DIESEL EMISSIONS
A ROYAL NAVY APPROACH

BY

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ABSTRACT

NO_x reduction through primary means is the preferred method for UK Minister of Defence Navy (MoD(N)) vessels. However, the vast array of engine types and expected emission level change has focused the Royal Navy on secondary treatment such as Non-Thermal Plasma and Selective Catalytic Reduction (SCR). The newly introduced IMO regulations now make the reduction of NO_x output from marine diesel engines a necessity.

It may be possible to meet the current IMO regulations by means of 'primary' engine measures, but it is likely that any further significant reductions would require a 'secondary' after-treatment technique. Investment appraisal in secondary methods will increasingly support new technology engine after-treatment retrofit. The uncertain nature of NO_x and particulate level legislation has reinforced the Royal Navy's commitment to remaining an informed customer on green issues. Through industrial partnering, the current naval build programme can incorporate these policy changes and enhance engine exhaust emission control from test cell to at sea marine diesel after-treatment.

Introduction

The aim of this article is to discuss the findings of the MoD(N) and AEA (Atomic Energy Agency) Technology development programme in considering Non-Thermal Plasma (NTP) as an alternative solution to Selective Catalytic Reduction (SCR) exhaust gas after-treatment. An evaluation of a naval SCR system was conducted in 1994.[1] Although technologically feasible, some concerns were raised, including the need for urea storage and SCR impracticability for submarines.

This article aims to describe plasma technology, general NTP applications and how diesel exhaust in a marine environment can be treated. The preliminary results from a continuing two-year laboratory programme are presented. A relative comparison to the previous SCR programme is then used to summarize the potential benefits of NTP as applied to the naval environment.

Emissions legislation

The recently adopted IMO regulations require the reduction of NO_x output from future marine diesel engines. The impending IMO NO_x levels[2] are generally possible to meet by means of 'primary' on-engine measures. Further significant follow-on reductions are likely to require a 'secondary' after-treatment technique. The established IMO limits are only intended for future build ships and all major conversions after 1 Jan 2000.[3] At present, there is no indication that NO_x limits will be implemented retroactively.

Although second tranche global NO_x reduction legislation may appear some way off, given the life cycle of a warship, consideration for suitable after-treatment equipment is necessary now. SCR is currently the only available technology proven at full scale to meet the 90% NO_x reduction levels. However, based on the laboratory scale results presented in this article, NTP is showing the potential of at least matching such a system when fully developed for marine applications. Legislation will not solve the NO_x problems and compromising existing NO_X

- Where possible, enclosures shall maintain their integrity, preventing ingress of oxygen and leakage of oxygen depleted fire products and aerosol.

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certification or alternatively unwarily embarking on engine work without regard for future implications will leave ship owners dangerously exposed.[4]

Emission reduction

Sulphur Oxides

One of the most significant pollutants being targeted is sulphur exhausted in the form of oxides of sulphur in part responsible for causing acid rain. Fortunately, the Royal Navy does not need to be concerned with sulphur emissions because discussion with the petroleum industry indicates that international pressure is driving the content of sulphur in fuel downwards. As any sulphur in the exhaust can only come from the fuel, removing sulphur from the fuel should eliminate the sulphur emissions. An added benefit is that the sulphur removal process also reduces metallic particulates from the fuel.

Of course every change carries a penalty and the effect that low sulphur fuel will have on the life of engine components is now being examined following reports of problems of engines running on low sulphur fuel in Scandinavia.

Carbon Monoxide, particulates and hydrocarbons

Turning now to carbon monoxide, particulates and hydrocarbons, excessive emissions of these is due primarily to inefficient combustion. Under steady state conditions this can be caused by inadequate time for the air to mix with the fuel at high loads, and insufficiently high in-cylinder air temperatures at low loads. During transients and under start up conditions the inability of the turbocharger to provide sufficient air to match the fuel input leads to the characteristic black smoke often seen when running diesel engines.

To promote complete combustion many manufacturers concentrate on the fuel injection system and incorporate higher injection pressures, finer injector nozzle holes and low sac nozzles in their engines.

Transient performance can be improved by fitting very responsive turbochargers with low Moments of Inertia, incorporating an externally supported 'air assist' system to accelerate the compressor during load application and fitting a smoke limiter to limit the fuel rack position during start up.

Oxides of Nitrogen

While sulphur and the carbon-based emissions can be tackled as discussed, the most difficult emission to control is the oxides of nitrogen produced by the engine. Because of its impact on the environment it is the subject of very restrictive legislation. The formation of oxides of nitrogen is dependent on three factors:

- (*a*) Temperature of combustion.
- (*b*) Residence time in the combustor.
- (*c*) Concentrations of nitrogen and oxygen.

In a diesel engine, the high efficiency that is derived from the high cycle maximum temperature that makes the diesel suitable for so many applications is also its 'Achilles heel' in terms of emissions. The temperatures in the kernel of the injector spray into a cylinder can reach temperatures of 2,800°C. Since gas turbine combustion maximum temperatures are presently constrained by material considerations to temperatures of about 2,000°C the NO_x problem is not so severe. However, Gas Turbine manufacturers will need to be careful about using materials to raise cycle temperatures and efficiency to reduce carbon dioxide or they will throw away their advantage.

The technologies available for combating NO_x production can be roughly grouped into those that reduce emissions by 30%, 60% and 90% of the levels now being produced. In table 1, methods of NO_x reduction are identified from a full range of past and current industry technologies.

TABLE 1 – *NO_x Reduction Techniques*[5]

Technique	Extent of Modification	Remarks	% Reduction in NO_x
Injection retardation	Engine adjust	• Relatively simple to implement. • Increases sfc.	<30%
Increased Trapped air/fuel ratio	New turbocharger		N/A
Increased injection pressure	New fuel pump, injectors, lines, cams	• 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	New piston crown design	• 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.	N/A
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, fuel system	• Only viable for engines under 100mm cylinder bore and new engine designs of under 100 mm bore diameter.	
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.	N/A
Emulsified Fuels (off engine i.e. pre-treatment)	Modified low pressure part of fuel system	• Maximum percentage of added water depends on capacity of injection pumps. • Requires water making facilities.	<60%
Water Injection (on engine i.e. primary)	New cylinder heads, camshafts, injectors, fuel and water systems	• Increase cost for injection equipment. • Requires water making facilities.	40%
Water Emulsification	New injectors, fuel pumps, etc. Modification of engine control system, water supply systems and fuel supply systems	• Increased cost for engine and auxiliary equipment • Requires facilities for fresh water production.	<50%

Humid Air Motor	Place for humidifier and droplet separator	• Relatively simple to implement. • Requires specialised skill in manufacturing.	<75%
Exhaust Gas re-circulation	Exhaust reconfiguration (add exhaust filter/cooler)	• Increased cost to engine. • Note internal EGR can be used in two stroke engines by reducing scavenge air.	<30% (30% H_2O)
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. • Power Supply and plasma unit required. • Limited to ships with additional generating capacity.	<97% (At lab scale)

<u>30% reduction</u>

The technologies to lower NO_x by 30% require only minor changes to current engine designs. In this group are:

(*a*) Obtain homogeneous fuel/air mixture by use of high injection pressures and a large number of spray holes.

(*b*) Using a high trapped fuel air ratio (increasing the air in the cylinder without a corresponding increase in fuel.

(*c*) Reduce the temperature of the charge air entering the cylinders to a low value at high loads by increasing charge air cooling.

(*d*) Retarding the injection timing. The use of these techniques allows for good reduction of oxides of nitrogen as illustrated here; however, it comes with a penalty of increased smoke and thus particulates. It also has a significant effect on fuel consumption.

(*e*) Exhaust Gas Recirculation (EGR) is effective at reducing NO_x levels because the principal exhaust components (carbon dioxide and water) have higher specific heat capacities than air and thus reduce peak cycle temperatures. Although as noted in table 1, it has been tested successfully, it will not be viable for production engines until an effective, reversible filter has been developed to cope with the particle content of the exhaust.

Water fumigation by either emulsifying the fuel and water or injecting water directly into the cylinder. This technique is promising because at high water/fuel ratios it can achieve 30-40% NO_x reduction with negligible fuel consumption penalty. However, more work needs to be done to look at the long-term effects of spraying water into the engine, particularly in terms of reducing engine availability and life and the added requirement for fresh water usage.

60% reduction

Reduction of up to 60% NO_x emissions will require major changes to an engine. Methods presently under research are:

(*a*) Injection pressures of the order of 1,400 – 1,600 bar instead of normal injection pressure of about 300 bar. This improves atomization and mixing and also shortens the injection period thus controlling fuel consumption.

(*b*) Variable injection timing allows the engine to be better tuned for transients and variable load operation. In its basic form it can be carried out mechanically either by an eccentric pivot or blending two cam forms together to allow the cam follower to bear on the cam most suitable for the operational duty. More promising is an electronically controlled injection pump that can control the period of injection as well as its timing. This is similar to systems now adopted for diesel truck engines.

(*c*) Detail design changes to existing features can also bring benefits. For example the low sac nozzles can be used to ensure minimal fuel drips after the needle valve closes and combustion chamber shape can be optimized to minimize crevices which trap hydrocarbons. Air supply must be ensured by using high air/fuel ratios and the charge air temperature must be rigidly controlled, especially at high powers to limit NO_x formation from high temperatures.

90% reduction

Reduction in NO_x emissions of up to 90% can be achieved by using the exhaust after-treatment process SCR. Here gaseous ammonia is mixed with the exhaust gases before passing over a catalyst which promotes reduction of NO_x combining the nitrogen of the NO or NO_2 molecule with that in the ammonia to create gaseous nitrogen. The reaction must take place within a tightly controlled temperature range of 300 to 400°C. This technique can also be used with an oxidizing catalyst that is effective in removing hydrocarbons and carbon monoxide.

The relatively rapid implementation of exhaust emission legislation in some countries and the ease with which a SCR plant can be added to an existing engine has prompted the adoption of the SCR for several land based applications.

Applicability

Turning now to applicability, the most important aspect of emissions measures, as with everything in naval vessels, is compromise. In the past, operational capability has driven the design of naval vessels and demanded the continual weapon system update. Marine systems and equipment were rarely changed or updated unless there was some specific shortcoming, which degraded the operational effectiveness or availability of the ship.

However, recent legislation and stated commitment of national leaders have altered this traditional way of doing business. The drive to obtain better fuel consumption has led to some changes, but the continued lobby of environmentalists has led to increasingly harder stances on sensitive environmental issues in the legislation of many countries and internationally through IMO. In the past it was acceptable for the Royal Navy to claim exemption from regulation, because it was in the national interest to do so. This is no longer the case and the Royal Navy has been directed to abide by international, national and regional legislation. The continued requirement for a blue water navy coupled with these directives will have an increasing influence on the machinery fitted to Royal Navy ships of the future.

The political will to impose regulations is evident from the recent initiatives in both the United States and Europe. We must recognize that although more pressing issues may occupy the agendas of many western governments, the environmental lobby is well organized and relentless.

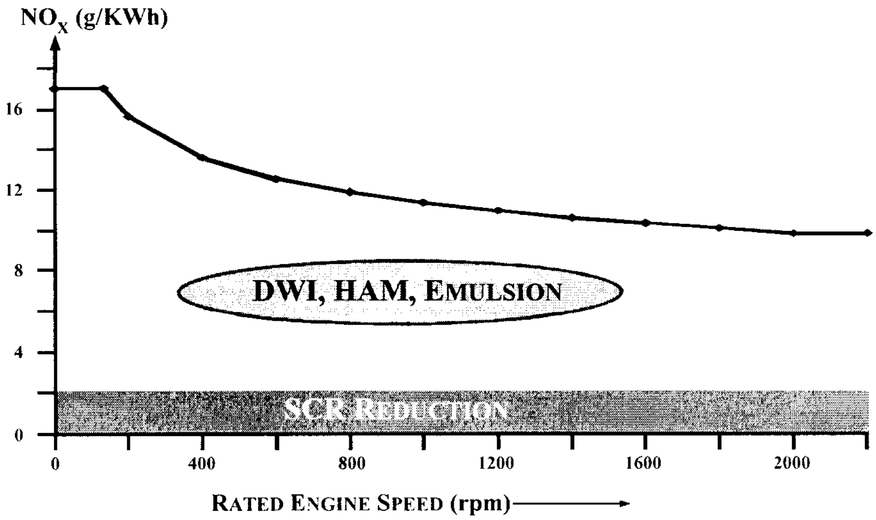

FIG.1 – IMO SCALE[6]

(FIG.1) illustrates a variety of relevant NO_x legislation and shows emission levels that may be achieved by the techniques discussed. From our viewpoint, it is necessary to divide ships into those that operate in coastal waters and those that operate world-wide.

The coastal vessels will fall under UK EPA (90) legislation and it should be possible to satisfy the emissions requirements of the Act using some of the techniques discussed under the 60% reduction of NO_x. Since the majority of the vessels that MoD operates fall into this category, the development of these techniques is very important to ensure that our diesel propelled auxiliary and minor war vessel fleet can continue to operate world-wide.

For world-wide operation the regulations that California were proposing to introduce in 1995 represent the target because this is the most stringent legislation proposed by any seaboard region and the Royal Navy is committed to respecting all national emission laws unless overriding requirements of national security dictate otherwise.

The need for compromise is evidenced by the need to reduce all emissions. Although legislation concentrates on NO_x emissions at present it is clear that when satisfactory measurement techniques are developed other emission levels will come under increasing scrutiny. The need to limit CFCs is illustrated by their high impact on the environment when compared with all other gases and of course these are now controlled by the Montreal protocols.

The use of SCR technology has raised the expectations of both politicians and environmental pressure groups as to what is achievable in terms of NO_x emissions reduction and best available technology legislation will ensure that national laws will be based on what can be achieved by selective catalytic reduction.

Our role has been to encourage industry to concentrate on primary methods of emission reduction. The ultimate aim of legislation must be to lower overall emission levels worldwide, whereas national regulations only force companies to apply technologies within their limited jurisdiction. SCR is encouraged by national legislation because it is a turn-key operation for use in coastal waters and can be promptly switched off as soon as the vessel is outside coastal limits. Primary methods, which can be developed to provide minimal operational shortcomings, allow ship operators to reduce their emission wherever they are operating.

Recent articles in the UK press record the problems of achieving a consensus by IMO representatives on how to apply NO_x legislation. Understandably countries are striving to protect their national industry and therefore are looking for more lenient regulations for some engine types, notably large slow speed engines which, in the marine environment, must be considered to be among the worst offenders for NO_x emissions. As representatives of our various governments and primary users of the world's oceans we must encourage a uniform standard of legislation for all engines based on an equitable assessment of their total contribution.

Various consortia are being formed to address diesel emissions as the diesel industry is becoming more aware that its larger engines will now be subjected to legislation. In the UK, the Royal Navy will be active in support of a consortium being formed between engine manufacturers and Ricardo (UK independent Research Company) to research reduction methods by changes to the combustion system. We have a twofold interest, to remain informed of latest advances and to support the search for primary methods for NO_x reduction.

We are also hoping to contribute to a programme aimed at developing an after treatment system which will not require an external source of reactant.

From the Royal Navy viewpoint we are faced with a number of problems.

(*a*) We must define the footprint of marine equipment for ships as the engine we choose will probably be in use for 30 to 40 years from the time the design is frozen.

(*b*) Present production engines will be incapable of meeting the regulations, which are in force since the turn of the century. Gas turbines have more scope to reduce their emission levels than diesel engines, but they suffer from poor part load fuel consumption. This is to be addressed by the Intercooled Regenerative Gas Turbine Engine, currently under development. Results of diesel engine research indicate that at present, state of the art primary method technology will be capable of satisfying all but the most stringent legislation presently being discussed; however, there is some doubt that primary methods will be able to cope with future legislation. SCR is not viewed as being acceptable for Royal Navy use, but other post combustion techniques under development may provide the answer (either solely or in combination with developed primary methods).

(*c*) The tight monetary control by governments, which combined with the naval operators' obsession with technological change in weapons' systems will limit the funding available to encourage manufacturers to concentrate on primary method exhaust reduction. That present laws encourage commercial operators to use SCR systems which are only activated in confined waters, does little to encourage manufacturers to pursue primary methods at their own expense.

(*d*) The unpredictability of legislators in determining acceptable levels in the future.

These represent considerable challenges over the next few years and the Royal Navy will endeavour to satisfy both legislators and operational requirements. As a point of discussion, and as a marine engineer of one NATO country serving with another NATO country, it is in our interest to press for introduction of measures beyond the year 2000 for new builds and to prevent the implementation of retroactive legislation on our vessels.

NON-THERMAL PLASMA TECHNOLOGY

Overview of Plasmas

A plasma consists of a charge of neutral mixture of atoms, molecules, free radicals, electrons and ions. The presence of these free radicals causes the plasma to be an extremely reactive medium. These and other plasma generated species can either react directly with pollutants in an exhaust stream or promote their removal e.g. through catalysis. Plasmas are generally produced through the electrical breakdown of a gas using electric fields. This field generates and then accelerates electrons. The electrons impact with neutral species in the gas causing ionisation and dissociation with the latter leading to free radical and other species generation.

Two forms of plasma can be generated by application of an electric field to a gas:

- 'Thermal' plasma.
- 'Non-thermal' plasma.

In a thermal plasma, also termed 'hot' or 'equilibrium', rapid collisional redistribution of input energy ensures that a thermal equilibrium is established between all the plasma constituents. Atmospheric plasmas are generally thermal and an example is given by the plasma welding torch. Very high temperatures are generated by very high input powers, input power being essentially converted into heat.

In the alternative non-thermal form of plasma, also termed 'cold' or 'non-equilibrium', input power is converted into electron energy and the gas is maintained at low temperature usually by operating at reduced pressure. The low pressures result in a reduced collision frequency between plasma constituents and hence collisional redistribution of energy is less efficient. The result is that the electrons have an excess temperature relative to the other plasma constituents. A household fluorescent lamp is an example of a non-thermal plasma in which electron temperatures of 11,000°C are reached at background gas temperatures of only 40°C. Non-thermal plasmas require a much lower electric field to breakdown the gas and a much lower power input to be sustained. Since the input energy remains primarily with the electrons, which produce the active species, this is a more efficient form of plasma for the removal the pollutants.

Plasma applications at AEA Technology

For a number of years AEA Technology have been developing production-viable technologies for the creation of non-thermal plasmas at atmospheric pressure. Plasmas of this type offer an alternative technique for the abatement of pollutants from a wide range of process and exhaust gas streams. The primary objective of the programme has been to demonstrate alternative approaches to plasma generation which are both cost effective and efficient for a given process. AEA Technology application areas include:

- Flue gas clean-up.
- Waste solvent treatment.
- Air filtration.
- UV waste water treatment.

- Internal combustion after-treatment.

Application to Diesel Exhaust After-treatment

AEA Technology's prototype system for diesel exhaust after-treatment operates on a surface discharge principle, particularly well suited to marine requirements of simplicity, compactness and robustness.[7]

The plasma is generated using an alternating high voltage of up 30kV peak to breakdown the gas between two electrodes. The product of the gas number density and the gap over which the electric field is acting determines the voltage at which a gas breaks down. If the region between the electrodes is packed with a material, the small gaps produced reduce the breakdown voltage that is required and eliminate the need for an expensive short pulse power supply. The voltage breakdowns are of the order of a few nanoseconds (10^{-9} sec) in duration and allow ultra-short current pulses to be produced in the reaction volume using a simple AC power supply. A non-thermal plasma is therefore produced with the exhaust gas remaining at a relatively low temperature compared to the electrons.

The result is an inherent cost saving and reduced maintenance requirement relative to other pulsed plasma concepts. Another advantage of this proprietary technology is that radio frequency interference is minimized by use of a single frequency AC power supply and screened reactor design. This surface discharge concept lends itself to scale up for low cost manufacture, being mechanically simple with no complex electrode system or resonant cavity. It can be constructed in a wide range of geometries to make optimum use of limited space and is of a reduced overall size relative to other plasma devices.

NO_x and Particulate Removal Processes

Chemical reduction of NO_x through the generation of nitrogen atoms in a plasma discharge in a diesel exhaust is energetically expensive[8] and would use a high proportion of the engine power. Furthermore with the levels of oxygen found in diesel exhaust, the plasma is oxidative and gas phase chemical reduction is relatively unimportant independent of the energy input.

A relatively new approach to exhaust aftertreatment is the application of non-thermal plasma or plasma-catalyst hybrid systems. These have the potential for treatment of both NO_x and Particulate Matter (PM) emissions. It has been shown that by combining plasmas with catalysts it is possible to chemically reduce NO_x. The most common approach is to use a 2-stage system relying upon the plasma oxidation of hydrocarbons (by O, OH radicals) to promote NO to NO_2 conversion (the plasma is used in the scheme described to convert NO to NO_2 before reduction on an NO_2 sensitive catalyst)as a precursor to NO_2 reduction over a catalyst. The presence of the hydrocarbons also suppresses further oxidation of the NO_2 to acidic species.

This process can then be summarized as:

$$\text{Plasma} + \text{NO} + \text{Hydrocarbons} + O_2 \rightarrow NO_2 + \text{Plasma Activated Hydrocarbons (PACs)}$$

followed by

$$\text{Catalyst} + NO_2 + \text{PACs} \rightarrow N_2 + CO_2 + H_2O$$

When simultaneous removal of NO_x and particluates is required the situation is different. Previous investigations[7] have reported that a suitably designed plasma reactor, containing a packing material designed to filter and retain particulate matter, can promote oxidation of the particulates in diesel exhausts at low temperatures. It has been suggested that the trapped particulates compete with the hydrocarbons for O and possibly OH radicals.

This is an important consideration in plasma catalyst systems employing an NO_2 selective catalyst, as the particulate oxidation may deplete the key radicals necessary for NO to NO_2 conversion. Thus for simultaneous NO_x and particulate removal, alternative catalyst formulations which are NO selective are required. This process can then be summarized as:

$$\text{Plasma} + \text{Hydrocarbons} + O_2 \rightarrow \text{PACs}$$

followed by

$$\text{Catalyst} + NO + \text{PACs} \rightarrow N_2 + CO_2 + H_2O$$

For combined NO_x and particulate removal the plasma can be controlled to maintain particulate oxidation and enhance NO_x removal. In this sense the system is a 'non-thermal plasma augmented catalyst.' The actual processes involved and its efficiency depend on the choice of catalyst material, the level of hydrocarbons in the exhaust and the amount of plasma power available.

In these examples the catalytic material also supports the plasma activity although this need not necessarily be the case.

SCOPE OF THE ROYAL NAVY/AEA TECHNOLOGY PROGRAMME

The overall objectives of the NTP development programme is for the system to be capable of removing high levels of NO_x with a target value of >90%. Together with the NO_x removal there is also a requirement for particulate removal of >70%. These values are to be achieved with a power budget of 5%. As the development progresses, ship integration issues and Integrated Logistic Support (ILS) are addressed. At the same time comparison is made with the SCR approach.

Target Specifications

The target specifications for a plasma system capable of treating the exhaust from a Royal Navy Type 23 Frigate VALENTA engine are detailed in Table 2.[7]

TABLE 2 – *Target specification for a Type 23 VALENTA Engine Plasma System*

NO_x reduction	> 90 %
Particulate reduction	> 70 %
Hydrocarbon reduction	> 80 %
Noise attenuation	Equivalent to silencer (> 25 dB(A))
Weight	Not greater than SCR
Efficiency effects (plasma power requirements)	Not greater than 5 % power increase
System lifetime (packing components)	Function of mean time between overhaul (30k hours)

Size

The aim is for the plasma to simply replace the existing silencer. (FIG.2)[7] demonstrates in concept how this might be achieved by installation of a plasma bed in the existing exhaust.

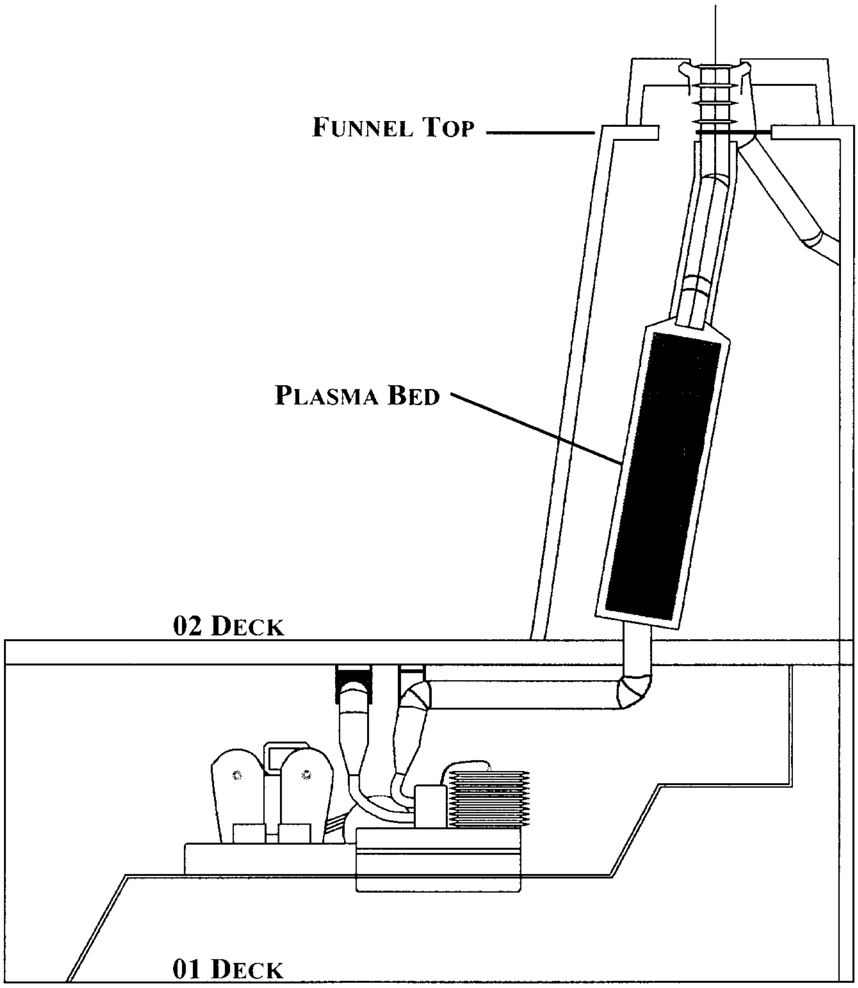

FIG.2 – POSSIBLE CONFIGURATION OF PLASMA BED IN THE EXHAUST

Programme

In anticipation of increasingly stringent future environmental legislation, (FIG.3)[8] shows that the UK MoD(N) is constantly assessing the suitability of future diesel exhaust control technologies for both NO_x and particulate emissions.

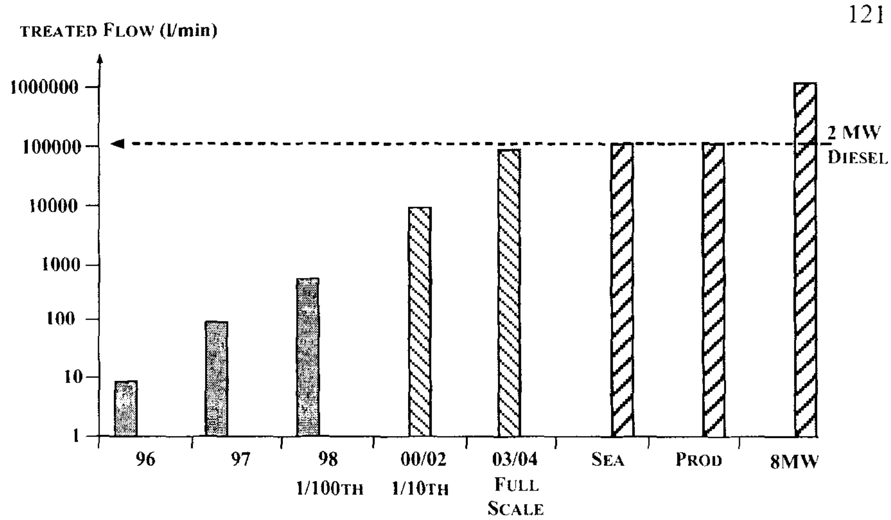

FIG.3 -NTP TIMELINE

In 1995 there was an SCR Demonstrator at Paxman engines in Colchester, UK and an SCR system was fitted on a Type 23 VALENTA at HMS *Sultan*. A five-phase NTP development program commenced in 1996. In 1999, Stage 1 was completed for materials/performance and Ship Integration/Safety Case and a 1/100th demonstration on T23 VALENTA at HMS *Sultan*. In 2000-02, Stage 2 will consist of a 1/10th demonstrator based on a 1.5 MW engine. Possible future work prior to industry considering production would be a full-scale demonstrator (1.5 MW) and sea trials on the prototype trimaran, RV *Triton*. The programme is sufficiently flexible that the timescales can be revised to align legislation and public perception with future MoD(N) ship build requirements (Type 45, Future Surface Combatant - FSC, Future Carrier - CV(F) and Future Attack Submarine - FASM).

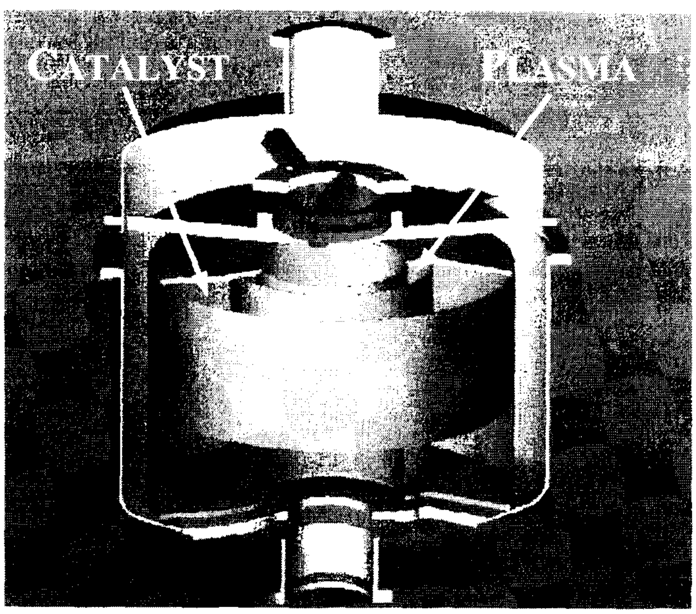

FIG.4 – SCHEMATIC OF THE 1/10TH SCALE NTP SYSTEM[9]

Comparison with the SCR system

In recent years SCR has been promoted as a suitable after-treatment technology for the marine community. SCR is commercially available and it has been fitted to a number of vessels.

The SCR process uses urea ($(NH_2)C_2O$), which is water soluble and non-toxic, mixed into a solution and then injected into the exhaust stream where pyrolysis yields ammonia. It reacts with the NO_x over a catalyst bed according to the reactions:

$$4NO + 2(NH_2)_2CO + 2H_2O + O_2 \rightarrow 4N_2 + 6H_2O + 2CO_2$$

and

$$6NO_2 + 4(NH_2)_2CO + 4H_2O \rightarrow 7N_2 + 12H_2O + 4CO_2$$

An oxidation catalyst is placed downstream of the SCR catalyst to remove any CO formed by partial pyrolysis of the urea and any unburnt hydrocarbons in the exhaust stream. It also acts to reduce ammonia slip in the exhaust.

As mentioned previously, the Royal Navy and GEC Alstom Paxman Diesels undertook a demonstrator trial of a commercially available SCR system to assess the implications of using this technology for warships.[9] The system was tested on a replica exhaust system of a Royal Navy Type 23 Frigate connected to a standard ship fit 1.3MW Paxman VALENTA 12RPA200Z engine. Comparison can be made between the potential benefits of the plasma and SCR systems as shown in Table 3.

TABLE 3 – *Comparison of the NTP and SCR systems*

	SCR	**NTP**
Silencer	Combined Silencer and converter replacing standard silencer.	Combined silencer and reactor (plasma bed) replacing standard silencer.
Principle of operation	A reducing catalyst followed by an oxidising catalyst requiring addition of a reductant (urea solution) prior to the reducing catalyst.	Electrically augmented catalytic converter requiring no additional consumable to achieve NO_x reduction and hydrocarbon oxidation. Requires electrical power. Uses hydrocarbons in the exhaust stream.
NO_x reduction	> 90%.	> 90%.
Transient response	Urea injection must be matched to NO_x production rate. NH_3 slippage possible.	No urea reductant therefore no NH_3 slippage problems.
Control response	Control of urea feed rate during transients difficult due to long response time of catalyst.	Effectively instantaneous response to changing NO_x levels during transients. Plasma input power level can be varied with load to ensure optimum power usage.
Low load running	Ammonium sulphate formation limits temperature range limited > 270°C. Clogging and corrosion of system. Low load SCR cutout required. (> 25% load)	No urea reductant so no ammonium sulphate formation. At temperatures < 120°C operation less efficient leading to emission of some untreated NO_x.
Catalyst fouling	Catalyst fouling/deactivation from fuel sulphur and deposition oil additives.	Presence of plasma ensures continuous cleaning of material (potential HFO operation).
Noise attenuation	Not as efficient as silencer.	Equivalent to silencer (25 dB(A)).

Weight	20 - 50 % additional weight to silencer	Target is similar to SCR
Space	Space requirement for the converter/silencer similar to original silencer.	Design such that same or less than as for present silencer. Requires space for power supply.
Additional storage *	Storage space for urea and additional fuel.	Storage space for additional fuel however no separate reductant storage space required.
Lifetime	Catalyst predicted lifetime 10 - 40k hours (a function of the fuel sulphur content and low load running).	Function of engine mean time between overhaul (30k hours). The system shows tolerance to the sulphur level in the fuel.
Capital cost	Capital cost approx. £20 - 35k per MW at 1-2 MW scale.	Target capital cost less than or comparable to SCR.
Operating cost *	Operating cost £1.5 – 2 per MWh (based on urea cost).	Target operating cost < £1.5 - 2 per MWh (function of fuel cost).

* Function of operational requirement

Conclusions

The emissions from marine diesel engines should be the main emphasis on the reduction of engine pollution where primary measures are preferred to reduce the emissions below the current limits. These internal measures bear significant potential for NO_x reduction already at the present state of the art. The key to the development and successful application of internal measures for emission reduction lies in a thorough understanding of the internal combustion and the combined emission generation processes.

Facing the huge costs and the significant problems of temporally and spatially resolved measurements inside diesel engines is vital to increasingly utilizing modern simulation tools to complement and explain experimental results. Only by this way the understanding of the processes needed to optimize emission behaviour within the given time and cost frames.

The Royal Navy has embarked on the secondary treatment of NTP as an alternative method to reduce present emissions levels and are confident that NTP will be commercially viable against SCR. The Royal Navy strategy states that:

(*a*) The RN willingness to abide by the emission legislation within the United Kingdom.

(*b*) The RN is committed to maintain a world-wide naval presence and thus must take steps to ensure that failing to meet local pollution regulations will not impair its operational capability.

(*c*) Selected Catalytic Reduction is not an emission reduction measure acceptable to the Royal Navy.

(*d*) The RN believes that legislation should be equitable and should not penalize any particular group of marine engines.

(*e*) Marine engineers must educate both the seaman officers and manufacturers of the seriousness of the impact posed by exhaust emissions legislation to all seagoing vessels.

The newly introduced IMO regulations now make the reduction of NO_x output from marine diesel engines a necessity. It may be possible to meet the current IMO regulations by means of 'primary' engine measures but likely that any further significant reductions would require a 'secondary' after-treatment technique.

Whilst 90% NO_x reduction legislation may appear some way off, given the life cycle of a warship it is necessary to consider suitable after-treatment equipment now. SCR is currently the only available technology proven at full scale to meet the lowest NO_x limits but offers significant disadvantages in the need to carry potentially large amounts of urea.

Based on a process that is electrically rather than chemically driven, NTP could approach the ultimate device for removing NO_x and particulate matter simultaneously from marine diesel exhaust.

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