# EMISSION CONTROL TECHNOLOGIES FOR OCEAN GOING VESSELS (OGVs)

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## NOMENCLATURE

ACFM: Actual Cubic Feet per Minute
APL: American President Lines
BASF: Baden Aniline and Soda Factory
CARB: California Air Resource Board
CCME: Candian Council of Ministries of Environment
CO: Carbon Monoxide
$CO_2$: Carbon Dioxide
CRT: Catalytic Reduction Technology
DPF: Diesel Particulate Filter
DPM: Diesel Particulate Matter
DWI: Direct Water Injection
EGR: Exhaust Gas Recirculation
EPA: Environmental Protection Agency
FDG: Flue Gas Desulfurization
GRE: Glass fiber Reinforced Epoxy
HAM: Humid Air Motor
HC: Hydro Carbons
HEI: High Energy Ionizer
HFO: Heavy Fuel Oil
IEM: Internal Engine Modifications
LA: Los Angeles, California
LB: Long Beach, California
LNT: Lean Nitrogen Trap
MD: Marine Diesel
MDO: Marine Diesel Oil
$NO_2$: Nitrogen Dioxide.
NOx: Nitrogen Oxides
OGV: Ocean Going Vehicles
OEM: Original Equipment Manufacturer
PLC: Programmable Logical Controller
PM: Particulate Matter
POLA: Port of Los Angeles
POLB: Port of Long Beach
RFO: Residual Fuel Oil
ROG: Relative Organic Gas
RTD: Research and Technical Development
Ro- Ro: Vehicle/ roll-on/ roll- off
SCR: Selective Catalytic Reduction
SCRT: Selective Catalytic Reduction Technology
SiNox: Silicon Based Nitrous Oxide Removing Catalyst/ Technology
SNCR: Selective Non- Catalytic Reduction
$SO_2$: Sulfur Dioxide

SOx: Sulfur Oxides
VFD: Variable Frequency Drive
VOC: Volatile Organic Compound

EXECUTIVE SUMMARY

Ocean going vessels (OGVs) contribute significantly to the economic activities and development of the state of California and the U.S. OGVs include general cargo ships, passenger ships, bulk carriers, oil tankers, vehicle/roll-on/roll-off (Ro-Ro) vessels, and containerships. The San Pedro Bay ports of Los Angeles (POLA) and Long Beach (POLB) are among the largest ports in the world. More than 40% of the U.S. containerized trade flows through these ports representing nearly $300 billion in annual trade. Economic forecasts project this trade to double by the year 2020 [Port of Los Angeles Inventory of Air Emissions (2005)].

A major adverse impact of this growth is the associated increase in local and regional air pollution. Emissions from marine diesel engines contribute significantly to the increase in particulate matter (PM), sulfur oxides (SOx), and nitrogen oxides (NOx). Figure 1 shows the distribution of the 2005 POLA emissions by category. It indicates that more than 50% of PM and diesel PM (DPM) and nearly all of the SOx emissions are from OGVs. This data shows nearly a 12% increase in PM emissions, but reductions of 6%, 4%, and 15% in NOx, SOx and CO respectively, when compared to the 2001 emission estimates. The reductions in NOx, SOx, and CO are due to the use of low sulfur and emulsified fuels, installation of diesel oxidation catalysts on stationary diesel engines, and use of new yard tractors with low emission diesel engines. Also fewer harbor crafts operated in the port during the 2001-2005 period. However, despite these gains, without further emission reduction efforts, growth will soon outpace these reductions in the future.

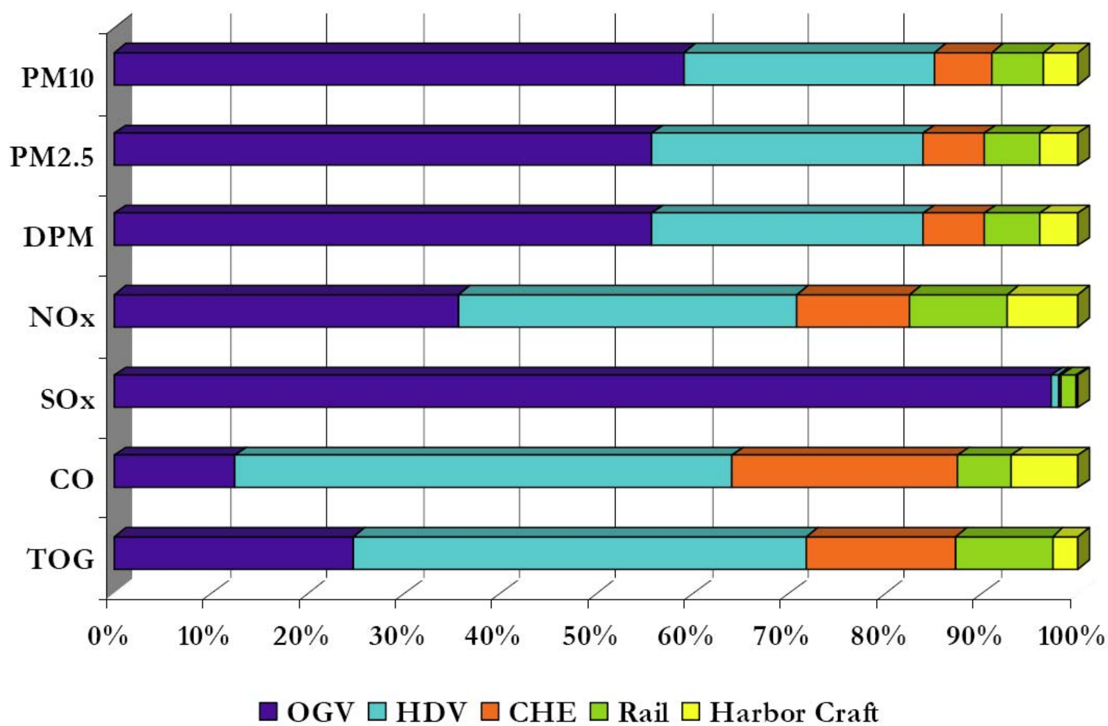



**Figure 1. Distribution of 2005 POLA Related Emissions**

The health impact from port related activities is significant. SOx is a major contributor to the ambient PM. The health impact of increased PM and NOx and other gases that form Ozone in the atmosphere include heart disease, respiratory illnesses, increased cancer risk and premature death. According to CARB (2006), within the State of California, emissions from ports and international goods movement activities are responsible for approximately 2,400 premature deaths annually, mostly from PM emissions. In response to these challenges, CARB has proposed strategies with implementation dates of 2006-2010, 2011-2015, and 2016-2020, that can significantly reduce emissions from ports and goods movement activities. For ships these strategies include the use of cleaner marine fuels and emulsified fuels, expanded vessel speed reduction programs, and engines with emissions lower than the standards set by the International Maritime Organization (IMO). Other proposed strategies covering the 2011-2020 dates include extensive retrofit of existing engines and highly effective controls on main and auxiliary engines. They also include designation of sulfur emission control areas, expansion of shore power and alternative controls, and use of cleaner vessels to serve California ports. Strategies for reducing emissions of harbor crafts, trucks, locomotives, cargo handling equipment, as well as improving efficiency and shifting modes of transportation are also proposed. With full implementation of these proposed strategies, the total estimated emission reductions of DPM, NOx, and SOx between years 2001 through 2020 will be 79%, 63%, and 78% respectively. This will lead to significant health benefits, reductions in premature deaths due to the reduced PM emissions, and improvements in the quality of life for portside communities.

OGV emissions can be reduced with several efficient and cost effective technologies. Particulate emissions abatement can be accomplished with switching to low sulfur fuel, application of seawater scrubbing filters, and installation of oxidation catalysts. Reduction of oxides of nitrogen can be accomplished with water injection techniques, selective catalytic reduction (SCR) systems, exhaust gas recirculation, and internal engine modifications. In general, carbon monoxides and hydrocarbon emissions of marine diesel engines are low and some of the techniques used for reducing other pollutants such as switching from heavy fuel oil to low sulfur fuel can further reduce these emissions.

This report provides the ship owners, operators and other constituents a concise and informative document that can help them plan their mitigation strategies for meeting the CARB and other US emission standards. It reviews and to a certain extent evaluates many methods and technologies for reducing emissions from OGVs. The type of technologies reviewed include engine optimization, engine process modifications, exhaust aftertreatment, use of cleaner fuel, and combinations of these measures.

Engine optimization technologies evaluated include optimizing combustion chamber geometry and residence time, the common rail fuel injection system, controlled lubricating process, higher compression ratio, changing injection nozzle geometry, and Miller cycle valve timing. Engine process modifications cover addition of water or ammonia to the combustion process, and exhaust gas recirculation (EGR). Exhaust after-treatments include scrubbing process, selective catalytic reduction (SCR), diesel particulate filters and oxidation catalysts.

Finally, alternative diesel fuels and some emerging technologies are reviewed. When data was available, cost effectiveness of technologies have been reported. This report also contains names and contact information for some of the providers of various technologies and additional references.

# 1. INTRODUCTION

Containerships, tankers and cruise ships play a major role in the economic activities of the region, the state, the nation and the world. California ports, especially the Los Angeles and Long Beach ports are among the most dynamic economic engines of the world. Port activities include shipping, freight trains, diesel trucks and cargo handling equipment. One of the by-products of these activities is a significant increase in regional air pollution. Increased concentrations of NOx, PM, CO, SOx and HC create unhealthy conditions with immediate symptoms ranging from eye and respiratory irritations to asthma attacks. Long-term exposures to these pollutants create severe health problems for the general population with children and elderly being at the highest risk (Vedal (1997)). A study by Gauderman et al (2004) on the effects of pollution on children's health in Los Angles has shown that pollution stunts lung growth and can cause premature death or life long health problems.

Increased pollution also impacts local climatic condition. A study by LaDochy (2005) on the relationship between temperature and pollution and annual number of days of dense fog at Los Angeles and Long Beach airports has shown strong correlation between increased air pollution and temperature, and a decline in the frequency of dense fog formation in these areas. LaDochy et al. (2007) also have studied air temperature patterns in California from 1950 to 2000, as it relates to the global warming and factors that contribute the most to the regional temperature changes. Their research indicates that areas with intense urbanization had the largest increase in temperature while the least warming was associated with rural, non-agricultural regions. The highest rate of warming was in Southern California with an average of 0.2 ºC per decade.

Diesel powered ocean going vessels (OGVs) are substantial contributors to the region's air pollution. These vessels emit hazardous air pollutants such as sulfur dioxide ($SO_2$), Nitrogen Oxides (NOx), and fine particulates. These pollutants can travel significant distances and contribute to the regions' air pollution while ships operate in ports and coastal zones. When not operating at ports, most marine vessels navigate relatively near shore, following the main shipping lanes. A study by Corbett et al (1999) has shown that almost 70% of the ships' emissions occur in a coastal zone with a width of about 216 nautical miles, resulting in significant increase in NOx and $SO_2$ levels along the coastal regions.

During the past decades, land-based diesel vehicles and stationary diesel sources have been subjected to stringent environmental regulatory requirements, resulting in significant technological developments in controlling emissions from these sources. However, less progress has been made in regard to the OGVs.

In December, 2005, the California Air Resources Board (CARB) released the draft emission reduction plan for ports and international goods movements in California (2006). The plan was revised in March 2006, after several public hearings. The plan specifies actions and regulations necessary to reduce emissions to 2001 levels by 2010, taking into account the substantial increase in goods movements predicted over this time frame. The plan anticipates reducing diesel related health risks by 85% by 2010 and continued reduction of emissions until attainment of applicable ambient air quality standards. Table 1 shows 2001 and estimated 2020 statewide emissions from ports and goods movements in California in tons per day. Here ship emissions are estimated from ship activities within 24 nautical miles from shore.

| Source | Diesel PM | | NOX | | ROG | | SOx | |
|---|---|---|---|---|---|---|---|---|
| | 2001 | 2020 | 2001 | 2020 | 2001 | 2020 | 2001 | 2020 |
| Ships | 7.8 | 23.3 | 953 | 254 | 2 | 7 | 60 | 180 |
| Harbor Craft | 3.8 | 1.8 | 75 | 39 | 8 | 4 | <1 | <1 |
| Cargo Handling Equipment | 0.8 | 0.2 | 21 | 6 | 3 | 1 | <1 | <1 |
| Trucks | 37.7 | 6.2 | 655 | 255 | 56 | 23 | 5 | 1 |
| Transport Refrigeration Units | 2.5 | 0.1 | 22 | 28 | 13 | 4 | <1 | <1 |
| Locomotives | 4.7 | 4.5 | 203 | 139 | 12 | 12 | 8 | <1 |
| Total | 57.3 | 36.1 | 1071 | 721 | 947 | 51 | 74 | 181 |

**Table 1. 2001 and 2020 Statewide Emissions from Ports and Goods Movement**

With full implementation of the CARB plan, significant reductions in four major pollutants NOx, SOx, PM, and reactive organic gases (ROG) are anticipated. Table 2 shows the breakdown of the projected emissions reduction from 2001 to 2020.

| Pollutant | Year | | | | | % Reduction 2001- 2020 |
|---|---|---|---|---|---|---|
| | 2001 | 2005 | 2010 | 2015 | 2020 | |
| Diesel PM | 57 | 53 | 32 | 17 | 12 | 79% |
| NOx | 1071 | 1080 | 807 | 544 | 393 | 63% |
| ROG | 94 | 90 | 71 | 50 | 39 | 58% |
| SOx | 73 | 94 | 42 | 16 | 16 | 78% |

**Table 2. Trends in Emissions from Ports and Goods Movement with Full Implementation of the CARB Plan Strategies (tons per day)**

The benefit to cost ratio, in terms of the reduced medical expenses remains very high and is estimated to be 3-8 to 1. Table 3 shows the details of the estimated costs and the benefit to cost ratio.

| | **Cumulative Benefits and Costs** |
|---|---|
| Cumulative Premature Deaths Avoided by Plan Strategies | 7200 |
| Cumulative Economic Value of All Health Effects Avoided | $34- $47 billion |
| Cumulative Costs to Implement Plan Strategies | $6- $10 billion |
| **Benefit- Cost Ratio** | **3-8 to 1** |

**Table 3. Benefit-Cost ratio for Plan Strategies Through 2020 (present value)**

To achieve the emission reductions goal in the Goods Movement plan, CARB is planning a comprehensive set of programs and regulations. For ships, CARB is planning to implement the use of cleaner low sulfur fuel in ship main and auxiliary engines, shore side power for ship and dockside, vessel speed reduction program and a "clean ship" program to bring cleaner new and retrofitted vessels to the California ports.

The objectives of the present study were to conduct a comprehensive survey of existing, developing, and planned technologies that are used or could be adapted and reasonably be used to control NOx, SOx, and PM emissions from the diesel cycle propulsion and auxiliary engines of OGVs, collect and assess available performance data for these technologies, and evaluate these technologies for meeting target emissions and for their initial, installation and operating costs and their adaptability for the current and new OGVs.

This study is organized with the primary goal of helping operators and other port constituents to plan their mitigation strategies in order to meet existing and future CARB and other regulations. It also supports the CARB "clean ship" element of the Goods Movement emission reduction plan.

## 2. MARINE DIESEL ENGINE EMISSIONS

Ocean going vessels with tonnage greater than 5000 use category 3 engines with specific displacements at or above 30 liters (US EPA (1999)). The "tonnage", a quantity which does not have a unit, is basically a measure of the size of the ship, the higher the tonnage, the larger the ship.

Category 3 engines are two-stroke engines and use heavy fuel oil. They have high fuel efficiency and thus their $CO_2$ emissions are low. However, they contribute significantly to SOx, NOx and PM emissions. These engines operate at low rpm (60-250), are connected directly to the propellers and are durable designs intended to operate 24 hours per day year-round. Their overall efficiencies are about 48-54 percent, depending on engine configuration, size, speed, load, and intake air temperature. These are reciprocating engines that can sustain their high efficiency over a wide range of loading conditions and intake air temperatures.

For vessels with tonnage less than 5000, the engines characteristics are different. They are mostly four-stroke engines with higher rated rpm that can reach 1000 or more. These engines are connected to the propellers through gear-trains and their efficiencies are few percentages lower than the two-stroke engines.

Ocean going vessels receive their power needs from main and auxiliary engines and boilers. The main engine is used for the propulsion system and they usually consist of one two-stroke engine. Auxiliary engines and the boilers are used for other functions of the ship such as electric power aboard the ship, HVAC and pumping systems, hydraulic systems, etc. The auxiliary engines are smaller engines with higher rpm and thus they are mostly four stroke engines.

There is usually more than one auxiliary engine. A recent study by Ritchie et al (2005) of Entec and IVL companies, commissioned by the European Commission Directorate General Environment, indicates that on the average ships have 3.5 auxiliary engines installed on board. Exhaust of diesel and gas engines contain nitrogen oxides, sulfur oxides, carbon oxides, hydrocarbons, and particulate matter. Figure 2 shows the intake and exhaust of a ship main engine.

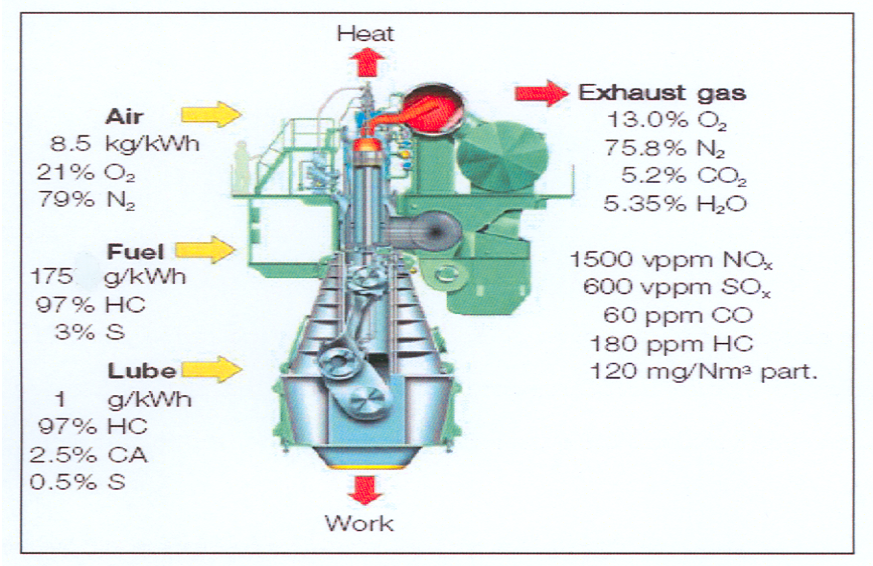



**Figure 2. Intake and Exhaust of a Ship Engine (Man B & W, 2004)**

Table 4, taken from Wartsila (2004), provides comparison of emissions of these components for diesel and gas engines without exhaust gas cleaning. As it can be seen carbon monoxide from marine diesel engines are significantly lower than those for the gas engines due to their high efficiency while the reverse is true for nitrogen oxides. Sulfur oxides are higher in diesel engine due to the high sulfur content in diesel fuel.

| Component | Diesel Engine | Gas Engine |
|---|---|---|
| Nitrogen oxides, $NO_x$ | 700 – 1.500 ppm (v/v) | 60 – 130 ppm (v/v) |
| Sulfur oxides, $SO_x$ | 30 – 1.000 ppm (v/v) | 0 – 3 ppm (v/v) |
| Carbon monoxide, CO | 20 – 150 ppm (v/v) | 200 – 500 ppm (v/v) |
| Hydrocarbons THC | 15 – 100 ppm (v/v) | 1.000 – 2.200 ppm (v/v) |
| Particulate matter PM | 20 – 100 mg/ $nm^3$ | |

ppm (v/v): parts per million by volume.
mg/ $nm^3$ : milligrams per nominal cubic meter (temperature = $0^o$ C and pressure = 101.3 kPa).

**Table 4. Exhaust Gas Components of Diesel and Gas Engines**

The primary source of NOx formation in an engine is from nitrogen in the intake air. Factors that affect NOx formation are combustion temperature, combustion residence time, and the degree of pre-mixing between fuel and air. High combustion temperature and residence time and low air-fuel pre-mixing result in higher NOx production. NOx emissions promote the formation of ozone and smog in the lower atmosphere. The presence of the ozone in the lower atmosphere is harmful to human health and vegetation.

The emissions of $CO_2$ and SOx in the engine exhaust are directly related to the carbon and sulfur content of the fuel and the amount of fuel burned. The lower the carbon and the sulfur content, the lower the emissions. SOx has a corrosive effect on the engine and is also harmful to the vegetation and human health. $CO_2$ is a greenhouse gas and causes global warming. In general, life cycle emission of $CO_2$ from diesel engines is significantly lower than the gasoline vehicles due to their high combustion efficiency (low specific fuel consumption).

The formation of particulate matter is dependant on combustion completeness and efficiency, the amount of lubricating oil used, and the amount of sulfur and ash in the fuel. Particulates less than 10 micron can reach deep into human lungs and are harmful to human health. Most of the PM from the ships is below this level.

## 3. COST EFFECTIVENESS

A major parameter for assessment and comparison of different technologies for reducing marine diesel emissions is their cost effectiveness. It is defined as:

$$\text{Cost effectiveness} = \$/\text{ton of pollutant removed} = \frac{\text{Annual cost of any measure}}{\text{Annual emission reduction of the measure}}$$

Annual costs include capital costs distributed over the life span of the equipment, and ongoing operation and maintenance costs.

Current methods for control of marine diesel engine emissions include engine optimization, engine process modifications, exhaust after treatment, use of cleaner fuel, and combination of these measures. Engine optimization techniques include measures such as optimizing combustion chamber geometry and combustion residence time, controlled lubricating processes, common rail system, higher compression ratio, changing injection nozzle geometry, and Miller cycle valve timing.

Engine process modifications include addition of water or ammonia to the combustion process, and exhaust gas recirculation. Exhaust after-treatment processes include scrubbing processes, selective catalytic reduction, diesel particulate filters, and oxidation catalysts. Figure 3 shows three different methods for reducing NOx emissions from a marine engine (Man B & W, 2004).

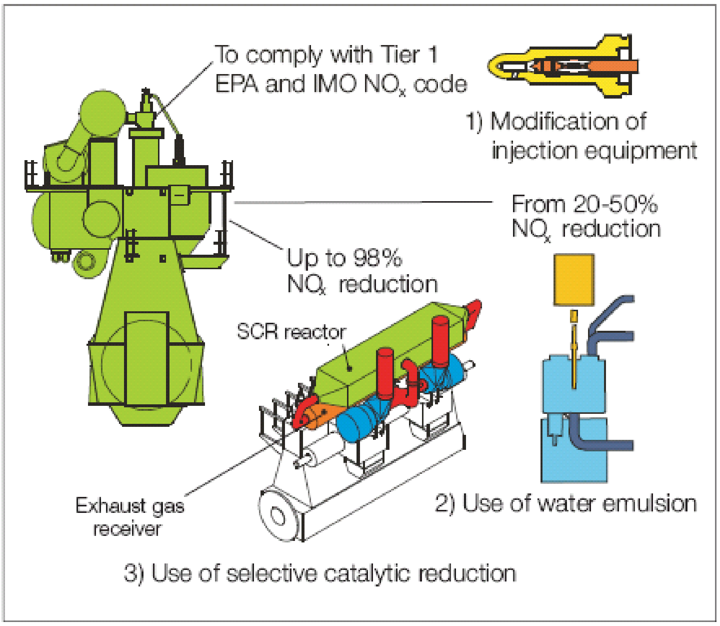



**Figure 3. Three different methods for reducing NOx emissions of a marine engine**

Ritchie et al (2005b,c) investigated the costs, emissions reductions, and cost effectiveness of NOx and $SO_2$ reductions using Internal Engine Modification (IEM), Direct Water Injection (DWI), Humid Air Motors (HAM) (or fumigation), EGR, SCR, and seawater scrubbing systems on ships. The IEM includes basic and advanced methods. The basic method was the use of the slide valves. The advanced methods included techniques such as common rail, retarded injection, Miller cycle valve timing, higher cylinder pressure, and low intake temperature.

Based on available field testing data and studies, the cost effectiveness of these technologies is listed in section 4. Section 5 includes discussion and summary of the cost effectiveness of these noted technologies.

## 4. METHODS FOR REDUCING MARINE ENGINE EMISSIONS

### 4.1 Engine Optimization

Engine optimization involves control of "in cylinder" parameters for reducing engine emissions and improving fuel economy. These parameters include peak cylinder pressure and temperature, injection pressure, compression ratio, fuel injection timing, air-fuel mixing (related to parameters such as fuel spray configuration), and others. Improving the engine's efficiency results in reduced fuel consumption and lower PM, CO, $CO_2$ and HC emissions. NOx emissions can be reduced with lower fuel injection pressure and delayed fuel injection and ignition which reduce combustion temperature and the duration of in-cylinder combustion gases at high temperature. However, this also reduces thermal efficiency. Methods for reducing combustion temperature also include reducing pressure and temperature of supplied air, optimization of the fuel injection method and system, compression ratio, and geometry of the piston-cylinder (combustion space), early inlet valve closing, delayed exhaust valve closing, and addition of water to the combustion space. Generally, methods used for reducing NOx emissions in the engine result in increased fuel consumption, as well as carbon oxides and particulate emissions. Thus, it is necessary to find a medium ground to balance NOx, $CO_2$, and particulate emissions or incorporate other emission control techniques.

Controls of diesel ignition and combustion processes have significant impacts on soot and NOx emissions. A well-developed fuel spray generates small fuel droplets which are delivered to the cylinder's space in a wide cone angle. The droplets mix with the injected air effectively, resulting in a quasi-homogeneous combustion process without soot formation at full range of load and speed (Ismailov et al (2007)).

### 4.2 Slide Valve

Slide valves have been used on slow speed-two-stroke engines for optimizing spray distribution in the combustion chamber, while the engine temperature is kept constant. The optimized spray distribution results in improved mixing and lower heat release as compared to the conventional fuel injectors, thus reducing NOx emissions. Figure 4 shows a conventional valve and a slide valve (MAN B&W (2004)).

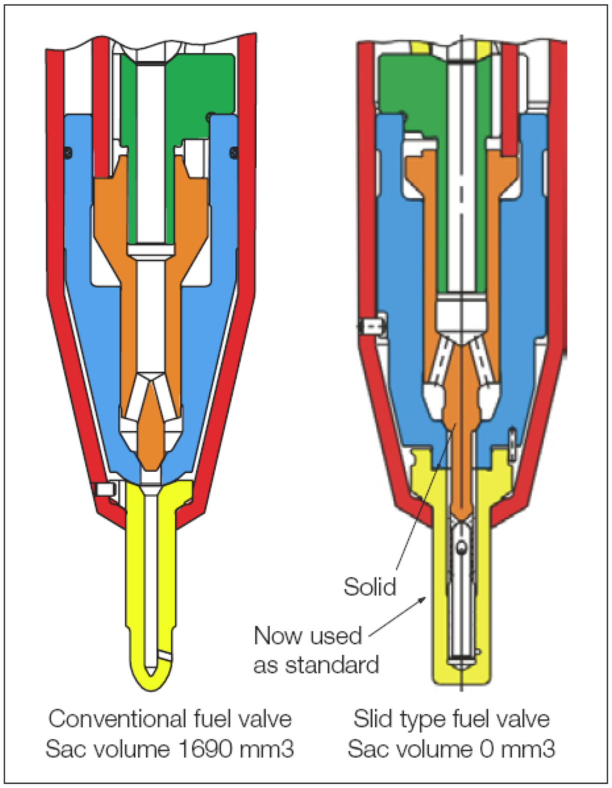



**Figure 4. Comparison of the Conventional Fuel Valve and Slide type Fuel Valve**

The difference between the conventional valve and the slide valve is the sac volume. The existence of the sac volume can result in the introduction of some fuel into the combustion zone as it leaks from the sac volume. If the combustion temperature is not high enough for a complete combustion, this results in fouling and increased soot and VOC emissions.

### 4.3. Cylinder Lubrication

Cylinder lubrication contributes significantly to the PM emission rate and the overall cost of the engine operation. MAN B&W (2001, 2002 and 2004) has developed a high pressure electronically controlled Alpha lubricating system, leading to lower feed rate and optimized lubricating processes. The new lubricating system works on the principle of injecting a specific volume of the oil, via a number of injectors, into the cylinder at a specific number of revolutions (4, 5, 6, or higher). The timing of the injection is controlled electronically to ensure direct delivery of the oil onto the cylinders' ring packs for maximum lubrication and minimum waste. Wartsila engines use improved piston-running behavior with a TriboPack design (Wartsila, 2003), which includes multi-level cylinder lubrication, among other features, for optimizing the lubricating process and reduction of PM emissions.

4.4 Common Rail

Common rail is a method to eliminate visible smoke from the exhaust, specially at low engine loads. Visible smoke generation is partly due to low injection pressure and striking of large fuel droplets on the hot surfaces during the combustion process. In this method, the fuel injection rate and injection pressure is controlled independently from the engine speed and load. Maintaining high pressure at lower loads prevents the formation of large fuel droplets during combustion and thus reduces visible smoke. Figure 5 shows the main components of the Wartsila common rail injection system which is comprised of high pressure pumps, accumulators, fuel injection valves, and the control oil pumps. The high pressure pumps are camshaft driven and supply fuel to two engine cylinders. Each pump is connected to an accumulator and the accumulators are connected through double-walled pipes. Fuel is fed from the accumulators to the cylinders through the injection valves which are controlled by electro-hydraulic actuators. This set-up and design allows individual control of injection timing and duration for optimized injection at different engine loading conditions.

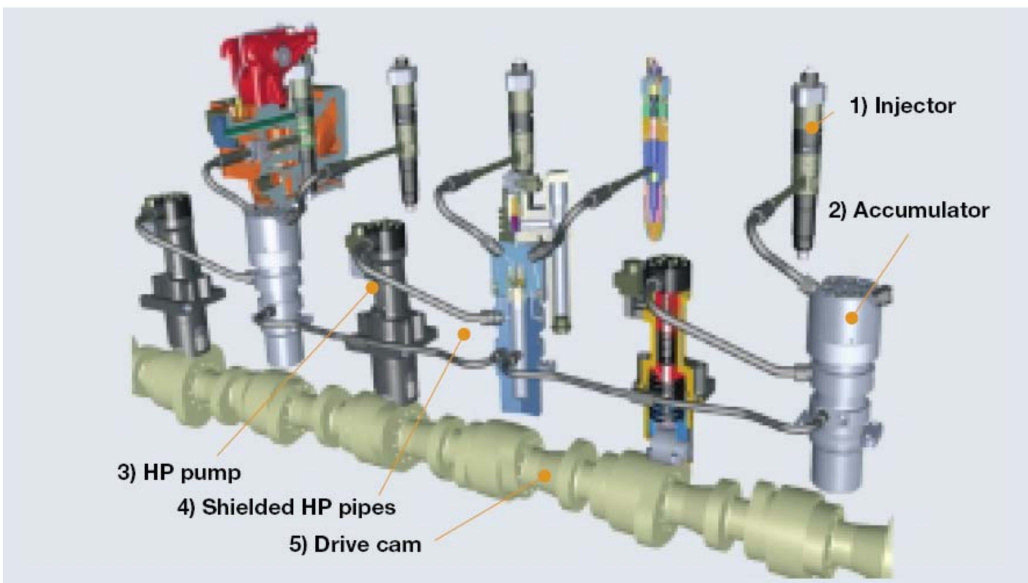



**Figure 5. Wartsila Common-Rail Components**

Figure 6 shows the effects of common rail on smoke emissions at different engine loads for a 2-stroke low speed engine. As can be seen, for engine loads less than 50%, common rail results in significant reductions in smoke emissions.

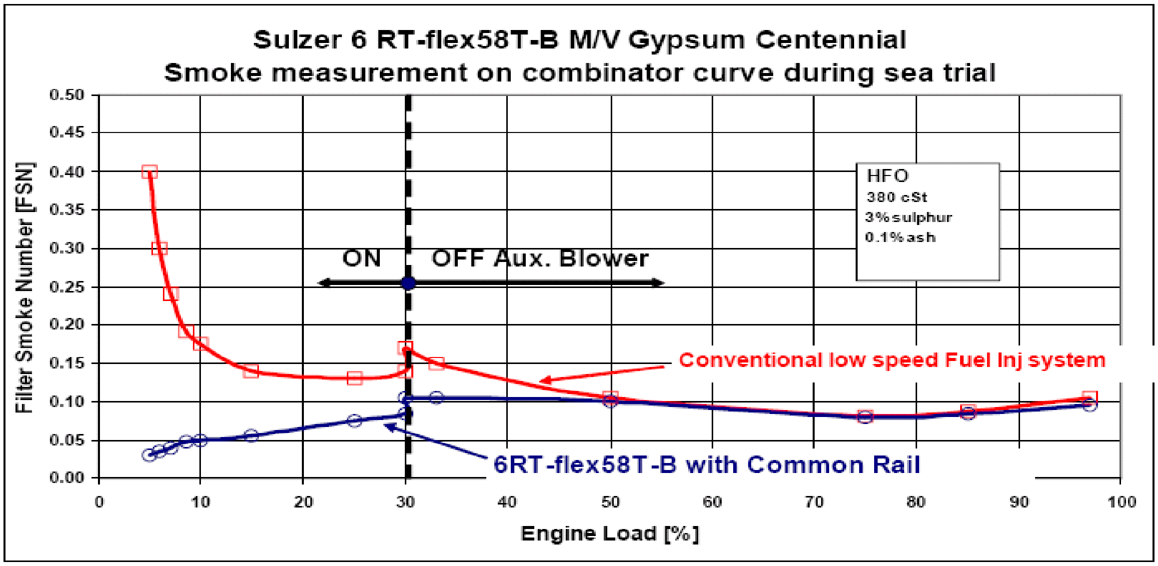



**Figure 6. Reducing visible smoke with common rail system for a 2-stroke engine (Hellen (2007)).**

Miller cycle is based on Otto cycle that incorporate charge air cooling, increased pressure during turbo-charging, lower compression ratio, and variable inlet air valve timing. In this approach, the temperature within the combustion chamber is reduced, resulting in reduced nitrogen oxides emissions. However, due to lower combustion temperature, the exhaust particulate emission is increased. Wartsila and Man B&W are among the marine engine manufacturers that have used Miller cycle as well as some of the other above mentioned engine modifications for reducing diesel exhaust emissions.

Table 5 shows the cost effectiveness of IEM (Ritchie et. Al. (2005b, c)). For the basic IEM study, the Wallenius Lines' ship, the MS Manon was used. The slide valves were supplied by Man B & W. For the advanced IEM methods, no case study was available. Instead, analysis was done, using available baseline data with reduction efficiencies ranging from 30% to 40%.

| Measure | Ship type | Emission | Small Vessel | Medium Vessel | Large Vessel |
|---|---|---|---|---|---|
| | | | $/ ton | $/ ton | $/ ton |
| Basic IEM (2 stroke slow speed only) | New | NOx | $10.84 | $8.13 | $8.13 |
| Basic IEM (2 stroke slow speed only), Newer engines | Retrofit | NOx | $10.84 | $8.13 | $8.13 |
| Basic IEM (2 stroke slow speed only), older engines | Retrofit | NOx | $54.21 | $21.68 | $13.55 |
| Advanced IEM | New | NOx | $88.54 | $29.81 | $17.17 |

**Table 5. Cost Effectiveness for Basic and Advanced IEM**

## 4.5 Engine Process Modifications

These processes include addition of water, urea or ammonia to the combustion processes, and exhaust gas recirculation.

### 4.5.1 Water Injection

A major benefit of water injection is reduced NOx emission. Injecting water increases cylinder pressure, due to added partial pressure of steam in the pre-combustion mixing process, and lowers flame temperature during the combustion phase. The flame temperature becomes lower and cooling losses are reduced with increased after ignition heat release. The three major methods of water injection are direct water injection, emulsified fuel, and fumigation. Water injection methods are well established technologies and are widely used. The following companies are among many that are involved in development of water injection systems.

| Company | Contact Information | Website Address |
|---|---|---|
| Seaworthy System, Inc. | 1067 Lombard St., Suite # 1<br>San Francisco, CA, 94109.<br>415-563-7777 | http://www.seaworthysys.com/ |
| Lubrizol Corporation | 29400 Lakeland Blvd.<br>Wickliffe, OH 44092-2298<br>Tel:1-440-943-4200<br>Fax: 1-440-943-5337 | http://www.lubrizol.com/ |
| MAN B & W | Kjeld Aabo<br>Director Customer Support<br>MAN DIESEL A/S<br>Teglholmsgade 41<br>2450 Copenhagen SV, Denmark | http://www.manbw.com/ |
| Caterpillar Diesel | Caterpillar Inc.<br>100, North East Adams Street,<br>Peoria, Illinois 61629<br>1 (309) 675-1000 | http://cat.com/cda/layout?m=8703&x=7 |
| Watsila | Mr. Goran Hellen<br>Head of Exhaust Emission Control<br>Performance and Testing<br>Research and Development<br>WARTSILA FINLAND OY | http://www.wartsila.com/ |
| Pielstick | Pielstick Service<br>Avenue de Chatonay<br>BP 427<br>44615 Saint Nazaire Cedex<br>FRANCE | http://www.pielstick.com/ |

**Table 6. Companies manufacturing Water Injection Systems**

## Direct Water Injection

In direct water injection, high-pressure water is injected into the cylinder during the fuel injection phase. The water-to-fuel injection weight ratio is 0.4 to 0.7 (Wartsila, 2006). It can reduce NOx by 50 to 60 percent. During the injection process, atomized water vaporizes and absorbs heat, reducing combustion temperature and increasing the heat capacity of the mixture surrounding the flame. This results in increased residence time and reduced emissions. Addition of water beyond the injection ratio limit will result in longer injection duration and higher soot formation.

The engine load plays a role in the amount of NOx reduction. In general, effective NOx reduction is obtained for engine loads higher than 40 percent. The advantage of the system is flexibility and ease of adjusting the water-to-fuel injection ratio to match the operation of different engines. However, the disadvantages are the cost associated with retrofitting the engines with the direct injection system and the additional tank required for the filtered clean water. Wartsila has tested the system on the passenger ship of the Silja Line's MS Silja Symphony with approximately 40% water to fuel ratio resulting in approximately 50% NOx reduction. Wartsila has completed the entire engine testing for the direct water injection using fuels with less than 3% sulfur contents.

Further research is required to assess this system's performance and additional maintenance costs from using high sulfur fuel. Table 7 shows the cost effectiveness for removing NOx, based on the results from the passenger ship the MS Silja Symphony.

| Measure | Ship type | Emission | Small Vessel | Medium Vessel | Large Vessel |
|---|---|---|---|---|---|
| | | | $/ ton | $/ ton | $/ ton |
| Direct water injection | New | NOx | $371.31 | $325.23 | $311.68 |

**Table 7. Cost Effectivness for for Removing NOx with Direct Water Injection ($/ton)**

## Emulsified Fuel

Emulsified fuel is obtained when water is mixed with diesel fuel before the emulsified fuel is injected into the engine. The optimum NOx reduction is limited to 20-30 percent. There are two approaches for adding water to the diesel fuel: Un-Stabilized and Stabilized emulsions. In Un-Stabilized emulsion, first the water and the fuel from two separate tanks are mixed in a pre-mixer using a swirl injector and then the mixture is fed through an emulsifier, making a homogeneous emulsion, which is fed to the engine fuel injector. This approach is effective for heavy diesel fuel, which is used by most ocean going vessels. Figure 7 shows the schematic of a pressurized fuel oil system with a homogenizer (Man B & W (2004)).

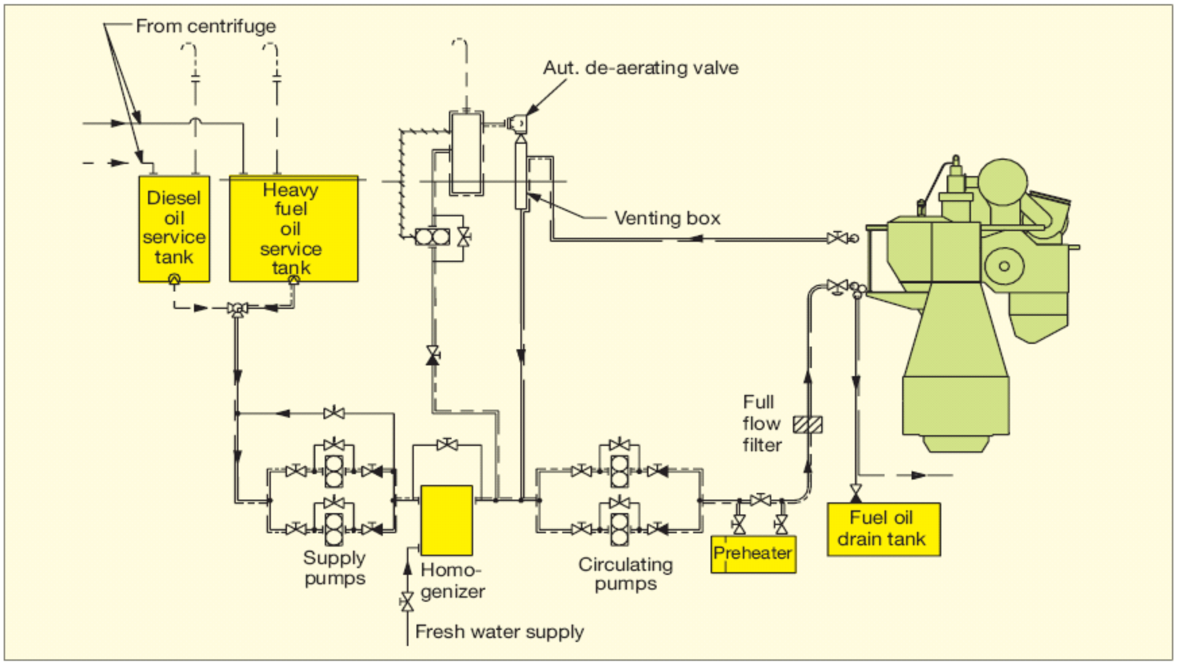



**Figure 7. An Un-Stabilized emulsion system**

Since fresh water is needed to produce emulsified fuel, the ship must either have a fresh water generator or a separate fresh water tank. If the fresh water is not available, then the seawater needs to be distilled to reduce its sodium content, before it is mixed with the fuel. High level of sodium in the water reacts with vanadium in the fuel oil, resulting in deposits on the valve seats and spindles, and subsequent leakages.

In December 2006, APL, the world's eight largest container carrier teamed up with CARB, the U.S. EPA, LA and LB ports, and four California air quality management districts to install and test an emulsification system on APL Singapore ship. The total funding of 1.3 million dollars for retrofitting the ship came from the seven partners that include the ports, the U.S. EPA and the four air quality management districts. Preliminary test on the water in fuel emulsion system has been carried out by the Sea to Sky Pollution Solutions (www.seatoskypollutionsolutions.com). Field testing aboard the ship is ongoing and results will be available in the near future.

In Stabilized emulsions, water and fuel are mixed off-board, before being supplied to the vessel. In this approach, a special chemical with a quantity of 1 percent to 3 percent of the fuel is added to the mixture to prevent separation of the diesel fuel and water. The mixture is then fed to the engine injection system for combustion. This approach has not been used by OGV operators due to its limited availability.

Depending on the type and size of the engines, the reductions in NOx and PM emissions can vary. For highway engines, NOx reduction is about 10 percent and PM reduction is about 55 percent. For the stationary engines, NOx reduction is 17 percent to 19 percents and PM reduction is about 17 percent. For the low power engines (less than 100 hp) PM reduction is higher at approximately 23 percent.

## Fumigation

Fumigation or humid air motors is a process that involves injecting water vapor in the intake air supplied to engine cylinders. This process reduces the local temperature in the cylinder and raises the specific heat of the air fuel mixture, which also contributes to elimination of hot spots in the engine cylinder. It is known that the minimum required temperature for NOx to form is between 1900-2000 ºC. With decreased temperature, NOx production decreases. Fumigation achieves 70-80 percent in NOx reduction without any increase in hydrocarbon emissions. The humidity-fuel ratio is about 3:1. Other benefits of the process include longer life of the engine components due to reduce cycle temperature and cleaner running engine due to reductions in carbon deposits. This technology however requires distilled water since salt in sea water can react with vanadium in the fuel to generate harmful deposits in the engine. Water is distilled using the engine's heat exchanger or the exhaust heat. The remaining saline water from the process is returned to the sea. The distillation process and the needed heat exchangers with extended surfaces increases the investment cost. According to Ritchie et. al. (2005b), a fumigation or humid air motors system has been tested on one ship, the MS Mariella with positive results. However, as they stated, the initial investment cost for installation of such system has prevented its wide application on OGVs. Table 8 shows the cost effectiveness for NOx removal for the test performed aboard the MS Mariella.

| Measure | Ship type | Emission | Small Vessel | Medium Vessel | Large Vessel |
|---|---|---|---|---|---|
| | | | $/ ton | $/ ton | $/ ton |
| Humid air motors | New | NOx | $242.12 | $207.79 | $178.88 |
| Humid air motors | Retrofit | NOx | $276.45 | $254.77 | $237.60 |

**Table 8. Cost Effectiveness with Humid Air Motors for NOx Removal ($/ton)**

## Exhaust Gas recirculation (EGR)

Another technique for reducing diesel NOx emissions is exhaust gas recirculation (EGR). In EGR system, input compressed air is mixed with a portion of pre-cooled filtered exhaust gas to increase its thermal capacity. The mixed gas has lower oxygen content and when it reacts with fuel during combustion, less oxygen is available for producing NOx. Lower peak combustion temperature results in lower NOx production. Man B&W (2004) used 20 percent recirculation rate and achieved 50 percent reduction in NOx at 75 percent engine load. They also report 20 percent reduction in PM and 10 percent reductions in HC, but 200 percent increase in CO and a slight increase in fuel consumption. For the EGR to be effective, the input exhaust gas should be free of PM. This is difficult to obtain, especially with the residual oil used for the ocean-going vessel. The presence of PM results in complications in turbocharger operation and increased deterioration and resistance due to the particles deposits within the combustion chamber, along piping, valves, and other components.

For OGVs using residual fuel, EGR also results in corrosion and contamination risks due to the existence of high sulfur and ash content in the exhaust. Possible application of the EGR system for OGVs would be for the auxiliary engines of ships with separate low sulfur fuel tanks. Another possibility is using combined systems of exhaust gas scrubber and EGR system for first eliminating the particulate emissions with the scrubber and then reducing NOx emissions with the EGR process. The following figure shows schematic of an EGR and a scrubbing system for a 4-stroke marine diesel engine (Man B & W (2004)). So far, the EGR system has not been tested on any OGV.

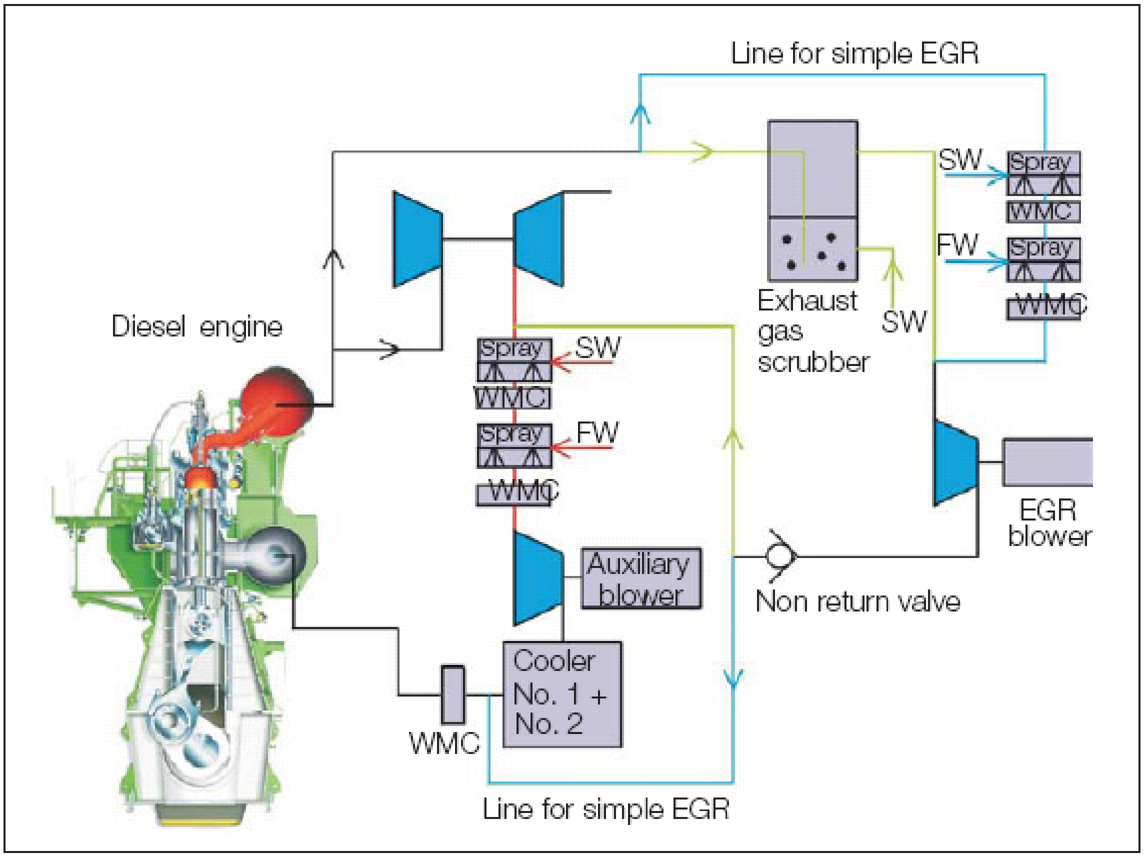



**Figure 8. EGR and Exhaust Gas Scrubber for a Marine Diesel Engine**

4.6 Selective Non- Catalytic Reduction (SNCR)

In SNCR method ammonia or urea is injected into the combustion chamber, or into the exhaust gas immediately after the combustion chamber to convert NOx to nitrogen and water. The reaction requires high temperatures in the range of 900-1000$^{O}$C. The process requires long combustion residence time to be effective. The limitation for this system is the reaction temperature. If the temperature goes above 1000 $^{O}$C, NOx production is increased and if it falls below 900 $^{O}$C, there will be ammonia slippage. In the present form, this approach is not effective due to cost associated with the significant amounts of ammonia and the extensive engine modifications required.

4.7 After Treatment Processes

The after-treatment processes are applied to the diesel exhausts after exiting the combustion chamber and do not affect the engine functions. These include selective catalytic reduction (SCR), seawater scrubbing, diesel oxidation filter, and diesel particulate filter.

4.7.1 Selective Catalytic Reduction (SCR)

In SCR systems, urea or ammonia is injected into the exhaust of the diesel engine at a temperature range of 290-350 ºC, and next the exhaust gas is guided through a catalytic converter. With effective mixing between the injecting agent and the exhaust gas, significant reductions in NOx emissions can be obtained. SCR system requires large space and additional tank to carry aquatic urea or ammonia. Figure 9 shows a urea SCR system for a four-stroke engine (Hellen (2007)).

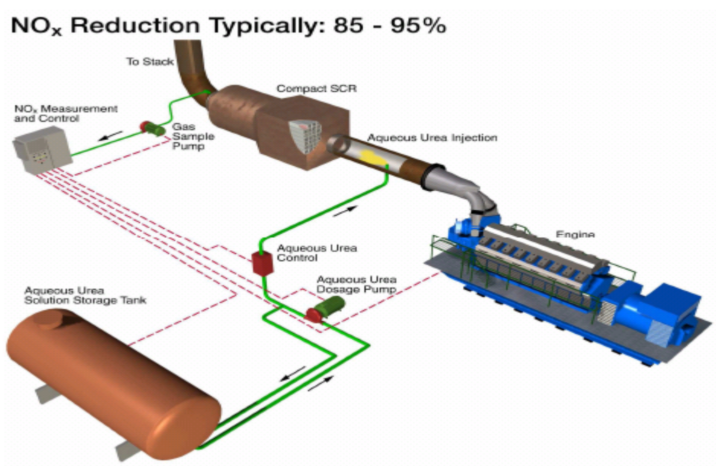



**Figure 9. SCR system for a 4-stroke marine engine**

If SOx is present in the exhaust, which generally is the case for vessels using residual fuel, then it oxidizes to form sulfuric acid, which causes high rate of corrosion and reduces system life. Since the presence of high level of SOx in the exhaust reduces the capacity of the catalyst to absorbs NOx, making it ineffective in reducing NOx emissions.

According to the European Environmental Board (EEB), in 2004, there were more than 50 ships fitted with SCR systems with more than half being of Swedish origin. The system generally replaces the exhaust silencer. Man B&W (2004) reports more than 90 percent reduction in NOx with marine engines equipped with SCR systems. The longest running SCR system is on the Swedish ABB Fläkt merchant ship with more than 50,000 hours of operation. For the total operation hours, the average reduction rates for NOx, HC, and CO were 97 percent or more, 88 percent, and 53 percent respectively. Table 9 provides a list of marine vessels with SCR systems (Hellen (2007)).

| Vessel | Engines | Delivery | Fuel | Reduction Agent | Notes |
|---|---|---|---|---|---|
| Aurora of Helsingborg | 1 X WV6R32 | 1992 | MDO | 40% urea water | |
| Silja Serenade | 1 X WV8R32 | 1995 | HFO 0.5%S | 40% urea water | |
| Silja Serenade | 1 X WV8R32 | 1995 | HFO 0.5%S | 40% urea water | |
| Gabriella | 1 X WV6R32 | 1997 | HFO 0.5%S | 40% urea water | Retrofit |
| Thjellvar | 2 X WV4R32 + 4 X WV12V32 | 1997 | HFO 0.5%S | 40% urea water | Compact SCR |
| Birka Princess | 4 X WV12R32 + 2 X WV6R32 + 1 X WV4R32 | 1999 | HFO + MDO | 40% urea water | Compact SCR, retrofit |
| M/V Spaarneborg | 1 X 7RTA52U + 2 X W6L20 | 1999 | HFO + MDO | 40% urea water | |
| M/V Schieborg | 1 X 7RTA52U + 2 X W6L20 | 1999 | HFO + MDO | 40% urea water | |
| M/V Slingeborg | 1 X 7RTA52U + 2 X W6L20 | 2000 | HFO | 40% urea water | |
| Visby | 4 X 12V46 + 3 X 9L20 | 2000 | HFO | 40% urea water | Compact SCR |
| Gotland | 4 X 12V46 + 3 X 9L20 | 2000 | HFO | 40% urea water | Compact SCR |
| Birka Exporter | 1 X WV16V 32 | 2000 | HFO | 40% urea water | Compact SCR, retrofit |
| Birka Transporter | 1 X WV16V 32 | 2002 | HFO | 40% urea water | Compact SCR, retrofit |
| Birka Shipper | 1 X WV16V 32 | 2001 | HFO | 40% urea water | Compact SCR, retrofit |
| Birka Paradise | 4 X 6L46 + 4 X 6L32 | 2002 | HFO | 40% urea water | Compact SCR |
| Tallink Victoria | 4 X 16V32LNE + 3 X 6R32LNE | 2002 | HFO | 40% urea water | Compact SCR |
| Balticborg | 1 X 9L46C | 2003 | HFO < 1% S | 40% urea water | |
| Newbuilding | 1 X 9L46C | 2004 | HFO < 1% S | 40% urea water | |
| Newbuilding | 4 X 6R32LNE | 2004 | MDO | 40% urea water | |

**Table 9. Marine Vessels with SCR System**

Ritchie et al (2005b) calculated the cost effectiveness of the SCR system, based on the field test aboard the ship the MS Sign. The system was supplied by Argillon GmbH. Table 10 shows the results.

| Measure | Ship type | Emission | Small Vessel | Medium Vessel | Large Vessel |
|---|---|---|---|---|---|
| | | | $/ ton | $/ ton | $/ ton |
| SCR outside $SO_2$ ECA | New | NOx | $668.53 | $508.63 | $475.20 |
| SCR outside $SO_2$ ECA | Retrofit | NOx | $730.87 | $552.90 | $515.86 |
| SCR inside $SO_2$ ECA | New | NOx | $490.56 | $383.05 | $359.56 |
| SCR inside $SO_2$ ECA | Retrofit | NOx | $553.80 | $427.32 | $400.22 |
| SCR, Ships using MD | New | NOx | $373.11 | $299.94 | $282.77 |
| SCR, Ships using MD | Retrofit | NOx | $436.35 | $344.20 | $323.43 |

**Table 10. Cost Effectiveness of the SCR system for removing NOx ($/ton)**

Reduction of NOx emissions can also be accomplished with a SCR system with hydrocarbons as the reducing agent. The system can use the on-board fuel tank as its reservoir and a control system to time the injection process to the engine timing to optimize the NOx reduction process. Sumiya et al. [1992] have shown 30 percent NOx reduction at a 450 ºC exhaust temperature with diesel fuel sprayed ahead of the catalyst bed. This approach has not been tested on any marine engine.

As it can be summarized, SCR systems are also well established technologies and are widely adapted in new marine vessels. The following (Table 11) is the list of major companies involved in design and development of SCR systems:

| Company | Contact Information | Website Address |
|---|---|---|
| Caterpillar Inc. | Glenn M. Luksik<br>(309) 578-7552<br>(309) 258-9726 Cell<br>(309) 578-2998 Fax<br>Email:<br>Luksik_Glenn_M@cat.com | http://www.cat.com |
| Clean Diesel Technologies Inc. | Dr. Walter G. Copan<br>(203) 327-7050<br>(203) 323-0461 Fax<br>Email:<br>wcopan@cdti.com | www.cdti.com/ |
| Engelhard. | Shawn Beavers<br>732-205-6062<br>732-205-5915 Fax<br>Kevin Hallstrom<br>(732) 205-6489<br>(732) 205-5687 Fax | www.engelhard.com/Lang1 |
| Johnson Matthey Catalytic Systems Division | Marty Lassen<br>(610) 341-3404<br>(610) 971-3116 Fax<br>Email:<br>lassem@jmusa.com | www.jmusa.com/about/catalysts.htm |
| Lubrizol | Kevin Snape<br>(440) 347-6798<br>(440) 347-4013 Fax<br>Email:<br>kesna@lubrizol.com | http://www.lubrizol.com/ |
| Argillon | Phone number (USA)<br>678 – 341 7500<br>678 – 341 7509 Fax<br>Dr. Wolfgang Schüttenhelm<br>++49 (0) 9574 81 – 861<br>++49 (0) 9574 81 – 628 Fax<br>Markus Gögerle<br>++49 (0) 9574 81-839<br>++49 (0) 9574 81-612 Fax<br>Email:<br>markus.goegerle@argillon.com | http://www.argillon.com/index.htm |
| Babcock Power Inc. | 800-797-4539<br>508-852-7548 Fax<br>Email:<br>info@babcockpower.com | http://www.babcockpower.com/ |

**Table 11. Companies Manufacturing SCR Systems**

4.7.2 Seawater Scrubbing Processes

The seawater scrubbing of the exhaust gas, removes sulfur oxides (SOx) and PM by passing the engine exhaust gases through a seawater scrubber installed in the engine exhaust system. When the seawater is sprayed into the exhaust, the scrubbing action removes the PM and the interactions of sodium and calcium compounds remove the sulfur oxides. The estimated reductions in diesel engine SOx, and PM are 75-80 percent and 25-30 percent respectively (Ritchie et. al. (2005c)). Solids removed during the process are collected in a sludge storage tank for disposal ashore.

Seawater scrubbing is effective in removing $SO_2$ from the exhaust. However, sometimes, the exhaust gas includes small amounts of $SO_3$. With the temperature of the scrubbed gas being less than the dew point temperature of $SO_3$ acid (125 to 175 ºC), there is a possibility of $SO_3$ reacting with the exhaust mist to form sulfuric acid vapor. This has the potential of local plume grounding and acid contamination.

One issue with the seawater scrubbing process is the quality of the discharged water and its environmental impact. In general, ships are equipped with a water treatment facility for bilge water. However, even with water treatment facility, extensive discharged water quality tests are needed to provide baseline data for development of limitations criteria and required treatments for particles and petroleum hydrocarbons of the type that are present in the seawater scrubbing discharged water.

The scrubbing process reduces the temperature of the scrubbed gas to close to ambient conditions. After impacting deflector baffles, which reduces droplet concentration of the discharged gas to about 50 mg/m$^3$, the gas is reheated to increase its temperature by 20 to 30 ºC. This eliminates the steam plume, before discharging exhaust to the atmosphere. Results of trials of using the EcoSilencer on the ship the Pride of the Kent have shown SOx reductions of 68-94 percents and PM reduction at around 31 percent. It is expected that with a new improved design of the scrubbing system, removal of over 90 percent of SOx and a higher rate for PM. A Holland America cruise ship is also in the process of testing a scrubbing system for SOx and PM removal and results will be available in the near future.

The cost effectiveness of the scrubbing system has been calculated based on the field tests aboard the ship the Pride of the Kent. The $SO_2$ reduction efficiency of the scrubbing system was assumed to be 75%. Table 12 shows the results.

| Measure | New/ Retrofit | Emission | Small Vessel | Medium Vessel | Large Vessel |
|---|---|---|---|---|---|
| | | | $/ ton | $/ ton | $/ ton |
| Sea water scrubbing | New | $SO_2$ | $352.34 | $317.10 | $289.10 |
| Sea water scrubbing | Retrofit | $SO_2$ | $520.37 | $483.33 | $455.33 |

**Table 12. Cost Effectiveness of a Scrubbing System for SOx removal ($/ton)**

The following is the list of the companies and their contact information that are involved in scrubbing technology.

| Company | Contact Information | Website Address |
|---|---|---|
| Marine Exhaust Solutions, Inc | Robert Clarke<br>(506)639-7531 | http://www.marineexhaustsolutions.com/index.asp |
| Krystallon Ltd. | 44 1903 738349 | http://www.krystallon.com/Default.aspx?PageID=8 |
| Branch Environmental Corp. | Bill Gilbert<br>(908)526-1114 | http://www.branchenv.com/contact.htm |
| Bionomics Industries | Ken Scifftner<br>(800) 311-6767 Ext. 113 | http://www.bionomicind.com/ |
| Ceilcote Air Pollution Control | (800)554-8673 | http://www.ceilcoteapc.com/ |
| Komax Systems, INC. | (800)726-0760 | http://www.komax.com/det-nox.htm |
| Tri-Mer Corporation | Kevin D. Moss :801-294-5422 | http://www.tri-mer.com |

**Table 13. Companies Involved in Seawater Scrubbing Technology**

### 4.7.3 Oxidation Reactors

The oxidation reactors are used to convert CO and HC gases into $CO_2$ and $H_2O$. They also can remove a portion of PM that is associated with the soluble organic compounds (VOC). The catalyst has the potential to remove CO by more than 90 percent and HC by about 70 percent. The percent removal of PM associated with the VOC is dependent on the exhaust temperature and is usually between 50-90 percent. Oxidation catalysts are generally used in conjunction with the SCR systems to remove $NO_x$, CO, and HC. In this case, the oxidation catalyst is placed upstream of the SCR system. High sulfur fuel reduces the effectiveness of diesel oxidation catalyst and results in production of sulfate particles. There has not been any trials of using the oxidation catalyst on OGVs.

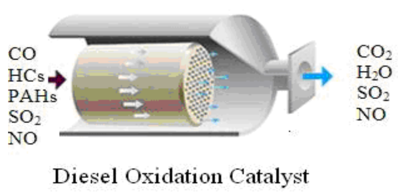



**Figure 10. Diesel oxidation catalyst**

### 4.7.4 NOx Absorber Catalyst (NAC)

The NOx absorber catalysts use “base metal oxide” and precious metal coating to absorb NOx during engine lean operating conditions. When the maximum NOx storage condition is met, the catalyst goes through a regeneration process to release the NOx absorbed. Regeneration of the catalyst requires elimination of excess oxygen in the exhaust. This is accomplished with either running engine under rich operating condition for a short period of time or by injecting fuel upstream of the catalyst to absorb the excess oxygen and convert NOx to nitrogen.

Sulfur in fuel oil poses challenges to the NAC and makes it ineffective and thus the NAC has not been a viable option for reducing NOx emissions of OGVs.

4.7.5 Lean NOx Trap (LNT)

Lean NOx catalysts have similar design characteristics as NOx absorber catalysts but without the regeneration process. Their successful operation depends on continuous injection of hydrocarbon upstream of the catalyst for converting absorbed NOx to nitrogen. This technology has very limited capacity even for meeting the 2007 California emission standards for diesel trucks and other mobile diesel engines. Therefore, LNT at its present form is not a viable option for reducing NOx on marine engines.

4.7.6 Diesel Particulate Filters (DPF)

Diesel Particulate Filters are used to filter out soot or particulate matter. The filters usually contains two chambers, one for the oxidation of NO to $NO_2$ using a platinum catalyst, and a second chamber with a ceramic filter where $NO_2$ reacts with the particulates to "burn them off," converting them to carbon dioxide and carbon monoxide gases and inorganic dusts. The DPFs are capable of trapping particles as small as 2.5 microns in diameter. Figure 11 shows a particle filter and typical muffler construction.

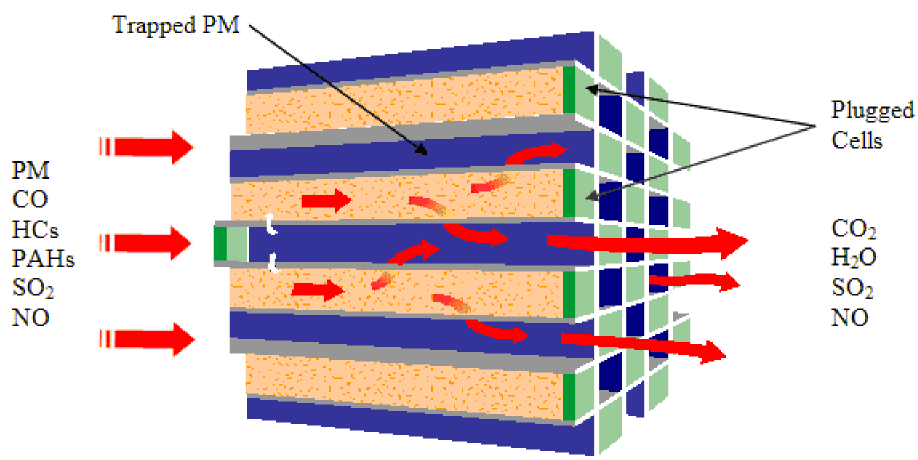


**Figure 11. Particulate Filter and Typical Muffler Construction**

Particulate filters are very sensitive to deactivation due to the presence of sulfur in the fuel. For NOx catalysts, the sulfur is absorbed along with the NOx, resulting in reduced NOx absorption capacity. During the regeneration process, a similar procedure as for NOx should be followed for removing the sulfur, except at a higher temperature. For the particulate filters, the existence of the sulfur in the fuel results in increased ash collection along with other particulates which requires extensive and frequent maintenance.

Although these technologies have been used for control of trucks' emissions with some success, they are not readily applicable to the OGVs, primarily due to high sulfur content of the marine fuel. However, with anticipated cleaner fuel standards, they may become viable options in the future.

4.8 Low Sulfur Diesel Fuels and Alternatives

Reduction of $SO_2$ and PM emissions of OGVs can effectively be accomplished with using low sulfur fuel. Most marine engines can switch to the low sulfur fuel without significant modifications. Current limited production level of low sulfur heavy fuel oil may prevent its wide applications in OGVs, beyond existing use in sulfur emission control area in coastal area near ports and along the shipping lanes. The European Union (EU) has already agreed on limiting sulfur content in heavy fuel oil to 1.5% for ships serving the English Channel, the North Sea and the Baltic Sea.

Another alternative is dual-fuel engines such as Wartsila's 32DF and 50DF models. Figure 12 shows the Wartsila 6L50DF dual-fuel marine engine. These engines operate in "natural gas mode" or "diesel mode". In natural gas mode, they have low gas pressure and high efficiency and are operated under lean fuel conditions, resulting in low emissions. As compared with the diesel mode using light fuel oil, the gas mode results in elimination of SOx emissions, and reducing NOx and PM emissions by approximately 80% and 90% respectively. With increasing regulations for reducing $CO_2$ emission, liquid natural gas (LNG) can be an alternative clean fuel for marine engines with 25 percent lower $CO_2$ emission as compared to the diesel fuel oil.


**Figure 12. A Dual-Fuel Marine Engine**

**Biodiesel**

Bio-diesels are renewable fuels that are extracted from animal fat and vegetable oils. The process includes reaction of oil and fat with methanol or ethanol to produce a lower viscosity fuel which has similar characteristics as diesel fuel. Pure biodiesel or B-100 can be used in diesel engines, but requires major engine modifications. A more common approach has been fuel blending with diesel fuel and 20% bio-diesel (B-20) which eliminates the need for engine modifications. Use of B-20 results in 10% reduction in CO and HC, 20% reduction in sulfate, and up to 15% reduction in PM. However, there will be some increase in NOx which can be up to 10%. A recent presentation by Howell (2007) indicates plan for expansion of bio-diesel capacity to 300 billion gallons annually in the U.S. and the current efforts to supports regulations that require 5% bio-diesel (B5) blend into the diesel fuel. Also there are plans to develop stand alone specifications for B6 through B20. There has not been any reported trial on using bio-diesel on marine engines. More information on this subject can be found at www.biodiesel.com.

**O2Diesel**

O2diesel is an ethanol-diesel fuel blend that has been discussed as an alternative for reducing diesel emissions. Ethanol is an oxygenate with high oxygen content (35%) that has been used in ethanol-diesel fuel blend. The regular O2diesel has approximately 7.7% by volume ethanol, about 0.6% additive and the rest is regular diesel fuel. There is also O2-B20 fuel which has the same amounts of ethanol and additive blended with 20% by volume biodiesel and 71.7% by volume regular diesel fuel. As compared with ultra low sulfur diesel, the O2diesel produce 20% less PM, about 4.3% less CO, and less than 1% reduction in NOx. For the O2-B20, the PM reduction is higher than 30% and CO and NOx reductions are higher than 8% and 3% respectively (Grotsky (2002)). There are some concerns about the operation safety of using O2diesel. O2diesel is very flammable and has the risk of fire and explosion. Until these concerns are addressed, O2diesel is not an attractive alternative for use on OGVs.

## Fuel Cell

Fuel cell technology has been under extensive developments and the current technology can produce up to 100 KW power. The fuel cell coupled with electric drives can produce enough power for small boats. However, for large ships and OGV's with more than 500 times power requirement, the use of fuel cells is probably in the far future. The ideal fuel for the fuel cell is hydrogen. At the present, there is no infrastructure for producing hydrogen on an industrial scale that can be used by large ships. In addition, many tankers running on fuel cells should go through modifications to add a tank for hydrogen fuel. Another current problem with the fuel cell as compared with the diesel engine is its much higher cost, for the same power production.

## Gas Turbine

Gas turbines have also been gaining attention as a substitute for diesel engines, due to their low PM and CO emissions. Since gas turbines have significantly lower engine efficiency than the diesel engines with the same capacity, the best alternative for using the gas turbine is as the auxiliary engine. In this case the carriers are required to have two tanks, one for the residual fuel and the other for the light fuel oil or natural gas which might not be economical. However, this might be a good option for LNG/CNG carriers. For the LNG carriers, the boil-off gas can be used to operate the gas turbine and the added tank is not required.

For LNG carriers, which are equipped with modern high efficiency two-stroke diesel engines, the boil-off gas can be used to generate steam for the propulsion system. Using the boil-off gas significantly reduces CO emission. However, in modern LNG carriers, the amount of boil-off gas is low and provides only 30-50% of the fuel needed to produce steam and heavy fuel is used for the rest. One alternative for the LNG carriers is to use low speed heavy fuel burning diesel engine and re-liquefy the boil-off gas and store it for sale.

## Diesel Fuel with Hydrogen

Addition of hydrogen as a diesel fuel modifier can reduce NOx emissions. Bika et al [2007] studied the effects of hydrogen as a modifier for both low sulfur diesel fuel and bio-diesel on a 1.9 liter turbo-charged diesel engine. Their results indicate reduction of NOx emission at all loads with 5% hydrogen input. Increasing the hydrogen input, results in NOx reduction at 20% of the load. However, the NOx emissions remain constant at 40% of the load but increases at higher loads.

4.9 Emerging Technologies and Research

**Intelligent Energy (IE)** is working on development of a membrane-based sulfur fuel management systems that can produce low sulfur fuel during the ship's journey in the open seas. The low sulfur fuel is to be used during the ship's operation near ports and coastlines. Figure 13 shows the membrane construction and module.

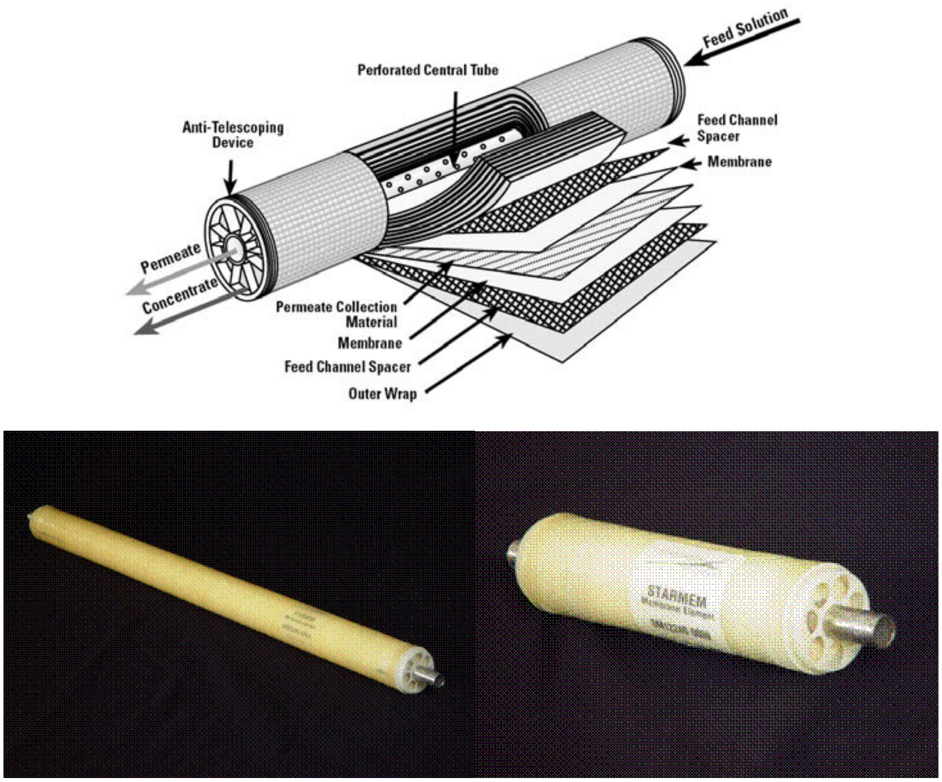



**Figure 13. Spiral Wound Membrane Construction and Polymeric Membrane Modules**

Intelligent Energy is working with two membrane types in its clean fuel processing systems. One membrane type includes a family of non-sulfur-selective pervaporation (permeation + evaporation) membranes (also referred to as high flux membranes, HFM). The other membrane type, which is widely used for separation and solvent recovery in petroleum refining, chemical, food, and beverage industries, is called STARMEM$^{TM}$, which is based on organic solvent nano filtration (OSN). The characteristics of the optimum membrane are application-specific**.**

These fuel sulfur management systems have been validated in a breadboard configuration in the IE laboratory. Current efforts are addressing optimization and system lifetime characterization. Prototype demonstrations are planned over the next 1-2 years, with commercialization expected for the following 1-2 years. More information can be found at [www.intelligent-energy.com](http://www.intelligent-energy.com)

**Amminex A/S** of Denmark has developed an ammonia storage and delivery system (ASDS) that allows the SCR aftertreatment system to work with direct ammonia gas injection. Here ammonia is stored by absorption in a dense solid called AdAmmine, consisting of an inorganic salt and ammonia. According to their report (Johannessen et al (2007)), it has the same capacity as the liquid ammonia and more than three time capacity as the urea-based AdBlue (AdBlue is the registered trademark for Aqueous Urea Solution 32.5%, AUS32). The system is still in the development stage for adaptation to passenger cars and trucks. The advantage of the system is low storage capacity and low power requirements for its operation. It also has long shelf life and is operational at sub-zero conditions. This is one of the attractive systems that can be developed and be adapted for the OGVs auxiliary engines. The solid ammonia can be stored on ship and be used for the SCR system while the ship is operating close to the coastline or at ports. Figure 14 shows the ammonia release process.

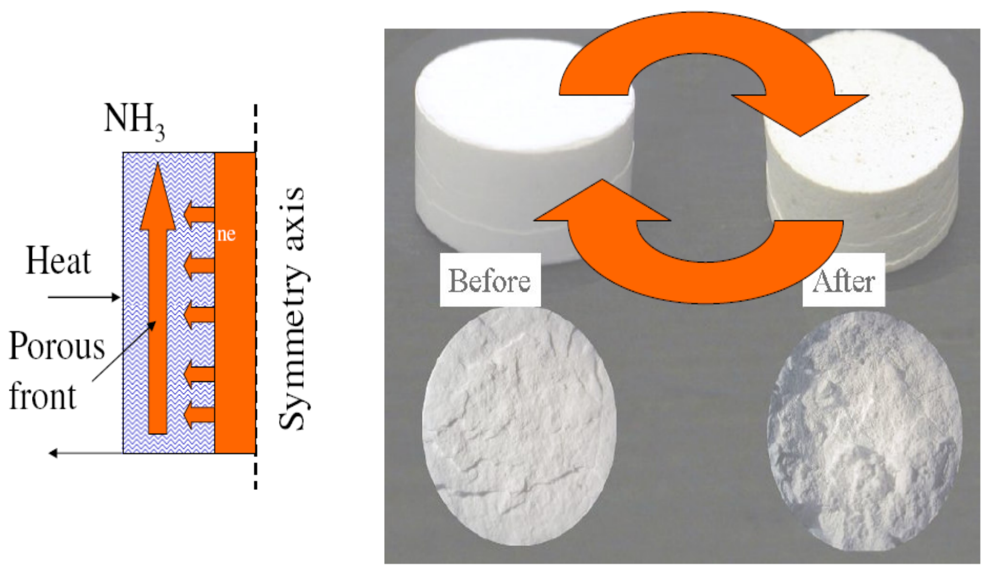



**Figure 14. Ammonia Release by Controlled Thermal Absorption**

**IP-Hercules** was a major project on high efficiency engine research and development on combustion with ultra low emissions for ships. It was an integrated project with members from industry (60%), user/operator companies (9%), universities (19%) and research organizations (12%). The members were from nine European Union countries (Austria, Czech Republic, Denmark, Finland, Germany, Greece, Italy, Sweden, and United Kingdom) and also Switzerland. The project was managed by coordinating partners (ULEME E.E.I.G.) housed in Germany with members from Wartsila and Man B&W companies. The work which was supported by the European Commission and Swiss Federal Government included research and technical development (RTD) activities, demonstration activities, and training and management activities. For the project duration (2003-2007), there were nine RTD activities as shown below (Figure 15):

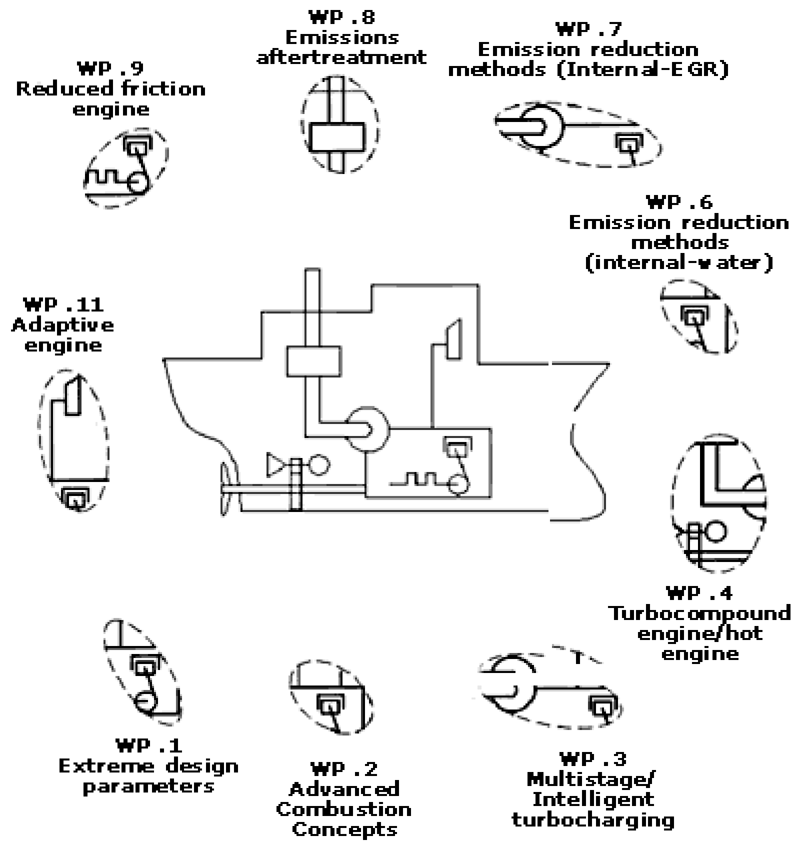



**Figure 15. Research and Technical development Activities for the IP-Hercules Project**

Demonstration activities consisted of full scale shipboard installation and testing for turbo-compound engine/hot engine, emission reduction using water injection, and electronically-controlled camless engine. The final year of the project was focused on training activities related to experimental and measurement methods, computational fluid dynamics and combustion, and process simulation.

The following table (Table 14) shows the objective and vision of the IP-Hercules for reducing marine engine emissions by years 2010 and 2020.

| **I.P. HERCULES VISION** | **Year 2010** | **Year 2020** |
|---|---|---|
| Reduction of fuel consumption and $CO_2$ emissions | -3% | -5% |
| Reduction of NOx (Relative to IMO 2000 standard) | -30% | -60% |
| Reduction of other emission components (PM, HC) | -20% | -40% |
| Improvement in engine reliability | +20% | +40% |
| Reduction of time to market | -15% | -25% |
| Reduction in lifecycle cost | -10% | -20% |

**Table 14. Emission Reduction Goals for IP-Hercules project**

In order to meet the objectives of the project, efforts are focused on innovations in the following areas:

Engines with “extreme” boost, m.e.p. design parameters
“New” combustion concepts
“Intelligent” variable flow area, multistage turbochargers
“Hot”-operating engine with combined steam cycle
Marine engines with water injection
Exhaust gas recirculation in heavy-fuel engines
New after treatment methods for heavy fuels (plasma, scrubbers)
New sensors and emission measurement methods
“Low-friction” engines
“Adaptive” control of engines

The first part of the Hercules project has been completed and the consortium has proposed a follow up to the first phase as “HERCULES-B” in a new large scale collaborative research project with the aim of implementing the results of IP HERCULES projects and to substantially improve the efficiency of the marine diesel propulsion systems and achieved significant fuel efficiency and emissions reduction (Wartsila (2007)). More details of the project can be found from the following web site which also provides results from part I research and demonstration activities:
http://www.ip-hercules.com/article/english/1/index.htm

## 5 DISCUSSIONS AND CONCLUSIONS

OGVs include containerships, oil tankers, passenger ships, Ro-Ro-vessels, cargo ships and bulk carriers. They are the primary means of carrying large cargos across the seas. Generally, OGVs have main and auxiliary diesel engines as well as steam boiler generators. Due to the high fuel cost, most of them use low grade fuel oil with high sulfur content in their engines. Emissions from these engine include high level of PM, NOX, and SOx. Sulfur in fuel contributes significantly to the high level of PM and SOx emissions. However, since diesel engines are fuel efficient, their CO and $CO_2$ emissions are significantly lower than from the gasoline engines. OGVs and shipping industry have been among the least regulated industries in terms of emissions controls. With increase in trade, the significant adverse health impacts from shipping and port activities will increase. Existing and proposed strategies and regulations by CARB, to control marine diesel engine emissions will result in significant reductions in PM, NOx, and SOx emissions. This will significantly reduce the adverse health impact associated with these emissions and reduce the cost associated with emission-related health problems such as cancer risk, heart failure and respiratory illnesses, and will improve quality of life for many communities.

This project focused on review and assessment of different methods and technologies for reducing emissions of diesel marine engines. Methods include engine optimization, engine process modification, exhaust after treatment, use of cleaner fuel and combination of these measures. Specific method and processes associated with these approaches are listed below:

5.1 Engine Optimization Process

1. Optimization of combustion chamber geometry
2. Optimization of combustion residence time
3. Control of lubrication process
4. Common rail system
5. Increased compression ratio
6. Improving injection nozzle geometry
7. Control of fuel injection process
8. Miller cycle valve timing

5.2 Engine Process Modifications

1. Addition of water, urea, or ammonia to the combustion process.
2. Electronic control of fuel injection and exhaust gas valve for meeting optimum emission reduction at all loads.
3. Exhaust gas recirculation with low sulfur fuel or in combination with the scrubbing system for reducing NOx emissions.

5.3 After Treatment Processes

1. Selective Catalytic Reduction (SCR) system for reducing NOx.
2. Seawater scrubbing system for reducing PM emissions.
3. Diesel Particulate Filter (DPF) for reducing PM emission in auxiliary engine using low sulfur fuel.

Table 15 through 17 show the effectiveness of some of these technologies in reducing various emissions, and the total tons of NOx and SOx removed annually, based on known shipboard installation and field testing (Ritchie et al (2005b,c)).

| | NOx | sfc | $SO_2$ | VOC | PM |
|---|---|---|---|---|---|
| Basic IEM (Slide Valves) | -20% | * | * | * | * |
| Advanced IEM | -30% | * | * | * | * |
| Direct water injection | -50% | * | * | * | * |
| Humid Air Motor | -70% | * | * | * | * |
| Exhaust Gas Recirculation (ships using RO but Switching to MD (accounting for $SO_2$ & PM reductions)) | -35% | * | -93% | +/- | >-63% |
| Exhaust Gas Recirculation (ships originally using MD) | -35% | * | * | * | * |
| Selective Catalytic Reduction | -90% | * | * | * | * |

**No Significant change**

**Table 15. NOx Reduction Efficiency of Different Measures as a Percentage of Baseline Emissions**

| | Vessel | | |
|---|---|---|---|
| | Small (t NOx/ year) | Medium (t NOx/ year) | Large (t NOx/ year) |
| Basic IEM (Slide Valves) | 43 | 144 | 361 |
| Advanced IEM | 70 | 230 | 577 |
| DWI | 117 | 384 | 962 |
| HAM | 164 | 538 | 1346 |
| EGR | 82 | 269 | 673 |
| SCR | 211 | 691 | 1731 |

**Table 16. NOx Emissions Reduction in Tons per Year per vessel**

| | Vessel | | |
|---|---|---|---|
| Current | Small | Medium | Large |
| $SO_2$ | 129 | 423 | 1056 |

**Table 17. SO2 Emission Reduction in Tons/Year Using Seawater Scrubbing**

As the data show, the most effective measure for reducing NOx emission is the SCR system, followed by the fumigation or humid air motor and direct water injection. The exhaust gas recirculation approach reduces NOx as well as SOx and PM when low sulfur marine diesel fuel is used. The use of marine diesel fuel with 0.5% sulfur content is an effective approach in reducing SOx and PM emissions. Regulations proposed by CARB (2006) could reduce SOx and PM emissions in California from OGVs and goods movements by nearly 80% by the year 2020.

Assessment of these measures involves cost effectiveness which is defined as the cost associated with each ton of emissions removed annually. The following tables show the cost effectiveness of these measures based on the data of Tables 18 and 19. For table 19, the estimated cost effectiveness outside the parentheses are based on the 2003 fuel cost estimates from Beicip-Franlab consulting company and those in the parentheses are based on the fuel cost from the same period, calculated from the conservation of clean air and water in Europe (CONCAWE) organization.

| Measure | Ship type | Emission | Small Vessel | Medium Vessel | Large Vessel |
|---|---|---|---|---|---|
| | | | $/ ton | $/ ton | $/ ton |
| Basic IEM (2 stroke slow speed only) | New | NOx | $10.84 | $8.13 | $8.13 |
| Basic IEM (2 stroke slow speed only), young engines | Retrofit | NOx | $10.84 | $8.13 | $8.13 |
| Basic IEM (2 stroke slow speed only), older engines | Retrofit | NOx | $54.21 | $21.68 | $13.55 |
| Advanced IEM | New | NOx | $88.54 | $29.81 | $17.17 |
| Direct water injection | New | NOx | $371.31 | $325.23 | $311.68 |
| Humid air motors | New | NOx | $242.12 | $207.79 | $178.88 |
| Humid air motors | Retrofit | NOx | $276.45 | $254.77 | $237.60 |
| SCR outside $SO_2$ ECA | New | NOx | $668.53 | $508.63 | $475.20 |
| SCR outside $SO_2$ ECA | Retrofit | NOx | $730.87 | $552.90 | $515.86 |
| SCR inside $SO_2$ ECA | New | NOx | $490.56 | $383.05 | $359.56 |
| SCR inside $SO_2$ ECA | Retrofit | NOx | $553.80 | $427.32 | $400.22 |
| SCR, Ships using MD | New | NOx | $373.11 | $299.94 | $282.77 |
| SCR, Ships using MD | Retrofit | NOx | $436.35 | $344.20 | $323.43 |

**Table 18. Cost Effectiveness of Different Measures for Removing NOx**

| Measure | New/ Retrofit | Emission | Small Vessel | Medium Vessel | Large Vessel |
|---|---|---|---|---|---|
| | | | $/ ton | $/ ton | $/ ton |
| Sea water scrubbing | New | $SO_2$ | $352.34 | $317.10 | $289.10 |
| Sea water scrubbing | Retrofit | $SO_2$ | $520.37 | $483.33 | $455.33 |
| Fuel switching: 2.7% S fuel to 1.5% S fuel | New | $SO_2$ | $1,854.73 ($1,111.21) | $1,852.02 ($1,111.21) | $1,847.50 ($1,111.21) |
| Fuel switching: 2.7% S fuel to 1.5% S fuel | Retrofit | $SO_2$ | $1,854.73 ($1,111.21) | $1,852.02 ($1,111.21) | $1,847.50 ($1,111.21) |
| Fuel switching: 2.7% S fuel to 0.5% S fuel | New | $SO_2$ | $1,300.03 ($1,526.79) | $1,299.12 ($1,526.79) | $1,295.51 ($1,526.79) |
| Fuel switching: 2.7% S fuel to 0.5% S fuel | Retrofit | $SO_2$ | $1,300.03 ($1,526.79) | $1,299.12 ($1,526.79) | $1,295.51 ($1,526.79) |

**Table 19. Cost Effectiveness for New and Retrofit Engines with Seawater Scrubbing System and Fuel Switching**

While the SCR approach is the most effective measure for removing NOx emissions, it is among the costliest. The most balanced approach seems to be the fumigation or humid air motor, followed by the direct water injection method.

For SOx and PM reductions, the fuel switching and scrubbing approaches are considered. Table 19 shows the cost effectiveness for these measures for new and retrofit engines and for switching fuel from 2.7% to 1.5% and 0.5% sulfur fuels. As expected, due to the current high cost of low sulfur fuel, the cost effectiveness of the fuel switching is is improved relative to the other measures. The scrubbing cost effectiveness is in line with the corresponding values for other measures for both new and retrofit engines.

The present cost of fuel switching may prevent ship operators from switching to low or ultra low sulfur fuels for their entire journey. However, requiring usage of low sulfur fuel by marine vessels within the 24 nautical miles offshore is an effective and viable option for reducing SOx and PM emissions near the coastal areas.

# 6 APPENDIX

## 6.1 Companies Providing Water Injection Systems

### Seaworthy System, Inc.

Seaworthy Systems, Inc. is a major manufacturer of the Un-Stabilized emulsion systems. The estimated reduction in NOx and PM emissions for their system on ocean going vessels are 20-25 percent and 50 percent respectively. Figure 16 shows their water-in-fuel homogenization emulsification system.

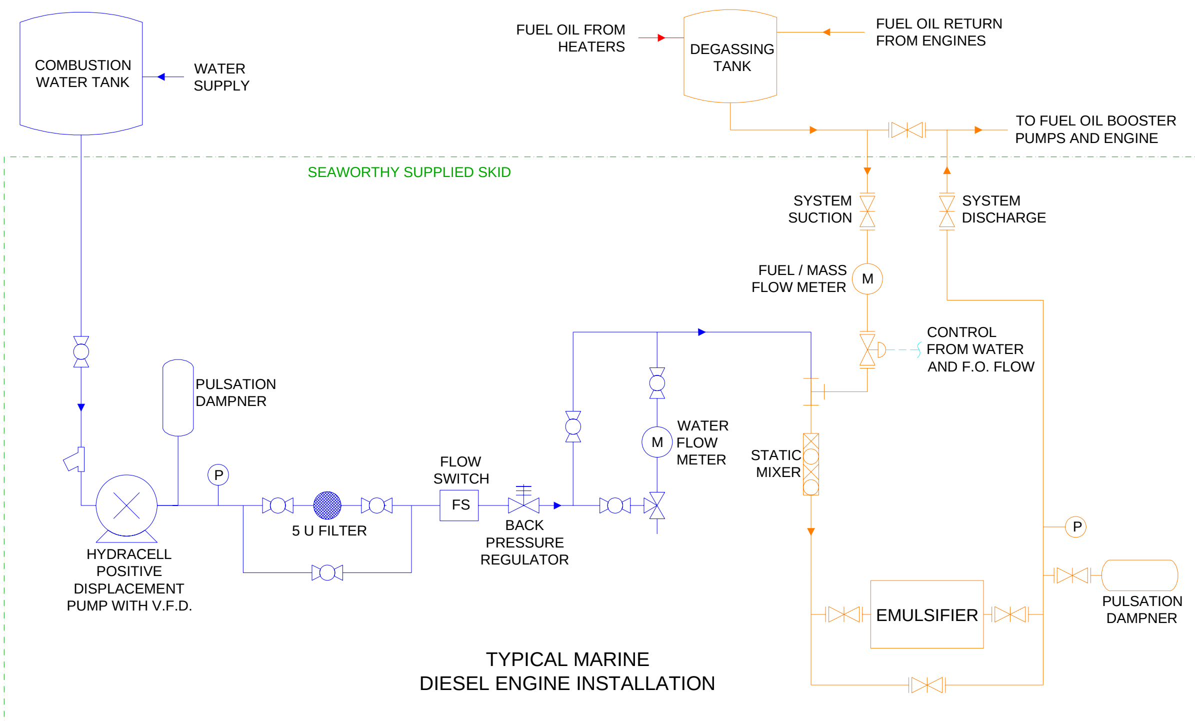



**Figure 16. Seaworthy Water-In-Fuel Homogenization Emulsification System**

The water-in fuel system comprises of an oil pump and integral homogenizer valve, a static mixer, a positive displacement water pump with VFD flow control, and a PLC-based control.

Effective water-in-fuel homogenization takes place at high pressure. Figure 17 shows the effect of different pumping pressure on the homogenization process.

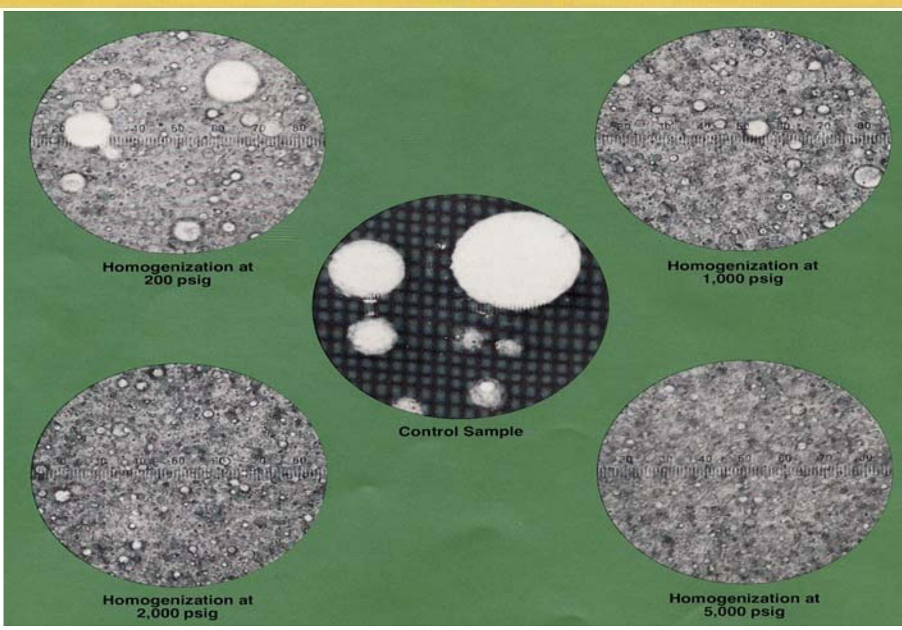



**Figure 17. Water-In-Fuel Homogenization at Different Pumping Pressure**

Their field test data on a two-stroke low speed engine shows the potential of the emulsification for reducing NOx reduction. Figure 18 shows their comparison field test results.

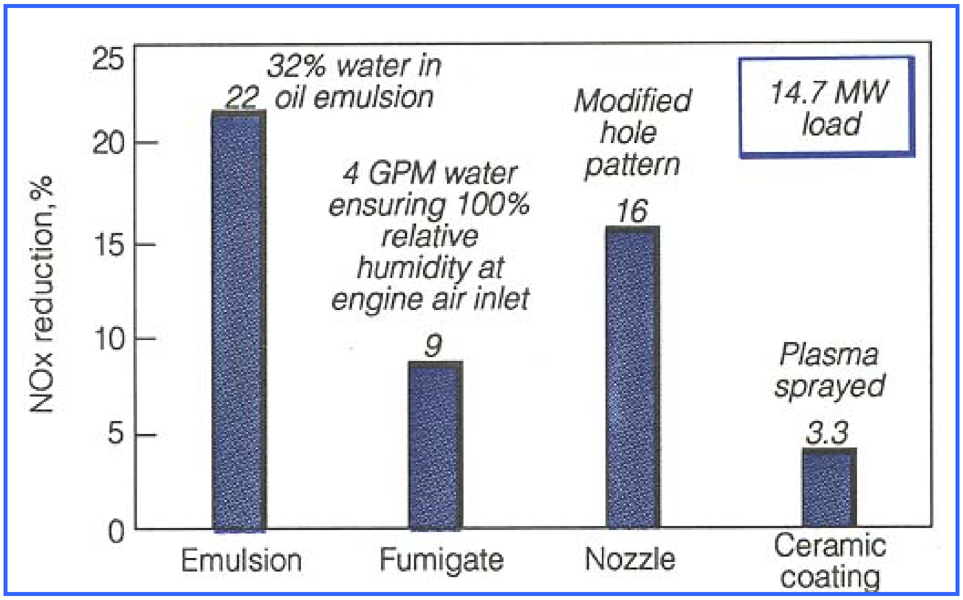



**Figure 18. Field Test Results for Different NOx Reduction Approaches**

As the results show the highest de-NOx method among these measures is the emulsion system.

### Lubrizol Corporation

A major manufacturer of the Stabilized emulsion system is Lubrizol Corporation with its system PuriNox, which can supply up to 20 million liters of emulsified fuel per year.

### MAN B & W

MAN B&W achieved 10 percent NOx reduction with a 10 percent water emulsified fuel for their two-stroke engine. In addition, their test results indicate significant reduction in NOx emission with emulsified fuel of 15-20 percent water content and retarded injection timing for engine loads below 80 percent.

### Caterpillar Diesel

Application of emulsified fuel with 10-30 percent water content to the Caterpillar diesel engines has resulted in significant reduction in NOx and soot emission with the highest reduction obtained for the fuel with 30 percent water content.

### Wärtsilä

Wärtsilä Corporation is a major supplier of ship machinery, propulsion and maneuvering solutions for all types of marine vessels and offshore applications. It claims its engines have the lowest emission levels in the market which is especially important for cruise ferries operating in environmentally sensitive areas or spending a lot of time in port close to densely populated areas.

Wärtsilä has used orimulsion instead of heavy fuel oils in their marine engine and obtained 30 percent reduction in NOx emission. Orimulsion is a mixture of bitumen and fresh water with small amount of surfactant. It has similar behavior as the fuel oil. Wärtsilä has two emerging fumigation systems: steam injected diesel (STID) and combustion air saturation system (CASS) which both operate based on the fumigation process. In STID, the combustion air and low-pressure steam are mixed before being injected into the combustion chamber. This results in higher oxidation and reduced soot formation. In CASS system, high-pressure water is injected directly into high-pressure heated air from a turbocharger, before being injected into the combustion chamber. The estimated NOx reductions for these systems are 25 percent and 50-60 percent respectively.

**Pielstick**

Pielstick is a French based company and a major manufacturer of fumigation system. The system uses seawater and is designed for four-stroke marine engines.

6.2 Companies Providing SCR Systems

**Clean Diesel Technologies**

The Clean Diesel Technologies is involved in designing and manufacturing diesel engine emission control systems for passenger cars, heavy-duty engines and stationary engines with focus on both NOx and particulate matter reduction. They have patented technologies, which are distributed through licensed suppliers for OME and retrofit markets. They are involved in the following technologies:

1. Selective Catalytic Reduction
2. Exhaust Gas Recirculation
3. Diesel Particulate Filters
4. Fuel Borne Catalysts

The SCR system injects a single fluid (assumed aqueous solution of urea) in the exhaust gas stream. The injector, ARIS, is a patented technology that claims to have the following advantages:

1. Precise control over urea dosage.
2. Better atomization for better ammonia dispersion.
3. Reduced ammonia slippage.
4. Better suited for retrofitting
5. Elimination of urea freezing, urea crystallization and nozzle fouling due to flow design.
6. Low cost due to reduced components due to elimination of air requirements for the cooling of the system.

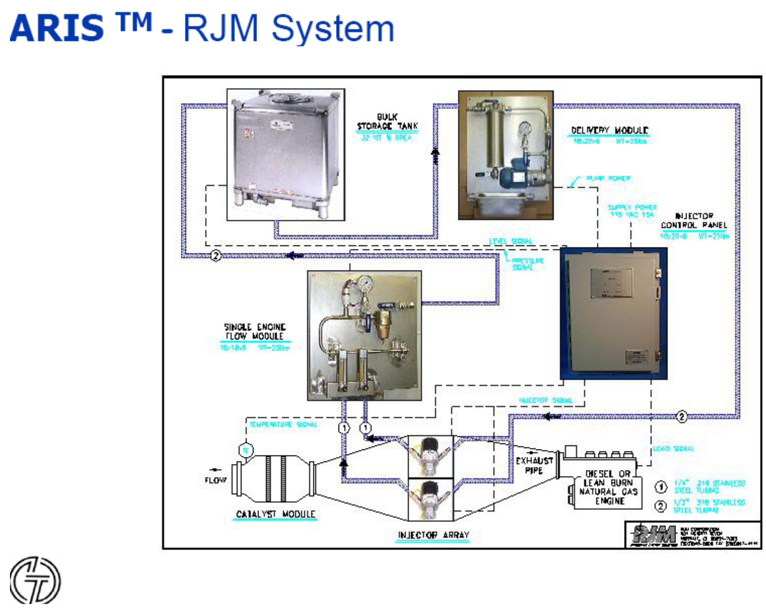



**Figure 19. The SCR injection system ARIS**

The system consists of the following components:

1. Storage tank: It holds the aqueous urea solution.
2. Delivery Module: The main component of the delivery module is the pump, which provides the motive force for the transfer of the fluid from the storage tank to the injector array.
3. Injector Control Panel: It is the heart of the entire system. It gets feedback from the engine regarding the load conditions, feedback from the catalytic converter regarding the temperature of the exhaust gases and regulates the pump of the delivery module.
4. Single Engine Flow module: This helps to maintain precise dosage of the solution into the exhaust gases by rerouting the excess fluid back to the storage tank.

At typical exhaust temperatures of 320-500°C, NOx reduction is between 70 percent and 90 percent.

**Argillon**

Argillon is a German based company that is involved in design and manufacturing of SCR system SINOx solutions for diesel emission controls, Ceramics, Insulators, Piezo Products and Alumina. Outside Germany, It has offices in Poland, USA and Malaysia. Argillon provides SINOx solutions for the following applications:

1. Steam and gas turbine power plants
2. Automotive Applications
3. Heavy fuel- oil fired engines and boilers
4. Marine applications
5. Stationary diesel and gas engines
6. Wood fired boilers
7. Waste incineration plants

## Approach and Components Used

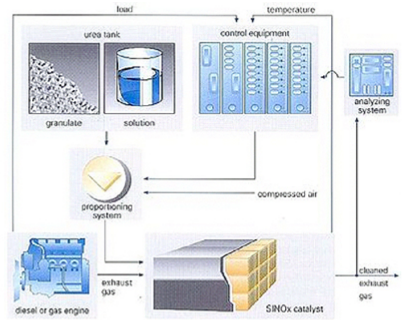



**Figure 20. Schematic representation of the SCR system (Argillon)**

Their SCR system has the following components:

1. Urea tank: Here the urea is mixed to generate the required strength of the aqueous solution.
2. Proportioning system: This decides the dosing of the aqueous solution to the exhaust gases. It is controlled via the SINOX catalyst. There are two main types of catalysts, the plate type and the honeycomb type. The plate type catalyst consists of a stainless steel carrier and a catalyst ($TiO_2$, Molybdenum or Tungsten oxide and Vanadium oxide). The honeycomb catalyst consists of purely catalytic material ($TiO_2$, Molybdenum or Tungsten oxide and Vanadium oxide). The choice of catalyst depends on the exhaust temperature and the particulate matter in the exhaust.
3. Air compression unit: It provides compressed air, which disperses the urea solution into the exhaust stream.
4. Analyzing and controlling system: The controlling system takes feedback from the engine (load conditions), exhausts gases (temperature) and decides the dosing required. The analyzing system provides feedback regarding the condition of the treated exhaust gases (i.e. monitoring ammonia slip).

The systems are rated to reduce NOx emissions by 95 percent.

## Tehag Diesel Emissions Management

This is a Switzerland based company that provides technologies to manage diesel emissions. It has a partner in the USA, Kaparta, Inc., that manufactures SCRs for exhaust gases from stationary and mobile diesel engines.

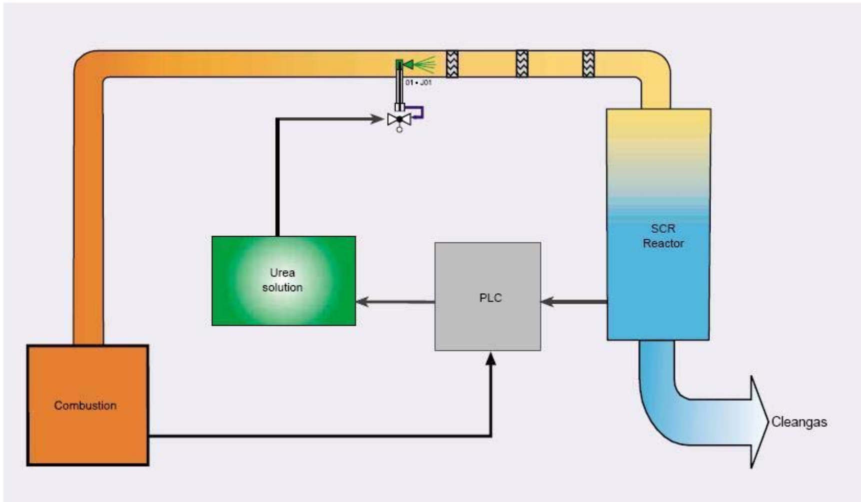



**Figure 21. Schematic representation of the SCR system. (Kaparta Inc.)**

As it can be seen in Figure 21, the Kaparta SCR system has the following components:

1. Storage tank: It is used to hold the aqueous urea solution.
2. Urea injector: This sprays the urea solution into the exhaust stream.
3. SCR reactor: The following picture shows the reactor. It holds three types of honeycomb- monolith shaped elements. The first type consists of is ceramic-based elements, which are either coated with, or has vanadium pentoxide bonded to it. The first stage removes the NOx components from the exhaust stream. The second stage consists of similar elements, which converts dioxins to hydrochloric acid. The third type of catalyst is made of clay and coated with precious metals that convert carbon monoxide and hydrocarbons to carbon dioxide and water vapor.

**Figure 22. SCR Reactor**

4. PLC Cabinet: This system gets the feedback regarding the load conditions from the engines and accordingly controls the dosing of the urea solution. The company claims to be able to use this system for retro- fitting old engines with minimum down time.

The system is claimed to have the capacity to reduce the NOx by 90 percent.

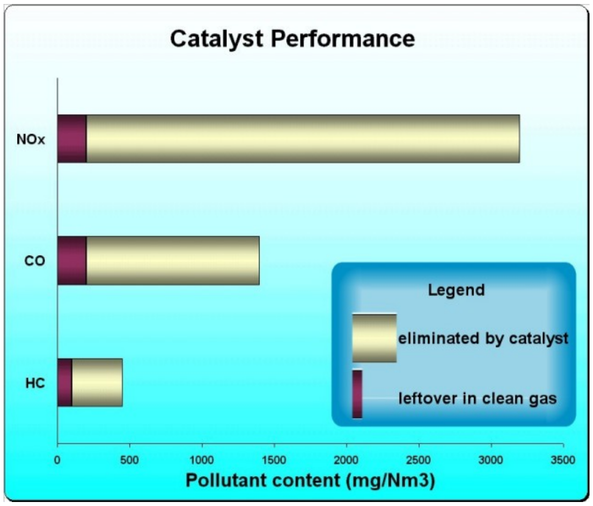



**Figure 23. Catalyst performance chart for SCR system (Kaparta, Inc)**

## Engelhard Corporation

Engelhard Corporation is involved in many facets of chemical engineering, from pigments to catalysts. They were recently bought by BASF and the businesses of BASF and Engelhard Corporation make up the Catalyst division of BASF. The SCR system designed and manufactured by BASF Catalyst is used for emission controls from vehicular diesel engines.

Their SCR system has similar components as others such as SCR catalyst, urea storage tank, urea pump, urea dosing system, urea injector/nozzle, and a control unit. This system uses Adblue, a 32.5 percent aqueous urea solution, also called AUS 32. In addition, the company also provides an integrated catalyst to avoid ammonia slip. The catalyst which is ceramic honeycombs with precious metal loading at about 5 g/ft$^3$ converts $NH_3$ to $N_2$ according to the following equation (Hunnekes et al (2006))

$$4NH_3 + 3\,O_2 \rightarrow 2\,N_2 + 6\,H_2O$$

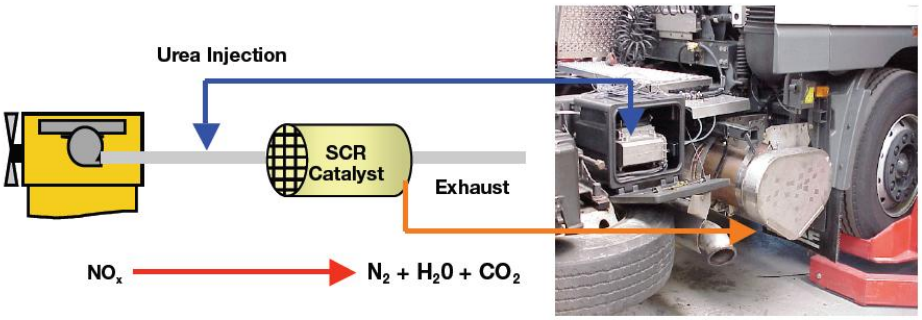



**Figure 24. SCR system attached to a mobile diesel engine (BASF)**

Nitrogen oxides in exhaust gases can be reduced by more than 80 percent. Trucks equipped with this technology can require up to 5 percent less fuel.

**Johnson Matthey Catalytic Systems Division**

This company has a worldwide presence in the field of catalyst, precious metals and fine chemicals. The catalytic division consists of Environmental Catalysts and Technologies, Process Catalysts and Technologies and the Fuel Cell sub-divisions. The SCR technology is applied in stationary industry for prime or back-up power, gas turbines and refinery heaters. It can also be used to retrofit truck engines.

The SCR system (Figure 25) is used in conjunction with the Continuously Regenerating Trap (CRT) Filter developed by Johnson Matthey. The CRT takes care of the particulate matter in the exhaust. Urea injection is air-assisted. The catalyst technology is either ceramic monolith substrates or metal based, depending on the allowable pressure drop across the catalytic chamber and cell densities required for maximum catalytic activity. The SCRT uses a commercially available urea injector and a Johnson Matthey- developed dosing system to accurately meter the amount of urea injected into the exhaust stream and hence eliminate any ammonia slip.

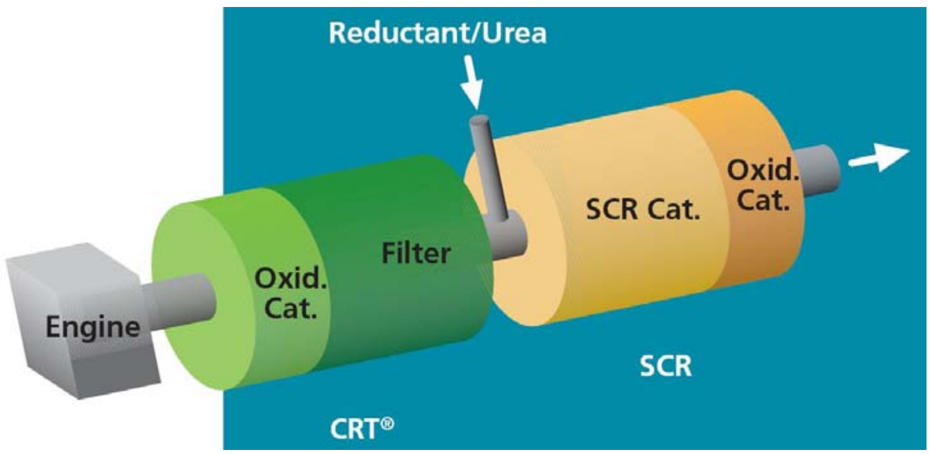



**Figure 25. Schematic representation of SCR technology (Johnson Matthey)**

As displayed in Figure 26, the system is expected to reduce Particulate Matter, Hydrocarbons and Carbon monoxide by over 90 percent and NOx by 70-90 percent.

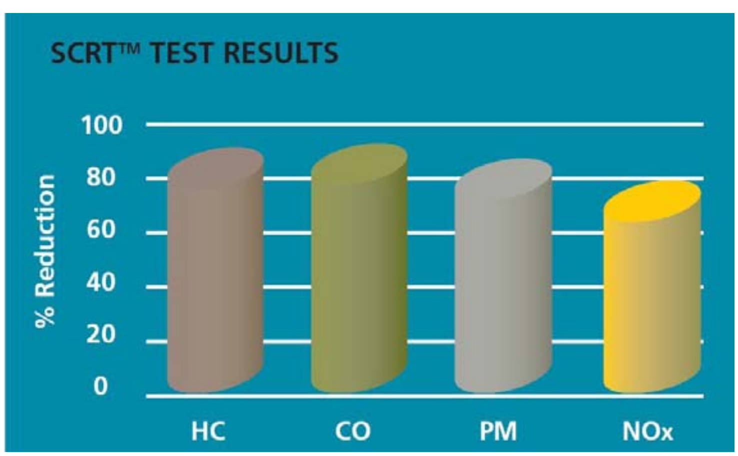



**Figure 26. SCRT performance (Johnson Matthey)**

**Babcock Power Environmental Inc.**

The company installs SCR systems that are used for the cleaning of flue gases in boilers. They are licensed to sell the Delta Wing Mixing Technology developed by Balcke Dürr GmbH.

The Delta Wing Mixing Technology (Figure 27) aims to develop vortices in the flow of the exhaust gases, which allows for an even distribution of oxygen, dust, ammonia, $SO_3$ and temperature through out the exhaust stream. These vortices consistently form in relation to the mixing device size, position, and orientation in the ductwork system. The vortices are not dependent on gas flow quantity and therefore will consistently form over a wide range of gas flows and boiler outlet conditions which eliminate the need to tune the SCR according to the load conditions and also minimize ammonia slip and the down time once retrofitting is done. Babcock Power Environmental has set up SCR systems that use anhydrous and aqueous ammonia and urea as the reductant. A typical SCR system includes reactors, all associated support steel, ductwork, isolation/bypass dampers, expansion joints, access/testing provisions, platforms/stairs, initial catalyst charge, fans if required, complete reagent unloading, storage and injection systems (Figure 28).

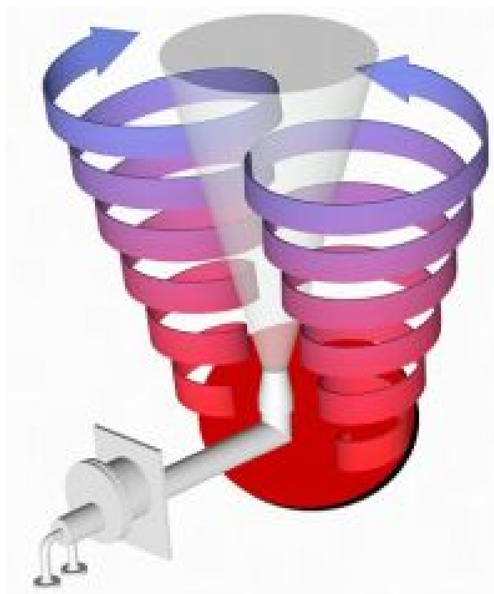


**Figure 27. Vortexes developed by the Delta Wing Mixing Technology**

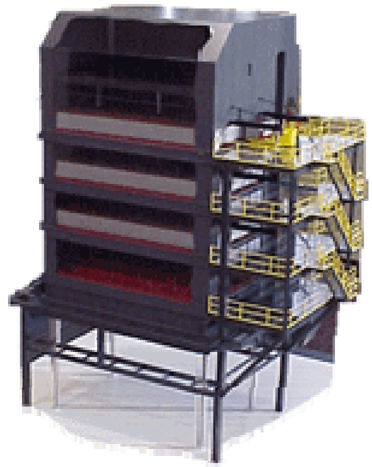


**Figure 28. A typical SCR system (Babcock Power Environmental Inc.)**

## 6.3 Companies Providing Seawater Scrubbing Systems

### Marine Exhaust Solutions (MES) Inc.

A division of the DME International in Canada has spent the past six years in research, development, and commercialization of an exhaust gas scrubbing technology for marine diesel engines. This technology is called the MES EcoSilencer, which utilizes advances in seawater scrubbing to achieve dramatic reductions in $SO_2$ emissions. It replaces the silencer in engine exhaust stack helping to reduce emissions, remove soot, reduce airborne noise and noxious fumes, which would otherwise be released into the atmosphere. The basic principle of operation for the Eco-Silencer relies on hot exhaust gases mixing in a turbulent cascade with seawater whereupon $SO_2$ in the exhaust is transferred to the seawater. The $SO_2$ reduction depends on water temperature and salinity. This new technology ensures that surface area for contact between gas and water is high, and sufficient time for absorption of pollutants is provided. The acidic gases, and particulate removed from the exhaust gas are passed through a water treatment system, which is designed to filter wastes on a continuous basis, and to provide outlet water that is environmentally safe. Recently completed trials have proven EcoSilencer seawater scrubbing system saves millions of dollars in potential low sulphur fuel cost premiums, and provides superior reduction rates for $SO_2$ removal over switching to low sulphur residual fuel. In fact, system trials have been so successful, that the company is prepared to offer a Guarantee of Performance with every installation. Depending on vessel's engine configuration, the EcoSilencer will reduce $SO_2$ exhaust emissions by up to 90 percent - with a performance guarantee that will allow it to burn the maximum 4.5 percent sulphur fuel and still surpass the regulated reduction to 1.5 percent sulphur fuel. It will also eliminate up to 90 percent of the visible PM (50 percent by mass), and 3 to 5 percent of NOx. Besides $SO_2$, NOx and PM removal, the Eco-Silencer also reduces exhaust odor and noise. EcoSilencers are suitable for installation on any engine size from 100 kW to 100,000 kW, easily handling changing engine load and work with any inlet seawater conditions and engine loading. Equipment operates over a range of insertion backpressure less than 100 mm $H_2O$. The EcoScilencer system has been designed for both commercial and yacht diesel engines. Specially designed for yacht diesel engines, the Super Yacht version of commercial EcoSilencer system provides superior performance in noise reduction; soot abatement, diesel smell, and oily water exhaust sheen. Particularly useful for dry stack applications the EcoSilencer allows the owner to run his auxiliary genset quietly, cleanly and continuously. At the same time the EcoSilencer replaces both wet and dry silencers in the engine room and the cool exhaust gas allows builders and designers space and flexibility in their dry stack design. Below is a schematic figure of the MES EcoSilencer.

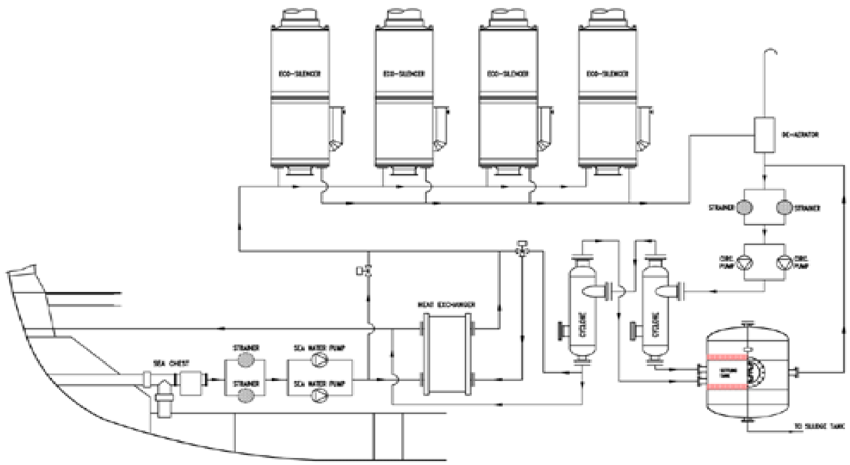


**Figure 29. MES EcoSilencer**

MES provides custom installations of their system to different applications.


**Figure 30. Before and after comparison for MES Super Yacht EcoSilencer**

The following table (Table 20) provides claimed pollution reduction for this system.

| Features | Performance |
|---|---|
| Soot removal | Up to 80 percent |
| Diesel smell | Dramatic reduction |
| Noise attenuation | 35 dB |
| NOx removal | Up to 7 percent |
| $SO_2$ removal | Up to 90 percent |
| Back pressure | 7-15 mBar |
| Construction | Nickel alloy |
| Engine Size | 80-3500 kW |
| Fuel Type | All fuels |

**Table 20. Pollution Reduction for MES Super Yacht EcoSilencer System**

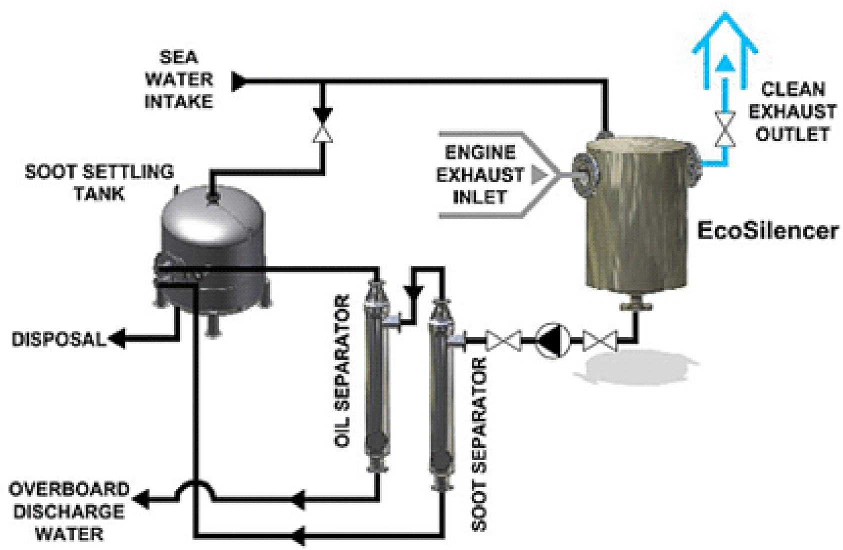
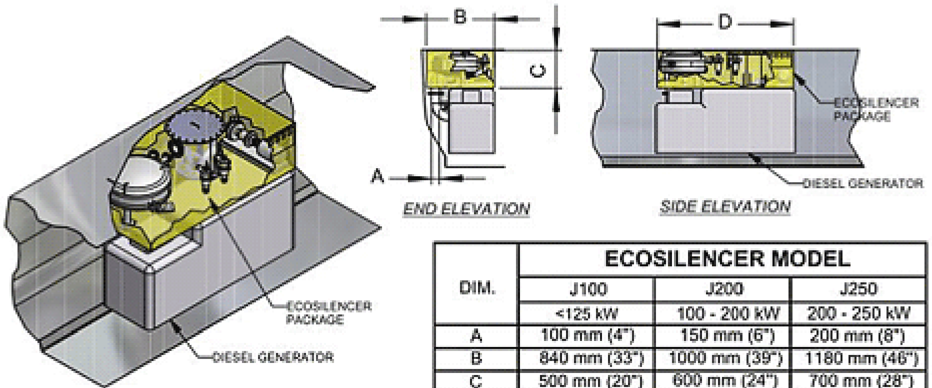



**Figure 31. The system - with soot removal and water treatment**

Containerized System for Compact Installation

Installations can be customized to meet the owners' needs.




| DIM. | ECOSILENCER MODEL | | |
|---|---|---|---|
| | J100 | J200 | J250 |
| | <125 kW | 100 - 200 kW | 200 - 250 kW |
| A | 100 mm (4") | 150 mm (6") | 200 mm (8") |
| B | 840 mm (33") | 1000 mm (39") | 1180 mm (46") |
| C | 500 mm (20") | 600 mm (24") | 700 mm (28") |
| D | 2400mm (94") | 2400mm (94") | 2400mm (94") |

**Figure 32. Containerized system for compact installation**

The latest trial of this system was performed onboard P&O line's passenger ferry, Pride of Kent, during autumn 2004. The trial comprised of four EcoScilencers on four 1.2 MW auxiliary engines. The trial lasted over 16 months during which the auxiliary engines were operational for approximately 11,680 hours.

Operating with a 2.5 percent sulphur fuel, $SO_2$ reduction rates of 68-94 percent have been achieved. By operating the system within the existing design parameters removal rates of 75 percent to 80 percent have been sustained. It is also worth noting that MES (2004) expected that with improved scrubber design, the EcoSilencer® will be able to sustain around 90 percent reduction in $SO_2$ emissions. A reduction efficiency rate of 75 percent was assumed in this study.

These tests were undertaken on 2.5 percent sulphur fuel, and are therefore likely to have shown a slightly higher $SO_2$ removal rate for engines using 2.7 percent sulphur fuel, the assumed baseline average for residual oil in this study. However since there is no data available for scrubbing efficiencies for engines using 2.7 percent sulphur, the scrubber efficiencies for 2.5 percent sulphur fuel were assumed. Measurements of NOx reductions recorded very low NOx removal rates. Therefore it is assumed that NOx removal is likely to be insignificant. VOC emission reductions were not measured. Since the EcoSilencer® scrubs the exhaust, it is likely to be able to remove PM, however this was not measured during the trial. A mass balance approach was used to estimate PM reduction experienced on the Pride of Kent.

For one engine running at 65 percent load, MES measured sludge production from the Pride of Kent as 0.2 g/kWh. Particles suspended in overboard water were measured as 450 to 790 mg/L. Using the average value of 620 mg/L, a water outflow of 60 t/h per unit, the amount of particles contained in the overboard water are equivalent to 0.05 g/kWh. Total particles removed were therefore up to 0.25 g/kWh.

Based on a PM emission factor of 0.8 g/kWh in the exhaust for the type of auxiliary engine used in MES's trials, the PM removal rate by the EcoSilencer® can be estimated at around 31 percent. However, this calculation assumed that all the sludge consists of particulates, and that the suspended solids in the scrubber inflow are negligible. Therefore particulate removal may be less, and a conservative estimate of 25 percent is used in this study.

The following pictures show the sludge tank, scrubber dover and the POK funnel for the ship "Pride of Kent".

**Figure 33. The Sludge Tank**

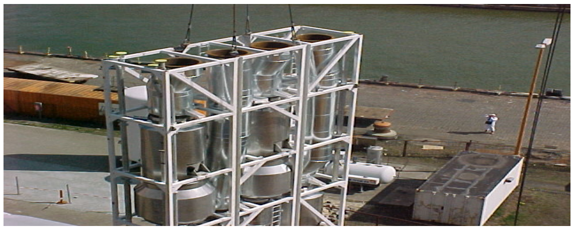


**Figure 34. The Scrubber Dover**

**Figure 35. The POK funnel**

## Krystallon

A supplier of on-board emissions control solutions to the marine industry is a BP Group Company and a joint venture between BP Marine and Kittiwake Developments Ltd. Krystallon's patented scrubbing technology combines different scrubbing techniques to produce a system with minimum weight, back pressure and physical size. The Krystallon Seawater Scrubber uses three key seawater scrubbing system components:

1. Exhaust Gas Scrubbing Technology –Alpha
2. Wash Water Treatment Technology -Beta

3. Continuous Monitoring Technology-Gamma

This system is suitable for installation within the funnel space on a typical ferry or cargo ship, with the water system fitted low in the engine room. This reduces installation cost and saves time, taking advantage of the existing space in this area. Weight is thus reduced to an absolute minimum with often negligible impact on ship stability. Operating back pressure is similar to existing exhaust gas silencers and within engine manufacturers' limits. It is designed for continuous wet run operation but capable of extended dry running under emergency conditions up to 450°C, and all irreplaceable system components have been designed for 20-25 year lifecycle. The Krystallon system uses seawater as a scrubbing medium to remove pollutants from the exhaust gas before discharge overboard. Beta Technology consists of special pipes, valves, couplings, water cleaning systems and a sludge handling plant to produce a tri-phase high efficiency water cleaning system. Krystallon uses GRE (Glassfibre Reinforced Epoxy) pipes, which unlike standard metal piping will last throughout the lifetime of the vessel due to its highly corrosion resistant epoxy, lightweight strength and low internal friction losses. Krystallon's Wash Water Treatment technology removes both hydrocarbons and particulate matter to extremely low levels prior to discharge overboard. The resulting particulate and oil sludge is then stored for safe on-shore disposal.

Preliminary test results from trial shipboard scrubbing installations have shown removal efficiency in excess of 95 percent for all contaminants sized above 0.003mm. Compared to un-scrubbed emissions systems where all particulates are freely discharged, this is a resounding environmental success for Krystallon. Krystallon emissions monitoring technology covers the monitoring of the sea water scrubber and discharges to the air and sea. The pollutants monitored for environmental air qualities are $SO_2$, NO, $NO_2$, $CO_2$ and water. Krystallon's continuous emissions monitoring technology is based on monitoring systems developed for large industrial plants such as refineries or power stations. The technology has been modified to suit the unique pressure and corrosion requirements of a shipboard environment yet retains the ability to measure dissolved hydrocarbons at part per billion (ppb) levels. In summary Krystallon's approach to pollution abatement technology is designed to achieve the following high standards and levels of reliability:

1. 100 percent sulphur removal
2. Over 80 percent particulate removal from the exhaust
3. Full instrumentation to monitor both scrubbing efficiency and water discharge quality
4. Provides compliance with current SECAs and addresses pending legislative changes
5. Meets EU requirements for 0.1 percent sulphur fuel for all vessels at berth in the EU from 1st January 2010
6. Exceeds existing and expected environmental criteria for air and water discharge quality
7. Performs all of the above, reliably over a 20-25 year life cycle

The following is the schematic of the Krystallon Exhaust Scrubbing System.

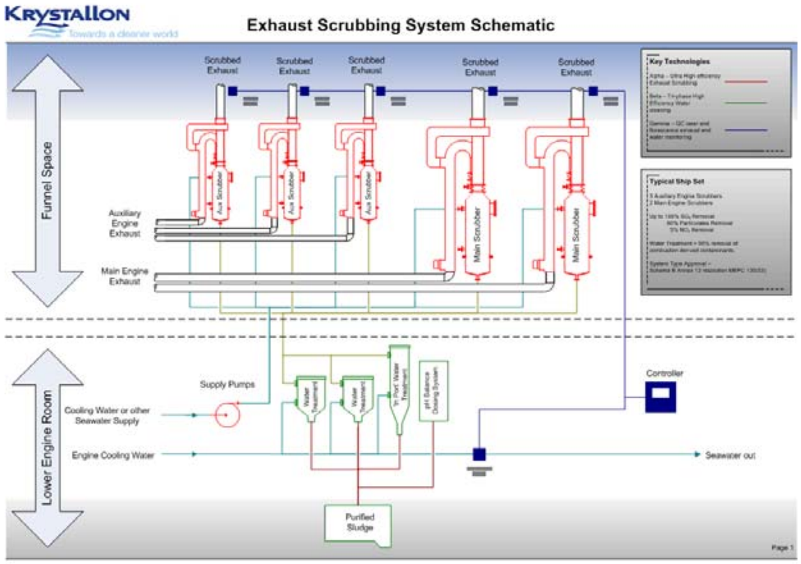



**Figure 36. Schematic of the Krystallon Exhaust Scrubbing System**

## Branch Environmental Corporation

They manufacture air pollution control equipment including scrubbers, thermal/catalytic oxidizers, air stripper, selective catalytic reduction systems, and other special systems. Their scrubber systems include

**Figure 37. Packed Towers (Top Left), Venturi Scrubbers (Top Right) and Jet Venturi Scrubbers (Bottom Left)**

1. Packed Towers: These scrubbers are primarily used for gas absorption, and provided in two configurations, cross-flow design for limited space and counter-flow design for greater efficiency. With standard capacity of up to 61,000 cfm (105,000 $m^3$/hr), these scrubbers provide the highest contact and greatest gas absorption capacity. By increasing the contact bed depth, higher and higher efficiencies can be achieved.
2. Venturi Scrubbers: These systems are used for applications involving either particulate removal from air or vent gases, or for both simultaneous dust and gas removal. The open and co-current design can handle insoluble solids without difficulty. Standard designs can handle flows up to 80,000 cfm (136,000 $m^3$/hr). Field erected units are capable of handling larger flows.
3. Jet Venturi Scrubbers: These scrubbers utilize the energy from the liquid sprayed under pressure to move the air, scrub the gas and remove dust, and are particularly suited for cases with high concentration of chemicals present in the gas, and for systems with varied gas flow. Since the water is pumped under pressure into the system with a high flow rate, variations in gas flow have very little impact on performance. The standard design has a capacity of 60,000 cfm (102,000 $m^3$/hr).

**Bionomic Industries**

They are a US manufacturer of scrubbing equipment, "prepackaged" skid-mounted scrubber systems, HEI (High Energy Ionizer) wet electrostatic and dry collection systems for a wide range of air pollution control, abatement and product recovery applications. Their products include:

1. ScrubPac VentClean System designed to scrub storage tank and railcar vent emissions caused by breathing and filling operations. This system is available in three model sizes M, L, and H to handle gas capacities from 0 to 800 cfm, and is available in two configurations. Type 1 uses water on a once-through basis, and type 2 uses water at a reduced consumption rate, or a chemical reagent such as sodium hydroxide on a recirculated batch basis. Typical applications include removing acids, alcohols, formaldehyde, amines, and almost any water-soluble contaminant.
2. ScrubPac ProClean Type CT Tower Scrubber System designed to remove water soluble gaseous contaminants at efficiencies needed to meet the EPA and state pollution control requirements. This system is available in two configurations to handle gas streams from 500 to 2500 cfm.
3. ScrubPac Custom Packaged Scrubber Systems range in size from 100 acfm to 50,000 acfm, and designed to remove, recover, and reconcentrate VOCs, NOx, Hydrogen sulfide and sulfur compounds, acids, ammonia, halogens and amines, and gaseous phase generated submicron particulate
4. BIONOxSOLVE NOx Scrubbing Solution is designed to be used as a direct chemical reagent replacement for existing NOx scrubbing systems. Its applications for removal of nitrogen dioxide emissions include catalyst calcining and preparation, precious metals dissolving, acid dipping and pickling of metals, semiconductor wafer and circuit board etching, nitrite and

nitrate chemical production, medicinal production, nitric acid storage and purging of soluble nitrogen oxide gases.

5. HEI (High Energy Ionizer) Wet Electrostatic Precipitator System (WESP) designed for low energy collection of fine or submicron particles in gas streams. Depending upon the particular contaminant properties and gas stream contents, the HEI WESP System can be configured in either a gas upflow or downflow configuration.
6. RotaBed Fluidized Bed Scrubber System designed to provide ultra high efficiency gas absorption or particulate removal, and is available in standard models from 130-122,900 acfm and larger sizes on a custom basis. The typical applications of this system include gaseous and particulate contaminant removal from processing operations in the chemical, pharmaceutical, pulp & paper, semiconductor, fertilizer, minerals, petroleum, and food industries, acid gas removal from high temperature thermal oxidizers, chlorine dioxide and sulfur dioxide removal in pulp and paper bleach plants, acid and alkali fume removal from pickling, galvanizing, and cleaning lines including HCL regeneration plants in the metals industry, odor control and VOC removal from process and waste treatment operations, and flue gas desulfurization at power generation facilities.
7. Counter-Current Packed Tower System designed to remove gaseous contaminants with efficiencies over 99.9% at low pressure drop, and are available for gas flow rates from 100 to 300,000 acfm. Typical applications include scrubbing and removal of gaseous contaminants, corrosive vapors, unwanted mists, and odor control, and direct condensation and gas subcooling.
8. Crossflow Scrubber System designed for gas flow rates from 1,000 to 50,000 acfm, to provide high removal efficiency on gaseous contaminants at low pressure drop. This system features a compact design for situations where building codes limit height of rooftop structures or lower absorption efficiencies are acceptable. Typical applications include scrubbing and removal of corrosive vapors and unwanted mists when a low height profile scrubber is desirable.
9. Tray Scrubber Systems designed to achieve high efficiency gas absorption with extremely low liquid throughput, and are available for gas flow rates from 1000 to 150,000 acfm. Typical applications include gas scrubbing where it is desirable for the scrubbing liquid to be fed on a once-through basis without recirculation. Ideal for removal of water soluble VOC compounds and reconcentration of acid gases and ammonia in solution, and removal of micron-sized solid particulate.
10. Ejector Jet Venture Scrubber System used for low gas flow solid particulate removal and gas absorption conditions. Typical applications include elimination of emissions from process vessels, reactors and storage tank vents, emergency vent scrubbing, and low gas flow solid particulate collection and gas absorption without the need for a fan.
11. Gas Atomized Venturi Scrubber System used for high efficiency collection of solid particulate down to 0.2 microns in size and removal of soluble gases from high temperature sources, scrubbing and removal of solid particulates

from humidified gas streams that can plug fabric filter collectors, and collection of sticky and scale-forming solids.

12. Spray Scrubber System designed to remove solid particulates and gaseous pollutants from chemical and fertilizer operations, to scrub out particulate and gaseous emissions from product dryers, and to control odor.
13. Dry and Dry/Wet Combination Scrubber Systems designed to scrub fine particulates and acid gases emitted from incinerators, furnaces and boilers, and gas phase particulate formations in electronics, chemical and heavy metals industries, and to remove sulfur dioxide and hydrochloric acid

**Komax Systems, Inc**

They manufacture static mixers, steam super heaters and reactors offered to all industries including power generation, waste water treatment, municipal water treatment, pulp and paper manufacturing, oil and gas wells, plastics, chemicals and foods. In the area of power generation, Komax has developed a scrubber/ mixer system for reducing NOx and other emissions from power generation plants. The main application is to mix vaporized ammonia into flue gas prior to a catalyst bed in a SCR to reduce Nitrous Oxide. The Komax design was the first model on a 1:12 scale to test performance. The pressure drop allowed was less than 0.02 bar or 0.7 inches of water with a gas flow rate of 4 million pounds per hour.

**Tri-Mer Corporation**

This company is located in Owosso, Michigan and is a global manufacturer of air pollution control systems for PM10, PM2.5, fine particulate, submicron PM, $SO_2$, NOx, Mercury, acids, fumes, dusts and oil mists. The company's primary focus is wet scrubbing and related equipment to handle particulate and corrosive gases. Its latest design is the Cloud Chamber Scrubber (CCS) for simultaneous removal of PM 10, PM2.5, submicron particulate, stationary diesel emissions, and soluble gases. The CCS removes particulates down to 0.1 micron with very high efficiency, while also treating ultra fine particulate and condensable below 0.1 micron. It offers performance superior to high-energy venturis, and electrostatic precipitators while effectively treating gases. Tri-Mer other major products include the Tri-NOX Multi-Chem System, a unique NOX destruct system, Vertical Flow Packed Bed Systems (Gas Scrubbers) for the prevention and efficient removal of inorganic gases, odors, and vapor fumes, Mercury Emission Scrubbers, Chrome Scrubbers, and Dust and Oil Mist Collectors. The company has a dozen additional lines of equipment and also provides system integration with equipment provided by others, such as cyclones and SCR.

Reviews of other companies involved in development of various forms of the scrubbing systems are given below. These technologies are used mainly for air pollution control and air cleaning processes.

6.4 Companies Providing Scrubbing Technology

**Duall Division, Met Pro Corporation**

They manufacture air and water quality control systems for the treatment of odors, corrosive fumes and toxic gas in industrial and municipal applications. Their major scrubbing products include AroBIOS Bios srubbers, Hexmaster dry scrubbers; fume and emergency gas scrubbers; BetaNox wet scrubbers; HydroLance wet dust collectors and particulate control systems; and odor control scrubbers.

**Kimre, Inc.**

They manufacture air pollution control systems. Kimre's main manufacturing plant is located in Miami, Florida, but its products are distributed not only in the United States but also in Europe and Asia. The company has developed a high performance interlaced mesh structure technology to be used for fluid separation and air pollution control. Based on this technology, Kimre, Inc. offers a range of products to remove solid and liquid particles below one micron while draining large volumes of liquid. Its scrubber and tower packing system is called NON-TANE, a structured, interlaced monofilament material, designed to facilitate breakup of the liquid phase, creating maximum surface area for mass transfer with the vapor phase. KON-TANE tower packing is manufactured in stackable, layered pads up to six inches (150mm) in depth. They are fabricated to fit any vessel in easily installed modules. High liquid to gas ratio, one-piece construction, easy installation, uniform volume and flow, exceptional transfer in cross-flow scrubbers, and improved transfer in vertical towers are some of the features and benefits of Kimre KON-TANE tower packing system.

**Advanced Industrial Technology Corporation**

They manufacture high performance gas scrubbers to meet a wide range of gas scrubbing needs. The company line of products includes High Energy Venturi Scrubbers and Horizontal Venturi Scrubbers for removal of smoke, fumes, submicron particulates, and dust, Jet Venturi Scrubbers for removal of particulates 0.5 microns and up, and obnoxious gases, Spray Cyclonic Scrubbers for removal of particulates over 2 microns with moderate gas absorption capability, HVC Scrubbers, a hybrid between Venturi scrubber and Spray Cyclonic Scrubber in performance characteristics to allow a wider range of application and service conditions, Impingement Tray scrubbers for removal of particulates 1 micron and up with good gas absorption capability, and Packed Bed Scrubbers for gas absorption and cooling.

**Airpol, Inc**

Established in 1968, and located in New Jersey, AirPol, Inc. is a manufacturer of air pollution control systems. The company's products include Absorbers (Spray Towers, Tray Towers, and Packed Beds), Venturi Scrubbers, Cyclonic Scrubbers, Dry and Semi-Dry Scrubbers, Wet Electrostatic Precipitators, and Quenchers. The typical application of Air Pol systems are in pulp and paper industry, and in wood products, incineration, chemical, and pharmaceutical industries.

**Amerex**

They manufacture industrial cyclone and fabric filters, gas and wet scrubbers, and heat recovery and gas cooling equipment applied in a wide range of industries including steel, cement and lime, mining, rock products, manufacturing, governmental steam and power, incineration, pulp and paper, and chemical.

**Wheelabrator Air Pollution Control, Inc.**

They are a member of Siemens Power Generation Group, they design and supply air pollution control technologies applied to industrial and power generating processes. Among the products are wet FGD scrubbers and spray dryer scrubbing systems for removal of $SO_2$ and acid gases from industrial coal-fired boilers, NoxOUT process, a selective non-catalytic reduction, for control of NOx emissions from stationary sources including boilers, furnaces, incinerators and retrofits, and wet electrostatic precipitators for removal of submicron particulates and mists.

**APC Technologies, Inc.**

They are located in Pittsburgh, PA and manufacture GA (Gas Purification) Packed Tower Scrubbers for control a variety of gas-phase contaminants, including acid gases (HCl, HF, SOx), odors, VOCs, and other chemical vapors and aerosols, and Venturi Purification Scrubbers for Control of a Variety of Fine Particulate, Aerosol, and Acid Mist Emissions. Applications for GP systems include aluminum processing, bakeries, biomass furnaces, chemical plants, coating processes, electronics parts manufacture, etching processes, food processing, foundries, incinerators (all types), landfill gas treatment, medical waste incineration, metal fabrication, pharmaceuticals, plating operations, pulp and paper manufacture, rendering, secondary metals, wastewater treatment plants, wood-fired boilers, and wood products manufacture, and for VP systems include acid plants, adhesives & sealants, asphalt plants, blast furnaces, chemical plants, lime kilns, municipal waste combustors, plastics and polymers, resins, roofing materials, rubber parts, and sludge incineration.

**Basic Envirotech Inc.**

They manufacture Boilers and Combustors that use solid waste materials as the primary fuel. The BASIC system uses an all-dry scrubbing filter process to collect non-combustible components from the flue gas stream. The BASIC Dry Acid Gas Scrubber meets the U.S. EPA and Canadian CCME requirements for acid gas emissions, particulate emissions, dioxin emissions, lead, cadmium and mercury emissions from Hospital, Medical and Infectious Waste Incinerators (HMIWI).

**Bay Products, Inc.**

They supply odor control systems. The company designs, and manufactures equipments for the treatment of odorous compounds in air stream. Among the company's products are OdorScrub chemical wet scrubbers. The OdorScrub system comes in both single and dual tower configuration. The dual tower mode allows for higher removal efficiencies and better caustic/bleach usage. The dual tower OdorScrub can also be configured to remove ammonia in the first stage with acid followed by H2S removal in the second stage with caustic/bleach.

**MikroPul**

They manufacture dust control and product recovery systems for industrial applications worldwide, and offer air filtration and dust collection devices for emissions control, gas cleaning, and product recovery. Among its products are wet and dry scrubbers and wet electrostatic precipitators. MikroPul's wet scrubbing systems are offered in five different designs including Mikrovane scrubbers with no moving parts, dynamic scrubbing with integral fan, High efficiency Venturi Scrubber, Multi-Venturi, and Packed Towers.

**Beco Engineering**

They design and supply advanced air pollution control systems, covering the full range of toxic, regulated and nuisance air pollutants. Beco has several wet scrubbing systems including the Smoke-Ring Vortex Scrubber, the Multi-MicroVenturi (MMV) Scrubber, The Venturi Recycle Tray Scrubber, and the Brush-Pack and e-Pack scrubbers. The Smoke-Ring Vortex design generates a series of stable standing vortices, or inverted "Smoke-Rings". Atomized spray droplets are injected into the gas flow and are trapped in the closed-ring rotational flows, creating a series of high-density droplet concentration zones. The "Smoke-Ring" scrubber's principal application is in ultra-low energy particulate scrubbing. Over 4,000,000 ACFM of "Smoke-Ring" scrubber capacity is now in service on fume scrubbing in the fertilizer industry alone. The MMV combines the principles of repeated venturi flow with multiple target impingements. Utilizing a 4-row bank of cylindrical elements separated by connecting partitions, the MMV generates successive micro-venturi flows and impingement stages in gas traversing the array. Injecting water spray upstream of the MMV array yields an effective mass transfer unit or particulate scrubber. The MMV is used for dust removal in the explosives industry and acid gas/particulate removal in the aluminum, steel and chemical industries. The VRT is different from other gas-liquid contact systems in which a two inch W.C. pressure drop generates a directed high liquid recycle flow around the tray without the use of a pump. This type of scrubber is now in service on many waste incinerator flu gas scrubbers, as well as in acid gas and odor removal applications. The e-Pack's ability to tolerate solids has made it suitable to be used in wet scrubbers for dust/mist removal, and "Brush-Pack" is used in packed bed scrubbers for removing fine particulates, including black powder, TNT, detergent powder, lime and foundry dusts and pitch.

**BELCO**

The company is a global manufacturer and supplier of air pollution control equipment and systems. Their products include:

1. EDV wet scrubbing systems. They are used for controlling flue gas particulate and $SO_2$ emissions from FCCUs, refinery incinerators, fired heaters, boilers, and other industrial applications.

2. LABSORB Regenerative $SO_2$ Scrubbing System, a wet scrubbing process for the removal and recovery of $SO_2$ from flue gas and process gas flows at petroleum refineries, metallurgical plants, power generation facilities and industrial plants.
3. NOx control systems including LoTox technology and SCR systems, advanced semi-dry scrubbing systems to remove particulate matter and acid gases from combustion flue gas while capturing mercury, heavy metals, dioxins and furans.

Wet Electrostatic Precipitators for removing acid mists, dust, particulate, metals, and condensable present in process gas streams.

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