

# MARINE POWER PLANT POLLUTANT EMISSIONS

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## ***Abstract***

This paper presents a comparison of toxic chemical emissions comprised in exhaust flows/fluxes of marine thermal engines of different types: diesel, gas and steam turbines (including boilers). Their impact on the environment was studied taking into account the engine type and its function in the ship power system.

**Keywords:** *marine power plan, emission, exhaust gas, diesel engines, gas turbines, steam turbines, boilers*

## **1. Introduction**

A ship differs in many aspects from other means of transport, such as trucks or railway [2]. In addition to transporting different types of goods or passengers, a ship must also contain accommodation and other necessary facilities for the crew. In many cases it must also be able to handle different kinds of cargo in the harbours. In order to make this possible, a ship must be capable of a high degree of selfsufficiency and of handling its own energy supply under very varying conditions. This is why ships are equipped with different types of energy suppliers. These are identified as the main engine, auxiliary engines and the boiler.

The principal sources of marine exhaust emissions are as follows:

- main engine – used for propulsion,
- auxiliary engine – used for the generation of electricity,
- boiler.

The propulsion engines installed in today's ships are of the following types:

- diesel engines
- gas turbines,
- steam turbines.

Steam for turbines is produced by burning fossil fuels. Steam powered vessels are rapidly disappearing from merchant fleets because their specific fuel consumption is approximately 300 g/kWh, which is nearly twice as much as that of a modern diesel engine.

## 2. Chosen Pollutant in Exhaust Gases

There is increasing interest at all levels of society into harmful emissions to the atmosphere. This section compares the emissions from the various propulsion system options [2].

**The diesel engine** has undergone a powerful development process resulting in a completely new generation of engines with considerably improved performance. The specific fuel consumption of a modern two-stroke diesel engine may be in the order of 160 g/kWh, as compared to 210 g/kWh for older engines. Today the largest two-stroke diesel engines have an output of over 80 MW, which should be sufficient even for future proposed high-speed container ships. Owing to the high efficiency of diesel engines, the emissions of CO<sub>2</sub>, CO and hydrocarbons are relatively low, however, high emissions of NO<sub>x</sub> are also characteristic of diesel engines. The same high combustion temperatures that give a high thermal efficiency in the diesel engine are also most conducive to NO<sub>x</sub> formation. By running on low quality fuels with a low fuel consumption, large diesel engines offer enormous savings in fuel costs compared with those of alternative prime movers.

On some smaller, more specialized ships such as cruise ships, diesel-electric engines have been installed. This means that the electrical output from several diesel-electric generators, running at constant speed, have been connected to each other. The propulsion then occurs by means of large electric motors, contrary to the conventional way wherein the propeller is fitted on a shaft connected directly, or via a driving gear, to the main engine. However, diesel-electric propulsion is still uncommon today except in cruise ships and in some of the smaller passenger-car ferries. As regards emissions, diesel-electric propulsion does not lead to any significant difference compared to a conventional installation and may experience a net increase in emissions due to the lower efficiency of the total system.

**Gas turbines** are characterized by the combination high output/low weight. As such they are widely used in military ships and in modern fast ferries. But their fuel efficiency is low (total approx. 215 g/kWh) as compared with diesel engines (approx 160 – 180 g/kWh), which makes them uneconomic for most commercial vessel applications. However, gas turbines are recently appearing in cruise ships where they are used to augment diesel-engined gensets. Princess Cruise's new Coral Princess, for instance, uses a 30,2 MW gas turbine (General Electric LM2500+) in conjunction with two Wartsila diesel engines (Model 9L46 @ 9.45 MW and Model 8L46 @ 8.4 MW). The gas turbine is used as a low-emission power source while hoteling as well as to meet peak power demands. The two diesels meet normal cruising power requirements. They have a fuel efficiency (85% load) of 180 g/kWh, as compared with 215 g/kWh for the LM2500+ gas turbine.

**Steam for steam turbines** may be produced by burning fossil fuels or by means of nuclear reactors. Steam powered vessels are rapidly disappearing from merchant fleets because their specific fuel consumption is approximately 300 g/kWh, which is nearly twice as much as that of a modern diesel engine. Some steam powered ore carriers apparently still ply the Great Lakes, and a single steam powered cruise ship visits the Port of Vancouver during the summer months. However, these vessels are a small minority of the total marine vessel fleet and hence steam engines will not be addressed in the following sections.

**Auxiliary engines** are running almost constantly in order to take care of part of the ship's power supply. Power is needed for pumps, cranes, cooling and heating plants, lighting, etc. Some ships have generators connected to the shaft of the main engine (known as shaft generators). These substitute for the auxiliary engines, usually while cruising at sea when the main engine is running. Since most ships turn off their main engines while in port, the auxiliary engines are the dominating source of emissions during the time spent in port. The older auxiliary engines burned lighter fuel oil (e.g. marine diesel oil) so that their emissions were cleaner than those from the main engine. However, modern auxiliary diesel engines are designed to burn the same heavy bunker oil as the main engines do.

Figure 1 presents a mass balance for a modern ship's main diesel engine burning bunker oil, with 8 kg/kWh coming into the engine as fuel, air and lubricating oil and with 8 kg/kWh leaving the engine as exhaust gas. About 0.4% of the exhaust is comprised of the emissions i.e. (NO<sub>x</sub>, SO<sub>x</sub>, hydrocarbons and particulate), while 6.2 % of the greenhouse gas CO<sub>2</sub>.

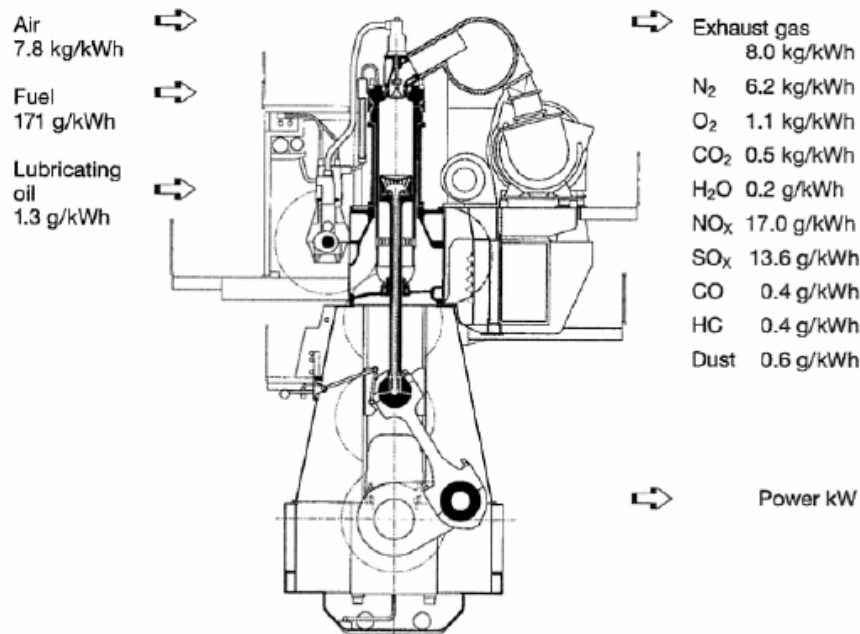


Fig. 1. Emissions from a modern diesel engine [3]

The following table 1 summarises the emissions for various types of propulsion system [2]. These figures are derived from various sources and are indicative only, since such factors as fuel composition and quality of maintenance can affect the values.

Tab. 1. Emissions from Marine Prime Movers [6]

Propulsion system	NO <sub>x</sub> g/kWh	SO <sub>x</sub> g/kWh	CO <sub>2</sub> g/kWh	Particulates g/kWh
2 Stroke Diesel Low Speed	17	12.9	0.058	0.5
4 Stroke Diesel Medium Speed	12	13.6	0.0612	0.4
Dual Fuel Diesel Electric	1.3	0.05	0.042	0.05
Dual Fuel Diesel Slow Speed	14.5	0.2	0.041	0.1
Steam Turbine	1	11.0	0.085	2.5
Gas Turbine	2.5	0	0.048	0.01

1. The figures for the 2-stroke and 4-stroke diesel engines are based on engines consuming heavy fuel oil, such as RMH 35 with a typical sulphur content of about 3.5 %.
2. The dual fuel diesel electric burn gas with a 1% pilot injection of light diesel such as DMA and the slow speed DFD is assumed to be burning gas with 1 % HFO pilot fuel.
3. The steam turbine option is based on dual fuel boilers with 50 % of the energy input coming from HFO and 50 % from boil-off gas.
4. The gas turbine is open cycle configuration and the fuel is 100 % gas, based on standard fuel combustors, even though “low NO<sub>x</sub>“ combustors are available.

## 2.1. Sulphur Oxides

Emissions of Sulphur Oxides ( $\text{SO}_x$ ) are purely a function of the sulphur content of the fuel and the amount of fuel consumed. The figures in the table are based on typical fuel oil with 3.5 % sulphur content. The primary fuel for the DRL (*Slow Speed Diesel with Reliquefaction*) option is HFO (*Heavy Fuel Oil*), hence the emissions level for this concept is significantly worse than the alternatives.

For the gas turbine based propulsion systems, where the primary fuel is gas, the emissions of  $\text{SO}_x$  compounds are zero in normal operations. For the short periods in service when gas is not available, i.e. for voyages to and from refit, the vessel will use light diesel fuel of DMA quality. These, compared to HFO, have a low sulphur content.

For the DFDE (*Dual Fuel Diesel Electric Engine*), the  $\text{SO}_x$  emissions are derived purely from the sulphur content of the pilot injection fuel and hence are very low compared with DRL burning HFO and steam turbine plants burning a mixture of HFO and boil-off gas (see Table 1 above).

As for DFDE, the high pressure injection DFD engine  $\text{SO}_x$  emissions are purely a function of how much pilot HFO is consumed.

The DRL option has no practical optionality for fuel choice, it cannot burn boil-off gas in the engines, therefore, considering the potential 40 year life of these vessels, this aspect represents a significant uncertainty about the long-term economics concerning the supply of the fuel for these engines. For the other alternative propulsion systems, they may operate with the primary fuel source as gas, with no sulphur content; and they also have the technical option of burning gas in port (subject to the terms of Sales and Purchase agreements). Whilst most of the effort has been about reducing the sulphur content of fuels in the first instance, alternative technical solutions, such as scrubbing of the exhaust gases to remove  $\text{SO}_x$  compounds, are considered feasible. However, there are issues relating to the treatment of the effluent scrub water and the space needed for the installation.

Whereas there is established methodology to put a value on  $\text{CO}_2$  emissions, there is currently no equivalent for  $\text{SO}_x$ .

## 2.2. Nitrogen Oxides

$\text{NO}_x$  emissions are a function of the combustion process. The key factors are the peak temperature achieved and the duration that the gases are at this peak temperature.

Slow speed diesel engines, as used in the diesel with reliquefaction option, are the worst offenders as far as emitting  $\text{NO}_x$  (see Table 1). The DFDE engine, however, is really operating as a gas engine and, as such, is inherently a low  $\text{NO}_x$  engine, particularly when compared with engines running on HFO. IMO MARPOL Annex 6 limits the  $\text{NO}_x$  emissions, based on the engine type. For slow speed diesels, the limit is 17 g/kWh and modern diesel engines will need careful maintenance to stay within these limits.

For the high pressure injection DFD (*High Pressure Gas Injection Slow Speed Diesel engine*), engine, earlier work indicated a reduction of about 15 % for the  $\text{NO}_x$  emissions compared to a conventional HFO-burning slow speed diesel engine.

For the gas turbine option, even with standard combustors,  $\text{NO}_x$  emissions are low compared to diesel engine technology. Should even lower levels be required, then technology exists in the form of dry, low- $\text{NO}_x$  combustors (DLN) for the gas turbines.  $\text{NO}_x$  can be removed from the exhaust gas by selective catalytic reduction.

## 2.3. Carbon Dioxide

Carbon Dioxide ( $\text{CO}_2$ ) emissions are primarily a function of the quantity of fuel burnt, but are also a function of the composition of the fuel being burnt. From this, it is clear that the efficiency

of the plant has a major impact on the quantity of carbon dioxide emissions, and this is demonstrated in Table 1 above, which shows the steam turbine as the worst in this respect. The next in this respect is the DRL (*Slow Speed Diesel with Reliquefaction*), option. The open cycle gas turbine option is better than the diesel with reliquefaction option and almost as good as the dual fuel diesel. All internal combustion options are significantly better than the steam plant.

## 2.4. Particulate Matter

Particulate matter emissions have become a serious health concern in many countries. This applies especially to particulate matter below the size of 10  $\mu\text{m}$  ( $\text{PM}_{10}$ ). Diesel engines are a main source of these particulates. Diesel engines burning low quality fuel emit significantly more particulate matter than those burning clean fuels, such as gas.

The dual fuel diesel emits few particulates compared with diesel engines running on HFO. In operation, the particulate emissions for steam turbine are a function of how much HFO is burnt and peaks during “soot-blowing” operations. However, the particles generated are considered sufficiently large (i.e. larger than  $\text{PM}_{10}$ ) do not present a health hazard.

Gas turbines burning gas emit virtually no particulates. There is currently no methodology for putting a value on particulates.

## 3. Current Methodologies and the Best Practices in Preparing Port Emission Inventories

The weakest link in deep sea vessel emission inventories is the emission factors for Category 3 ship engines (according to EPA Marine Compression Ignition Engine Categories, Category 3 ship engine – displacement  $\geq 30$  liters per cylinder, use to OGV (*Ocean Going Vessels*) propulsion and with approximate Power Ratings  $> 3000$  kW). [4]

Emission factors continue to be derived from limited data. Emission testing of OGV is an expensive and difficult undertaking; and thus, emissions data are relatively rare. In most cases, the power generated is only estimated, leading to inaccuracies in the overall emission factors.

### 3.1. Propulsion Engine Emission Factors

The most recent study of emission factors was done by Entec, and these factors are generally accepted as the most current set available. Entec analyzed emissions data from 142 propulsion engines and included 2 of the most recent research programs, Lloyd’s Register Engineering Services in 1995 and IVL Swedish Environmental Research Institute in 2002. Entec lists individual factors for three speeds of diesel engines: SSD (*Slow-speed diesel*), MSD (*Medium-speed diesel*), HSD (*High-speed diesel*) and ST (*Steam turbines*) and three types of fuel RO (*Residual oil*), MDO (*Marine diesel oil*) and MGO (*Marine gas oil*). Starcrest used these factors in their PoLA inventory with the following assumptions:

- all main engines operate only on RO (intermediate fuel oil 380 or similar specification with average sulfur content of 2.7 percent),
- slow speed engines have maximum engine speed of less than 130 rpm,
- medium speed engines have a maximum speed of greater than 130 rpm and typically over 400 rpm,
- all turbines are steam boiler turbines.

Currently recommended emission factors are shown in Table 2.

Tab. 2. Emission Factors for OGV Engines using Residual Oil [g/kWh][4]

Engine	NO <sub>x</sub>	CO	HC	PM <sub>10</sub>	PM <sub>2.5</sub>	SO <sub>2</sub>
Slow-speed diesel	18.1	1.40	0.60	1.08	0.99	10.3
Medium-speed diesel	14.0	1.10	0.50	1.14	1.10	11.1
Steam turbines	2.1	0.20	0.10	1.55	0.66	16.1

### 3.2. Auxiliary Engine Emission Factors

As with propulsion engines, the most current set of auxiliary engine emission factors comes from ENTEC. STARCREST used these emission factors for the Port of Los Angeles inventory, and they are considered the most up to date.

There is no need for a low load adjustment factor for auxiliary engines, because they are generally operated in banks. When only low loads are needed, one or more engines are shut off, allowing the remaining engines to operate at a more efficient level.

Tab. 3. Auxiliary Engines Emission Factors for [g/kWh][4]

Engine	Fuel	NO <sub>x</sub>	CO	HC	PM <sub>10</sub>	PM <sub>2.5</sub>	SO <sub>2</sub>
Slow-speed diesel	RO	14.70	1.10	0.40	1.14	1.10	11.1
Medium-speed diesel	MDO	13.90	1.10	0.40	0.75	0,28	6.16
Steam turbines	MGO	13.90	1.10	0.40	0.42	0.23	2,05

### 3.3. Boiler Emission Factors

In addition to the auxiliary engines which are used to generate electricity onboard ships, the most OGVs also have boilers used to heat RO to prepare it to use in diesel engines and to produce hot water.

Auxiliary boiler emission factors are given in terms of fuel usage, rather than power, so a fuel consumption rate also needs to be determined. During its vessel boarding program, Starcrest gathered enough data to estimate the consumption rate to be 0.0125 tonnes of fuel per hour. Auxiliary boiler emission factors, given in kilograms of emissions per tonne of fuel used, are given in Table 3.

Tab.4. Auxiliary Boiler Fuel Emission Factors, kg/tonne Fuel Consumed [4]

Emission Factors kg/tonne Fuel Consumed	
Pollutant	kg/tonne
NO <sub>x</sub>	12,30
CO	4,60
HC	0,38
PM <sub>10</sub>	1,30
PM <sub>2.5</sub>	1,04
SO <sub>2</sub>	54,0

## 5. Conclusion

The presented comparison of NO<sub>x</sub> content for various ship engines showed their highest concentration in diesel exhaust gas (see Table 1 and Table 2). It is valid for both the main and the auxiliary engines. A similar conclusion can be drawn for the contents of sulphur compounds. In the case of these engines well-known and extensively studied methods of reduction of emissions are applied, which allow meeting the requirements of IMO MARPOL Convention [5, 7].

Better results in this field are obtained for gas turbines, which are the cleanest sources of energy. However, exhaust gas from boilers of steam turbines are characterized by the worst results of all, with high contents of SO<sub>2</sub>, NO<sub>x</sub> and CO. The need to lower concentrations of these compounds in exhaust gas of boilers is caused by both the requirements of environmental protection and operational efficiency and points to new directions of further studies.

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