondary impact on NS as compared to ECA fuel consumption. While initial investment roughly tracks total plant size, propulsion, and ship's service, it is offset by the overwhelming influence of fuel consumption.

A similar conclusion can also be determined when viewing operations, maintenance, and repair (OM&R) expenses. The transpacific containership, for example, demonstrates that even exceptionally low expenses cannot overcome a low percentage of fuel consumed within an ECA. The Sensitivity section of this report, which follows below, further analyzes the impact of fuel consumption, expenses, and installation expenses on Net Savings.

6.2 Technology Comparisons

The Net Savings and annual operating savings were calculated for the four different scrubber technologies reviewed in this report. This analysis demonstrates the impact of equipment and installation costs, equipment specific parasitic electrical loads, chemical expenses, and OM&R expenses on life cycle costs. Each of the technologies was compared using a single vessel/route combination, the U.S. west coast containership. This combination was selected as the median case with a power plant size of 19 megawatts and an ECA fuel consumption of approximately 9,500 metric tons per year. The analysis is summarized in Table 13. A description of the technologies, assumptions, and a discussion follows the table.

Table 13 Life Cycle Cost Analysis, Impact of Various Scrubber Technologies

Analysis: Impact of Various EGCS Technologies on Single Vessel *Amounts in Present Value.* *Totals and sub-totals rounded to 100,000.* *Savings compared to burning distillate in ECA.*		Containership US West Coast (All Cases)			
		Open Loop Scrubber	Closed Loop Scrubber	Hybrid (Open & Closed Loop) Scrubber	Dry Chemical Scrubber
NET SAVINGS, LIFE CYCLE	***(1,000 USD)***	**12,700**	**9,000**	**10,500**	**3,400**
Operating Savings, Annual	(1,000 USD/yr)	2,600	2,300	2,500	1,700
Initial Investment, One Time	***(1,000 USD)***	***3,600***	***5,400***	***5,100***	***7,200***
Equipment	(1,000 USD)	2,500	3,500	3,300	5,400
Engineer/Review/Training	*(% equip)*	9%	11%	11%	7%
Installation	*(% equip)*	50%	60%	60%	40%
Fuel Cost Savings, Life Cycle	***(1,000 USD)***	***17,100***	***17,400***	***17,200***	***17,500***
Fuel cost savings, annual	*(1,000 USD/yr)*	2,744	2,792	2,757	2,809
ECA residual/scrubber	*(m.tons/yr)*	9,877	9,732	9,836	9,684
Scrubber parasitic load	*(% fuel)*	2.5%	1.0%	2.1%	0.5%
ECA distillate option	*(m.tons/yr)*	9,173	9,173	9,173	9,173
Distillate calorie correction	*(% fuel)*	-4.0%	-4.0%	-4.0%	-4.0%
Residual heat & process	*(% fuel)*	-0.8%	-0.8%	-0.8%	-0.8%
ECA residual baseline	*(m.tons/yr)*	9,636	9,636	9,636	9,636
Fuel burned inside ECA	*(%)*	51%	51%	51%	51%
Chemical Expenses, Life Cycle	***(1,000 USD)***	***0***	***1,700***	***300***	***5,700***
Chemical expenses, annual	*(1,000 USD/yr)*	0	273	55	908
Chemical cost	*(USD/ton)*	0	350	350	375
Chemicals consumption	*(% fuel weight)*	0.0%	8.0%	1.6%	25.0%
OM&R Expenses, Life Cycle	***(1,000 USD)***	***800***	***1,300***	***1,300***	***1,200***
OM&R expenses, annual	*(1,000 USD/yr)*	140	220	216	198
Operating engineer	*(% position)*	30%	50%	50%	30%
M&R of equipment	*(% equip cost)*	2.0%	2.0%	2.0%	2.0%
Investment Terms			*Analysis based on NIST Handbook 135, published 1995*		
Base (Analysis) Date		1-Jan-15	Residual April 2015 *(USD/m. ton)*		338
Construction Date		1-Jul-16	Distillate Premium *(USD/m.ton)*		325
Service Date		1-Jul-17	Rate of Inflation		3.0%
Service Period	*(years)*	10	Discount Rate		10.0%
Operating Engineer	*(1,000 USD/yr)*	300	Energy & Chemical Escalation		3.5%

Scrubber Technology Assumptions

An overview of each technology in provided in Section 5. This section highlights key assumptions that drive the net savings calculations.

- **Open loop (seawater scrubbing)**: The pumping of large seawater volumes results in a relatively high parasitic load. The process uses the naturally occurring alkalinity of the seawater to react with the sulfur oxides. Consequently, no chemicals need to be consumed for the process thereby eliminating that potential expense. The operating engineer burden is considered moderate at 30% due to fewer components to monitor and maintain as compared to the closed loop technology.
- **Closed loop (caustic soda scrubbing)**: The closed loop technology requires significant chemical consumption. These technologies indicate consumption rates of 50% caustic soda solution in the range of 12 to 22 kg for each megawatt-hour of engine operation to scrub 2.7% sulfur fuel oil. Assuming an engine efficiency of 195 grams per kilowatt-hour of engine operation, this works out to a chemical consumption rate of 8% of fuel by weight. Caustic soda prices fluctuate significantly, with a "typical" price of $350 per ton used to reflect current markets.

  Maintenance and operations estimates were increased slightly in comparison to open loop given the additional equipment, in particular the centrifuge. Likewise, engineering and installation costs were increased slightly from open-loop estimates.
- **Hybrid (seawater and caustic soda scrubbing)**: The hybrid system allows an operator to operate in closed loop mode when in zero discharge areas, and then in open loop mode when allowed. This flexibility, however, comes at the expense of having a more complicated system installation. The parasitic loads of the system will depend on the percentage of the time that the system is operated in its respective modes, and is assumed to be 20% of the time in these calculations. The chemical consumption rate will follow a similar pattern. Installation and operating engineer burden followed the closed loop considerations, due to system complexity.
- **Dry chemical (granulate packed bed)**: A dry chemical scrubber removes SO_x from exhaust gas by means of a reactor filled with calcium hydroxide granulate. System chemical consumption is based on predicted granulate consumption rates and a vendor-supplied estimate of $320 per ton of granulate.

  This technology does not have an effluent stream. It does however generate a waste disposal stream that is similar in size to the chemical supply stream, estimated at $55 per ton for disposal. That amount is added to the estimated chemical cost. The parasitic loads of the system are low as there is no seawater or recirculation loop pumping.

Scrubber Technology Initial Investment Estimates

For each of the subject ships, initial investment costs of scrubbing technologies have been broken down into equipment, engineering/review/training, and installation.

Equipment prices are estimated based on over thirty data points provided by nine sources, including all four considered technologies. These prices are plotted in Figure 12 with a trend line fitted between the data points for each considered technology type. The trend line equations were used to estimate equipment costs. The pairing of scrubbers to each of the four vessel cases is described above in the vessel/route combinations section.

The US West Coast containership was used for analyzing the impact of technology selections. From a baseline of installation and commissioning of 50%, a decrease to 40% is applied for the dry chemical system given that its equipment is almost exclusively interfaced with the exhaust stream. An increase to 60% is applied to the closed-loop and hybrid systems as they have almost double the number of components as compared to open-loop systems.

Engineering, review, and training expenses are estimated at 9% of the equipment cost using the open loop system as a baseline. Similar to the scaling of installation and commissioning, this estimate is scaled to 7% for the dry chemical system due to its simplicity, and 11% for the closed-loop and hybrid systems as they are relatively complex.

Given that a limited number of scrubbers have been installed, there remains uncertainty with both the equipment costs and the support costs. Also, each ship is unique and will require a custom cost estimate. As such, these budgets are rough order of magnitude.

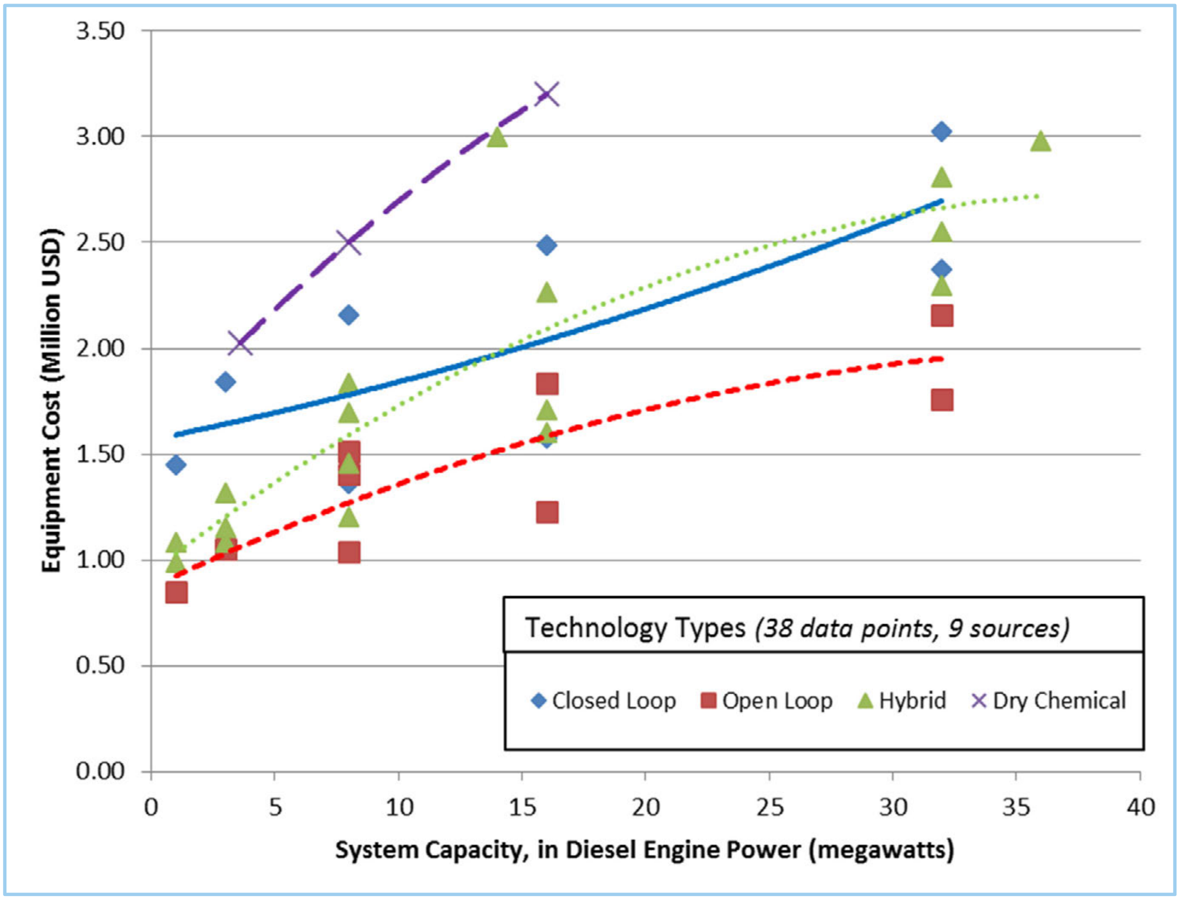


Figure 12   Equipment Cost by Technology Type

6.3 Analysis Methods and Assumptions

This section discusses analysis methodology and the assumptions made for fuel cost estimating and expenses.

Analysis Methodology

This analysis follows the guidance provided in the *Life-cycle Costing Manual for the Federal Energy Management Program 1995 Edition* (Reference 0). The methodology was established by the Federal Energy Management Program for the evaluation of water and energy conservation projects. This analysis, however, uses alternative values for inflation, energy escalation, and discount rates.

All amounts are displayed in constant dollars. Nominal discount and escalation rates are adjusted to real rates, accounting for predicted inflation. The initial investment is calculated as a one-time amount. Fuel and chemical consumptions are calculated as uniform expenses modified to account for escalation. Operation, maintenance, and replacement (OM&R) expenses are calculated as uniform expenses without escalation.

The scrubber life cycle is estimated at ten years, at which time any residual value of the asset is only adequate to pay for decommissioning of the system. Projections past 2025 were avoided as advances in technology may justify additional refitting of vessels, and due to uncertainty in predicting fuel and chemical costs.

Fuel Cost Estimating Assumptions

The analysis of potential scrubber Net Savings is significantly impacted by the cost differential between residual and distillate marine fuel oil. Unfortunately, the prediction of fuel futures is a complex and uncertain task. Determining the future price of marine fuel oil, and more specifically the price differential between fuel grades is still more complex. The following factors are only a few that impact future fuel cost differentials:

- Global and local economic trends affect the demand for limited fuel resources.
- Shore-side trends may reduce industrial consumption of high-sulfur residual marine fuel oil in favor of natural gas and clean coal.
- The refit of existing refineries and the construction of new refineries, particularly in the Middle East, will increase the supply of distillate marine fuel oils.
- Marine environmental regulations that phase out the consumption of residual marine fuel oil will put additional demand on limited distillate marine fuel oil supplies.
- The extent to which marine vessels adopt scrubbing technology may ease increased demand on distillate marine fuel oil supplies.
- New technology provides access to previously unavailable oil and gas formations, increasing supply.

Recent dramatic drops in fuel costs overall have temporarily eased ship operations costs, and as a consequence reduce the urgency to implement scrubbers. For example, the price of distillate is currently about the same price as residual was in July of 2012. However, those swings do not necessarily reduce the value proposition of installing a scrubber, as it is the cost differential that matters most. Considering a few snapshots over the last seven years, that differential has remained much more consistent, in the range of $255 to $396 per ton premium – a 55% swing, while at the same time residual fuel has ranged between $222 and $744 per ton – a 235% swing. In other words, the differential is significantly more stable than the baseline cost. This relatively stable differential is partially driven by the fixed time and energy required to produce the distillate.

Despite drop in fuel prices, the differential remains attractive.

The cost of residual fuel has seen a dramatic drop in the last year from being consistently over $600 per metric ton, to now being closer to $300 per metric ton. While this greatly reduces expenses for shipping operations, there has been almost no change in the price differential between residual fuel oil and distillate. In other words, the fuel cost savings and advantage to the ship owner remains.

This Guide simplifies fuel costs futures by assuming a fixed escalation rate of 3.5% and the current differential between in residual and distillate marine fuel oils of $325 per metric ton. The escalation rate is based on historical marine distillate fuel differentials and is generally supportive of a ten-year life cycle for a system installation. The model is conservative, as several of the above listed market factors could result in this differential growing at a much more rapid rate. Ship operators are encouraged to apply their own fuel oil futures predictions to the analysis.

Table 14 Historical Marine Fuel Prices, and Base Date Assumption

	Residual as IFO 380 *(USD/metric ton)*	Distillate as Marine Gas Oil *(USD/metric ton)*	Differential *(USD/ metric ton)*	Differential *(%)*
High % Differential Example (December 2008)	222	529	307	138%
Low % Differential Example (February 2012)	744	1,025	281	38%
Guide 1st Release (January 2011)	541	796	255	47%
Guide 2nd Release (July 2012)	599	995	396	66%
Analysis Base Date (April 2015)	338	663	325	96%

Expenses

Annual maintenance and repair expenses, based on supplier input, are assumed to be 4% of the initial equipment costs. This assumes that the scrubbers are always in operation while fuel oil is being consumed, with proportional reductions for time outside of an ECA when the units are secured.

Operating engineer time was based on the size of the scrubber with units larger than 10 megawatts requiring 40% of an engineer's time, and smaller units requiring 20%. This assumes that the scrubbers are always in operation while fuel oil is being consumed, with proportional reductions for time outside of an ECA when the units are secured.

The cost of the engineer will vary significantly based on the rating of the position and the flag of the ship. The analysis assumes a Second Engineer (First Assistant Engineer) and fully burdened costs for maintaining a position on a US merchant ship.

Burning residual marine fuel oil requires significant heating, purifying, and waste management efforts that require energy, maintenance, and operational efforts. Typically, the tanks and combustion fuel lines are heated by waste heat generated steam, meaning that energy costs are relatively low. A percentage, 0.8% of fuel consumption, is assumed to be expended for managing the residual marine fuel oil.

A 5% correction factor is applied to account for the difference in heating value of distillate on a weight basis, as compared to residual marine fuel oil. Much of this correction is due to the sulfur content of the residual marine fuel oil. On the other hand, distillate is lighter, and therefore requires a higher volume for storage, and more importantly, for piping work and mechanical systems. This volume difference results in a loss of pumping efficiency. The baseline assumes an aggregate 4% reduction in weight based fuel consumption when burning distillate. Although not directly impacting efficiency, the lighter distillate reduces the distance a marine vessel can travel with the same volume of fuel oil.

6.4 Sensitivity Analysis

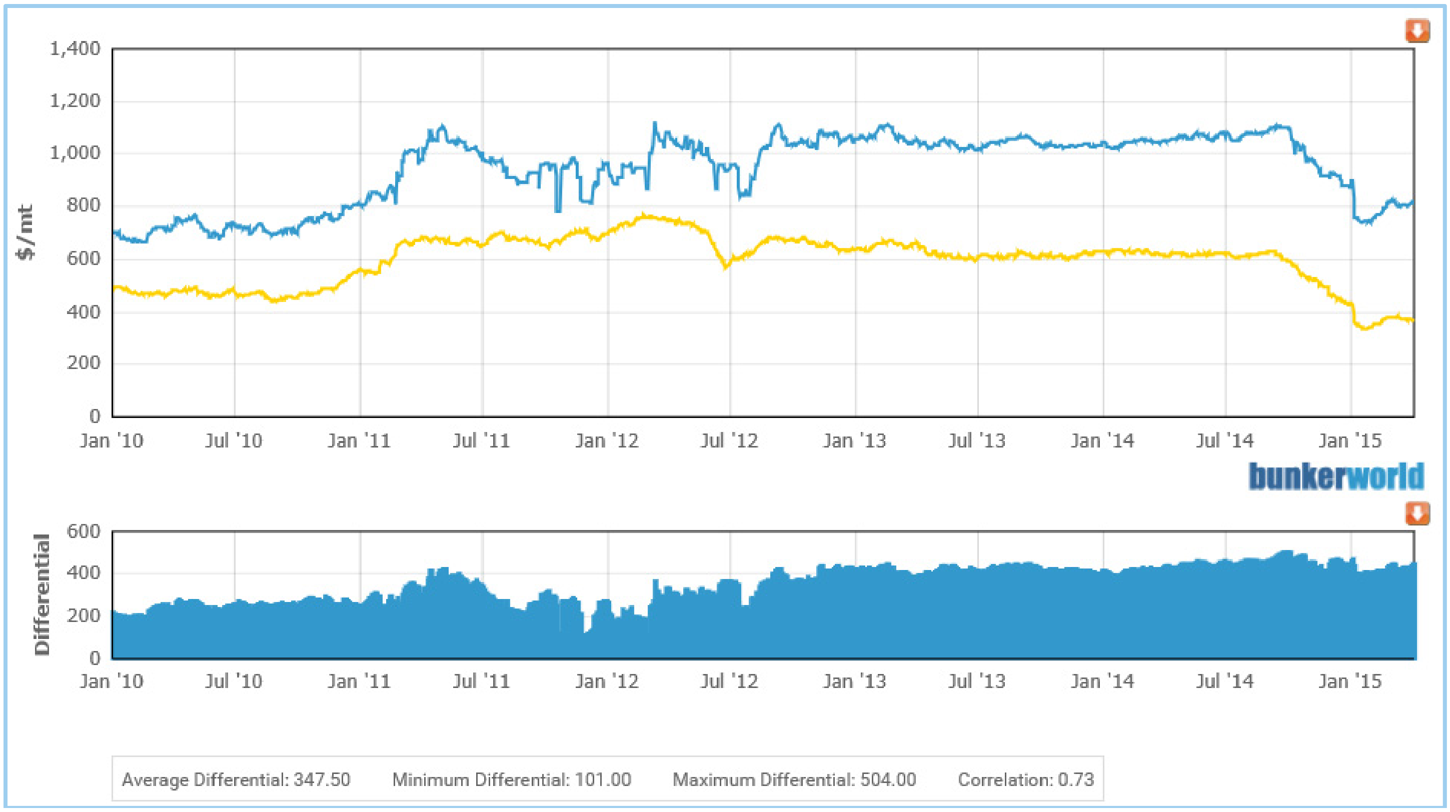
A review of the impact that certain factors might have on the Net Savings predictions was performed. Each variable was selected to demonstrate either a high sensitivity that a ship operator must consider carefully, or a low sensitivity that should not overly distract key decision making.

The analysis considered the baseline case of the US West Coast Containership operating an open loop scrubber. Each factor was then varied by a percentage on the x-axis with the resulting Net Savings scaled on the y-axis.

- **Fuel Consumed in an Emission Control Area (ECA) – High Sensitivity**: The analysis is highly sensitive to the quantity of fuel consumed in an ECA. Fortunately, many ship operators can predict and to some extent control this element of their operating profile. The trend line follows much the same pattern as distillate cost premiums. This sensitivity indicates that a vessel must burn 4,000 metric tons (about 40% of its fuel consumption) annually within an ECA to maintain a positive Net Savings. The trend line, moreover, indicates that as consumptions passes 7,500 metric tons annually, the Net Savings starts to become compelling.
- **Distillate Premium – High Sensitivity**: The analysis is highly sensitive to cost differential between distillate and residual fuel oils. While fuel prices are difficult to predict, the differential has tended to stay within the range of between $200 and $400 per metric ton over the last five years. The Net Savings calculations assume current differential of $325 per metric ton, and use a conservative fuel escalation rate of 3.5%, which is just above consumer price index. The trend line shows the impact of this range, and what savings could be realized should the differential increase to $450 per metric ton.
- **Installation Expenses – Low Sensitivity**: A decrease in installation expenses to a very low 20% of equipment cost, has a relatively low impact only increasing Net Savings by 7%. It is suggested that the baseline installation expense is adequate for initial investigation into the viability of a scrubber project. A detailed installation cost estimate and shipyard bid should be performed in order to determine required capital for the project.
- **OM&R Expenses – Low Sensitivity**: The sensitivity analysis adjusted the maintenance and repair between 2% and 10% at the same time as the percentage of time an operating engineer dedicated to scrubber operations was varied between 20% and 100%. The sensitivity roughly followed the results of installation expenses.

Table 15 Sensitivity of Baseline US West Coast Containership

Sensitivity Analysis *Amounts in Present Value.* *Totals and sub-totals rounded to 100,000.* *Savings compared to burning distillate in ECA.*		**Open Loop Scrubber (All Cases)** **Containership US West Coast (All Cases)**				
Fuel Consumed within ECA by Weight		20%	40%	60%	80%	100%
Fuel Consumed in ECA	(m.tons/yr)	3,885	7,771	11,656	15,542	19,427
Net Savings, Life Cycle	(1,000 USD)	2,400	9,200	16,000	22,800	29,600
Operating Savings, Annual	(1,000 USD/yr)	1,000	2,000	3,100	4,200	5,300
Distillate Premium vs. Residual		$250	$300	$325	$400	$450
Net Savings, Life Cycle	(1,000 USD)	8,500	11,400	12,800	17,100	20,000
Operating Savings, Annual	(1,000 USD/yr)	1,900	2,400	2,600	3,300	3,800
Installation to Equipment Cost Percentage		20%	40%	60%	80%	100%
Net Savings, Life Cycle	(1,000 USD)	13,700	13,200	12,800	12,300	11,900
Operating Savings, Annual	(1,000 USD/yr)	2,600	2,600	2,600	2,600	2,600
OM&R Expenses as Percentage of Equipment						
Operating engineer	(% position)	20.0%	40.0%	60.0%	80.0%	100.0%
M&R of equipment	(% equip cost)	2.0%	4.0%	6.0%	8.0%	10.0%
Net Savings, Life Cycle	(1,000 USD)	12,900	12,300	11,600	11,000	10,300
Operating Savings, Annual	(1,000 USD/yr)	2,600	2,500	2,400	2,300	2,200



Average Differential: 347.50 Minimum Differential: 101.00 Maximum Differential: 504.00 Correlation: 0.73

Figure 13 Differential in USD, Marine Gas Oil vs. HFO 380, North American Pacific 2010 thru Present (Bunkerworld)

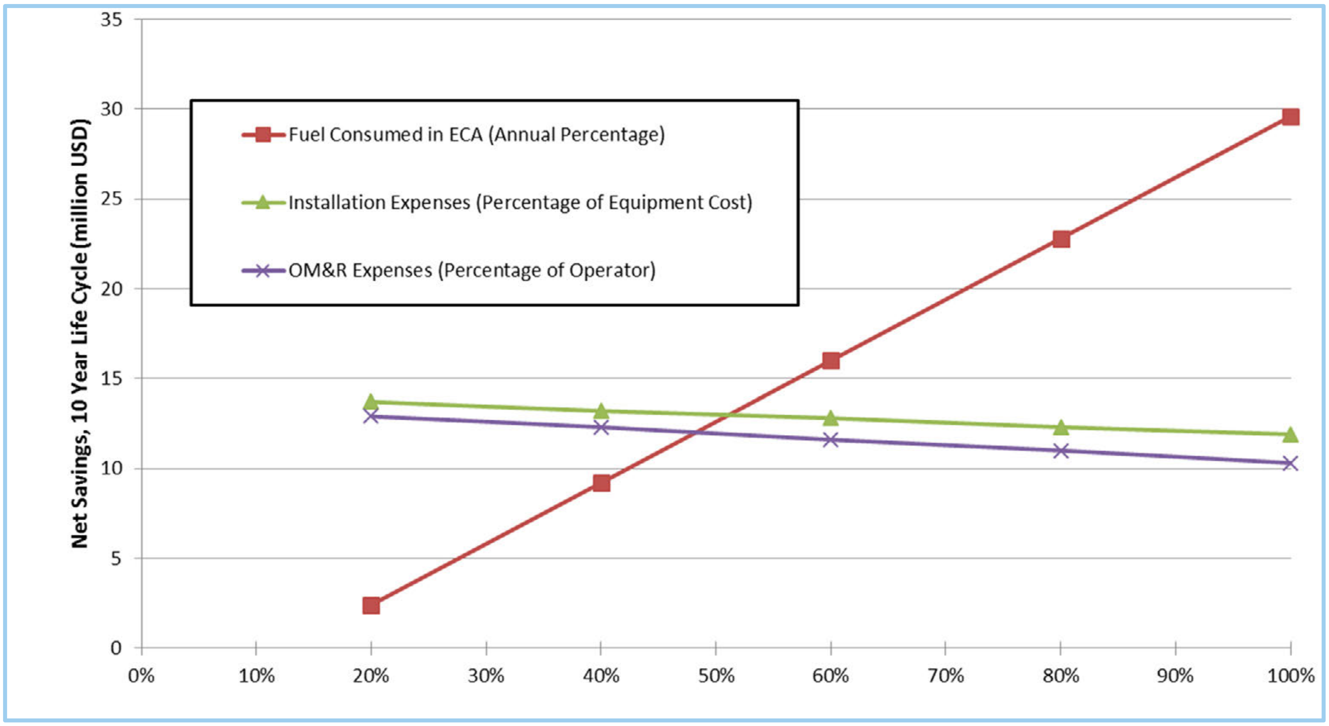


Figure 14 Sensitivity Analysis, West Coast Containership using Open Loop scrubber

7. Integration, Operations, and Maintenance Challenges

Installation of an exhaust gas cleaning system (scrubber) will place additional demands on those responsible for plant operation and maintenance. The decision to install a scrubber should consider the additional labor required to sustain operation. Depending on a ship's current operations and maintenance profile, installation of a scrubber may require additional crew. This section will outline the major sources of additional labor associated with each type of system.

At this time, there is insufficient empirical data from which to derive actual operating and maintenance data. In order to quantify the labor requirements of a scrubber system, a comparison shall be drawn between each major scrubber component and more common (existing) shipboard equipment of similar complexity.

What follows are discussions (grouped by system) identifying the general complexity and labor requirements of each component.

7.1 Physical Integration Challenges – All Systems

The installation of exhaust gas cleaning systems (scrubber) present integration challenges to new builds and retrofits alike. Appendix A provides summary information of several scrubber including footprints, weights, and backpressures. This will provide each operator a baseline on which to begin discussions with suppliers on integration. Key considerations include:

- **Weight and stability**: Weights will vary significantly by scrubber rating and type. The primary weights of concern are the scrubbers themselves as they are positioned high and even a 20 ton wet weight could be of significant concern for ships that have limited remaining stability margin.
- **Water handling systems**: These systems can be significant for any of the wet systems, but particularly for open loop and hybrid systems. For example, a 50-megawatt plant with an open loop scrubber will require 4,500 cubic meters an hour of wash water. This wash water would require about 0.5 megawatts of power to run, and a 760 mm pipe (30-inch diameter).
- **Machinery and stack arrangements**: In the case of new builds, the scrubber will become a primary component for arrangements and weight allowances. For retrofits, fitting this equipment into existing spaces will be a significant challenge and in some cases may require installation of the scrubber unit in the weather or new above the main deck enclosure.
- **Exhaust backpressure**: Most engines can tolerate approximately 3.0 kPa of backpressure (12 inches of water) without significant degradation of power or adverse effects. Exceeding the allowance will degrade performance by approximately one percent for each additional 3 kPa of backpressure. Depending on the scrubber design, exhaust piping and silencers may be required. If exhaust piping and silencers are required, then backpressure allowances should be included.
- **Electrical power**: The demands of these systems can be significant, reaching 2% of the nominal power of the engines that the scrubber is serving, potentially requiring additional generating capacity.
- **Failure modes**: Being integral to diesel engine operations, failure modes and effects, or other analysis, should be conducted to assure that a scrubber failure will not result in loss of ships service or propulsion power.

7.2 Open Loop Seawater System

An open loop seawater system is comprised of the following:

- **Scrubber**: The scrubber is a passive device that relies on the hydraulic pressure of an external supply pump for proper operation. Internally, the scrubber is divided into multiple sections for processing of the exhaust gas. There are few, if any, moving parts, although internal bypass dampers may be included. Regular inspection, de-fouling, and operational checks are required. Internal filtration elements in the scrubber will require periodic replacement. The scrubbers are similar in size and service profile to exhaust gas economizers. The Owner should anticipate a maintenance profile similar to inert gas system scrubbers commonly found on tank ships.
- **Pumps and Strainers**: Strainers and centrifugal pumps are ubiquitous in shipboard plants. The service demands of the external scrubber pumps are essentially the same as those used for other auxiliary services such as seawater cooling with the addition of a variable speed control drive. The pumping demand is significant for open water systems, typically similar to the engine cooling water demand. This service profile makes for a predictable operation and maintenance schedule.
- **Wash Water Treatment Filter**: The wash water treatment filter is generally a passive filtration assembly relying on fluid velocity and cyclonic baffles to effect centrifugal separation of sludge. With no moving parts or consumable elements, the device would only require periodic inspection and de-fouling.
- **Sludge Handling**: Sludge that is separated out in the wash water treatment filter must be retained on board and periodically discharged to a shoreside reception facility. The sludge may be retained in existing shipboard sludge tanks, but the pump-out interval will decrease requiring more frequent sludge transfers. Existing reports on scrubber sludge indicates that it is not hazardous, and therefore does not need to meet IMO Annex I handling requirements. However, Annex VI does not allow incineration of scrubber sludge.
- **Effluent Monitoring**: Instrumentation used to monitor effluent conditions will require periodic calibration, inspection, and possible element replacement. The monitoring of turbidity is a common function of oil content monitors used in shipboard oily water separators. It is reasonable to expect that the degree of intervention required will be similar for the scrubber effluent instrumentation. scrubber monitoring will, however, be continuous and require monitoring of at least three parameters, in comparison to oil content monitor of a single parameter performed only periodically.
- **Exhaust Gas Monitoring**: The instrumentation used for monitoring of scrubbed exhaust gas is not unlike that used in tank vessel inert gas monitoring. Scrubber monitoring, however, will be continuous as per regulation, and require monitoring of more difficult parameters such as SO_2. The Owner should anticipate the need for periodic or annual calibration, servicing of calibration gases, inspection, and possible filter element replacement.
- **Controls**: The controls for an open loop system should not impose any significant operational or maintenance costs. Modern PLC/microprocessor controls are robust and generally do not require any attention beyond periodic inspection and testing of the power supplies.

7.3 Closed Loop Freshwater System

A closed loop freshwater system is comprised of the following:

- **Scrubber Sump**: The scrubber sump is a passive device, acting simply as a reservoir where the solution is allowed to stabilize. The sump has no internal moving parts and, besides periodic inspection, would require little or no operator intervention.
- **SW/FW Heat Exchanger**: The seawater (SW)/fresh water (FW) heat exchanger is required to remove heat that is absorbed by the solution as it passes through the scrubber. Although this is a passive device, the Owner should anticipate the need for regular disassembly and cleaning of both FW and SW sides of the heat transfer surfaces.
- **Pumps and Strainers**: The SW and FW circulation pumps will experience the same operational demands as those present in the open loop system. Again, this represents a predictable addition to the ship's maintenance workload.
- **Sodium Hydroxide Unit**: The NaOH unit is used for storage and dosing. Generally, it is a passive device and should require little operator intervention. However, the loading of the alkaline solution is a critical operation that requires diligence and strict adherence to safety procedures. Due to the hazardous nature of the chemical, Owners should plan for a tightly controlled evolution requiring several crew members to remain present and fully attentive during a transfer. This procedure would take place at regular intervals during port stops and is a significant addition to the list of duties assumed by the ship's crew.
- **Water Treatment Device**: The water treatment device may be a mechanized centrifugal separator similar to those commonly used for fuel oil or lube oil processing or a chemical precipitation and separation unit. An Owner should expect at least the same degree of operator intervention, regular operational checks, and moderate to frequent disassembly and cleaning. Precautions are required prior to servicing equipment that may have residual caustic materials.
- The system contains additional elements that are substantially similar to those found in the open loop system. These components include:
    - Scrubber.
    - Effluent monitoring devices.
    - Exhaust gas monitoring devices.
    - Controls.
    - Sludge handling.

7.4 Hybrid System

The hybrid system has the ability to operate as an open loop system at sea and to operate as a closed loop system in port. The system composition is virtually the same as the closed loop system. Through the use of isolation valves, the circulation pumps can serve different roles depending on which mode the system is being used.

One substantial deviation from the closed loop system is that the hybrid system must have two separate wash water treatment devices: one for each mode of operation. The open loop mode requires a large device capable of processing 100% of the system flow rate; whereas the closed loop treatment device only processes a fraction of the system flow rate.

7.5 Dry System

A dry system is comprised of the following:

- **Absorber**: The absorber (also called the reactor) is the primary component involved in the dry scrubbing process. It is a large assembly mounted in the exhaust uptake, which funnels hot exhaust gas through a bed of calcium hydroxide pellets. The gas comes in direct contact with the pellets causing a chemical reaction, which removes entrained SO_x. The device is passive, relying on external conveyors to feed unspent pellets and remove spent pellets. The absence of moving parts makes the device relatively easy to maintain, but periodic inspections of the internals should be conducted.

- **Conveyors**: Conveyance of the dry chemical reactants and byproducts to and from the absorber is accomplished with mechanical conveyor belts. These are similar to those used in bulk ship cargo handling, and require frequent inspection and planned maintenance of the rotating elements and belts.

- **SCR Reactor**: The selective catalytic reduction (SCR) reactor is the component where NO_x are removed from the exhaust gas via chemical reaction with an injected chemical. A liquid reactant such as ammonia or urea is injected and mixed into the exhaust stream, thereby reacting with the NO_x and precipitating benign byproducts. The reactor itself has no moving parts, but it is reliant on external pumping and chemical storage devices.

- **Exhaust Gas Blower**: A large volume blower is used to pull treated exhaust gas from the outlet of the absorber. As with similar large blowers (e.g. inert gas [IG] system blowers, forced draft fans), the device will require regular operational checks and moderate maintenance tasks.

- **Isolation and Bypass Dampers**: The dampers used to divert the flow of exhaust gas through or around the absorber are essentially large butterfly valves designed for service in high temperature applications. Such dampers prevail in tanker inert gas systems for gas isolation. Periodic maintenance of seals and damper actuators will be required.

- **Calcium Hydroxide Storage**: A closed, dry storage hopper is used as a reservoir for the unspent calcium hydroxide pellets. The hopper itself requires little or no attention from the ship's crew, but regular dry bulk loading operations must be carried out and supervised. It is improbable that all shoreside terminals will have the necessary handling equipment for loading the product in bulk. Therefore, the Owner should plan for the contingency that the bulk products may need to be loaded in packaged form and transferred (internally) by the ship's crew to the hopper. Depending on the intervals between loading and the volumes being loaded, this process could require significant labor if performed as described. Hydraulic cranes or similar means must be added to the vessel if they are not already installed.

- **Gypsum Storage**: As with the calcium hydroxide pellets, the reaction byproduct gypsum must be retained onboard and discharged at regular intervals. A similar challenge is faced in the respect that not all shoreside terminals will have equipment or reception facilities that can easily remove the spent pellets en masse. Possible ship-based solutions include the following:
    - Compressed air "blow tanks" similar to those used for transferring bulk drilling mud in offshore supply vessel applications. This requires a large pressure vessel tank and dedicated air compressor(s) to affect dry bulk transfer. It also requires a shoreside facility that can accept large flow rates of dry bulk material through a pipeline.
    - Manual option: essentially, the reverse of the loading option described above. This would require that the vessel have on-board portable containers, which can be filled by the crew at the base of the gypsum storage hopper. Portable containers are then removed by crane or hoist.

- The system contains additional elements that are substantially similar to those found in the wet systems. These components include: Exhaust gas monitoring devices, and Controls.

7.6 Summary

The following tables compare the components for each type of system to the conventional or existing shipboard equipment items.

The addition of any type of scrubber will increase the workload for shipboard engineering personnel. The ability of a ship's crew to absorb this increase in workload is dependent on the current manning levels and utilization. These factors are in many ways linked to the ship type.

For instance, the engineering plant on board an oceangoing containership is less complex than the plant on board a tank vessel. A tank vessel carrying oil or chemicals has onboard cargo pumping and inert gas systems which do not exist on dry cargo ships, and which require constant supervision during cargo operations. Therefore, it is possible that the engineering department on a dry cargo ship may be capable of absorbing the additional workload without an increase in manning.

The ship type also carries with it certain regulatory barriers, which may further limit a crew's ability to carry the additional workload. Crews on board US-registered tank ships are limited by the Oil Pollution Act of 1990 (OPA 90) to work no more than 12 hours in a 24 hour period. It would not be possible for an Owner to make the crew work longer days to compensate for the increase in workload.

In summary, the table and discussions are intended to give the reader a general sense of how much burden a scrubber will introduce. Ultimately, the Owner must weigh this information against known variables such as ship type, crew utilization, and watch-keeping regulations. A prudent approach may be to start operations with an additional crew member specifically trained to operate the scrubber, and subsequently shift these burdens to other crew members as possible.

8. Financing Options and Market Factors

8.1 Financing Options

Some ship operators may have difficulty in capturing the cost advantage due to chartering arrangements. A common charter arrangement is for the ship operator to pay for capital expenses as well as operating, maintenance, and repair expenses. However, the charterer commonly pays for fuel oil. As a result, the ship operator installing a scrubber would be burdened with all expenses and no possible cost savings. Ship operators might consider special terms on a case-by-case basis with charters. Such terms might include charterer to absorb cost of retrofit and appreciate the resulting fuel cost savings, or a split of the retrofit cost and fuel cost savings.

As a result, scrubber installations have seen more rapid uptake in markets where capital, operating, and fuel expenses are born by the same or closely associated groups. This is generally true in the cruise ship, ro-ro, and containership markets. In other words, the same group that bears the expense of installing a scrubber is able to realize the fuel cost savings. Each group will need to build a combination of debt and equity financing to pay for the installation costs. Debt financing is a commercial loan, typically underwritten by the value of the vessel itself. Equity financing is taken from the groups working capital.

Financial companies, i.e. Clean Marine Energy, have recently entered the market in an attempt to close the gap between the groups that pay for capital, operating, and fuel expenses. These companies will pay for the scrubber installation and put into place a financial structure in order to recuperate the investment and gain a profit based on the fuel cost savings between residual and distillate fuel oils. The structure is similar to the power purchase agreements (PPAs) popular in the commercial solar industry. In the scrubber case, the shipping group agrees to pay a surcharge above the cost of the residual fuel price, and most likely still less than the distillate price. The term is typically five years, at which point the shipping company might then own the scrubber and future fuel cost savings.

8.2 Acquisitions, Partnerships, and Growing Experience

As with any new or developing technology, the ship operator should proceed with caution. Successful selection, integration design, installation, and commissioning of a scrubber will require careful consideration and significant effort. The ship operator should expect that a scrubber installation will require ongoing support, and potential upgrades, particularly for early installations. As such, the relationship with the supplier and confidence in continued support are important factors when selecting a system.

A broad poll of scrubber technology providers in early 2012 identified only seven operational shipboard units, see Table 13. The majority of these systems are being used on auxiliary engines or only a portion of the propulsion plant. The poll also indicated another four units that underwent testing, but were no longer operational.

The experience of the industry is expected to grow rapidly over the next few years. Hamworthy and Wärtsilä have reported eleven additional orders combined. Additional technology providers, including those with significant shore-side experience, are bringing prototype projects to the market.

The scrubber market has seen a number of acquisitions and partnerships announced in the past few years. This trend is positive, as it results in major marine equipment suppliers putting their reputations, experience, and development capacity behind scrubber product lines. These developments include:

- Krystallon was an early developer of scrubbers, installing open loop prototypes on board the *Pride of Kent* and the *MS Zaandam*. Krystallon was acquired in 2009 by Hamworthy, a marine equipment supplier with 2010 revenue of £2.14B. Hamworthy announced an expansion of installation base to include four new Ro-Ro vessels in late 2011.
- Wärtsilä is an early developer on closed loop scrubbers testing an auxiliary unit on the *MT Suula* between 2008 and 2010. Wärtsilä installed a second shipboard system on the *Containerships VII* in 2011. Wärtsilä, with 2010 annual sales of €2.6B, acquired Hamworthy, adding the Krystallon system to their product line, in January 2012.
- Couple Systems, founded in 2007, is an early developer of a dry chemical scrubber with a 2009 pilot project on the *MV Timbus*. MAN Diesel & Turbo announced a cooperative agreement to jointly develop and market the system. As of 2011, MAN employed 14,039 people and achieved revenues of €3.6B.
- Aalborg Industries was an early developer of a hybrid open/closed loop scrubber with a 2010 pilot project on the Ro-Ro vessel *Tor Ficaria*. Aalborg had sales of SEK 3.1B in 2010 and was acquired by Alpha Laval in 2011. Alpha Laval supplies a broad range of heat transfer, separation, and fluid handling products to several industries including marine. Alpha Laval's sales in 2010 totaled SEK 24.7B (approximately €2.6B) and employed 12,600 people.
- Green Tech Marine partnered and was then acquired by Yara Group in January 2015. The Yara Group had an annual turnover of USD 14.6 billion in 2013, with USD 2.3 billion in estimated earnings (EBITDA).

8.3 Fuel Availability after World Sulfur Cap

The marine market faces unknown market pressures when the world sulfur cap is exercised. On the one hand, it could be a boom for scrubbers, perhaps even leading to a "light" version of a scrubber that only needs to remove 85% of the sulfur to meet a relatively easy 0.5% sulfur fuel cap, as compared to a tough 97.1% to meet the 0.1% sulfur ECA cap. In this scenario, there will remain an adequate supply of high-sulfur and low-sulfur fuel oil.

An alternative scenario is that scrubbers are not taken-up broadly, and the marine market requires a major increase low-sulfur fuel oil. The IMO is due to provide an assessment in 2018 on this issue. Based in part on that assessment, the IMO may choose to delay the Global 0.5% sulfur fuel cap from 2020 to 2025. The switch to natural gas, even if it is not widespread in the marine market, will relieve some of the pressure on low-sulfur diesel fuels when the world-cap is eventually implemented.

9. References

1. "MariNO$_x$ Marine Diesel Engine Emissions Monitoring System Cost Savings and Increased Profit," (product brochure), Martek Marine, 11 January 2007.
2. 40 CFR Parts 80, 85, 86, 94, 94, 1027, 1033, 1039, 1042, 1043, 1045, 1048, 1051, 1054, 1060, 1065, and 1068 [EPA–HQ–OAR–2007–0121; FRL–9097–4], *Control of Emissions from New Marine Compression-Ignition Engines at or Above 30 Liters per Cylinder*, US Government Printing Office, 30 April 2010.
3. American Petroleum Institute (API) Technical Issues Workgroup, *Technical Consideration of Fuel Switching Practices*, API, 3 June 2009.
4. *An Estimate of Operating Costs for Bulk, Ro-Ro, and Container Ships*, Bureau of Transport Economics (BTE), September 1982.
5. *Basic Principles of Ship Propulsion*, MAN B&W Diesel A/S, Copenhagen, Denmark, December 2011.
6. Behrends, B.; Liebeseit, G., *A Theoretical Environmental Impact Assessment of the Use of a Seawater Scrubber to Reduce SO$_x$ and NO$_x$ Emissions from Ships*, Research Centre Terramare, Wilhelmshaven, Germany.
7. *Bunker Fuel Charges Fact Sheet*, Transpacific Stabilization Agreement (TSA) Carriers Organization, <http://www.tsacarriers.org/fs bunker.html>, Accessed 8 December 2010.
8. California Environmental Protection Agency, *Advisory to Owners or Operators of Ocean-going Vessels Visiting California Ports*, Marine Notice 2001-2, California Air Resources Board, November 2011.
9. California Environmental Protection Agency, *Regulation on Fuel Sulfur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline*, Marine Notice 2009-1, California Air Resources Board, 5 May 2009.
10. California Environmental Protection Agency, *Water Quality Control Plan: Ocean Waters of California (California Ocean Plan)*, California State Water Resources Control Board, 2009.
11. *Containership Propulsion – beyond Post-Panamax*, MAN B&W Diesel A/S, Copenhagen, Denmark, October 2009.
12. Corbett, J.; Wang, C.; Winebrake, J.; Green, E., *Allocation and Forecasting of Global Ship Emissions*, Clean Air Task Force, Boston, 11 January 2007.
13. *CSNO$_x$ Greenhouse Gas Abatement Technology: Update of CSNO$_x$ Performance on Singapore Registered Ship*, Ecospec Global Technology Pte. Ltd., January 2010.
14. Dow, Tom M., "Cruise Ship Shore Power Project", presentation at American Association of Port Authorities 2006 Cruise Ship Seminar, San Diego, California, 8 February 2006.
15. Dupont, "Marine Scrubbing by BELCO," SMM Workshop 2010, Exhaust Gas Cleaning Systems Association (scrubber), Hamburg, Germany, 8-9 September 2010.
16. Ecospec Global Technology Pte Ltd (Ecospec), "CSNO$_x$ Greenhouse Gas Abatement Technology," presentation at 60th Session of the IMO Marine Environment Protection Committee, London, UK, 24 March 2010.

17. Environmental Protection Agency (EPA), *Control of Emissions from New Marine Compression-Ignition Engines at or Above 30 Liters per Cylinder*, *Final Rule*, 40 CFR Parts 80, 85, 86, et al., US Government Printing Office, 30 April 2010.
18. Environmental Protection Agency (EPA), *Global Trade and Fuels Assessment – Future Trends and Effects of Requiring Clean Fuels in the Marine Sector*, US Government Printing Office, November 2008.
19. Environmental Protection Agency, *Draft Vessel General Permit 2013*, US Government Printing Office, 30 November 2011.
20. Environmental Protection Agency, *Particulate Matter*, <<http://www.epa.gov/airtrends/aqtrnd95/pm10.html>>, Accessed 14 March 2012.
21. Environmental Protection Agency, *Vessel General Permit for Discharge Incidental to the Normal Operation of Vessels (VGP)*, US Government Printing Office, 5 February 2009.
22. European Environmental Bureau, European Foundation for Transport and Environment, Seas At Risk, and the Swedish NGO Secretariat on Acid Rain*, Air Pollution from Ships*, European Environmental Bureau, November 2004.
23. *Evaluation of Low Sulfur Marine Fuel Availability – Pacific Rim*, Starcrest Consulting Group, LLC, July 2005.
24. *Evaluation of Low-Sulfur Marine Fuel Availability – Pacific Rim*, ADP No. 030507-513, Starcrest Consulting Group, July 2005.
25. Exhaust Gas Cleaning Systems Association (scrubberA), *Exhaust Gas Cleaning Systems Association News,* June 2012.
26. ExxonMobil, “Low Sulfur Fuel: Impacts on the Marine Industry,” position paper, June 2009, <http://www.exxonmobil.com/lubes/exxonmobil/marine/files/LSF_Bulletin.pdf>.
27. Filancia, Arnauld, “Reducing Emissions from Shipping: Wärtsilä’s Solutions,” presentation at Sustainable Shipping Awards, London, UK, 15 July 2009.
28. *Fuel Switching Advisory Notice*, American Bureau of Shipping (ABS), March 2010.
29. Fuller, Sieglinde K. and Peterson, Stephen R. *Life-cycle Costing Manual for the Federal Energy Management Program 1995 Edition,* NIST Handbook 135, US Department of Commerce, Technology Administration, National Institute of Standards and Technology, February 1996
30. General Dynamics Corporation/NASSCO, *TOTE Orca Class Trailership Fact Sheet*, General Dynamics Corporation/NASSCO, 14 December 2010.
31. Gregory, Don, “Marine Exhaust Gas Cleaning Systems: An Overview of the Challenges and Solutions,” presentation at The European Fuels Conference, Paris, France, 13 March 2012.
32. *Guide to Marine Emissions Control*, Simulation Tech, Inc., 2010.
33. Hamworthy Krystallon*, Scrubbing Technology Update Presentation*, Exhaust Gas Cleaning Systems Association SMM 2010 Workshop, Hamburg, Germany, 2010.
34. Hansen, O.; Jacobsson, J.; Jamttjam, J.; Cooper, D.; Flodstrom, E., *The Demo Project*, PriceWaterhouseCoopers and The Swedish Environmental Research Institute, Stockholm, 22 April 2005.
35. Hayman, S., “California Low Sulfur Fuel Requirements: Exhaust Gas Scrubbers?”, email, California Air Resource Board, 17 November 2010.
36. Henriksson, T., “SO_x Scrubbing of Marine Exhaust Gases,” *Wärtsilä Technical Journal*, February 2007.
37. *Holland America Line and Hamworthy-Krystallon Sea Water Scrubber Technology Demonstration Project Final Report to USEPA*, Holland America Lines, 31 March 2010.
38. Horizon Lines, *China-US Transpacific Route and Sailing Schedule*, Horizon Lines, <http://www.horizonlines.com>, Accessed November 2010.

39. Hoy-Petersen, Nils C., *An EGCS conceived by Shipowners for Shipowners*, Clean Marine AS, December 2010.

40. Hughes, E., *IMO Perspective on MARPOL Annex VI*: *The MARPOL Effect: Sulphur Emissions, Annex VI and the Supply Chain*, IMO, 19 November 2010.

41. ICIS, *Caustic Soda Prices and Pricing Information*, <http://www.ICIS.com>, Accessed July 2009.

42. International Maritime Organization (IMO), *Guidelines for Exhaust Gas Cleaning Systems*, IMO, Marine Environment Protection Committee, Resolution MEPC.184(59), 57/21, Annex 4, July 2009.

43. International Maritime Organization (IMO), *Guidelines for Onboard Exhaust Gas-SO_X Cleaning Systems*, IMO, Marine Environment Protection Committee, 53/24/Add.1, Annex 12, 22 July 2005.

44. International Maritime Organization*, 2009 Guidelines for Exhaust Gas Cleaning Systems*, IMO, Marine Environment Protection Committee Resolution MEPC.184(59), 17 July 2009.

45. International Maritime Organization, *2009 Guidelines for Exhaust Gas Cleaning Systems*, IMO, Marine Environment Protection Committee Circular 59/24/Add.1, 17 July 2009.

46. International Maritime Organization, *Amendments to the annex of the protocol of 1997 to amend the international convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto (Designation of the United States Caribbean Sea Emission Control Area and exemption of certain ships operating in the North American Emission Control Area and the United States Caribbean Sea Emission Control Area under regulations 13 and 14 and Appendix VII of MARPOL Annex VI)* Resolution MEPC.202(62), IMO, Marine Environment Protection Committee, 15 July 2011.

47. International Maritime Organization, *International Convention for the Prevention of Pollution from Ships (MARPOL) Consolidated Edition 2011,* 5th Edition, IMO, London, UK, 2011.

48. International Maritime Organization, *Prevention of Air Pollution from Ships, Advice by GESAMP on the Interim Criteria for Discharge of Wash Water from Exhaust Gas Cleaning Systems for Removal of Sulphur-oxides*, IMO, Marine Environment Protection Committee Circular No. 59/4/19, 8 May 2009.

49. International Maritime Organization, *Prevention of Air Pollution from Ships, Wash Water Discharge Criteria for scrubber-SO_X Units*, IMO, Marine Environment Protection Committee Circular No. 55/4/7, 4 August 2006.

50. International Maritime Organization, *Regulations for the Prevention of Air Pollution from Ships*, IMO, Marine Environment Protection Committee Circular No. 58/23/Add 1, Annex 13, 17 October 2008.

51. International Maritime Organization, *Report of the Marine Environment Protection Committee on Its Fifty-Eighth Session*, IMO, Marine Environment Protection Committee Circular No. 58/32/Add.1, 17 October 2008.

52. International Maritime Organization, *Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines*, IMO, Marine Environment Protection Committee Circular No. 58/23/Add 1, Annex 14, 17 October 2008.

53. Karle, I.M.; Turner, D., *Seawater Scrubbing – Reduction of SO_X Emissions from Ship Exhausts,* The Alliance for Global Sustainability, Göteborg, 2007.

54. Knudsen, O., *Exhaust Gas Cleaning, Aalborg*, Aalborg Industries, July 2010.

55. Leigh-Jones, C. *The Case for Scrubbers, Worldbunkering.com,* <http://worldbunkering.com/articles/environment/0014-the-case-for-scrubbers.html>, 30 August 2009, Accessed 15 June 2009.

56. Lewis, Mark, *The Impact of Tightening Bunker Specifications on the International Fuel Oil Market*, FUJCON 2011, Fujariah, 14-16 March 2011.

57. *MAN Diesel & Turbo at a Glance,* press release, MAN Diesel & Turbo, <http://mandieselturbo.com/article_001475.html>, accessed 18 July 2012.

58. *Marine Exhaust Gas Scrubber, MEPC Correspondence Group on Wash Water Discharge Criteria*, The European Association of Internal Combustion Engine Manufacturers, 29 March 2007.

59. *Marine Project Guide-Wärtsilä 20*, Wärtsilä, January 2004.

60. Marttinen, V., "Feasible SO_x Solutions," Wärtsilä's Environmental Seminar in Helsinki, 18 July 2010.

61. Meech, Robin, *Emission Control Areas (ECAs)*, Regional Workshop on the Ratification and Implementation of MARPOL Annex VI, IMO Regulational Marine Pollution Emergency Response Center for the Mediterranean Sea (REMPEC), Athens, Greece, 26-27 October 2010.

62. *New Compact Scrubber Showing Promising Results in Full-Scale Trial onboard Royal Caribbean Ship*, corporate press release, Green Tech Marine, 19 *Understanding Exhaust Gas Treatment Systems: Guidance for Ship Owners and Operators,* Lloyd's Register, June 2012.

63. New York State Department of Health, "Fine Particles (PM2.5) Questions and Answers," << *http://www.health.ny.gov/environmental/indoors/air/pmq_a.htm*>>, Accessed 14 March 2012.

64. *Notes on Heavy Fuel Oil*, American Bureau of Shipping, Houston, Texas, 1984.

65. Pjetraj, M. *Condensible Particulate Matter: Regulatory History and Proposed Policy*, NC DAQ Stationary Source Compliance Branch, 27 January 1998.

66. Pöyry Finland Oy, *Marine Exhaust Gas Scrubber Tests at M/S "Containerships VII" 2 December 2011,* Report No. 16ENN0004.90.Q850-002, 21 February 2012.

67. *Propulsion Trends in Bulk Carriers*, MAN Group, Copenhagen, Denmark, 22 December 2010.

68. *Propulsion Trends in Container Vessels: MAN B&W Two-stroke Engines*, MAN Group, Copenhagen, Denmark, 19 September 2008.

69. *Propulsion Trends in Tankers*, MAN Group, Copenhagen, Denmark, 2 October 2007.

70. Rushing, Amy; Kneifel, Joshua D; and Lippiatt, Barbara C., *Energy Price Indices and Discount Factors for Life cycle Cost Analysis – 2010*, NISTIR 85-3273-25, US Department of Commerce, Technology Administration, National Institute of Standards and Technology, May 2010.

71. Tany Tay, "Ecospec Marine Exhaust Gas Scrubbers," email, Ecospec, 5 July 2012.

72. Tetra Tech, Inc. and UltraSystems Enviromental Incorporated, *Final Report: Low-Sulfur Marine Fuel Availability Study for the Port of Long Beach and Port of Los Angeles*, Port of Long Beach and Port of Los Angeles, 14 April 2008.

73. *Tier III Compliance: Low Speed Engines*, product brochure, MAN Diesel & Turbo, June 2010.

74. Toombs, P., *Emission Regulations and The Impact of Exhaust Gas Cleaning System Technology*, Marine Exhaust Solutions, May 2010.

75. United States Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), and National Ocean Service, *Distances between United States Ports*, National Ocean Service, 10th Edition, 2009.

76. US Coast Guard, *Avoiding Propulsion Loss from Fuel Switching: American Petroleum Institute Technical Considerations,* Marine Safety Alert No. 03-09, United States Department of Homeland Security, Washington, DC, 16 June 2009.

77. US Energy Information Administration, *Assumptions to the Annual Energy Outlook*, US Government Printing Office, December 2013.

78. US Environmental Protection Agency, *Proposed 2013 Vessel General Permit for Discharges Incidental to the Normal Operation of Vessels (VGP) Draft Fact Sheet*, US Government Printing Office, 2011.Office of Policy and Plans, *North American Cruise Statistical Snapshot, 2011*, US Department of Transportation Maritime Administration, March 2012.

79. US Environmental Protection Agency, *Summary and Analysis of Comments: Control of Emissions from New Marine Compression-Ignition Engines at or Above 30 Liters per Cylinder*, US Government Printing Office, December 2009.
80. US Environmental Protection Agency, *Vessel General Permit for Discharges Incidental to the Normal Operation of Vessels (VGP)*, US Government Printing Office, 5 February 2009.
81. van Rhynbach, E.; Briers, K., *Fuel Storage & Handling Systems and the Costs of Operating in ECAs*, Herbert Engineering, presentation, Society of Naval Architects & Marine Engineers Symposium, Operating Ships within Emission Control Areas (ECA's), San Francisco, California, 28-29 April 2010.
82. Wärtsilä Finland Ecotech Scrubber Team, *Public Test Report: Exhaust Gas Scrubber Installed Onboard* MT Suula, Wärtsilä , 20 June 2010.
83. World Shipping Council, *Record Fuel Prices Place Stress on Ocean Shipping*, World Shipping Council, 2 May 2008.
84. Zoeteman, P.; "Closing the Loop, Exhaust Cleaning Systems," *Bunkerspot*, August/September 2010, Vol. 7, Issue 4, pp. 38-39.
85. *IMO Pollution Prevention and Response (PPR 2) Summary Report*, Lloyd's Marine Register, January 2015.
86. *Treasured Waters: Protecting Our Coastal and Marine Resources*, US Environmental Protection Agency Office of Water, EPA/842/B-96/001, June 1996.
87. International Maritime Organization*, Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Related Thereto (Annex 13)*, IMO, Marine Environment Protection Committee Resolution MEPC.176(58), 10 October 2008.
88. *New Requirements for the Upcoming 2013 US EPA Vessel General Permit*, ABS Trends, American Bureau of Shipping, 1 October 2013.
89. *Assessment of Possible Impacts of Scrubber Water Discharges on the Marine Environment*, Danish Ministry of the Environment, Environmental Protection Agency, Project No. 1431, 2012.
90. Einemo, U.; "No Ban on Open Loop Scrubbers in Sweden," Bunkerworld, 27 November 2014.
91. *BIMCO & IBIA Bunkering Guide*, BIMCO, International Bunker Industry Association, October 2010.
92. *Exhaust Scrubbers – What You Need to Know*, Bureau Veritas, March 2014.
93. *Guidance for Complying with the California Ocean-Going Vessel Fuel Regulation During the Air Resources Board Sunset Review Process*, California Air Resources Board, Marine Notice 2014-1, August 2014.
94. *Amendment and Compilation of Chapter 11-54 – Hawaii Administrative Rules*, Hawaii State Department of Health, 15 November 2014.
95. *CSNO*$_X$, product brochure, Ecospec Technology Pte Ltd, accessed July 2015.
96. Einemo, U.; "Current procedures a 'bottle neck' for scrubber approvals," Sustainable Shipping News, 16 April 2014.
97. *Scrubbers – An Economic and Ecological Assessment*, CE Delft report for the Nature and Biodiversity Conservation Union (NABU), March 2015.
98. London, A.C.; "Green Group Claims Scrubbers Destroy Marine Life," TradeWinds News, 20 March 2015.
99. "Icy Waters Between Marine Players and NABU after Scrubber Report," press release, Insatech Marine, 19 March 2015.
100. "Dry Exhaust Gas Cleaning for Ships," informational presentation, Couple Systems GmbH.

101. *Exhaust Gas Scrubber Washwater Effluent*, US Environmental Protection Agency – Office of Wastewater Management, EPA-R-11-006, November 2011.

102. *Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012, amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels*, Official Journal of the European Union, L 327/1, 27 November 2012.

103. "ExxonMobil Launches ExxonMobile Premium HDME 50 Marine Fuel," press release, ExxonMobil, 9 July 2014.

104. "Implementing continuous monitoring systems: Class society perspective," presentation by Dr. Fabian Kock, A Practical Guide to Scrubbers North America, Miami, Florida, USA, 17-18 November 2014.

105. *Framework for the National System of Marine Protected Areas of the United States of America*, National Marine Protected Areas Center, a collaboration between the National Oceanic and Atmospheric Administration and Department of the Interior, March 2015.

106. *Bunker Delivery Note and Fuel Oil Sampling*, International Maritime Organization, MEPC.1/Circ.508, 9 May 2015.

107. *Emission Control Area (ECA) SO_X Requirements: Guidance to INTERTANKO Members for the Selection of Compliance Alternatives*, International Association of Independent Tanker Operators (INTERTANKO), July 2012.

108. *Information on North American Emission Control Area (ECA) Under Marpol Annex VI*, International Maritime Organization, MEPC.1/Circ.723, 13 May 2010.

109. "New Couple Systems EGCS Dry Scrubber + Compact SCR," presentation by Dan Lingenberg, Couple Systems GmbH, Green Ship Technology Conference, Hamburg, Germany, 12-14 March 2013.

110. Einemo, U.; "Norway highlights shortcomings in IMO scrubber guidelines," Sustainable Shipping News, 31 January 2014.

111. Einemo, U.; "Stringent washwater criteria 'could eliminate' some scrubbing technology," Sustainable Shipping News, 6 February 2013.

112. *The EU Sulphur Directive and DFDS' Response*, informational brochure, DFDS, February 2014.

113. US Environmental Protection Agency, *Vessel General Permit for Discharges Incidental to the Normal Operation of Vessels (VGP)*, US Government Printing Office, 19 December 2013.

114. 33 US Code §§ 1901-1915, *Act to Prevent Pollution from Ships*, 29 December 2000.

Appendix A Exhaust Gas Cleaning Systems Technology Survey

This Appendix summarizes the Ship Operations Cooperative Program (SOCP) marine exhaust gas cleaning system (EGCS) supplier survey results.

The following information was provided by equipment suppliers, and comprises self-certified data on their system particulars and performance. The purpose of this data is to allow SOCP members to identify one or more technologies that may be suitable for their ship(s). Members may then contact suppliers directly for detailed integration and commercial discussions.

Response	Description
None	Confirms a zero quantity.
DNA	Inquiry does not apply to technology.
TBD	Inquiry either not answered or unclear.

A1. Supplier Summary

Systems are compared at a high level in the following table, reflecting February 2015 data. System details are provided on the following pages.

†	Supplier Name	Unit Size* Range (MW)	System Types	Claimed Reductions	Shipboard Experience (Vessel Installations)
1	Alfa Laval	1 to 80	Open Loop Closed Loop Hybrid	98% SO_x up to 80% PM	29 Installs >50,000 Total Hours
2	Clean Marine	1 MW and up	Open Loop Closed Loop Hybrid	>98% SO_x Up to 85% PM	4 Installs
3	CROE®	1 to 80	Open Loop Closed Loop Hybrid	99% SO_x 30-80% PM 30-80% HC	8 Installs
4	Ecospec	8-18	Closed Loop Open Loop	TBD	3 Installs
5	Ecospray		Closed Loop	TBD	24 Installs
6	Envairtec	1 to 25	Dry	95% SO_x 90% PM 90% HC	5 Installs >10,000 Total Hours
7	Ionada	Up to 120 MW	Membrane	99%+ SO_x	1 Install 200 Total Hours
8	Mitsubishi	6 to 70	Open Loop Closed Loop Hybrid	>98% SO_x	1 Install
9	SAACKE	3-10	Open Loop	99% SO_x 80% PM	1 Install >10,000 Total Hours
10	Wärtsilä	1 to 70	Open Loop Closed Loop Hybrid	99% SO_x 60% PM	74 Installs >100,000 Total Hours
11	Yara	TBD	Open Loop	TBD	16 Installs

* Unit size refers to diesel engine size served. Boiler units are not considered in this survey.
† Vendors are listed alphabetically and not by price or efficiency.

A2. Alpha Laval

Contact	Sales Lead: René Diks, +31 (0)24 352 3100 Email: rene.diks@alfalaval.com Website: www.alfalaval.com/puresox		
Technology Type(s)	PureSO$_x$ EGC system, open, closed, hybrid, u-type, inline	**Other Products**	Over the course of 2015 Alfa Laval will launch the inline version of PureSO$_x$
Exhaust Monitoring IMO Scheme	Scheme B	**Development Phase**	PureSO$_x$ 2.0 is a proven technology
System Availability	1 MW to 80 MW		
Failure Modes	U-type: bypass Inline: dry-running	**Failure Recovery**	The problem must be solved after which the system will return to normal operation automatically. The EGC can be remotely checked for troubleshooting by Alfa Laval.

Unit Size* (MW)	Scrubber Type	Power ECA/ at Sea/ in Port	Scrubber Backpressure/ Wash water	Wet Weight/ Diameter/ Length	Installed Vessels/ Hours
20	Hybrid RoRo Vessel	Max. 270 kW SW (ECA) Max. 136 kW SW (non ECA Max. 207 kW FW	100 mm H2O 1322 m3/hr (low alkalinity)	33 tonnes 4800 mm 11600 mm	6 Vessels (Ficaria Seaways > 20000 hrs)
28	Hybrid ConRo Vessel	Max. 247 kW SW (ECA) Max. 348 kW FW	100 mm H2O 1175 m3/hr	35 tonnes 4200 mm 10300 mm	6 Vessels (Plyca > 20000 hrs)
21,6	Hybrid (2x) RoRo Vessel	Max. 270 kW SW (ECA) Max. 135 kW SW (non ECA Max. 291 kW FW	100 mm H2O 1450 m3/hr (low alkalinity)	2 systems, each: 12,5 tonnes 3100 mm 7400 mm	3 Vessels

Unit Size* (MW)	Scrubber Type	Power ECA/ at Sea/ in Port	Scrubber Backpressure/ Wash water	Wet Weight/ Diameter/ Length	Installed Vessels/ Hours
24	Hybrid RoPax Vessel	Max. 301 kW SW (ECA) Max. 134 kW SW (non ECA Max. 258 kW FW	100 mm H2O 1800 m3/hr (low alkalinity)	31 tonnes 4700 mm 10900 mm	3 Vessels
18,9	Hybrid RoPax Vessel	Max. 293 kW SW (ECA) Max. 158 kW SW (non ECA Max. 260 kW FW	100 mm H2O 1300 m3/hr (low alkalinity)	29.9 tonnes 4400 mm 10600 mm	1 Vessel
23,5	Closed loop (2x) Cruise vessel	Max. 148 kW FW (ECA)	100 mm H2O	16 tonnes 3200 mm 8600 mm	4 Vessels
14	Open loop Container vessel	Max. 159 kW SW (ECA)	100 mm H2O 736 m3/hr	13 tonnes 3000 mm 9200 mm	2 Vessels
12,6	Open loop RoRo vessel	Max. 136 kW SW (ECA) Max. 70 kW SW (non ECA	100 mm H2O 840 m3/hr (low alkalinity)	16,5 tonnes 3500 mm 8900 mm	2 Vessels
18,9	Open loop RoRo vessel	Max. 246 kW SW (ECA) Max. 123 kW SW (non ECA	100 mm H2O 1157 m3/hr (low alkalinity)	33 tonnes 4200 mm 10200 mm	2 Vessels

* Unit size refers to diesel engine size served. Boiler units are not considered in this survey.

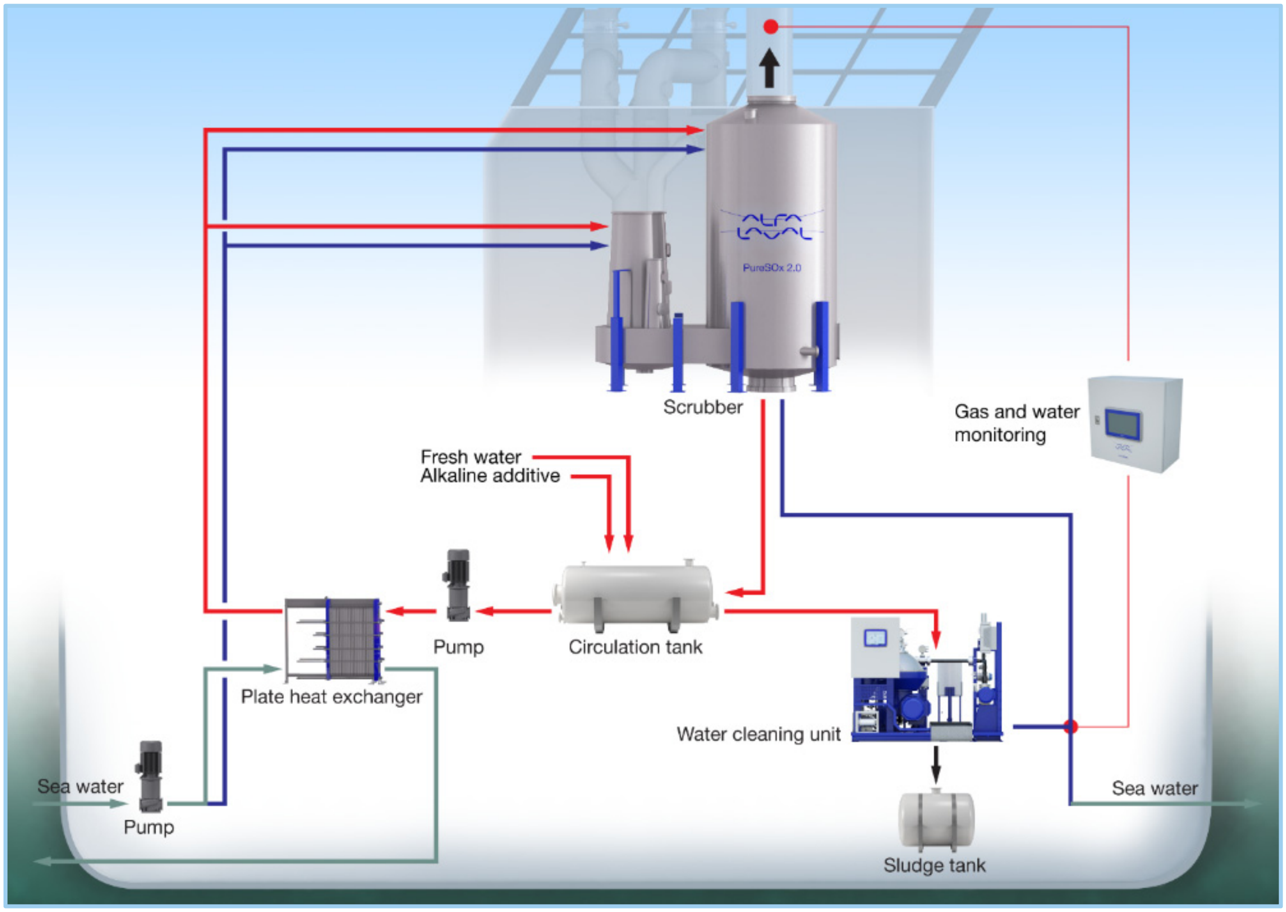
Waste Streams

Wash Water Generation	**50 tons/MW-hr Open Loop Mode** **0.1 tons/MW-hr Closed Loop Mode**
Must discharge in port?	**No, in closed loop zero discharge**
Discharge pH at 4 meters (IMO)?	**6.5 based on calculation model**
Discharge pH at 0 meters (EPA)?	**> 6 in closed loop**
Wash Water Filtration Method	**Alfa Laval PureSO$_x$ H2O water cleaning unit**
Sludge Residue Quantity	**< 0.2 kg/MW-hr**
Disposal Method?	**Can be treated as normal sludge**
Solid Waste Quantity	**DNA**
Disposal method?	**DNA**

System Details

Technology Type	**Open Loop/ Closed Loop/ Hybrid/ Other**
Electrical Load (kW per MW-hr)	
ECA	**10-12 kW/MWhr**
At Sea	
Chemical Usage at 3.5% HFO (kg per MW-hr)	
Chemical and Concentration	**Caustic / 50% solution**
ECA	**20-25kg/MWhr**
At Sea	
FW Consumption at 20 Celsius (kg per MW-hr)	
ECA	**Depending on ships operating profile and SW temperature**
At Sea	
Exhaust Handling: Pressure drop at full load (kPa)	**1 kPa**
Does unit serve as silencer/spark arrestor?	**yes**
System failure block free flow of exhaust?	**no**
Multiple engine inlet capable?	**Yes, with bypass**
Wash Water – Open Loop (tons per MW-hr)	
ECA	**50 tons/MWhr**
At Sea	
Wash Water – Closed Loop (tons per MW-hr)	
ECA	**Depending on ships operating profile and SW temperature**
At Sea	

System Description (Provided by Supplier)



Alfa Laval PureSOx is a scrubber system specifically developed for SOx abatement. At sea since 2009 and launched commercially in 2012, the system has been continuously optimized and has now entered its second generation. PureSOx 2.0 combines the proven PureSOx scrubber technology with innovations leading to greater compactness and flexibility.

PureSOx has been shown to reliably remove more than 98% of the SOx content in exhaust gas, as well as up to 80% of the particulate matter (PM). This exceeds the requirements set by IMO in MARPOL Annex VI. Even during periods of rapid change in engine load, SOx levels are kept well within ECA emission limits, as has been demonstrated during thousands of hours at sea.

PureSOx is available in open-loop and closed-loop configurations, as well as a hybrid configuration with the advantage of both open- and closed-loop modes. The system can also be configured with multiple inlets, which allows one scrubber to handle the exhaust gas from several sources.

The reference list for PureSOx is substantial, comprising more references than any other single SOx scrubber technology. It includes both main and auxiliary engine installations as large as 28 MW, as well as repeat orders from major industry players. All PureSOx systems ever supplied are still in use and operating within ECA limits.

PureSOx builds on Alfa Laval core expertise, including over 40 years of marine scrubber experience and world-leading strengths in centrifugal separation. The system is also backed by Alfa Laval's global organization, which can provide service and support at any time, anywhere in the world. This chapter provides a complete introduction to the PureSOx system, including a summary of the support, documentation and resources offered by Alfa Laval as a supplier.

A3. Clean Marine

Contact	Sales Lead and Phone: Atle Haugen - +4791348783 Email: aha@cleanmarine.no Website: www.cleanmarine.no		
Technology Type(s)	Hybrid	**Other Products**	Only EGCS
Exhaust Monitoring IMO Scheme	Scheme B	**Development Phase**	
System Availability	1 MW and up		
Failure Modes	Bypass to atmosphere	**Failure Recovery**	

Unit Size* (MW)	Scrubber Type	Power ECA/ at Sea/ in Port	Scrubber Backpressure/ Wash water	Wet Weight/ Size (HxWxL)	Installed Vessels/ Hours
31.5 MW +3 boilers	Hybrid - Allstream	Max. power rqmt: 400kW	No backpressure 900 m3/hr	47 tonnes 20x9.8x5.6 meters	2 Vessels 250 Hours
11.2 MW + 3 Boilers	Hybrid - Allstream	Max. power rqmt: 280kW	No backpressure 560 m3/hr	30,5 tonnes 16.8x8.9x4.7 meters	2 Vessels Not delivered
17.2 MW + Boiler	Hybrid - Allstream	Max. power rqmt: 280kW	No backpressure 560 m3/hr	33.2 tonnes 17x8.9x5 meters	1 Vessel 250 Hours
12.55 MW +3 boilers	Hybrid - Allstream	Max. power rqmt: 220kW	No backpressure 400 m3/hr	20,4 tonnes 15.9x7.7x4.4 meters	2 Vessels Not delivered
10 MW +boiler	Hybrid – Allstream Retrofit	Max. power rqmt: 240 kW	No backpressure 400 m3/hr	17.2 tonnes 13.7x6.9x3.7 meters	1 Vessel 2000 Hours

* Unit size refers to diesel engine size served. Boiler units are not considered in this survey.
** All Clean Marine EGCS delivered have boiler(s) connected.

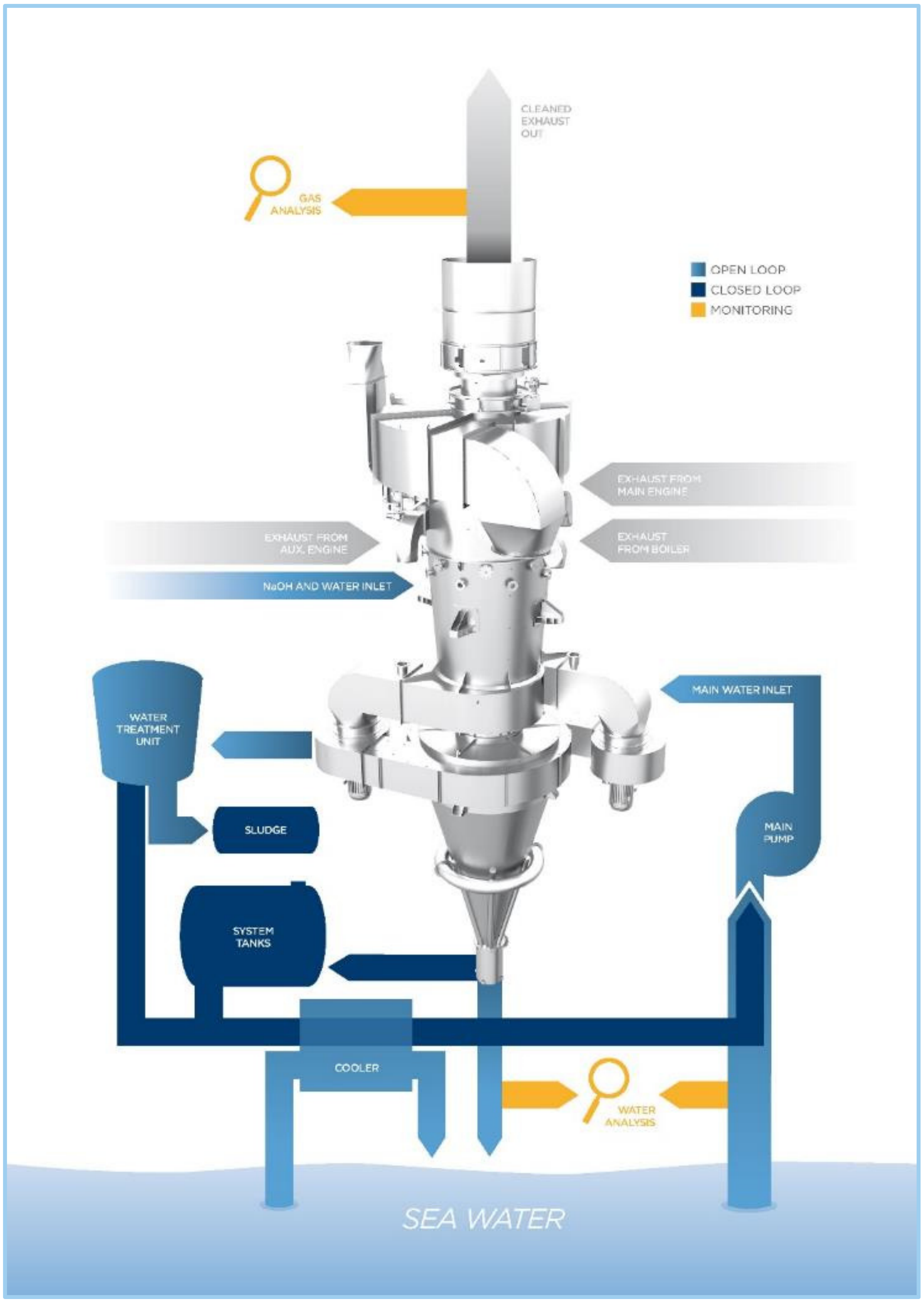
Waste Streams

Wash Water Generation	**4 liters/kg exhaust gas Open Loop Mode 0/MW-hr Closed Loop Mode**
Must discharge in port?	**No, in closed loop zero discharge**
Discharge pH at 4 meters (IMO)?	**>6.5**
Discharge pH at 0 meters (EPA)?	**>6**
Wash Water Filtration Method	**Filter**
Sludge Residue Quantity	**30 liters/mt HFO in Closed Loop. No sludge in Open Loop**
Disposal Method?	**Discharge to shore or sea within IMO limits**
Solid Waste Quantity	**5 kg/mt HFO**
Disposal method?	**Delivered to shore**

System Details

Technology Type	**Open Loop/ Closed Loop/ Hybrid/ Other**
Electrical Load (kW per MW-hr)	**1.5-2% of treated power**
ECA	**Depending on operational profile**
At Sea	**Depending on operational profile**
Chemical Usage at 3.5% HFO (kg per MW-hr)	**Open loop – Max. 40 liters/mt HFO Closed loop – Max 85 liters/mt HFO**
Chemical and Concentration	**NaOH (Caustic soda) – 50% solution**
ECA	**Depending on operational profile**
At Sea	**Depending on operational profile**
FW Consumption at 20 Celsius (kg per MW-hr)	**None**
ECA	**Depending on operational profile**
At Sea	**Depending on operational profile**
Exhaust Handling: Pressure drop at full load (kPa)	**None**
Does unit serve as silencer/spark arrestor?	**Yes**
System failure block free flow of exhaust?	**No**
Multiple engine inlet capable?	**Yes**
Wash Water – Open Loop (tons per MW-hr)	**4 liters/kg exhaust**
ECA	**Depending on operational profile**
At Sea	**Depending on operational profile**
Wash Water – Closed Loop (tons per MW-hr)	**None**
ECA	**Depending on operational profile**
At Sea	**Depending on operational profile**

System Description (Provided by Supplier)



The Clean Marine EGCS gas and liquid interface unit has a high speed cyclone incorporated in the design providing a unique high PM and sulphur trapping efficiency. The proprietary AVC (Advanced vortex chamber) technology creates a vortex motion of gas and liquid inside a patented chamber. When a stream of gas enters the spiral chamber, it is accelerated and twirled into very high velocity vortex that is being manipulated by different sets of vertical blades and air funnels, and without moving parts. The physical force-pattern separates fine particles from the gas or liquid by pushing the particles to the center of the system with no wear or clogging risks. This results in efficient separation performance and lower operational and maintenance costs.

The Clean Marine EGCS is a unique Allstream system: all exhaust sources (boilers included) are served by one common EGC unit without any additional back pressure. This makes it a cost-efficient option for vessels with many exhaust sources, as the one EGCS unit simultaneously serve several combustion units. An integrated fan and gas recirculation feature ensures that the back pressure in the exhaust pipes and hence the efficiency of the combustion units is undisturbed. A fail safe automatic gas bypass feature allows the ships to continue operating without disturbances should the system fall out of operation.

The Clean Marine system works equally well in open loop (liquid one time through) and closed loop (liquid recirculation) modes while seawater and an alkali (NaOH in 50% solution) is used to regulate the sulfur trapping efficiency. As the systems works independently of the combustion units and the cleaning efficiency is governed by the alkali feed only, the operation of the system is simple and robust. In Open Loop the system will ensure the vessel meets the 0,1% sulphur limit also in brackish water, rivers and estuaries. The alkali is automatically dosed and used to regulate the sulfur trapping efficiency when surrounding seawater does not have the sufficient buffering capacity.

Further, the use of alkali as a neutralizing agent enables the Clean Marine EGCS to meet the current pH limit for washwater discharges with good margin. The quality of discharged washwater exceeds IMO regulations and meets the much stricter US EPA requirement of a pH of no less than 6 at the ship's overboard discharge.

The close to neutral pH in effluent water also means it is less corrosive to the hull and piping, thus providing a longer life time of the system and less maintenance cost.

Clean Marine also offers the only open loop EGCS which complies with the most stringent Environmental Class notation offered by DNV GL: "Clean Design". In order to qualify for the "Clean Design" notation the pH must be no less than 6 at the overboard discharge, with the exception that during maneuvering and transit, the maximum difference between inlet and outlet of 2.0 pH units is allowed.

A4. CR Ocean Engineering (CROE®)

Contact	Sales Lead and Phone: Nicholas Confuorto, +1 (973) 455-0005 ext. 110 Email: nconfuorto@croceranx.com Website: www.croceanx.com		
Technology Type(s)	CROE® Marine Scrubbing Systems (Open Loop, Caustic Assist™ Open Loop, Closed Loop or Hybrid Designs are available)	**Other Products**	Land based scrubbers (Open Tower, packing, Jets, High Energy Venturis and Horizontal Cross-Flow designs)
Exhaust Monitoring IMO Scheme	Scheme B	**Development Phase**	Fully developed and based on 60 years of on-land operating experience - Commercial
System Availability	1 MW to 80 MW		
Failure Modes	Scrubber has Dry operation capability and allows engine to continue to exhaust gas normally even if problems occur with the pumps or any other component. Bypass is not required.	**Failure Recovery**	When issues are resolved the pumps are placed back in operation and scrubber will resume scrubbing of pollutants.

Unit Size* (MW)	Scrubber Type	Power ECA/ at Sea/ in Port	Scrubber Backpressure/ Wash water	Wet Weight/ Diameter/ Length	Installed Vessels/ Hours
6	Closed Loop	32 kW ECA 0 kW at Sea 0 kW in Port	<100 mm H2O <0.5 m3/hr	7 tonnes 2200 mm 7000 mm	1 Vessels TBD Hours
6	Open Loop	80 kW ECA 0 kW at Sea 0 kW in Port	<100 mm H2O <350 m3/hr	6.7 tonnes 1900 mm 7600 mm	1 Vessels TBD Hours
16	Open Loop	189 kW ECA 0 kW at Sea 0 kW in Port	<100 mm H2O <1000 m3/hr	8.4 tonnes 2600 mm 7700 mm	1 Vessels TBD Hours
12	Hybrid	72 kW ECA 0 kW at Sea 0 kW in Port	<100 mm H2O <700 m3/hr for open loop mode	7.5 tonnes 2400 mm 7200 mm	>5 Vessels TBD Hours

* Unit size refers to diesel engine size served. Boiler units are not considered in this survey.

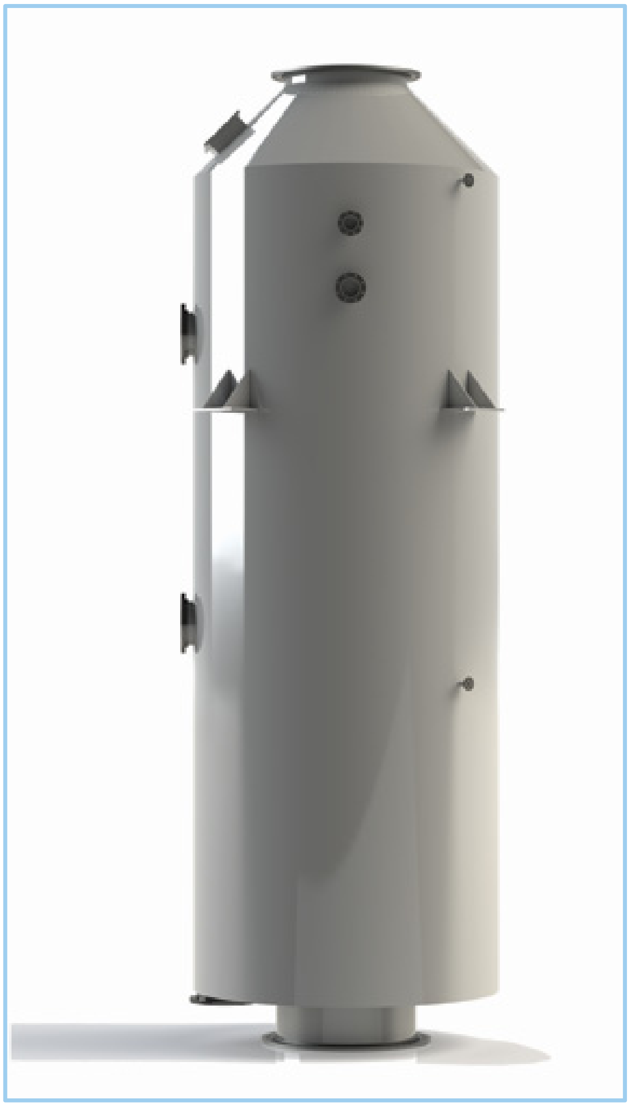
Waste Streams

Wash Water Generation	**Open Loop Mode - Varies based on fuel used and water temperature.** **Closed Loop Mode – Varies based on fuel used and operating conditions**
Must discharge in port?	**No, in closed loop zero discharge is possible**
Discharge pH at 4 meters (IMO)?	**YES**
Discharge pH at 0 meters (EPA)?	**YES**
Wash Water Filtration Method	**Centrifuge and/or positive filtration as may be required**
Sludge Residue Quantity	**0.1 – 0.5 kg/MW-hr depending in fuel quality**
Disposal Method?	**At shore disposal same as engine room sludge**
Solid Waste Quantity	**0 kg/MW-hr**
Disposal method?	**DNA**

System Details

Technology Type	**Open Loop/ Closed Loop/ Hybrid/ Other**
Electrical Load (kW per MW-hr)	
ECA	**12/5/6-12 kW per MW-hr**
At Sea	**0 kW per MW-hr**
Chemical Usage at 3.5% HFO (kg per MW-hr)	**For Closed Loop operation only**
Chemical and Concentration	**As 100% NaOH (can use any concentration)**
ECA	**8-12 kg per MW-hr**
At Sea	**0 kg per MW-hr**
FW Consumption at 20 Celsius (kg per MW-hr)	**For Closed Loop operation only**
ECA	**10-20 Kg per Mw-hr**
At Sea	**0 Kg per Mw-hr**
Exhaust Handling: Pressure drop at full load (kPa)	**<0.98 kPa**
Does unit serve as silencer/spark arrestor?	**YES**
System failure block free flow of exhaust?	**YES**
Multiple engine inlet capable?	**YES**
Wash Water – Open Loop (tons per MW-hr)	
ECA	**4 – 6 tons per MW-hr**
At Sea	**0 tons per MW-hr**
Wash Water – Closed Loop (tons per MW-hr)	
ECA	**0.05 – 0.07 tons per MW-hr**
At Sea	**0 tons per MW-hr**

System Description (Provided by Supplier)



CR Ocean Engineering LLC (also known as CROE) is a leading air pollution reduction technology supplier offering a full range of systems customized to a client's specific needs. With its roots dating back to 1917 and with more than 60 years of scrubbing systems experience, CROE is part of one of the oldest and most reputable air pollution control companies in the world. CROE's global headquarter is located in Parsippany, NJ and it has developed a network of fabrication shops and service/sales offices located across the globe. It's well proven, state of the art technology, offers the shipping industry a low cost, high reliability alternate to high-sulfur fuel. Furthermore, CROE offers full process and mechanical guarantees with each scrubbing systems. When using a CROE scrubbing system, ship owners can continue using the lower cost high-sulfur fuel oil even in the Environmental Controlled Areas (ECA) without concerns.

The CROE scrubbing system is designed to be lighter, smaller, more efficient and more cost effective than most competing scrubbing systems. It requires low backpressure, has an all metal construction, requires no bypass, replaces the silencer and can run dry without concerns. A complete washwater treatment system is also provided by CROE as part of the scrubbing system. The CROE Scrubbing System is available in Open Loop (Seawater), Closed Loop (Freshwater) or Hybrid configurations (able to switch from one configuration to the other on demand).

In most cases the CROE scrubbers utilize the structure that is presently being used to support the silencer without any major modification to that structure or the funnel itself. CROE also offers its state of the art Caustic Assist™ feature for clients operating in areas where the alkalinity and salinity are very low but wish to use our Open Loop configuration.

A5. Ecospec

Contact	Sales Lead and Phone: Tany Tay; +65 6412 7788, +65 98280954 Email: tany@ecospec.com Website: www.ecospec.com		
Technology Type(s)	cSOx, complete closed loop system	**Other Products**	ElMag, corrosion control BioMag, biofouling control ScaMag, boiler water treatment
Exhaust Monitoring IMO Scheme	Scheme B	**Development Phase**	Commercialised
System Availability	3 MW onwards		
Failure Modes	The System is designed to run dry. Interrupted operations are not an issue	**Failure Recovery**	The problem must be solved, after which the system will return to normal operation automatically.

Unit Size* (MW)	Scrubber Type	Power ECA/ at Sea/ in Port	Scrubber Backpressure/ Wash water	Wet Weight/ Diameter/ Length	Installed Vessels/ Hours
2 x 9 MW	cSOx, complete closed loop system	1 to 3% kW of plant capacity ECA, at Sea and in Port	Less than 200mm H2O 300-640 m^3/hr	11 tonnes 2000 mm 7000 mm (all per tower)	1 Vessel Since end Dec. 2014
1 x 8 MW	cSOx, complete closed loop system	1 to 3% kW of plant capacity ECA, at Sea and in Port	Less than 200mm H2O 300-700 m^3/hr	10 tonnes 2200 mm 6500 mm	1 Vessel Over 1 year
1 x 11 MW	CSNOx, open loop system	1 to 3% kW of plant capacity ECA, at Sea and in Port	Less than 200mm H2O 740 m^3/hr	10 tonnes 1500 mm 7400 mm	1 Vessel Over 1 year

* Unit size refers to diesel engine size served. Boiler units are not considered in this survey.

Waste Streams

Wash Water Generation	**This is a complete closed loop system. Water being circulated in the system is 40 tons/MW-hr.**
Must discharge in port?	**Zero discharge as it is a permanently closed system.**
Discharge pH at 4 meters (IMO)?	**DNA**
Discharge pH at 0 meters (EPA)?	**DNA**
Wash Water Filtration Method	**Not required**
Sludge Residue Quantity	**5 kg/MW-hr**
Disposal Method?	**Shore based reception**
Solid Waste Quantity	**0.5 kg/MW-hr**
Disposal method?	**Shore based reception**

System Details

Technology Type	**Closed Loop**
Electrical Load (kW per MW-hr)	
ECA	**1 to 3% kW of plant capacity**
At Sea	**1 to 3% kW of plant capacity**
Chemical Usage at 3.5% HFO (kg per MW-hr)	
Chemical and Concentration	**NaOH 25% concentration**
ECA	**13**
At Sea	**13**
FW Consumption at 20 Celsius (kg per MW-hr)	
ECA	**50~170 (depends on exhaust gas temperature)**
At Sea	**50~170 (depends on exhaust gas temperature)**
Exhaust Handling: Pressure drop at full load (kPa)	
Does unit serve as silencer/spark arrestor?	**Yes, it can replace the silencer**
System failure block free flow of exhaust?	**Not required (The System is designed to run dry)**
Multiple engine inlet capable?	**Single engine**
Wash Water – Open Loop (tons per MW-hr)	**DNA**
ECA	
At Sea	
Wash Water – Closed Loop (tons per MW-hr)	
ECA	**40**
At Sea	**40**

System Description (Provided by Supplier)

The fundamental working principle of the cSOx system lies in the ULF wave technology. ULF is a form of non-thermal pulsed low frequency electro-magnetic wave. This wave energized the water in a tank installed with our proprietary components. The treated water is then sprayed into the cSOx tower where the SO2 is removed.

Concurrently, a partial amount of Carbon Dioxide (CO2) is eradicated allowing only cleaned exhaust gas to be released into the atmosphere. Though the primary function of cSOx is to remove SO2 in the exhaust gas down to equivalent of 0.1% sulphur in the fuel to meet the IMO MEPC (Marine Environment Pollution Committee) regulations for the SECA and ECA regions discussed in the above section, the simultaneous removal of CO2 enables the vessel to achieve a carbon neutral position when the system is in operation. This is designed to address upcoming regulations for further reduction in CO2. This is a feature no other system in the market is capable of.

Port authorities around the world are moving towards zero discharge. cSOx being a truly complete closed loop system, there is no necessity to discharge waste water overboard at any time thus operators need not have to concern themselves with meeting the wash water conditions at any port. With a complete closed loop system like cSOx, it also eliminates the need for changeover between the different operational modes like in the hybrid systems. Thus reduces the capital cost for additional monitoring equipment and the maintenance cost related to them.

Due to its unique ULF treatment of the water, the cSOx system does not need large amount of cooling water as seen in conventional chemical systems. It therefore rids of the necessity for a new sea chest.

The ULF treatment is always maintained at alkaline condition. The non-corrosive nature of the water even after reaction with the gases also means Corten steel can be used for the reaction tower, it is not necessary to have the high cost super duplex steel. Similarly, metallic piping is used for this system, doing away with the difficult to install and costly GRE pipes.

The cSOx system also does not depend on the salinity of water to function therefore reducing the need of producing more of the much needed freshwater onboard, maintaining the existing operating cost. The system can operate with different types of water: seawater, freshwater, brackish water. Thus, allowing vessels installed with cSOx to operate freely around the world and yet meeting the regulations.

cSO$_X$ towers within the funnel space, replacing the silencers

The cSOx system has the most compact design in the market. With the shortest tower in the market for SOx removal, the volume of water required is at a much lower quantity. This in turn translates to much lower pumping requirements and therefore lower power consumption.

In conventional EGCS systems, an extraction fan has to be installed for these systems to function. This is not required in the cSOx system. All these features mentioned above translate to lower capital cost and operating cost, maintenance cost in the long run. The most distinctive feature of the cSOx system is its upgradability. Should your organization wish to remove higher amount of CO2 and even NOx to meet future regulations, the cSOx system can be enhanced to meet your requirements with minimal modifications. This will assist owners to prepare for more stringent regulations to come.

A6. Ecospray Technologies

System Description (Provided by Supplier)

The ECO-SO_x SEA WATER DeSO_x TOWER - OPEN LOOP system is used in marine applications for the removal of sulphur oxide pollutants from the exhaust gases of on-board diesel engines operating with fuel oil containing up to 3.5% sulphur, or heavy fuel oil (HFO).

Ecospray's proprietary marine SO_x scrubbing technology is based on a two stage treatment process: in the first, the gas is cleaned of dry pollutants (gaseous hydrocarbons, soot, aggregates) through a particulate filter containing Ecospray's patented catalytic ceramic filter elements. In a second stage, the gas is further scrubbed with seawater, attaining a guaranteed SO_x removal efficiency of greater than 99%.

ECO-SO_x SEA WATER DeSO_x TOWER - OPEN LOOP uses sea water only, exploiting at the maximum extent its intrinsic alkalinity to neutralize the SO_x contained in the exhaust gas.

SO2 removal either fully meets or very often even exceeds the IMO limits at both low and high diesel engine loads thanks to the installation of proprietary spray nozzles and a very specific configuration of the ECO-SO_x tower (sieve tray stage + spray banks). This configuration helps to also optimize the quantity of seawater injection at engine low loads.

Furthermore, due to its compact size, the ECO-SO_x tower can be installed in place of an existing silencer, thus saving valuable space and weight on-board.

Due to prior treatment of the exhaust gases in the filter, the sea water employed for scrubbing is discharged devoid of pollutants (hydrocarbons, metals, particulates) ensuring complete compliance with the limits of stipulated by IMO standards.

The installation of this technology, i.e. CDF and/or CatOx upstream of the DeSO_x tower, provides the great advantage to reduce at the same time the emissions at the funnel of aromatic hydrocarbon, CO and odor, as well as to maintain the water discharged from the tower intrinsically very clean with turbidity and PAH values well below the IMO limits. Therefore, no washwater treatment is required.

If economizers are installed, like in case of all cruise ships and many ferries, Ecospray technology offers also the important feature to improve the economizers' efficiency reducing their plugging and fouling, thus requiring much less maintenance too.

The Ecospray ECO-SO_x SEA WATER DeSO_x TOWER - HYBRID system for marine exhaust gas cleaning is designed to be able to operated in either Open Loop or Closed Loop mode. The operator has the freedom to select the preferred mode, as dictated by the location of the ship (offshore areas with low alkalinity sea water versus the conditions in the port area). The ECO-SO_x Hybrid system is extremely flexible in that it works with two independent but integrated scrubbers arranged in series. The first stage scrubber operates in Closed Loop while the second stage scrubber is activated only in Open Loop. With the hybrid system there is never any overlap between the two separate water circuits, thereby allowing a very high level of operating flexibility.

A7. Envairtec

Contact	Sales Lead and Phone: Olaf Knuppel, +49 (0)40 - 526 000 900 (dw. 911) Email: ok@envairtec.com Website: www.envairtec.com		
Technology Type(s)	Dry Scrubber	**Other Products:**	SCR for the reduction of NO_x
Exhaust Monitoring IMO Scheme	Scheme B	**Development Phase**	Commercial
System Availability	1 MW to 25 MW		
Failure Modes	none.	**Failure Recovery**	None.

Unit Size* (MW)	Scrubber Type	Power ECA/ at Sea/ in Port	Scrubber Backpressure/ Wash water	Wet Weight/ Diameter/ Length	Installed Vessels/ Hours
3,6	Dry Scrubber	3600 kW ECA 3600 kW at Sea 0,0 kW in Port	60 mm H2O DNA m3/hr	82 tonnes 7200 mm 2400 mm	3 Vessels 7000 Hours
8,7	Dry Scrubber	8700 kW ECA 8700 kW at Sea 0,0 kW in Port	60 mm H2O DNA m3/hr	106 tonnes 3490 mm 2830 mm	1 Vessels 2000 Hours
1,8	Dry Scrubber	1800 kW ECA 1800 kW at Sea 1800 kW in Port	60 mm H2O DNA m3/hr	31 tonnes 2400 mm 1870 mm	1 Vessels 2000 Hours

* Unit size refers to diesel engine size served. Boiler units are not considered in this survey.

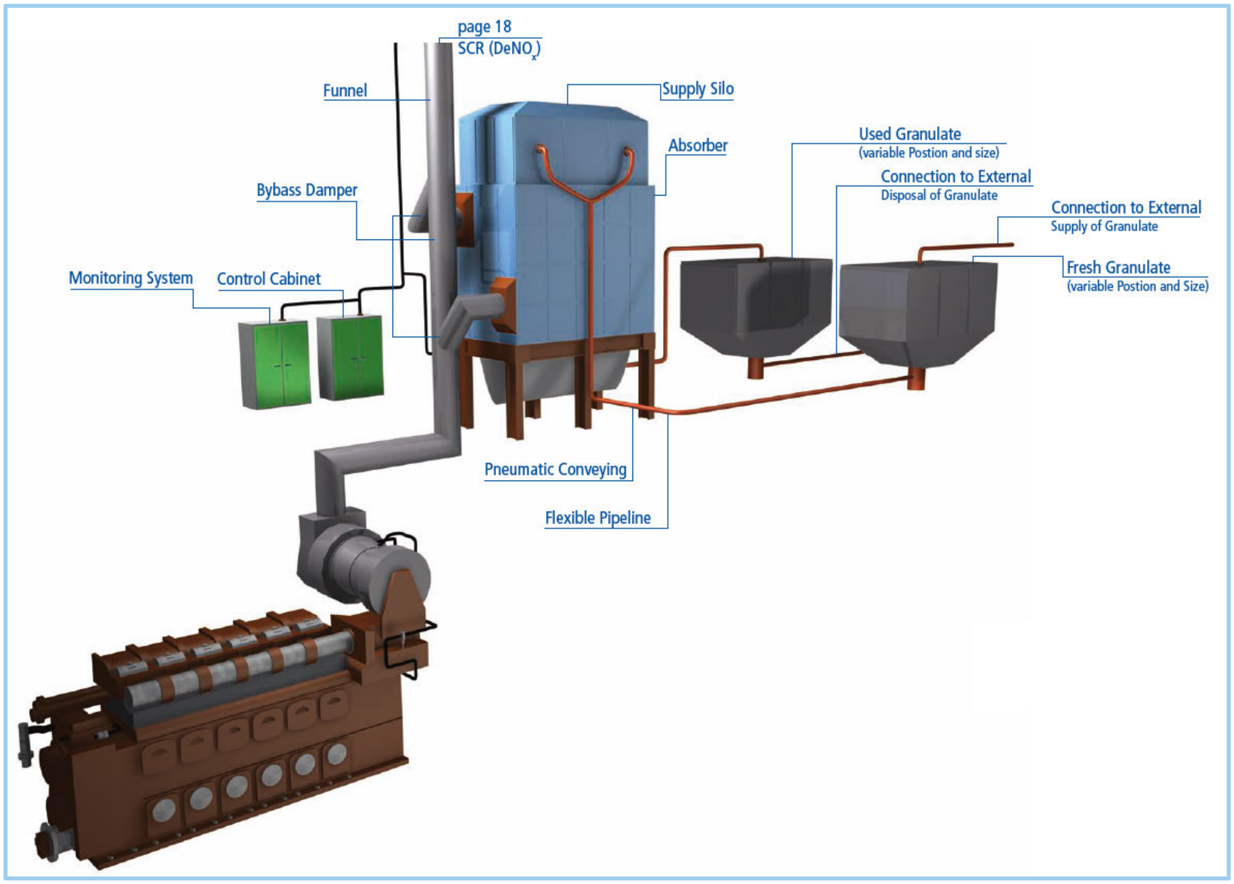
Waste Streams

Wash Water Generation	DNA tons/MW-hr Open Loop Mode DNA tons/MW-hr Closed Loop Mode
Must discharge in port?	DNA
Discharge pH at 4 meters (IMO)?	DNA
Discharge pH at 0 meters (EPA)?	DNA
Wash Water Filtration Method	DNA
Sludge Residue Quantity	DNA kg/MW-hr
Disposal Method?	DNA
Solid Waste Quantity	35 kg/MW-hr @ 1.5 % sulfur in fuel
Disposal method?	Pneumatic Conveying

System Details

Technology Type	Dry Scrubber
Electrical Load (kW per MW-hr)	
ECA	8
At Sea	8
Chemical Usage at 1.5% HFO (kg per MW-hr)	35
Chemical and Concentration	Ca(OH)2 granulate @ 90 %
ECA	35
At Sea	35
FW Consumption at 20 Celsius (kg per MW-hr)	
ECA	DNA
At Sea	DNA
Exhaust Handling: Pressure drop at full load (kPa)	0.6
Does unit serve as silencer/spark arrestor?	Yes
System failure block free flow of exhaust?	No
Multiple engine inlet capable?	Yes
Wash Water – Open Loop (tons per MW-hr)	
ECA	DNA
At Sea	DNA
Wash Water – Closed Loop (tons per MW-hr)	
ECA	DNA
At Sea	DNA

System Description (Provided by Supplier)



The exhaust gas is discharged into the DryEGCS absorber and flows horizontally through the packed-bed from the granulate. The SO2 molecules contained in the exhaust get in contact with the granulate and a chemical reaction takes place:

$$Ca(OH)_2 + SO_2 + \frac{1}{2} O_2 \rightarrow CaSO_4 + H_2O$$

$$Ca(OH)_2 + SO_3 + H_2O \rightarrow CaSO_4 + 2\,H_2O$$

which turns the calcium hydroxide into calcium sulfate (gypsum).

The granulate is fed into the packed-bed reactor from above, removed from below and transferred to the residue silo. It removes the rough sooty particles and other residues from the exhaust gas and acts quasi as a particle filter.

The exhaust gas is supplied to, and removed from, the absorber via so called triangular-form cascade channels. The channels are alternately closed on the housing walls, so that the exhaust gas is forced to take the path through the packed bed.

The dwell time of the exhaust gases in the granulate both stages is a few seconds, which guarantees an almost complete separation of sulphur oxides (> 90 %). The stockage container for the fresh calcium-hydroxide granulate is integrated above the absorber. The packed-bed absorber should be operated directly behind the turbocharger of the ship’s diesel engines and therefore at an exhaust gas temperature of approximately 270°C to 370°C with a maximum temperature of 415° C due to the temperature limitation of the boiler steel.

A8. Ionada

Contact	Sales Lead and Phone: Robert Clarke +1 289 474 5330 Email: robert.clarke@ionada.com Website: www.ionada.com		
Technology Type(s)	Membrane Scrubber ™	**Other Products: SCR for the reduction of NO_x**	
Exhaust Monitoring IMO Scheme	Scheme A	**Development Phase**	Commercially available
System Availability	0.1 MW to 15 MW		
Failure Modes	TBD	**Failure Recovery**	TBD

Unit Size* (MW)	Scrubber Type	Power ECA/ at Sea/ in Port	Scrubber Backpressure/ Wash water	Wet Weight/ Diameter/ Length	Installed Vessels/ Hours
2 MW	Membrane	37 kW ECA 0 kW at Sea 10 kW in Port	75- mm H2O DNA - m3/hr	12 tonnes 3200x2400 mm 5500 mm	TBD
7 MW	Membrane	147 kW ECA 0 kW at Sea 50 kW in Port	75- mm H2O DNA - m3/hr	36 tonnes 3200x2400 mm 7500 mm	TBD

* Unit size refers to diesel engine size served. Boiler units are not considered in this survey.

Waste Streams

Wash Water Generation	ZERO tons/MW-hr Open Loop Mode ZERO tons/MW-hr Closed Loop Mode
Must discharge in port?	DNA - No O/B Discharge
Discharge pH at 4 meters (IMO)?	DNA - No O/B Discharge
Discharge pH at 0 meters (EPA)?	DNA - No O/B Discharge
Wash Water Filtration Method	DNA - No O/B Discharge
Sludge Residue Quantity	DNA - No wash water
Disposal Method?	DNA – No sludge generated
Solid Waste Quantity	7.6 kg/MW-hr K_2SO_4
Disposal method?	Pumped ashore and sold as revenue offset

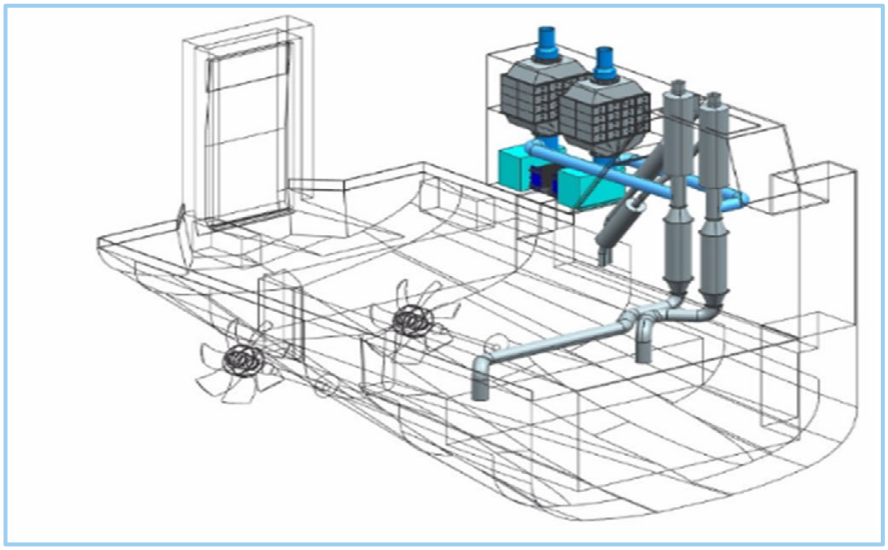
System Details

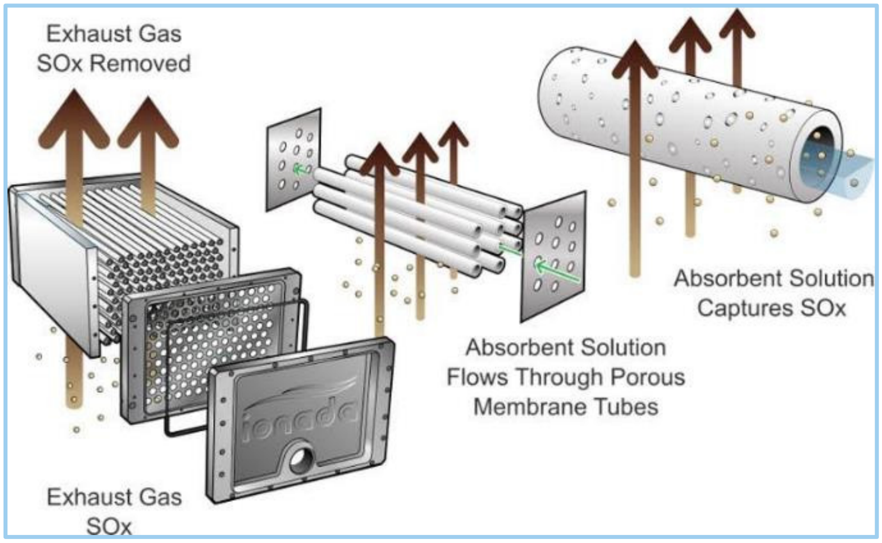
Technology Type	Dry Scrubber
Electrical Load (kW per MW-hr)	
ECA	10 - 12
At Sea	0
In Port	3 (assumes 1.5 MW load)
Chemical Usage at 1.5% HFO (kg per MW-hr)	
Chemical and Concentration	50% Aq Potassium Carbonate K_2NO_3
ECA	6 kg/MW hr
At Sea	
In Port	
FW Consumption at 20 Celsius (kg per MW-hr)	
ECA	.005 m^3/MW hr
At Sea	0
In Port	0
Exhaust Handling: Pressure drop at full load (kPa)	10
Does unit serve as silencer/spark arrestor?	yes
System failure block free flow of exhaust?	no
Multiple engine inlet capable?	yes
Wash Water – Open Loop (tons per MW-hr)	DNA – no wash water generated
Wash Water – Closed Loop (tons per MW-hr)	DNA - no wash water generated

System Description (Provided by Supplier)

Ionada's Membrane Scrubber™ is similar to wet scrubbers. Both use a basic liquid absorbent to react with the acidic sulfur dioxide gas. The key difference is we do not spray the liquid absorbent into the exhaust stream to mix with the exhaust. Instead, we suspend the liquid absorbent in membranes to come in contact with the exhaust but not mix with the exhaust. Only the sulfur dioxide is absorbed. The result is an EGCS solution that has all the advantages of traditional closed loop scrubber with none of the wash water discharge drawbacks.

- Zero Wash Water Discharge
- Modular 'Plug-n-Scrub' design – provides leasing options to ship owners.
- No PAH discharge
- No turbidity discharge
- No pH discharge
- Fully VGP Compliant, No risk of being banned from operation in any port due to discharge restrictions.
- No sludge disposal fees
- Scale to any engine size





A9. Mitsubishi Heavy Industries, LTD

Contact	Sales Lead and Phone: Toshiyuki Komiya, +81-3-6716-3217 Email: toshiyuki_komiya@mhi.co.jp Website: http://www.mhi-global.com/index.html		
Technology Type(s)	EGC system, combined open loop (sea water), and closed loop (fresh water) No dry chemical	**Other Products**	
Exhaust Monitoring IMO Scheme	Scheme B	**Development Phase**	Prototype and Commercial
System Availability	6 MW to 20 MW (~70MW,under development)		
Failure Modes	If an critical failure occurs, the bypass valves open and the exhaust gas flow will bypass the EGC system.	**Failure Recovery**	After the problem has been solved and recovery conditions are satisfied, the system will return to normal operation sequentially.

Unit Size* (MW)	Scrubber Type	Power ECA/ at Sea/ in Port	Scrubber Backpressure/ Wash water	Wet Weight/ Diameter/ Length	Installed Vessels/ Hours
14	Hybrid	TBD	100 mm H2O 950 m3/hr (open loop) TBD (closed loop)	46 tonnes 4000 mm 12500 mm (Including the Sump. Tank)	1 Vessels 0 Hours (Under construction)

* Unit size refers to diesel engine size served. Boiler units are not considered in this survey.

Waste Streams

Wash Water Generation	**Open Loop Mode: 67 tons/MW-hr** **Closed Loop Mode: 0.14 kg/MW-hr**
Must discharge in port?	**TBD**
Discharge pH at 4 meters (IMO)?	**> 6.5**
Discharge pH at 0 meters (EPA)?	**> 6.0**
Wash Water Filtration Method	**Porous ceramic filter**
Sludge Residue Quantity	**Dependent on engine operation and fuel usage**
Disposal Method?	**Dispose from filling station by the dedicated Sludge Pump**
Solid Waste Quantity	
Disposal method?	

System Details

Technology Type	**Hybrid**
Electrical Load (kW per MW-hr)	
ECA	**TBD**
At Sea	**TBD**
Chemical Usage at 3.5% HFO (kg per MW-hr)	
Chemical and Concentration	**50% NaOHaq**
ECA	**30 kg/MW-hr (Closed Loop Mode)**
At Sea	**0 kg/MW-hr (Open Loop Mode)**
FW Consumption at 20 Celsius (kg per MW-hr)	
ECA	**280 kg/hr at 14MW (Closed Loop Mode)**
At Sea	**0 kg/hr (Open Loop Mode)**
Exhaust Handling: Pressure drop at full load (kPa)	**100 mmH2O**
Does unit serve as silencer/spark arrestor?	**No**
System failure block free flow of exhaust?	**Yes**
Multiple engine inlet capable?	**Yes**
Wash Water – Open Loop (tons per MW-hr)	
ECA	
At Sea	**67 tons/MW-hr**
Wash Water – Closed Loop (tons per MW-hr)	
ECA	**TBD**
At Sea	

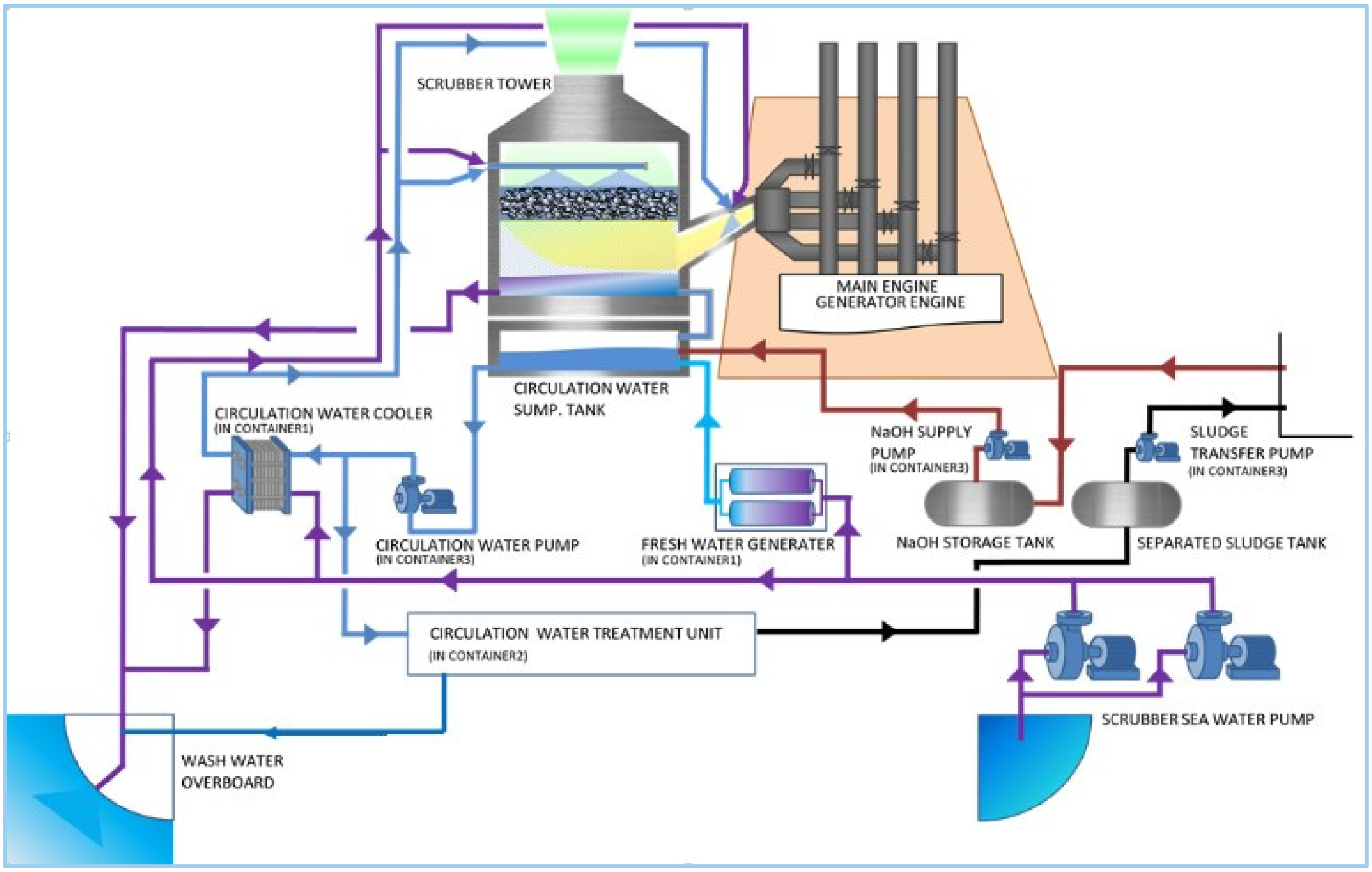
System Description (Provided by Supplier)

Overview of the system

This exhaust gas cleaning system (EGCS) is a hybrid wet scrubber system possessing two exhaust gas cleaning modes: fresh water closed-cycle mode and seawater open-cycle mode. Under current planning, the seawater open-cycle mode will be operated in global regions where the fuel oil sulfur content is regulated to 0.5% or less, mainly from the year 2020 on. The fresh water closed-cycle mode will be operated in ECAs (Emission Control Areas) where the fuel oil sulfur content is strictly regulated to 0.1% or less, mainly from the year 2015 on. This exhaust gas cleaning system is connected with the exhaust gas pipe of the main engine and some diesel generator engines via the dampers and has the capability to treat the total exhaust gas discharged from the main engine and diesel generator engines.

Product concept

Mitsubishi Heavy Industries, Ltd. (MHI) has developed installation technology of Exhaust Gas Cleaning System enclosed in some standard-size ISO containers on exposed deck. Most system components such as heat exchanger, pumps and water treatment unit are packed in 20-ft or 40-ft containers and arranged to maximize available space and facilitate maintenance in the containers. Multi stream scrubber tower and associated exhaust gas dampers will be installed in new funnel and replaced in place of existing funnel. Mitsubishi Hybrid SO$_x$ Scrubber System is ideal for ships that do not have enough space in the engine room and enable the ship owners to minimize retrofitting cost and out of service period. Regarding caustic soda (NaOH) storage tank and separated sludge tank, MHI can provide dedicated ISO tank containers which are high reliability and easy to install in the way of intended purpose as an option, although the owner can obviously adopt hull construction tank fabricated by shipyard. The benefit of using ISO tank containers is easy to install and enable flexible operation because of the portability. In any case, the tank capacity should be decided in view of the owner's intentions.



A10.SAACKE

Contact	Sales Lead and Phone: Stipe Skoric, +38598415218 Email: s.skoric@saacke.hr Website: http://www.saacke.com/products/exhaust-gas-cleaning/		
Technology Type(s)	Wet	**Other Products**	Firing solutions for marine and industrial applications
Exhaust Monitoring IMO Scheme	Scheme B	**Development Phase**	Fully certified open loop
System Availability	3 MW to 10 MW		
Failure Modes	YES.	**Failure Recovery**	YES.

Unit Size* (MW)	Scrubber Type	Power ECA/ at Sea/ in Port	Scrubber Backpressure/ Wash water	Wet Weight/ Diameter/ Length	Installed Vessels/ Hours
6	WET	5500 kW ECA 5500 kW at Sea 1100 kW in Port	300 mm H2O 270 m3/hr	23 tonnes 2600 mm 8600 mm	1 Vessel 10,000 Hours

* Unit size refers to diesel engine size served. Boiler units are not considered in this survey.

Waste Streams

Wash Water Generation	
Must discharge in port?	Yes
Discharge pH at 4 meters (IMO)?	>6.5
Discharge pH at 0 meters (EPA)?	6.5
Wash Water Filtration Method	Dry soot separation upstream gas washing, no water filtration
Sludge Residue Quantity	None
Disposal Method?	Manual in port
Solid Waste Quantity	1.2 kg/MW-hr
Disposal method?	Manual

System Details

Technology Type	Open Loop/ Closed Loop/ Hybrid/ Other
Electrical Load (kW per MW-hr)	Open loop only
ECA	33
At Sea	33
In Port	60
Chemical Usage at 3.5% HFO (kg per MW-hr)	None
Chemical and Concentration	None
ECA	None
At Sea	None
FW Consumption at 20 Celsius (kg per MW-hr)	
ECA	None
At Sea	None
Exhaust Handling: Pressure drop at full load (kPa)	25
Does unit serve as silencer/spark arrestor?	Yes
System failure block free flow of exhaust?	Yes
Multiple engine inlet capable?	Yes
Wash Water – Open Loop (tons per MW-hr)	
ECA	43
At Sea	43
In Port	120
Wash Water – Closed Loop (tons per MW-hr)	TBD
ECA	TBD
At Sea	TBD

System Description (Provided by Supplier)

This is a system for SO_x reduction and removal of solid particles occurring in exhaust gases from diesel engines and boilers. The main feature of this system is dry separation of soot and other harmful matters contained in exhaust gases. Separated particles are collected in a dry manner for further manual disposal on shore.

A11.Wärtsilä

Contact	Sales Lead and Phone: Timo Granberg Tel. +358 10 709 0000 Email: timo.granberg@wartsila.com Website: www.wartsila.com		
Technology Type(s)	Open Loop Closed Loop Hybrid Systems	**Other Products**	Scrubber also act as a PM scrubber.
Exhaust Monitoring IMO Scheme	Scheme B	**Development Phase**	Commercial
System Availability	1 MW to 70 MW		
Failure Modes	If an interruption occurs the system can be by-passed	**Failure Recovery**	Problem must be solved and normal operation can continue
Wärtsila has more than 137 scrubbers in the order book and ~80 of these are installed. We will there for as an example only describe one of each system in below table.			

Unit Size* (MW)	Scrubber Type	Power ECA/ at Sea/ in Port	Scrubber Backpressure/ Wash water	Wet Weight/ Diameter/ Length	Installed Vessels/ Hours
Total 40 MW	Open loop	~ 450 kw **	150 mm H2O	7000 tonnes 2000 mm 10 000 mm (H) 4 units	1 Vessels 2000 Hours
Total 12 MW	Closed loop	~80 kW **	150 mm H2O 45 m3/hr	10 tonnes 3400 mm 6000 mm	1 Vessels 12,000 Hours
Total 31 MW	Hybrid	~400 kW at Sea ~90 kW in Port	150 mm H2O 45 m3/hr	31 tonnes 4500 mm 9000 mm (H) 6 tonnes 2450 mm 7300 mm (H)	1 Vessels 10,000 Hours

* Unit size refers to diesel engine size served. Boiler units are not considered in this survey.
**Operates 100 % in ECA, do not use scrubber in port.

Waste Streams

Wash Water Generation	45 m3/MW-hr Open Loop Mode 30 m3/MW-hr Closed Loop Mode
Must discharge in port?	No, in closed loop zero discharge
Discharge pH at 4 meters (IMO)?	6.5
Discharge pH at 0 meters (EPA)?	6
Wash Water Filtration Method	Yes, both in open and closed loop mode
Sludge Residue Quantity	With dewatering unit 1.0 kg/MW-hr closed loop With dewatering unit 0.05 kg/MW - hr open loop
Disposal Method?	With dewatering unit to be delivered a shore in filter bags
Solid Waste Quantity	NA
Disposal method?	NA

System Details

Technology Type	Open Loop/ Closed Loop/ Hybrid/ Other
Electrical Load (kW per MW-hr)	
ECA	Depends on load
At Sea	Depends on load
Chemical Usage at 3.5% HFO (kg per MW-hr)	Only closed loop operation 17.5 liter/MWhr
Chemical and Concentration	NaOH 50 % solution
ECA	Depends on load
At Sea	Depends on load
FW Consumption at 20 Celsius (kg per MW-hr)	No use for FW
ECA	N / A
At Sea	N / A
Exhaust Handling: Pressure drop at full load (kPa)	15 kPa
Does unit serve as silencer/spark arrestor?	Yes, it does in some cases
System failure block free flow of exhaust?	Yes
Multiple engine inlet capable?	Yes
Wash Water – Open Loop (tons per MW-hr)	45 m3/MWhr
ECA	Depends on load
At Sea	Depends on load
Wash Water – Closed Loop (tons per MW-hr)	30 m3/MWhr
ECA	Depends on load
At Sea	Depends on load

System Description (Provided by Supplier)

Open loop system

The system is a sea water based exhaust gas cleaning system based on the principle of scrubbing. The EGC unit is manufactured in high grade steel and designed to run continuously in a wet (scrubbing) condition. The EGC unit is designed to pre-treat the exhaust gas and intimately mix the gas with water to remove SO_X and particulate matter. Flue gas pipes are conducted to the EGC unit. The water supply is extracted from the sea chest and pumped to the EGC unit, where the water is sprayed in three stages. The first stage is in the venturi, in order to improve gas flow, reduce back pressure and catch particulate matter and sulphur. The second and third stages are inside the EGC unit body. Internal demister at the top of the body effectively prevents water droplets to be carried away with the outlet gas flow. A bypass arrangement is recommended and is permitting operation of the combustion units e.g. during EGC unit service breaks. If required, an exhaust gas fan and a deplume system is arranged after the EGC unit shut-off valves.

In open loop mode the wash water is drained from the EGC unit and cleaned in a wash water treatment system. This system consists of a residence tank, pumps, multi-cyclones and sludge tank(s). The residence tank allows the particulates to settle and the multi-cyclone purifies the water. From the multi-cyclone the sludge is separated to a sludge tank and the clean water is circulated back to the residence tank. The cleaned wash water is discharged overboard from the clean side overflow in the residence tank.

Hybrid system

The system is a sea water based exhaust gas cleaning system based on the same principals as for open loop. The system can operate in open loop or closed loop.

In open loop mode the wash water is drained from the EGC unit and cleaned in a wash water treatment system. This system consists of a residence tank, pumps, multi-cyclones and sludge tank(s). The residence tank allows the particulates to settle and the multi-cyclone purifies the water. From the multi-cyclone the sludge is separated to a sludge tank and the clean water is circulated back to the residence tank. The cleaned wash water is discharged overboard from the clean side overflow in the residence tank.

In closed loop mode the wash water (seawater) is circulating from EGC unit to a process tank. The wash water is cooled down by a sea water heat exchanger and buffered to correct pH with alkali addition. From process tank there is a small bleed-off. The bleed-off is treated by a bleed off treatment unit (separator) and discharged from the clean side overflow or led to a holding tank for zero-discharge operation.

Closed loop

The system is a sea water based exhaust gas cleaning system based on the principle of scrubbing. The EGC unit is manufactured in high grade steel and designed to run continuously in a wet (scrubbing) condition. The EGC unit is designed to pre-treat the exhaust gas and intimately mix the gas with water to remove SO_X and particulate matter. Flue gas pipes are conducted to the EGC unit. Internal demister at the top of the body effectively prevents water droplets to be carried away with the outlet gas flow. A bypass arrangement is recommended and is permitting operation of the combustion units e.g. during EGC unit service breaks. If required, an exhaust gas fan and a deplume system is arranged after the EGC unit shut-off valves.

The water supply is extracted from the sea chest and pumped to the EGC unit, The wash water is circulating from EGC unit to a process tank. The wash water is cooled down by a sea water heat exchanger and buffered to correct pH with alkali addition. From process tank there is a small bleed-off. The bleed-off is treated by a bleed off treatment unit and discharged from the clean side overflow or led to a holding tank for zero-discharge operation.

A12. Yara

Contact	Sales Lead and Phone: Daniel Strandberg, +47 91722346 Email: daniel.strandberg@yaramarine.com Website: www.yaramarinetechnologies.com		
Technology Type(s)	Open Loop Hybrid Systems	**Other Products**	DNA
Exhaust Monitoring IMO Scheme	Scheme B	**Development Phase**	Commercial
System Availability	16 to 50 MW		
Failure Modes	TBD	**Failure Recovery**	TBD
Yara acquired Green Tech Marine, renamed Yara Marine Technologies in January of 2015.			

System Description (Provided by Supplier)

Hybrid System (Open loop not shown)

Yara's Green Tech Marine open loop system is similar to the hybrid, except in the hybrid the wash water goes back to a process tank, instead of overboard. The seawater is also dosed with Magnesium Oxide to maintain the cleaning capacity of the water. Advantages of the Hybrid system:

- The system can operate in all waters regardless of seawater alkalinity or temperature.
- Automatic change between open and closed loop depending on GPS coordinates.

Green Tech Scrubbers are the only scrubbers working with harmless Magnesium Oxide as alkali in closed loop and no dangerous caustic soda. Magnesium Oxide is supplied as powder, and is easily available all across the globe.

- Our inline scrubber can handle any sulphur content in the fuel up to 3,5%S in both open and closed loop mode
- We offer high quality scrubbers at competitive prices, with the lowest lifecycle cost in the market.
- Our in-line scrubbers have no moving parts or bypass, easily installed in the funnel area.
- Our is standard high grade stainless steel, and we can offer extended guarantees against corrosion
- The inline scrubber system only requires approximately the same space as the silencer it replaces, simplifying installation.
- MgO as alkali requires/occupies less storage space than caustic soda
- Your operational cost using Magnesium Oxide will be only ¼ of the corresponding cost of using caustic soda, as Magnesium is a superior alkali when operating in zero washwater discharge areas (ports/coastlines).