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Guide to Exhaust Emission Control Options

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Summary

This paper is the 5th in a Series for the CIMAC Committee. It is designed to be an informative guide into diesel emissions, their reduction and their measurement. Although, this paper should be read in its entirety, it is divided into five sections as follow:

- MARPOL Legislation – this section gives a brief breakdown of the new MARPOL Legislation 73/78 ANNEX VI as it applies to the Marine Industry and diesel engines.
- Diesel Emissions – this section is written to provide the reader with a basic understanding of diesel emissions and their impact on the environment.
- Emission Reduction – there are a number of techniques which have been proven to reduce diesel emissions, however, their success highly depends on the role and purpose, age, speed, etc. of the diesel engines fitted onboard individual ships. This section will hopefully be aid in understanding these techniques and how they are suited for individual applications.
- Gas Monitoring – Along with ANNEX VI of MARPOL 73/78 is the technique code, which provides the procedures for measuring diesel emissions. This section provides a brief outline of the technical code and the tools available for measuring diesel emissions.
- References – Further reading is essential to totally understand why legislation is necessary to reduce diesel emissions, how it will be enforced and what is the way ahead for ship builders and owners. These references should provide the reader with sufficient understanding of the diesel emissions dilemma and where used extensively in the writing of this paper.

This publication is intended for the Internet, and with the aid of hypertext, the reader can jump to those sections of this paper, which provides the most interest however; an attempt at answering the following basic questions will be made.

- What does the MARPOL legislation mean?
- What restrictions does the new legislation impose?
- What is the technical code?
- What are diesel emissions?
- Why are diesel emissions a concern?
- What are the different techniques available for emissions reduction?

- How are the different techniques for emission reduction suitable for each application?
- How are emissions measured?
- What emissions measuring equipment is most suitable for?
- What are engine groups and families?
- What is future technology bringing about to further reduce engine emissions?
- What other changes to legislation can be expected in the future?

In reading this paper, the ship owner or builder must remember that the best solution for his given application may be entirely unique to his application. A number of the techniques for combating diesel emissions may have to be applied to suit a given application.

Finally, questions on this paper would be welcomed and can be addressed to the CIMAC committee.

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Contents

1. Introduction

1.1. Background

The International Maritime Organisation (IMO) recently adopted Annex VI to the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78)[1]. In part, Annex VI sets the limits for NOx emissions which will be applicable to ship's propulsion and auxiliary engines greater than 130kW. This regulation, yet to be ratified, will affect all new vessels constructed after 1st January 2000. Furthermore, this regulation will also affect engines over 130kW, which undergo major conversion after 1st January 2000.

The adoption of this new legislation has far reaching affects for all ship builders and ship operators. Diesel manufacturers and researchers have been investigating a variety of techniques in the hope of reducing diesel emissions as far as reasonably practicable. These techniques have been divided into three areas of study: pre-treatment, primary (internal) methods and secondary (after-treatment) methods. All these techniques have to some extent been successful in reducing engine emissions however, their effectiveness and the effect they have on the engines themselves may not be completely known or understood. Furthermore, the intended role and purpose of different ships many mean that some techniques may not be adaptable for a given ship design.

Although emissions legislation has been predominately aimed at reducing NOx, it is widely anticipated that in the 21st century, all forms of emissions will have regulations imposed. It is therefore important to understand what these emissions are, and how they are formed to ensure that by adopting one form of technology to combat NOx will not have a detrimental affect on other emissions which will incur additional costs further down stream.

1.2. Aim

The aim of this paper is to discuss the diesel engine emissions and the technologies and methodologies available to help reduce these emissions and the MARPOL

[1] United States Environmental Protection Agency, VPCD-99-02 (Marine) dated January 19, 1999.

legislation. This paper first discusses the various emissions from diesel engines and then addresses the methods available to combat them. This paper is written as an informative guide and attempts to address those questions typical of a ship builder or operation that is faced with complying to the new legislation.

1.3. Scope

This paper addressees the following:

- MARPOL Annex VI Legislation - section two of this paper discusses in some length what the new legislation entails and discusses ratification of the new legislation.

- Certificates of Compliance - this is also briefly discussed in section 2 of this report. Details of obtaining certificates of compliance are also discussed later in this paper.

- Emissions - the types of emissions from diesel engines, and their effect on the environment, are discussed in section 3 of this report.

- Emission Reduction Techniques - understanding what emissions are and what is being legislated will go along way in understanding the techniques available to diesel manufacturers to combat emissions. These are discussed at length in section 4 of this paper along with the merits and demerits of each technique.

- Emission Testing - at some point, diesel manufacturers and ship owners will have to demonstrate that their engines are emission compliant. The emission testing procedure is described briefly in section 5.

- Emission Testing Equipment - continued on in section 5 is a brief list of equipment, which has been accepted in determining diesel emissions.

2. MARPOL Legislation

Annex VI and the Technical Code of MARPOL 73/78 adopted in January 1999 has two significant implications for ship operators. Firstly, it specifies that the sulphur content of fuel oil must not exceed 4.5% m/m world wide, or 1.5% m/m for ships operating within SOx Emission Control Areas. Secondly, and perhaps more importantly, it specifies that diesel engines for new ships constructed and for new installations after 1 January 2000, the generation of NOx will be restricted within the following limits:

a. 17.0 g/kWh when the maximum engine speed is less than 130 rpm;

b. 45.0*n(-0.2) g/kWh when the maximum engine speed is more than 130 but less than 2000 rpm; and

c. 9.8 g/kWh when the maximum engine speed is greater than 2000 rpm.

This restriction is summarised by the graph in Figure 2.1 and is based on the total calculated weighted NOx emissions. The calculated weight is based on the relevant test cycle (i.e. based on the role and purpose of the engine) and measurement methods specified by the Technical Code.

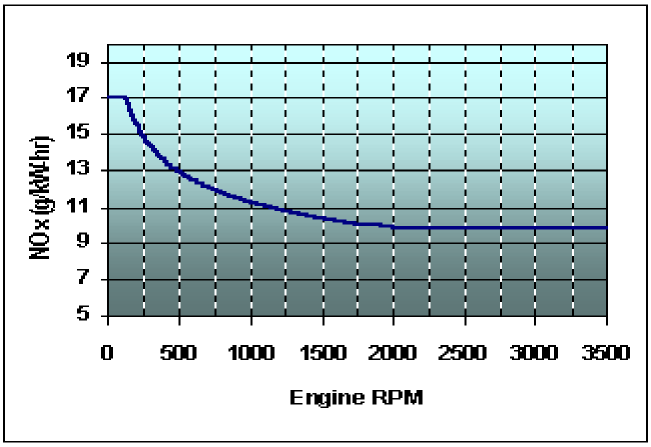

Figure 1.1: - NOx restrictions for new ships and major conversion 1 January 2000

2.1. Ratification

Although IMO have adopted the new Annex VI to the International Convention for the Prevention of Pollution from Ships, the Annex will not go into force until it is ratified by the participating nations.

Annex VI specifies that the Annex will not come into force until twelve months after the date on which not less than fifteen member states have signed up to the act. The total combined gross tonnage of those members who have signed up to the act must represent no less than 50 percent of the gross tonnage of the world's merchant shipping. There is no time limit for this to occur so it could happen relatively quickly or take many years to be ratified, however, the best estimate is that ratification will occur by 2003.

2.2. Engine International Air Pollution Prevention Certificates

Once Annex VI of MARPOL 73/78 has been ratified, engine manufacturers will have to demonstrate that their engines meet the new guidelines. This will be accomplished by obtaining an Engine International Air Pollution Prevention (EIAPP) Certificate. These certificates will be issued for an engine family or engine group after compliance with the NOx Technical Code is demonstrated. It is likely that the testing for diesel engine emissions will be delegated to classification societies. Full engine testing procedures are provided later on in this article.

2.3. Interim procedures

As it many take several years for Annex VI to be ratified, the Marine Environmental Protection Committee (MEPC) has issued Interim Draft Guidelines for the Application of the NOx Technical Code. This interim procedure is completely voluntary but will allow engine manufacturers to demonstrate that their engines are NOx compliant prior to ratification of Annex VI. The interim programme will allow engine manufacturers to obtain a Statement of Compliance for their engines, which, it is envisaged, will be taken into account when EIAPP certificates are issued on ratification of the Annex.

2.4. Effect on Ship Builders and Owners

The new MARPOL regulations have an immediate effect for ship builders and owners. Firstly, ship owners will have to ensure that accurate records are kept of the type of fuel being used by their engines. Fuel suppliers will be required by regulation 18 of the MARPOL legislation to provide documentation as to the sulphur content of their fuel. Secondly, for new ships and ships which are undergoing modification to their main and auxiliary engines will be required to provide EIAPP certification as to their emission levels.

Ship Builders and Owners must now become aware of the various methods available to reduce engine emissions. Some methods are more suitable than others for a given application. In some instances, in the case of new ships, the ship design and layout may require significant change to implement engine emission reduction measures.

3. Emissions

3.1. Background

The major pollutants in diesel exhaust emissions are a direct result of the diesel combustion process itself. In general, the major components are as shown in Figure 3.1. While the type of fuel used plays a major part in determining the composition of the emissions, the major factor that determines the amount of NOx, is engine speed. In way of comparison, Table 3.1 demonstrates how emissions vary with engine full speed.

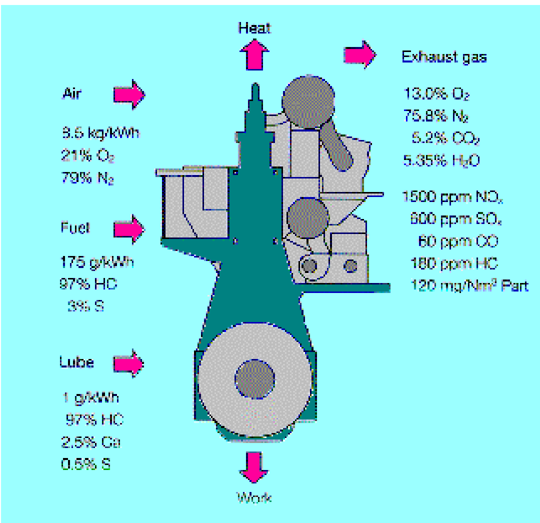

Figure 3.1:- Typical emissions from low-speed diesel engine[2]

Pollutant	Medium Speed Engines (g/kWh)	Low Speed Engines (g/kWh)
NOx	1.2	17
CO	1.6	1.6
HC	0.5	0.5
CO_2	660	660
SO_2	4.2x%S	4.2x%S
	where S = content	sulphur (%m/m)

Table 3.1:- Emission comparison between low and medium speed diesels engines.[3]

[2] Emission Control Two Stroke Low Speed Diesel Engines, MAN B&W Diesel A/S, December 1996.

[3] Marine Engineers Review June 97, The Institute of Marine Engineers, England

Each of these emissions will be discussed in turn in the following paragraphs and are summarised in Table 3.2.

3.2. Sulphur Oxides

The formation of Sulphur Oxides (SOx) in exhaust gases is caused by the oxidation of the sulphur in the fuel into SO_2 and SO_3 during the combustion process. As indicated in Table 3.1, the amount of SOx formed is a function of the sulphur content of the fuel used and therefore the only effective method of reducing SOx is by reducing the sulphur content of the fuel. Unfortunately, low-sulphur fuels are more expensive to purchase (10 to 20% greater cost, when switching from 3.5% to 1% sulphur) and there is a practical lower sulphur limit desired as desulphurisation of fuel lowers the lubricity of the fuel which can lead to increase wear on fuel pumps and injectors.

The regulation of SOx is predominately a regional issue, however, international pressure is growing for the oil producers to reduce the sulphur content of all fuels in order to control this problem at the source. The current EU Directive is that the sulphur content of fuels must remain below 0.2% with the aim of reducing this limit to 0.1% by the year 2008. Presently, most navies use 1% low-sulphur fuels. Special Areas have been set up, such as the Baltic, where the use of low sulphur fuels is mandatory.

If required, desulphurisation of diesel exhaust gases can be achieved by wet scrubbing. The flue gas is first passed through a quencher where it is cooled down to saturation temperature. The SOx is subsequently washed out with a neutralising agent (calcium bound in lime-milk or seawater) in a scrubber.

SOx formed from diesel exhaust is corrosive and in part is neutralised by an engines lubricating oil which is typically base. In the atmosphere however, SOx combines with moisture to form H2SO4, which then falls as acid rain, and has been linked to environmental damage.

3.3. Carbon Dioxide

CO_2 is one of the basic products of combustion and although diesels are one of the most efficient engines for the combustion of fossil fuels, the only way to reduce CO_2 is to either reduce the amount of fuel burned or by increasing thermal efficiency. Alternative low carbon to hydrogen ratio fuel could be used but this is unlikely to be a viable solution on board ships before 2010.

Diesel engines currently meet the CO_2 guidelines, however meeting stricter regulations on the permissible production of CO_2 is theoretically possible, but practically achieving these standards would be difficult. CO_2 is not toxic however, has been linked to the 'greenhouse effect' and global warming.

Finally, although CO_2 is a concern with respect to the 'greenhouse effect', Marine Transport, in terms of power produced, is the most favourable when compared with the Transport of goods world-wide by land, rail or air.

3.4. Carbon Monoxide

CO is formed due to the incomplete combustion of organic material where the oxidation process does not have enough time or reactant concentration to occur completely.

In diesel engines, the formation of CO is determined by the air/fuel mixture in the combustion chamber and as diesels have a consistently high air to fuel ratio, formation of this toxic gas is minimal. Nevertheless, insufficient combustion can occur if the fuel droplets in a diesel engine are too large or if insufficient turbulence or swirl is created in the combustion chamber.

3.5. Hydrocarbons

The emission of unburned hydrocarbons (HC) generally results from fuel, which is unburned as a result of insufficient temperature. This often occurs near the cylinder wall (wall quenching) where the temperature of the air/fuel mixture is significantly less than in the centre of the cylinder. Bulk quenching can also occur as a result of insufficient pressure or temperature within the cylinder itself. Still further, HC production may also be a result of poorly designed fuel injection systems, injector needle bounce, excessive nozzle cavity volumes or fuel jets reaching a quench layer.

While HC emissions from diesel engines is generally within acceptable limits, further reduction would most likely only be possible using secondary oxidation catalysts.

3.6. Smoke/Particulates

The composition and properties of diesel particulates varies greatly and is therefore difficult to define. Furthermore, there is not a quantitative relationship between the smoke opacity and the particulate emission. Particle emissions from diesel engines can originate from:

a) agglomeration of very small particles of partly burned fuel;

b) partly burned lub oil;

c) ash content of fuel oil and cylinder lub oil; or

d) sulphates and water.

The most effect method of reducing particulate emissions is to use lighter distillate fuels however, this leads to added expense. Additional reductions in particulate emissions can be achieved by increasing the fuel injection pressure to ensure that optimum air-fuel mixing is achieved, however, as fuel injection pressure increases, the reliability of the equipment decreases. Much research has also been conducted on cyclone separators, which are effective for particle sizes greater than 0.5µm while electrostatic precipitators are more effective, capable of reduction emissions by up to 99%. Unfortunately, precipitators are expensive, prone to clog and are large in size.

3.7. Nitrogen Oxides

While SOx is predominately a regional issue, NOx is a global issue and the new MARPOL regulations will have a significant impact for ship owners and ship builders.

NOx is formed during the combustion process within the burning fuel sprays and is deemed one of the most harmful to the environment and contributes to acidification, formation of ozone, nutrient enrichment and to smog formation, which has become a considerable problem in most major cities world-wide.

The amount of NOx produced is a function the maximum temperature in the cylinder, oxygen concentrations, and residence time. At cylinder temperatures, nitrogen from the intake air and fuel becomes active with the oxygen in the air forming oxides of nitrogen. Increasing the temperature of combustion increases the amount of NOx by as much as 3 fold for every $100^{o}C$ increase. NO is formed first in the cylinder followed by the formation of NO_2 and N_2O, typically at concentrations of 5% and 1%; respectively. NO_2 is soluble and washed out by rain which increases the acidity level of the soil.

The best way to reduce NOx generation, is to reduce peak cylinder temperatures and there are a number of ways that this can be done, however all methods cause a certain loss in engine efficiency which increases the engines sfc.

3.8. Summary

The following table provides a summary for the pollutants discussed above.

Emission	Source
SOx	Function of fuel oil sulphur content
CO_2	Function of combustion
CO	Function of the air excess ratio and combustion temperature and air/fuel mixture.
HC	Very engine dependant but a function of the amount of fuel and lub oil left unburned during combustion.
Smoke/Particulates	Originates from unburned fuel, ash content in fuel and lub oil.
NOx	Function of peak combustion temperatures, oxygen content and residence time.

Table 3.2: - Summary of pollutants

4. Emission Reduction Techniques

4.1. Background

There has been considerable research lately on methods for reducing emissions from diesel engines. The majority of this research has been centred on reducing NOx emissions, which will form the basis of further discussion in the following paragraphs. Nevertheless, the methodology in reducing other forms of emissions will also be discussed.

Competition by diesel manufacturers has meant that there are several viable solutions in achieving a NOx compliant engine, however, there must always be a monetary penalty for reducing NOx. The ship builder or owner must be aware that the final solution in achieving NOx compliance may be totally unique to the ship application and may be based on such things as operating profiles, water stowage facilities, electrical generation capabilities, etc. to name a few. It is hoped that this section of the report will clarify the issues surrounding the various NOx reduction techniques.

4.2. NOx Reduction Technologies

NOx reduction technologies can be divided into three basic categories namely: pre-treatment, Internal measures and after-treatment. Pre-treatment methods are concentrated on the source of the NOx, that being the fuel itself. Internal measure or primary methods alter the engine configuration to, in some form or another, alter the combustion process. After-treatment or secondary methods are fitted externally to the engine and are applied directly to the combustion gases. These methods are demonstrated in Figure 4.1. The various methods available to reduce NOx concentrations in exhaust gases is summarised in Table 4.1 below.

4.3. Pre-treatment

Pre-treatment methods generally fall with three categories:

- Denitration of fuel
- Using alternative fuels

- Water addition to fuel

4.3.1. Denitration of fuel

4.3.2. Alternative Fuels

There are at this stage two alternative fuels under investigation for use in diesel engines namely, methanol and liquid petroleum gas (LPG). Methanol has been the subject of much research over the last few years. Methanol does not contain any sulphur and therefore, SOx from emissions is completely eliminated. By combining methanol and EGR, NOx can be reduced as much as 50%. Nevertheless, all this does not come without a penalty and the reduction of this penalty has been the focus of the research, which is currently underway.

Methanol has bad ignition qualities and is corrosive in nature. The absence of sulphur means that the lubricity of this fuel is very low. Additionally the use of methanol would require modification to engine injection system. Methanol is a more expensive fuel than distillate and would also incur additional costs in modifications to fuel storage tanks and for the need for leak detection systems. There will also be large-scale logistic problems associated with the stowage and the obtaining of this type of fuel in foreign ports.

The use of LPG, on the other hand, is well advanced and in place at many generating power plants and LNG tankers. The LNG is also low sulphur and with the use of pilot injection can reduce engine NOx emissions by 60%. Nevertheless, the major problem of storage on other than LNG ships would constitute a significant problem, which has yet to be overcome. As a conservative industry, ship builders and owners would not want to be compromise or be perceived as compromising safety on board their vessels.

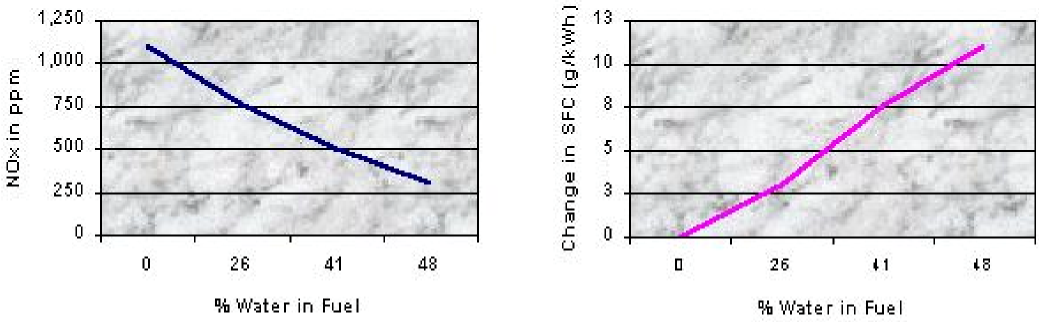

Figure 4.1: - Effect of water emulsification on NOx and SFC

4.3.3. Water addition to fuel

Emulsion fuel involves adding water to the fuel. Tests have been conducted with up to 30% water in fuel mixture, resulting in a 30% reduction in engine NOx emissions. NOx reduction is achieved by reducing the bulk temperature of combustion. The ultimate affect of adding water to fuel on engine components and lubricating oil is not known but is the subject of continuous research. The use of emulsion fuel would require additional equipment for generating the water/fuel mixture. An additional water tank would be required and may present a problem for smaller ships where water storage is a problem and for those ships where water making facilities are inadequate or not existent.

4.4. Primary Methods

Primary methods involve changes to the combustion process within the engine and fall under four main categories:

- Modification of combustion
- Modification of scavenge/charging air
- Water injection
- Exhaust gas re-circulation
- Humid Air Motor

Each of these categories is discussed below, however there are trade-offs with improving NOx emissions on other emissions such as particle matter and CO, as shown in Figure 4.2. Manufacturers must use a synergetic approach to gain a

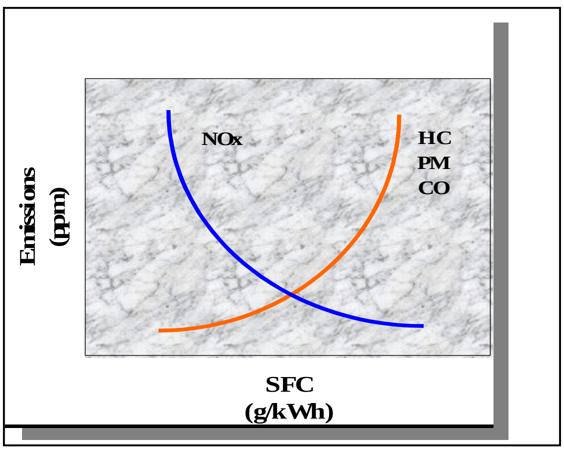

Figure 4.2:- The NOx Trade-off

competitive edge by balancing the reduction of one type of engine emission against another, keeping in mind that fuel economy must not suffer.

4.4.1. Modification of Combustion

There are a considerable number of ways to modify the combustion process, each with a centred at addressing a particular emissions problem, i.e. reducing NOx, particulates, or CO. Some of the methods below must be combined in order to realise any particular change in emissions.

Modification of combustion includes:

- Injection timing retardation
- Increase in injection pressure
- Modification of Compression ratio
- Optimisation of induction swirl
- Modification of injector specification
- Change in number of injectors
- Pre-chamber type of combustion
- Modification of shape of combustion chamber.

4.4.1.1. Injection timing retardation

Retarding the injection timing is one of the simplest techniques for reducing NOx. The effect of injection retardation is to reduce the maximum combustion pressure and hence temperature. By using this simple technique, a reduction of up to 30% can be achieved however, a penalty of up to 5% in sfc results, as the engine efficiency is reduced.

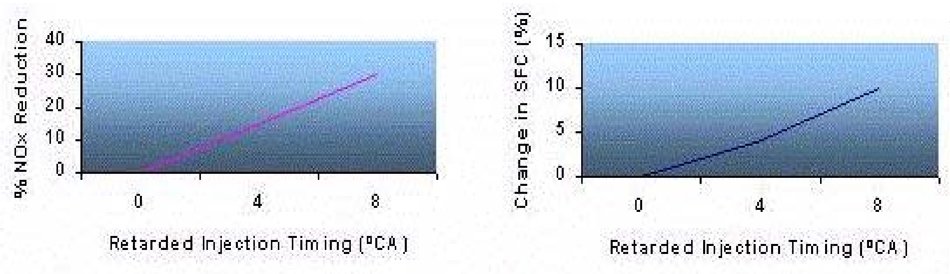

Figure 4.3: - Effect of fuel injection retardation on NOx generation

Alternatively, rate modulated injection can be used to smooth the cylinder pressure rise by adjusting the rate of the fuel supplied. Typically, this is only effective in medium/high speed diesels at part load.

With either of these methods, considerable component redesign (such as camshafts, electronic injection, etc) may be required and are therefore, more suitable to new engine designs.

4.4.1.2. Increase of Injection Pressure

Increasing the injection pressure on its own does not have any effect on reducing NOx, however, is generally combined with other NOx reduction techniques such as injection retardation. Increasing Injection Pressure leads to better atomisation of the fuel and therefore a reduction in Particulates and CO. Since combustion is cleaner, it will tend to be hotter at the kernel as well, which will in fact increase NOx reduction. Therefore, this method must be combined with other modifications to reduce NOx generation.

Increasing Injection Pressure requires stronger injection equipment and therefore added cost.

4.4.1.3. Modification of Compression Ratio

Increasing the compression ratio increases the maximum cylinder pressure and thus cylinder temperature and NOx. Therefore, in order to reduce NOx, this method must be combined with other NOx reduction techniques such as injection retardation. With injection retardation, a NOx reduction of 10 to 30% can be achieved.

The purpose of increasing the compression ratio would be to overcome some of the efficiency loss due to injection retardation and therefore decrease the sfc.

Increasing the compression ratio has no real effects on engine price provided this is done during the engine design phase.

4.4.1.4. Optimisation of Induction Swirl

The optimisation of Induction Swirl improves the combustion process and again will not in itself reduce NOx. Thus this method must be combined with other techniques to achieve NOx reduction. The benefit is that there is no real additional cost associated with this technique. There is presently great debate as to the benefits of swirl with respect to NOx reduction, nevertheless, the latest accepted opinion is that the piston crown must be designed for maximum local turbulence but ensure that the turbulence does not impinge on the cylinder walls thereby increasing localised cooling.

4.4.1.5. Modification of Injector Specification

Changing the fuel nozzle design has proven to have significant impact on NOx reduction. Considerable research has been conducted on injector fuel nozzle designs, and Table 4.1[4] demonstrates the effect on nozzle design on emissions generation. Recently much attention has been given to mini-sac type nozzles, which have been capable of reducing NOx by as much as 30%. A mini-sac nozzle is shown in figure 4.4.

	NOx	CO	Smoke	ΔSFOC
	ppm/15%/O_2	ppm/15%/O_2	BSN	g/bhph
Standard valve nozzle	1594	109	0.35	0.0
6-hole nozzle	1494	108	0.23	+0.4
Slide type fuel valve	1232	87	0.18	+1.8

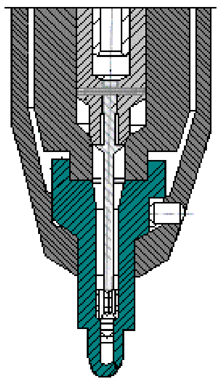

Figure 4.4: - mini-sac fuel injector

4.4.1.6. Change in Number of Injectors

There has been some research into increasing the number of injectors per cylinder. Increasing the number of injectors enables the combustion process to be better controlled and therefore more efficient combustion. It has been reported that a decrease in NOx from 30% is achievable, however there is a cost penalty associated

[4] Source:- Emission Control Two-Stroke Low-Speed Diesel Engines, MAN B&W Diesel A/S, December 1996.

with the need to have additional injectors, piping and associated equipment. As well as additional equipment, a significant increase in maintenance costs can be expected.

4.4.1.7. Pre-chamber Type of Combustion Chamber

Modification of Shape of the Combustion Chamber

4.4.2. Modification of Air Intake System

Modification of the Air Intake System can take the form of either the addition of scavenge/charge air cooling or the modification of the scavenge/charge air pressure.

4.4.2.1. Scavenge/Charge Air Cooling

Theoretically, providing cooler inlet air can lower the amount of NOx generated during combustion. Tests have shown that a 14% reduction is possible by lowering the air inlet temperature from 40 to 25^{o}C, however, the success of this method is greatly dependent on atmospheric conditions. Furthermore, the scavenge air for low and medium speed engines is already fairly low and therefore, this method would only prove more suitable for high-speed diesels.

Cooling the engine scavenge/charge air would increase the cost of an engine due to the additional water supply and cooler requirement. Also, cooling the air inlet temperature too much could lend itself to combustion stability problems.

4.4.2.2. Increasing the Scavenge/Charge Air Pressure

This method would not reduce NOx if implemented on its own, as an increase in cylinder pressure would result in corresponding increase in cylinder temperature. Combines with other methods such as injection retardation, however, could result in a NOx reduction of 10 to 40%.

There should be no real affect on engine cost per say if this method was implemented however, as it would need to be combined with other techniques, one would expect the engine cost to be higher.

4.4.3. Water Injection

Water injection (Figure 4.5) involves adding water directly into the cylinders during combustion through a special injector. As with emulsion fuel, NOx reduction of up to 40% is achieved by reducing the bulk temperature of combustion but has an advantage in that ignition delay at part load may be avoided. The limitation for implementing this modification is the capacity of the present fuel system. Separate pumps for the fuel and water are needed along with modifications to the fuel delivery lines and injectors to accommodate a water/fuel ration of 0.8. Potential drawbacks are higher costs and the potential for severe corrosion problems.

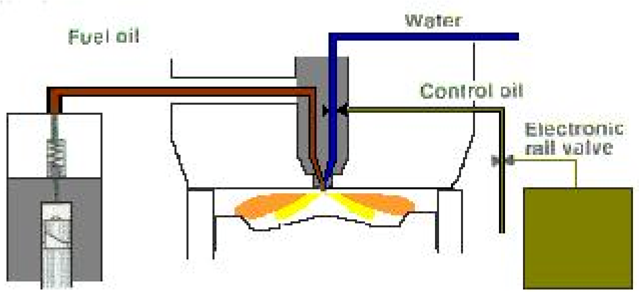

Figure 4.4: - Direct Water Injection

Mitsubishi has been investigating Stratification of water in fuel. This technique involves injecting water using the same injector as the fuel. Although this eliminates the need for an additional fuel injector, electronic fuel injection is required to control altering the fuel then water injection process and therefore, is likely to come at a significant extra cost.

4.4.4. Exhaust Gas Re-circulation

Exhaust Gas Re-circulation (Figure 4.6) has proven to be successful at reducing NOx levels due to the higher specific heat capacities of the principal exhaust components (CO_2 and H_2O) in comparison with air. The overall effect is to reduce peak cylinder temperatures. The drawbacks with EGR include increased smoke and particulate levels and increased engine costs. The inserting a particle trap in the exhaust gas re-circulation path can reduce smoke and Particulates.

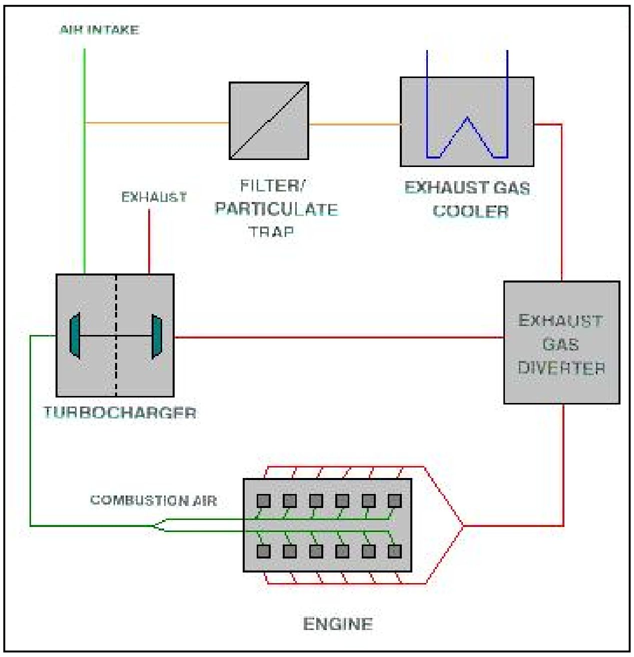

Figure 4.6: - Exhaust Gas Re-circulation

4.4.5. Humid Air Motor

Humid Air Motor is an alternative to water injection currently being investigated by some diesel engine manufacturers. These motors consist of pumping water (possible sea water) into the engine through the inlet air manifold. Similar reductions in NOx emissions to water injection can be expected using this technique but the long term effects of using seawater (if used) is not known. Costs are likely to be in the region of direct water injection however, this technique may be retrofitted onto older engines.

4.5. Secondary Methods

Secondary, or after-treatment, is centred on treating the engine exhaust gas itself either by re-burning the exhaust gas or passing it through a catalyst or plasma system. There has been much development in selective catalytic reduction (SCR) and plasma (NTP) systems over the last few years. Secondary methods, however, require a step change in capital cost, maintenance and through-life costs over primary methods.

4.5.1. Re-burning

This technology consists of using fuel as a de-oxidiser into the exhaust system. Fuel is re-introduced into the exhaust gas, which is then re-heated in a boiler but at significant less temperature than the combustion within the diesel itself. Using this method significantly reduces NOx, however, the thermal efficiency of the cycle is significantly less than the diesel itself. Furthermore, there will be a significant cost and space requirement increase.

4.5.2. Selective Catalytic Reduction

The SCR method utilises the fact that NOx can be converted with ammonia into nitrogen and water in a catalyst. Currently, the most critical problems inherent with this method are the toxicity of the reagent in a marine environment, the investment and operational costs, and the space and weight problems of implementing this solution. However, the reward is up to a 95% reduction in NOx. This is the area that is presently receiving an enormous amount of research in order to make this method as practical in all respects as possible and to minimise the amount of ammonia slip experienced during transient responses.[5]

Superimposing the numerous primary methods available will not have a significant effect on the total amount of NOx, which can be eliminated from the exhaust, and doing so will lead to a significant engine cost increase.

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[5] VOLLENWEIDER, J., Emissions Control of Marine Diesel Engines - The Slow-Speed Engineering Industry View", IMarE Conference on Emissions from Large Diesel Engines, London, November 1993.

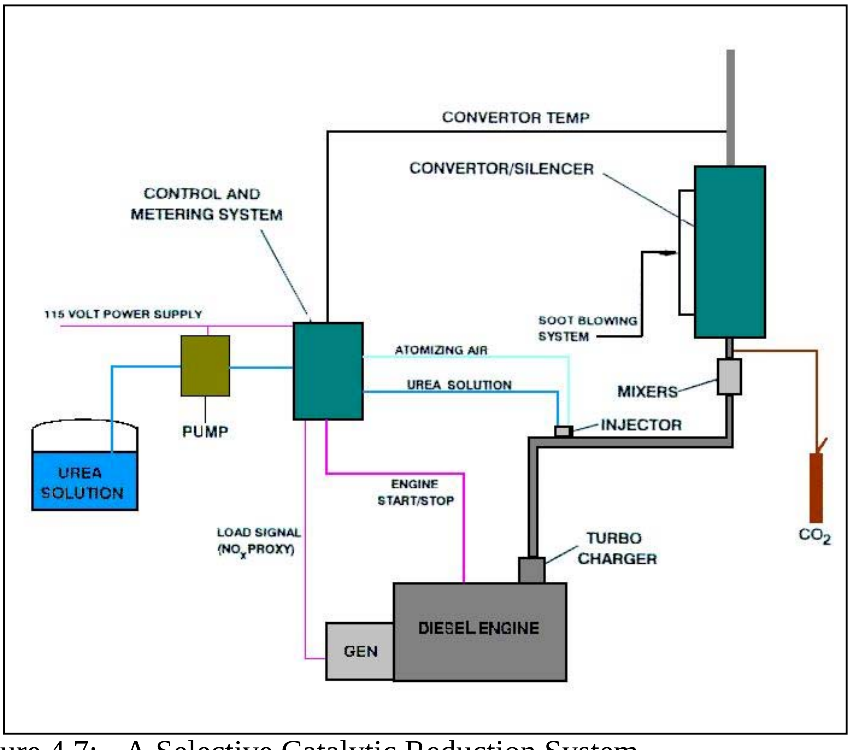

Figure 4.7: - A Selective Catalytic Reduction System

4.5.3. Plasma Reduction Systems

Plasma is a partially ionised gas comprised of a charge of neutral mixture of atoms, molecules, free radicals, ions and electrons. Electrical power is covered into electron energy and the electrons create free radicals, which destruct pollutants in exhaust emissions. The plasma is reactively hot but thermally cool which means that after treatment, little heating, if any, of the exhaust gas results.

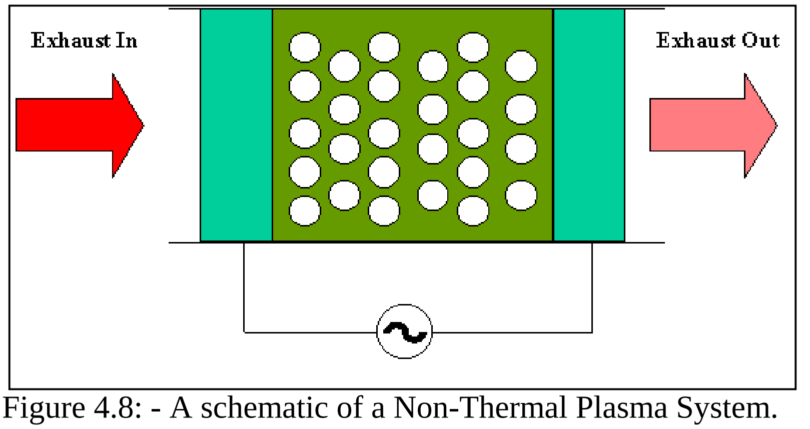

Figure 4.8: - A schematic of a Non-Thermal Plasma System.

For a number of years, AEA Technology has been developing production viable technology for the creation of non-thermal plasma at atmospheric pressure and to date, systems have been developed for incinerator flue gas clean-up, waste solvent treatment, air filtration, UV waste water treatment. AEA's latest work has been in the development of Non-Thermal Plasma Systems (NTP) for diesel engine exhausts. A schematic of a NTP System is shown in figure 4.8.

The prototype solution for diesel exhaust after-treatment is based on a surface discharge and can be assumed to be an electrically augmented catalyst. The plasma is generated using an alternation high voltage to breakdown the gas between two electrodes. The region between the two electrodes is packed with a material resulting in voltage breakdowns in the voids between the material. The duration of the voltage breakdowns is only of the few nanoseconds. A non-thermal plasma is produced which, augmented by the catalyst, breaks down the exhaust emissions.

Although the NTP System is still in is prototype phase for marine use, production costs should be relatively low cost. The system is compact and extremely flexible in terms of size and shape. Experiments to data have shown that a NOx reduction of up to 97% is achievable. When compared against the ISO 8178 C1 cycle, the NOx reduction performance of Figure 4.9 was achieved[6].

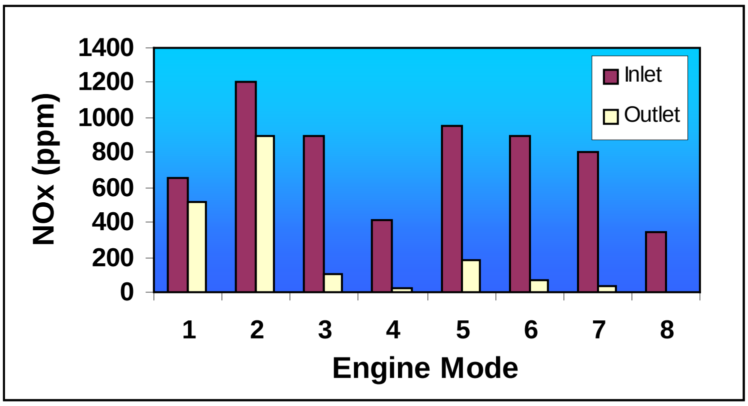

Figure 4.9: - NOx Reduction Performance of Non-Thermal Plasma

4.6. Summary

Table 4.3 provides a of the various NOx reduction techniques.

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[6] Non-Thermal Plasma for Marine Diesels, AEA Technology Presentation to Mar Power 99, 25-26 March 1999.

Technique	Extent of Modification	Remarks	% Reduction in NOx	Cost of Investment $/MW	Cost of Operation $/MW
Injection retardation	Engine adjust	• relatively simple to implement • increases sfc	<30%		
Increased Trapped air/fuel ratio	New turbocharger	•			
Increased injection pressure	New fuel pump, injectors, lines	• required to be used in conjunction with other primary methods • increase in cost to fuel injection equipment • reduction in reliability and increase maintenance cost of fuel injection equipment	N/A		
Modification of Compression Ratio		• must be used in conjunction with other primary methods • no effect on engine price	N/A		
Modification of Induction Swirl	New combustion chamber design	• must be used in conjunction with other primary methods • no effect on engine price			
Modification of Injector Specification	New injectors	• relatively simple to implement • no significant cost increase to engine	<30%		
Change in Number of Injectors	New cylinder heads, injectors, pumps, cams	• significant cost increase as additional pumps, injectors, etc needed	<30%		

Pre-chamber Type of Combustion Chamber	Redesign of combustion chamber	•			
Reduction in charge air temperature	Improved charge air cooling	• Only really viable on high speed engines • Increase cost to engine	<14%		
Increase in Scavenge/ Charge air pressure	Improved Turbocharger or turbo blower	• Must be combined with other primary reduction measures. • No real cost increase to engine			
Water Injection	New cylinder heads, camshafts, injectors, fuel and water systems	• Increase cost for injection equipment • Requires water making facilities	<40%		
Exhaust Gas re-circulation	Exhaust reconfiguration (add exhaust filter/cooler)	• Increased cost to engine	<30%		
Selective Catalytic Reduction	External modifications to engine	• Urea storage required onboard • Ammonia slippage problems • Additional costs to procure and operate	<95%		
Non-Thermal Plasma	External modifications to engine	• relatively simple technology • increased costs • no additional equipment needed • limited to ships with additional generating capacity	<97%		

5. Exhaust Gas Monitoring Techniques

5.1. Introduction

To obtain an Interim Certificate of Compliance, the engine manufacturer must combine his engines into an engine group. An engine from this group is then selected for emissions testing. The tests to be conducted on this engine must meet the MARPOL Annex VI NOx technical code.

It can also be expected that diesel engines will be tested onboard from time to time. Therefore, an understanding of how the tests are conducted is beneficial to both diesel manufacturers and ship owners.

This section discusses the types of emissions test equipment being used today and then goes on to discuss the ISO 8178 test cycles and emission measurement procedures.

5.2. Evaluation Systems

Emissions evaluation equipment can be divided into two categories, either extractive or non-extractive[7].

5.2.1. Extractive Systems

Extractive systems are permanently installed and require additional equipment to process the exhaust gas sample. The cost of extractive systems can very significantly however, they have the advantage of being able to be remotely located in a controlled environment, easier to operate, calibrate and maintain. Furthermore, extractive systems can be set up to monitor exhaust gas emissions from more than one engine.

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[7] Marine Information Note MIN 41 (M+F): - Research Project 396: Exhaust Gas Monitoring Evaluation of Exhaust Gas Monitoring Equipment for Shipboard Use, MSA January 1999.

5.2.2. Non-extractive Systems

Non-extractive systems predominately use infrared or ultra-violet techniques. The advantages to these types of systems are that they tend to be more portable and provide more rapid responses. However, these systems tend to be difficult to calibrate. Non-extractive systems measure the exhaust gas emissions without extracting the exhaust gas from the uptake system.

5.3. Chemiluminescence

Chemiluminescence or HCD (Heated Chemiluminescence Detector) is considered the accepted standard for laboratory and test cell measurement of NOx and was, in fact, the only available NOx detector available during the development of the IMO Technical code. Subsequently, infrared analysers have been developed.

Chemiluminescence analysers need to have a continuous supply of clean dry air, otherwise, damage to the analyser components will result. If installed onboard, instrument air, if available, can be used for this purpose.

5.4. Infrared Analysers

Non-dispersive infrared (NDIR) analysers have been used and many will satisfy the NOx technical code requirements. The NDIR are considered non-extractive devices and are capable of measuring CO and CO_2. Although these devices allow for rapid response and therefore quick emissions measurement, they are difficult to calibrate.

5.5. Ultra-violet

The UV analysers are particularly useful for measuring SO2 in the exhaust gas and come in extractive and non-extractive devices. UV analysers are not suitable for the measurement of NOx.

5.6. Test Procedures

An international test standard (ISO 8178) has been developed for all non-road diesel engines which incorporates gaseous and particulate emissions measurement[8].

The ISO Standard consists of ten parts as shown in Table 5.1 as is centred on providing engine manufacturers with standard procedures to enable them to achieve a Certificate of Conformity for their engines.

The ISO Standard standardises the test cycles to be used and the procedures for determining the emissions themselves.

[8] ISO Bulleten Number 305 dated 21th June 99.

Document	Title
Part 1	Test bed measurement of gaseous and particulate exhaust emissions
Part 2	Measurement of gaseous and particulate exhaust emissions at site
Part 3	Measurement of exhaust gas smoke under steady state conditions
Part 4	Test cycles for different engine applications
Part 5	Test rules
Part 6	Test report
Part 7	Engine family determination
Part 8	Engine group determination
Part 9	Test bed procedure for the measurement of smoke from off-road diesel engines
Part 10	In-use procedure for the measurement of smoke from off-road diesel engines

Table 5.1: - ISO 8178 Documentation

5.7. Test Cycles

Before commencing the emission tests, it is important to determine the test cycle as this determines the test cycle to be used. There are 15 difference test cycles of which only four can be readily applied for marine diesels. These test cycles are broken down as follows:

Test Cycle E2 is used for all constant speed marine engines for ship main propulsion including variable pitch propeller sets and electric propulsion.

Test cycle type E2	**Speed**	100%	100%	100%	100%
	Power	100%	75%	50%	25%
	Weighting Factor	0.2	0.5	0.15	0.15

Table 5.2: - The E2 Test Cycle

Test cycle type E3 is used for propeller law operated main and auxiliary engines.

Test cycle type E3	**Speed**	100%	91%	80%	63%
	Power	100%	75%	50%	25%
	Weighting Factor	0.2	0.5	0.15	0.15

Table 5.3: - The E3 Test Cycle

Test cycle type D2 is used for constant speed auxiliary diesel engines.

Test cycle type D2	**Speed**	100%	100%	100%	100%	100%
	Power	100%	75%	50%	25%	10%
	Weighting Factor	0.05	0.25	0.3	0.3	0.1

Table 5.4: - The D2 Test Cycle

Test cycle type C1 is used for variable speed, variable load auxiliary engines. The intermediate speed for this test cycle is determined by the manufacturer but generally falls within 60 to 75% of the rated speed.

	Speed	**Rated**				**Intermediate**		**Idle**	
Test cycle type C1	**Torque**	100%	75%	50%	10%	100%	75%	50%	0%
	Weighting Factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

Table 5.5: - The C1 Test Cycle

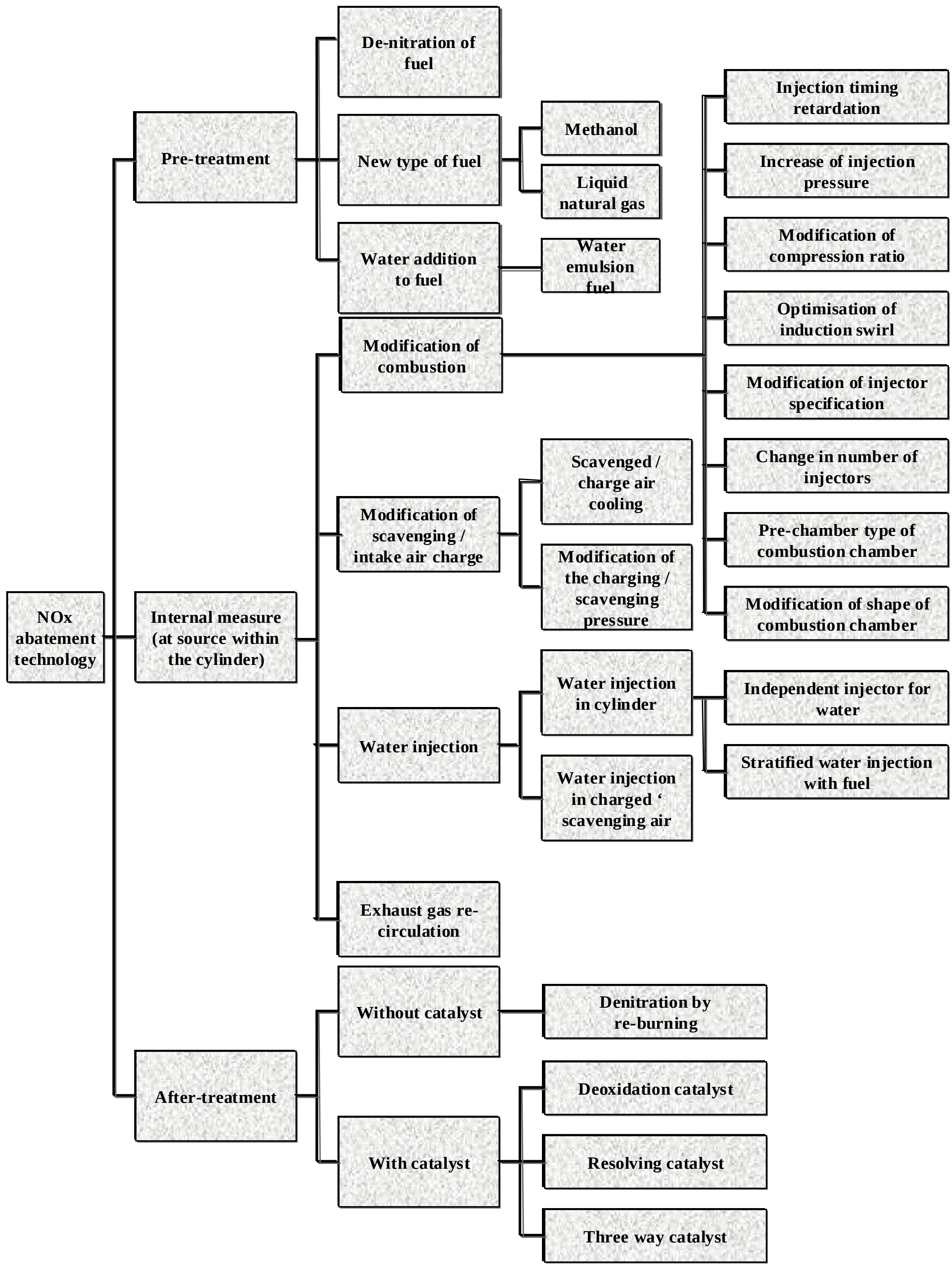
5.8. Emission Measurement Procedures

The emission measurement procedures

5.9. Engine Families and Groups

As engine manufacturers have a variety of engines ranging in size and application, the ISO Standard allows the organising of engines into families or groups. This will reduce the amount of individual engine testing necessary to obtain Certification. The subdividing concept allows engines that are mass-produced to be divided into engine families and those which are built in small numbers to be divided into groups. By definition, an engine family is a manufacturer’s grouping which through their design, are expected to have similar exhaust emissions characteristics i.e., their basic design parameters are common. When testing an engine family, the engine, which can be expected to develop the worst emissions, is selected for testing.

The engine group concept has been derived for large marine diesels, which are not mass-produced. By definition, an engine group is a manufacturer’s grouping of engines that require adjustment or modification to ensure that they comply with the emissions standards and perform to these standards on site.


De-nitration of fuel
Pre-treatment
New type of fuel
Methanol
Liquid natural gas
Water addition to fuel
Water emulsion fuel
Modification of combustion
Injection timing retardation
Increase of injection pressure
Modification of compression ratio
Optimisation of induction swirl
Modification of injector specification
Change in number of injectors
Pre-chamber type of combustion chamber
Modification of shape of combustion chamber
Modification of scavenging / intake air charge
Scavenged / charge air cooling
Modification of the charging / scavenging pressure
NOx abatement technology
Internal measure (at source within the cylinder)
Water injection
Water injection in cylinder
Independent injector for water
Stratified water injection with fuel
Water injection in charged ' scavenging air
Exhaust gas re-circulation
Without catalyst
Denitration by re-burning
After-treatment
With catalyst
Deoxidation catalyst
Resolving catalyst
Three way catalyst

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7. About the Authors

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Don obtained his BEng in Mechanical Engineering at the Royal Military College in Kingston Ontario, Canada and subsequently obtained in Marine Engineering Certificate of Competency in the Canadian Navy, serving on board various ISL and DDH 280 class warships. After completing his last Marine Engineering appointment Don attended the Royal Naval Engineering College Mandaon in Plymouth England, where he obtained his MEng in Marine Engineering before being appointed as the Diesel Development Officer for the Naval Support Command in Foxhill, Bath, UK. After 18 years, Don retired from the Navy and joined British Aerospace, Land and Sea Systems as a Senior Consultant and is the Technical Authority for Marine Diesel Engines.

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Glenn is presently the Canadian exchange officer serving as the Diesel Development Officer within the propulsion section of the Ship Support Agency. His areas of responsibility include Exhaust Emissions, Condition Monitoring and providing advice on future diesel purchases. Prior to joining the section, he received his MSc in Marine Engineering from University College London. Lt Cdr Walters previously served as the Marine Systems Engineering Officer of the submarine HMCS ONONDAGA.