THE IMPACT OF ENGINE EMISSIONS LEGISLATION ON PRESENT AND FUTURE ROYAL NAVY SHIPS

BY

LIEUTENANT COMMANDER R. E. J. ENGLISH BASc MSc MCGI CF
AND
COMMANDER D. J. SWAINSON CEng MIMechE RN
(Director General Fleet Support (Equipment and Systems)—ES213)

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ABSTRACT

The article identifies the impending engine emissions legislation, the technology available to comply with this legislation and the impact on current and future naval ships. The Naval Support Command is developing technical solutions to the proposed regulations and has been investigating technologies ranging from simple engine adjustments to exhaust gas treatment systems. Sulphurous emissions are not considered a problem for Royal Navy ships because of the low sulphur content of its fuel. Nitrogen based emissions are significantly more difficult to reduce. The solution will depend upon factors such as the ship's mission, its prime mover fit, and Ministry of Defence policy.

Introduction

The 1992 environmental summit in Rio de Janeiro highlighted both the need to do something about the continued pollution of the environment and the difficulty of achieving consensus among nations on the sensitive issues involved. Generally speaking, international agreement is only achieved after years of work by government officials, industrial representatives and professional lobbyists. Any agreement reached must then be subjected to political scrutiny within each country prior to becoming law.

The lengthy time frame of achieving this consensus encourages nations to enact their own legislation. In the absence of any agreed emission law, it is the regional or national legislation which concerns the Royal Navy. The lead time for changes to these laws is much shorter than that required for international agreements and can be influenced by internal pressures which are unique to each country.

The entire marine engineering community, both civilian and military, will soon have to contend with engine emissions legislation. Until recently regulations have primarily affected road transport and stationary plants. That is about to change. The International Maritime Organization (IMO), under the auspices of the United Nations, is preparing a new annex to the Maritime Pollution regulations which will attempt to reduce engine emissions (especially for reciprocating internal combustion engines). These regulations may be in force as early as the autumn of 1997. Due to regional and national proposals, nearly all shipping (civilian and military) will be affected by emissions regulations.

Although the best available figures estimate that global shipping is only a minor contributor to worldwide atmospheric emissions, governments are under pressure from environmental lobby groups to take decisive action on all producers of pollutants. In addition, research sponsored by Norway has shown that selected countries, such as the Scandinavian nations which are wedged between the heavy trading routes of the Baltic and North Seas and rely heavily upon marine transportation, are more affected by maritime exhaust emissions than a global average indicates.

Aim

The aim of this article is to explore the impact of impending engine emissions legislation on in-service Royal Navy ships and the design of new ships.

Scope

This article deals primarily with diesel exhaust emissions control with some discussion applicable to gas turbines. Impending regulations, available and developing technologies and the impact of emissions control on the design and operation of ships are also discussed. Due to the nature of the imminent legislation, the focus is upon reducing the levels of oxides of sulphur and nitrogen.

Regulations

The IMO regulations proposed to come into effect in 1997 concentrate on reducing oxides of sulphur (SO_x) and nitrogen (NO_x). The land based use of Selective Catalytic Reduction (SCR) equipment to reduce NO_x emissions has raised the expectations of both politicians and environmental pressure groups. While graded introduction is anticipated, best available technology legislation will ensure that national laws will ultimately be based on what can be achieved by selective catalytic reduction or equivalent technology as these can reduce NO_x levels by over 90%. Most proposed regulations are aimed at the reciprocating engine but the California Air Resource Board (CARB) has also proposed emissions limits for gas turbines.

Most European countries are waiting to see what limits IMO sets but they may apply even stricter rules if they are not satisfied with the emissions limits proposed by IMO. The Baltic States have declared the Baltic Sea a 'Special Region'[1] thus creating the opportunity for tighter regulations because of the region's heavy reliance on marine transportation.

Although current proposals concentrate on SO_x and NO_x emissions, it is clear that, when satisfactory measurement techniques are developed and when current regulations are met, limits and levels of other emissions will come under increasing scrutiny. Stricter regulations are expected in 5 year cycles. Regulations for other emission species (such as Unburnt Hydrocarbons (UHC) and Particulate Matter (PM)) can be expected in the next century. It is almost certain that, in the years ahead, ships will be faced with even lower limits for more and more emissions species.

California, historically the North American lead on environmental issues, has proposed what will be the strictest regulations. The proposed California regulations for 1995 represent the target for the RN's blue water ships. In order to operate on a worldwide basis, these ships must be able to comply with the regulations of those countries in whose waters they operate. The projection of sea power necessitates frequent transits in other countries' coastal waters, normally as a welcome visitor, and thus the RN must be prepared to comply with their laws. Some would argue that, if it is necessary to enter another country's waters in an interventional role, respecting that nation's laws is not a prime concern. This may apply in a global conflict but recent operations in support of peacekeeping efforts in the former Yugoslavia have required warships to remain in the confined waters of friendly nations for extended periods to enforce UN sanctions.

The Environmental Protection Agency in the USA has proposed a system of fees which would heavily penalize polluters and encourage ships to treat their exhaust emissions. It is possible that California will put its proposals on hold and evaluate the federal proposals that are being defined as an alternative.

Policy

MoD policy

MoD policy on the environment states that the MoD will comply with UK legislation and international conventions and regulations to which the UK is a signatory. Crown immunity will only be invoked where operationally necessary. This prohibits the use of the warship exemptions present in so many regulations. MoD policy also requires the Royal Navy to respect host nation regulations and to be seen to be taking a lead in environmental issues. As a highly visible instrument of government, the MoD must ensure that the public has a positive perception of its efforts in this field.

Royal Navy policy

Royal Navy policy is still being defined. A strict interpretation of the letter and intent of MoD policy implies that, if the Royal Navy is to remain a blue water navy capable of deploying anywhere in the world, it must be able to comply with the most stringent regulations coming into effect (i.e. those of California) at least for the period of operating in the relevant controlled waters.

The problem

From the Royal Navy viewpoint, a number of problems must be faced:

(*a*) The footprint of marine equipment for ships must be defined well in advance of the build to allow for weapon system development and production. However, the engine is likely to be in use for 30 years and could still be in use 50 to 60 years from the time the design is fixed.

(*b*) Present production engines are incapable of meeting the regulations which may be in force by the turn of the century. Gas turbines are more likely to be compliant, but they suffer from poor part load fuel consumption. The development of the Inter-Cooled Regenerative (ICR) gas turbine should start to address the fuel consumption issue, but it is still under development at the moment and only for multi-MegaWatt applications.

(*c*) The continuing fiscal restraint imposed by governments, combined with the operators' fixation with technological change in weapons systems, will limit the funding available to encourage manufacturers in their exhaust emissions reduction development programmes.

(*d*) The unpredictability of future legislative levels, based on experience of other environmental issues, impedes significant progress on this issue. Policy and design solutions are difficult to develop when the regulations are not in place.

Emission control technologies

There are generally two families of emissions control technologies (FIG. 1):

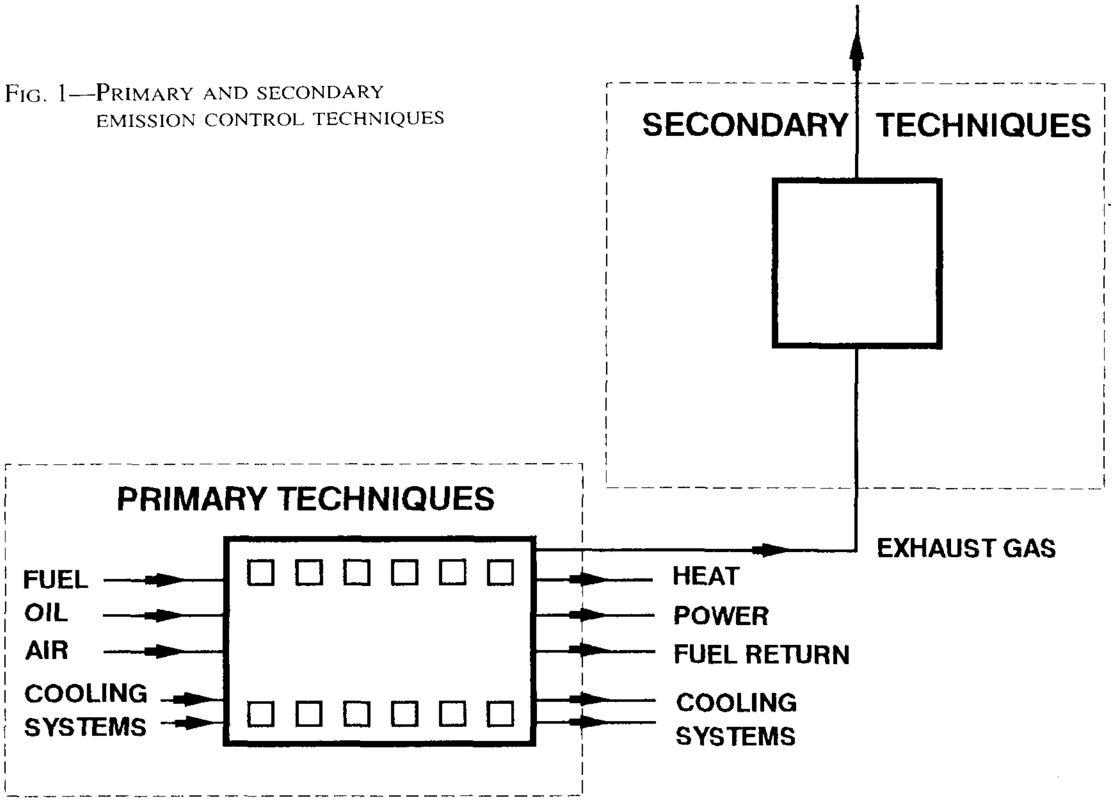
Primary technologies

Those measures incorporated into the engine or its supply systems.

Secondary technologies

Those measures fitted downstream of the engine in its exhaust system.

FIG. 1—PRIMARY AND SECONDARY EMISSION CONTROL TECHNIQUES



Oxides of sulphur

One of the most significant pollutants being targeted is sulphur exhausted in the form of SO_x which is a significant contributor to acid rain. Any significant amount of sulphur in the exhaust is primarily related to the fuel; therefore reducing sulphur in the fuel should reduce sulphur emissions.[2] The Royal Navy does not anticipate having to take specific action to reduce sulphur levels in fuel. F-76 is considered to be a low sulphur fuel (<1%) and the petroleum industry is being forced by international pressure to reduce sulphur levels in all fuels. If sulphur levels are reduced, SO_x levels will fall.

Of course every change carries a penalty. The effect that low sulphur fuel will have on the life of engine components is now being examined, following reports of problems with engines running on low sulphur fuel in Scandinavia. These problems centre on the lubricity provided by sulphur compounds in fuels for devices with very fine clearances, such as injectors.

Oxides of nitrogen

While sulphur emissions can be dealt with fairly easily, a far more difficult emission to control is the produced by the engine. Because of its impact on the environment it is the subject of very restrictive proposed legislation. The collective term NO_x in this context pertains to nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O). These gases contribute to smog and acid rain and can cause respiratory problems if directly ingested.

Technical solutions to the NO_x problem

The solution will depend upon a number of factors including a ship's mission, its engine fit and detailed government policy on engine emissions. A vessel whose peacetime mission would restrict it to home waters may only be required to comply with local UK regulations. There are some suggestions that vessels, such as tug boats, could be considered as a part of the emissions burden of its base rather than as an independent unit. Ships with an international mission, such as major surface combatants, may be required to comply with the most stringent regulations proposed anywhere (i.e. the California proposals) in order to ensure complete operational flexibility. It is possible that the solution will have to be customized for each class of ship, if not each ship.

Four potential situations present themselves. Ships may have to:

(*a*) Resort to waivers.

(*b*) Comply with proposed IMO regulations by implementing fairly minor changes to the engines.

(*c*) Comply with or exceed proposed IMO regulations by:
- Extensive engine modifications.
- Selection of low emissions rated engines, with possible increases in fuel consumption and maintenance in comparison with incumbent engines in anticipation of more robust IMO regulations in the future.

(*d*) Comply with CARB limits by the use of:
- Secondary techniques.
- Primary techniques in combination with changes/restrictions to operating profiles.
- Restrict operations in order to use exemptions.

Primary NO_x reduction techniques

The formation of oxides of nitrogen is dependent on three factors:

(*a*) temperature of combustion.

(*b*) residence time in the combustion chamber.

(*c*) concentrations of nitrogen and oxygen.

Most of the research conducted into the reduction of oxides of nitrogen by primary methods has concentrated on reducing the temperature of combustion. A diesel engine's high efficiency is derived from the high maximum cycle temperature. It is this efficiency which makes the diesel suitable for so many applications but is also its Achilles heel in terms of NO_x emissions. The problem is exacerbated by the exponential relationship between temperature and nitrogen oxide formation with a rapid increase in levels at temperatures above 1400°C. It is not surprising that high NO_x levels are generated with temperatures in the kernel of the injector spray reaching 2800°C. Since gas turbine combustion maximum temperatures are presently constrained by material considerations to approximately 2000°C, the NO_x problem is not so severe. However, gas turbine manufacturers will need to be careful about increasing efficiency through raising cycle temperatures or they will quickly lose their advantage in NO_x emissions.

Table I, based upon a report commissioned by the MoD, identifies the more well established primary techniques, their effectiveness and the extent of modifications that may be necessary for implementation. A secondary exhaust treatment system is also identified for the purpose of comparison. Primary NO_x reduction techniques range from relatively minor one-time engine adjustments to major modifications:[3]

(*a*) Retarding injection timing reduces peak pressures and thus lowers maximum combustion temperature.

(*b*) Reducing the temperature of the charge air entering the cylinders at high loads by increasing charge air cooling, results in a lower temperature at the end of compression. This method has limited applicability due to the restricted range of air temperatures.

(*c*) Peak temperature can also be reduced by increasing the amount of air trapped in the cylinder, without a corresponding increase in fuel.

(*d*) High injection pressures and emissions optimized injector design will create a more homogeneous fuel/air mixture thus reducing the extent of rich combustion zones at high temperatures.

(*e*) 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 system, which controls the period of injection as well as its timing. The number of discrete load/speed settings would be constrained only by the capabilities of the control system which operates the solenoid. This is similar to systems now adopted for diesel truck engines.

(*f*) Variable rate injection attempts to prevent a large pressure rise by injecting fuel at a low rate to initiate combustion followed by rapid injection of the remaining fuel.

(*g*) Pilot injection attempts to achieve an effect similar to variable rate injection by injecting a small amount of fuel ahead of the main fuel charge.

(*h*) There is some controversy about high or low rate of injection techniques. Proponents of high rate injection claim that it prevents combustion after the end of the expansion stroke. Opponents claim that it increases peak pressures and temperatures and thus creates even more NO_x. High rates of injection may be beneficial for particular engine designs depending on factors such as injection system and combustion chamber design.

TABLE I—*NO_x reductions techniques*

Technique	NO_x Reductions Achieved	Extent of Modifications Required
Retard Injection	30%	Engine adjustment.
Reduce Charge Air Temperature	30%	Installation of improved charge air cooling.
Increase Trapped AFR	25%	New turbocharger.
Increase Injection Pressure	20%	New fuel pumps. injectors, fuel lines.
Variable Injection Timing	?	New cams, injectors and controllers.
Variable Rate of Injection	20%	New cams, injectors and controllers.
Pilot Injection	15%	New injectors and controllers
High/Low Rate of Injection	?	New injectors, pumps and controllers.
Exhaust Gas Recirculation	40%	Exhaust reconfiguration. Exhaust filter and cooler.
Water Addition	60%	Water production storage. New cylinders heads, cam shafts, injectors, fuel and water systems. Controller modifications.
Selective Catalytic Reduction	95%	External to engine. Reagent storage. Reactor heating. Silencer replaced by reactor.

These techniques reduce NOx levels but they can also increase smoke and particulate levels. Techniques such as retarding the injection timing increase fuel consumption.

Exhaust Gas Recirculation (EGR)

EGR (FIG. 2) is effective at reducing NO_x levels due to the higher specific heat capacities of the principal exhaust components (carbon dioxide (CO_2) and water) in comparison with air. Peak cylinder temperatures are thus reduced. This technique has been tested successfully and is used in some heavy goods vehicle diesel engines. Drawbacks include increased smoke and particulate levels. It will become more viable for production marine engines when an effective soot filter has been developed to cope with the increased particle content of the exhaust.

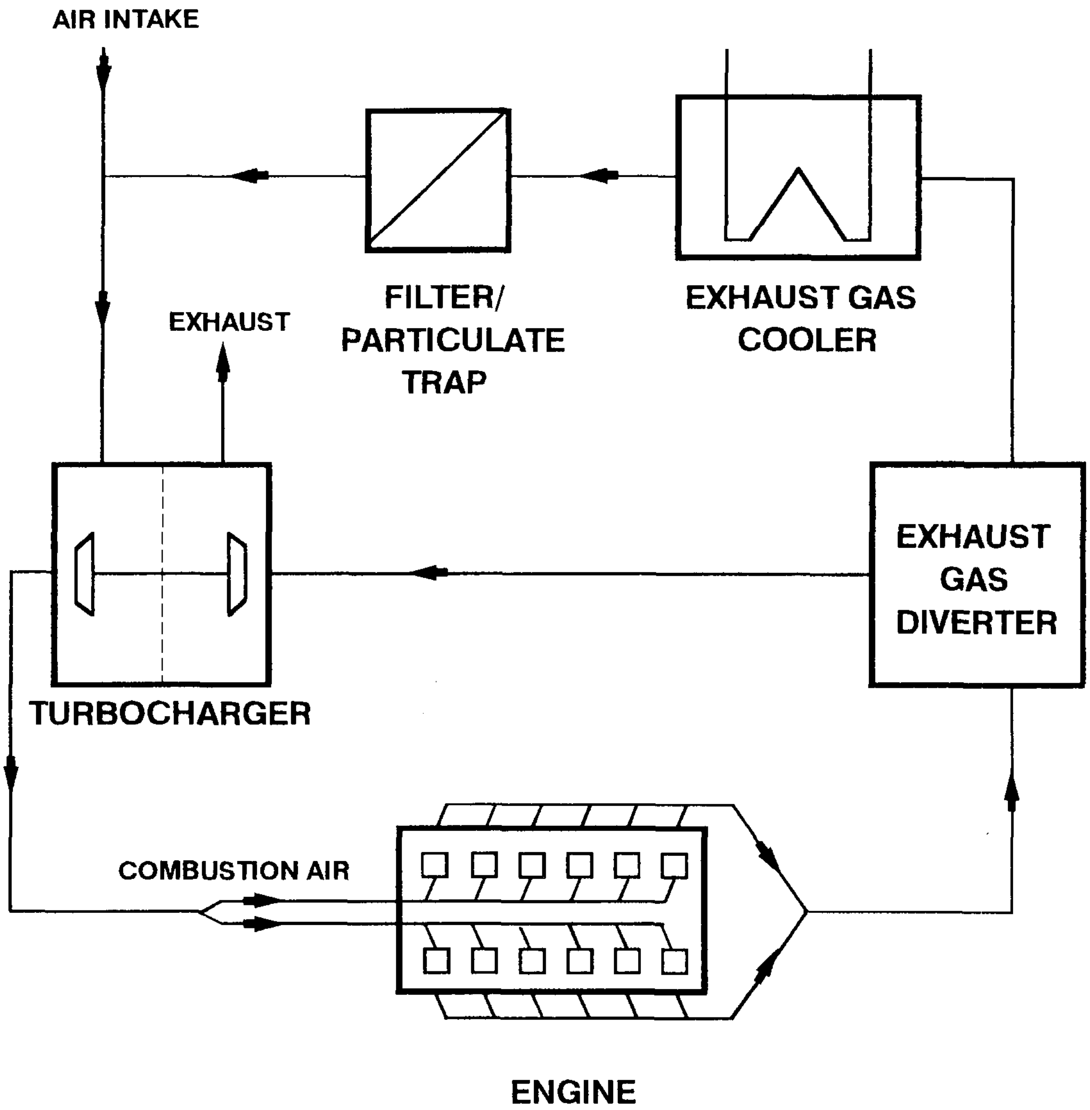


FIG. 2—EXHAUST GAS RECIRCULATION

Water treatment techniques (FIG. 3)

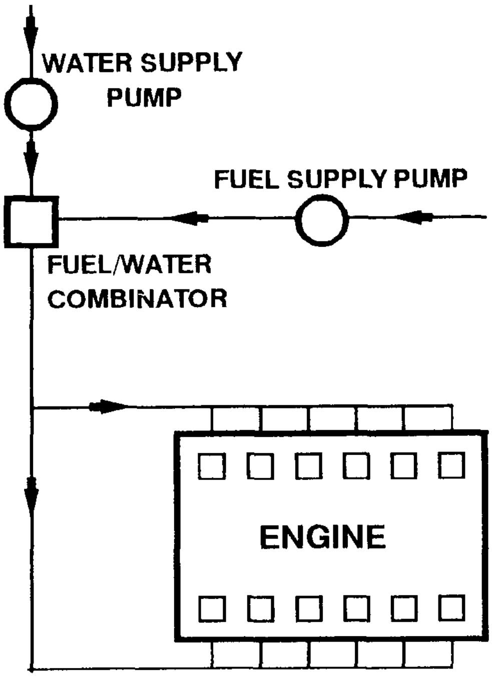


FIG. 3—WATER TREATMENT

Water can be added to the combustion chamber by either mixing the fuel and water, fumigating the intake air or injecting water directly into the cylinder. These techniques are promising. At high water/fuel ratios, up to 60% NO_x reduction[5] can be achieved 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. Water injection techniques must be evaluated to ensure that corrosion problems in pumps, injectors, fuel lines, and the engine are not created. It may be necessary to control water injection to prevent free water in the engine on low load running and engine shut down.

In order to achieve substantial NO_x reduction, these systems require a significant amount of water. Initial indications are that this water must be at least of potable quality and more likely of near boiler feed water quality in order to prevent corrosion problems in the engine or associated systems. There are design proposals that may reduce the water quality required. Possible sources include increased water storage capacity or a water production facility with the commensurate increase in power required to operate it. It may be possible to use engine exhaust evaporators and thus put waste heat to use. Exhaust gas boilers and evaporators have not been an unqualified success in naval vessels.

Primary techniques in combination

It may be possible to combine emission control techniques in order to achieve greater reductions in NO_x levels. Work in combining techniques has only recently started and it should not be assumed that the effects of such combinations will be directly cumulative because of the interactions that take place in the combustion chamber.

Secondary techniques

Over 90% of NO_x can be removed through the use of an exhaust gas after treatment process known as Selective Catalytic Reduction (SCR) (FIG. 4). Oxides of nitrogen are encouraged to form gaseous nitrogen (N_2) and water by use of a catalyst and a chemical re-agent. Ammonia or urea is mixed with the exhaust gases upstream of a catalyst embedded into a matrix. The reaction must take place within a temperature range of 300 to 450 °C. This technique can be used in combination with an oxidising catalyst which is effective in reducing hydrocarbon and carbon monoxide (CO) levels. SCRs are at least a technical solution to the NO_x problem. Because of the relatively rapid implementation of exhaust emission legislation in some countries, the ease of adding a SCR to an existing engine has made it the method of choice in many land-based applications. This idea is spreading to the commercial marine environment. Marine installations are at sea in the Baltic and Californian waters.

Marine SCRs have been in service for over 10,000 running hours. It has been suggested that the catalyst and its supporting substrate can be recycled but waste material disposal could be a problem. The SCR reactor can apparently be as small as the standard silencers used with large (multi MW) engines and can in fact replace silencers as they have similar noise attenuation capabilities. The main drawbacks of SCR technology for a warship would be:

(*a*) Cost (procurement and operating).

(*b*) Requirement to store large quantities of reagents (i.e. 8–10% of fuel capacity for urea) or to produce large quantities of water for mixing with urea pellets.

There is work under way to develop a catalyst system for diesels, which would be similar to those catalysts used for spark ignition petrol engines. Work is also under way in industry to develop novel exhaust gas treatment systems that do not rely upon chemical reagents.

Cost of emissions control

A rough order of the costs for implementing some No_x control measures is included in Table II[3] (an update of the figures given in reference 2). These costs relate to hardware costs for the actual technique. No account is made of increased manpower requirements, maintenance or the provision of extra equipment, for example water production facilities for water fumigation.

TABLE II—*Typical investment and operating costs for selected NO_x emissions reduction measures for diesel engines*

Technique	NO_x Reduction	Investment Costs (£/kW)	Operating Costs (£/MWh)
Selective Catalytic Reduction*	> 95	80–100*	1.50–2.00
Injection Retardation	< 30	—	1.88
Exhaust Gas Recirculation**	< 40	19–38	0.63
Direct Water Injection**	< 60	38–47	0.31

Notes:

* Price will be driven by demand and should fall with increasing market size.

**Investment costs are based on manufacturing and are therefore unlikely to come down with demand. Increased through life maintenance costs are anticipated with these techniques which may erode their apparent cost advantage.

Monitoring systems

Simple, robust and inexpensive gaseous emissions monitoring systems are not yet readily available. These systems will become more important if very strict regulations come into effect. Portable monitoring systems will be necessary to ensure that legislation is enforceable. They will be needed for at least three purposes:

(*a*) 'Real time' closed loop control of controllable systems based upon actual emissions levels instead of parameters such as actuator position.

(*b*) Enforcement, inspection, and surveillance by inspecting authorities.

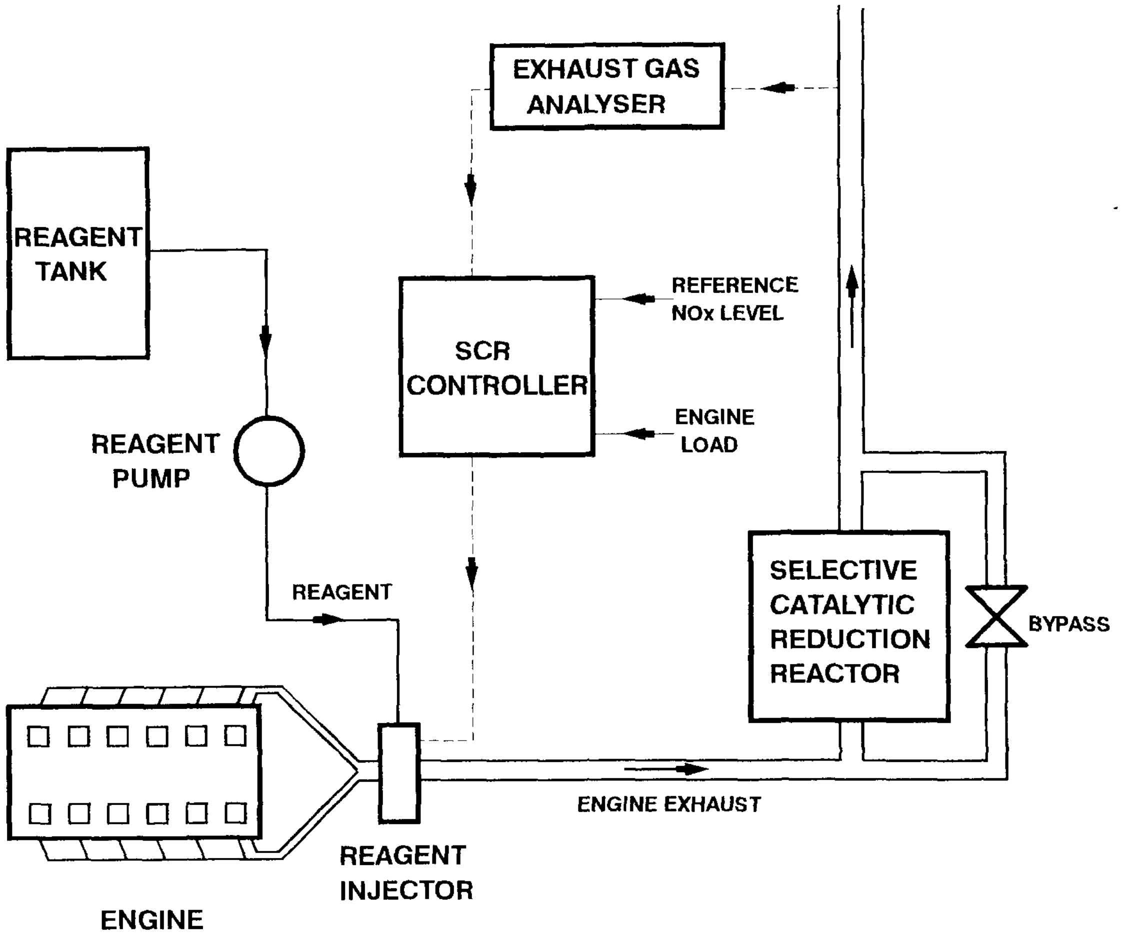


FIG. 4—SELECTIVE CATALYTIC REDUCTION SYSTEM

(*c*) Verification of the correct operation of emission control equipment through 'black box recorders'.

Impact of emissions control equipment on naval ships

Changes to operating profiles such as reducing speed must be very carefully considered, as operational effectiveness may be diminished. Emissions other than NO_x and total fuel consumed may increase. Without emissions reduction measures, Royal Navy ships may face restrictions on their access to ports/nations based upon their environmental performance.

The costs of procuring and operating naval vessels will increase. There may be an increase in the maintenance work load for systems which add to the complexity of the engine operation. Ships will require more time and resources to conduct this maintenance. There will also be an added administrative burden to ensure that certification, inspection, record keeping and verification procedures are followed.

Conclusions

Legislation restricting the levels of gaseous emissions from diesel engines will be coming into effect. These regulations are aimed initially at SO_x and NO_x. Further regulations on CO, CO_2, UHC, and PM are likely. It is entirely possible that these regulations will be reviewed and tightened regularly. The ultimate aim of legislation must be to lower overall emission levels worldwide.

Emissions legislation will have an impact on the present fleet and on new naval ship designs. The in-service fleet will be faced with issues such as restrictions on their operations, increased fuel consumption and engine modifications. New ship designs will have an emissions requirement in staff targets, requirements and procurement specifications. Procurement and operating costs for new ships will increase marginally in order to comply with stated MoD policy.

The proposed SO_x limits do not present an immediate problem for Royal Navy vessels. Sulphur levels in its F-76 fuel are less than levels proposed by the IMO.

If the inter-cooled regenerative technology improves gas turbine fuel economy without significant detriment to emissions and if the technology becomes available for small power ratings (i.e. 0.5–5 MW), gas turbines stand a good chance of replacing reciprocating engines in naval ships.

A number of technical solutions to the NO_x problem are becoming available. The technology selected will depend upon the marine regulations, cost, and effectiveness. Solutions may be unique to each ship's design and mission.

Some primary method technologies will be capable of satisfying all but the most stringent legislation presently being discussed; however, at the rate at which legislation is changing this may not suffice. Primary methods cannot achieve levels proposed by CARB. If future regulations are not anticipated, the navies of the world will have to continue funding unscheduled development.

SCR may be a solution for some ships of the Royal Navy, but other post combustion techniques under development may provide an alternative, and perhaps a better solution (either solely or in combination with developed primary methods). If SCRs are selected for ship designs, warships will have to store and handle reagents such as urea in fairly large quantities. It is possible that the best route to follow from an environmental standpoint is to minimize specific fuel consumption (and thus CO_2, CO, PM, and UHC) and remove NO_x through the use of SCRs.

Monitoring systems will provide a method for improving emissions reduction system control and a mechanism for enforcing regulations.

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