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TP 14373E

Cost-Benefit Study of Marine Engine NOx Emissions Control Systems

A Case Study of the MV *Cabot*

Prepared for
Transportation Development Centre
of
Transport Canada

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Unless otherwise indicated, all monetary amounts are in Canadian dollars.

Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

Un sommaire français se trouve avant la table des matières.

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16. Abstract

This study examined the direct costs, environmental emissions reduction benefits and applicability of six NOx emissions control technologies developed for use on marine diesel engines: continuous water injection to the charge air (CWI), fuel-water emulsions (FWE), direct water injection (DWI), exhaust gas recirculation (EGR), humid air motor (HAM) and selective catalytic reduction (SCR). The cost and environmental benefits of each technology were estimated based on their hypothetical application on a Canadian case study vessel, the M.V. *Cabot*.

CWI appears to be the most cost-effective system for low levels of NOx reductions, and would be best used for trimming NOx emissions to meet minimum IMO limits. FWE is a promising, medium-cost technology for achieving medium levels of NOx reduction, and appears to be a practical retrofit solution. DWI may be effective for medium levels of NOx reduction, but may not be a practical technology for engine retrofits. The relatively new HAM system, despite high initial capital costs, appears to be a practical, cost-effective method of achieving medium to high levels of NOx reduction, and can be retrofitted in the engine room without need for new water supply. SCR has the highest unit cost of the five technologies analyzed, but can achieve almost complete NOx reduction, making it best suited for vessels operating in regions having very stringent environmental control programs and financial incentives.

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16. Résumé

L'étude a consisté à examiner les coûts directs, les avantages du point de vue de l'environnement et l'applicabilité de six technologies de réduction des émissions de NO_X conçues pour des moteurs diesel marins : injection continue d'eau dans l'air de suralimentation (CWI, *continuous water injection*), émulsions carburant-eau (FEW, *fuel-water emulsion*), injection directe d'eau (DWI, *direct water injection*), recyclage des gaz d'échappement (EGR, *exhaust gas recirculation*), humidification de l'air d'admission (HAM, *humid air motor*) et réduction catalytique sélective (SCR, *selective catalytic reduction*). Le coût et les avantages pour l'environnement de chacune des technologies ont été évalués d'après leur application hypothétique à un navire canadien, le NM *Cabot*.

La CWI semble être le système le plus économique pour réduire par de faibles marges les émissions de NO_X. Elle serait donc particulièrement à propos pour obtenir de faibles réductions de NO_X afin de satisfaire aux exigences minimales de l'Organisation maritime internationale (OMI). La FWE est une technologie prometteuse et moyennement coûteuse, qui mène à des réductions moyennes des NO_X. Elle semble en outre représenter une solution de rattrapage pratique. Quant à la DWI, elle permet elle aussi des réductions moyennes des NO_X, mais elle se révèle peu propice à une installation en rattrapage. Le système HAM, qui est relativement nouveau, semble offrir un bon rapport coût-efficacité, en dépit de coûts d'immobilisation élevés. En effet, il permet des réductions de NO_X allant de moyennes à fortes et il peut être installé en rattrapage sans qu'il soit nécessaire de prévoir un nouveau circuit d'alimentation en eau. Parmi les cinq technologies étudiées, la SCR est associée au coût unitaire le plus élevé, mais elle permet d'éliminer presque totalement les NO_X. C'est donc la technologie qui convient le mieux aux navires exploités dans des régions qui appliquent des programmes très rigoureux de protection de l'environnement et qui peuvent bénéficier d'incitatifs financiers.

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Executive Summary

Introduction

This study examined the direct costs, environmental emissions reduction benefits and applicability of six NOx emissions control technologies developed for use on marine diesel engines. The six identified technologies were: continuous water injection to the charge air (CWI), fuel-water emulsions (FWE), direct water injection (DWI), exhaust gas recirculation (EGR), humid air motor (HAM) and selective catalytic reduction (SCR). The cost and environmental benefits of each technology were estimated based on their hypothetical application on a Canadian case study vessel, the M.V. *Cabot*, a RoRo container ship with a 14,600 gross rated tonnage.

The costs of each marine NOx control technology for the M.V. *Cabot* are summarized in Table 1. Costs for exhaust gas recirculation (EGR) technology were not developed because it is currently not a viable option for marine engines. The NOx reduction levels ranged from 22% to 95%, and the unit costs ranged from a savings of $143 per tonne to a cost of $552 per tonne of NOx reduced.

Table 1: Cost of NOx Control Technologies for the M.V. *Cabot*

	Installed Cost ($)	Operating Cost/(Savings) ($/y)	Annualized* Cost/(Savings) ($/y)	NOx Reduction (%)	Unit Cost ($/tNOx)
Continuous Water Injection	$51,000	($32,000)	($26,000)	22%	($143)
Fuel-Water Emulsions	$325,000	$54,000	$91,000	50%	$217
Direct Water Injection	$413,000	$137,000	$184,000	50%	$443
Humid Air Motor	$1,048,000	$1,500	$120,000	70%	$206
Selective Catalytic Reduction	$1,156,000	$306,000	$436,000	95%	$552

* Annualized costs include operating costs and total installed costs amortized at 10% over 23 years.

The lowest cost technology evaluated was continuous water injection (CWI) to the charge air. Evaluated at the maximum NOx reduction level achieved during official testing, CWI had the lowest total installed costs, the only identified fuel savings, and the lowest NOx reduction potential (22%). The most expensive technology was selective catalytic reduction (SCR). This achieved the highest possible NOx control (90-99%), but with high capital and installation costs and high operating costs due to urea consumption. Fuel-water emulsion (FWE) and humid air motor (HAM) systems achieved medium-level NOx reductions at a moderate cost. HAM systems were very capital intensive, but had negligible operating costs and achieved very good environmental performance. FWE systems had relatively low initial costs, but incurred some slight fuel penalties. Direct water injection technology was another medium-level reduction technology, but had slightly higher capital and operating costs.

Case Study Vessel: M.V. *Cabot*

For this study, a benchmark vessel was selected to serve as the basis for the cost-benefit analysis. The M.V. *Cabot* is one of three ice-class RoRo container ships operated year-round by the commercial shipping company Oceanex, based in Montreal, Quebec. The *Cabot* makes regular weekly round-trip runs between Montreal and St. John's, Newfoundland. Built in 1979, it has a gross rate tonnage of 14,597 and is powered by two twin Pielstick PC2.5 V12 engines rated at 5.8 MW each (11.6 MW total). The ship uses IFO 180 fuel oil most (91%) of the time and marine diesel when near port (9%). The engines operate for 6,000 hours per year, at an average load of 85% of MCR over approximately 48 weekly runs. Using an assumed uncontrolled NOx emissions rate of 14.0 g/kWh, the total uncontrolled NOx emissions are estimated at 831 t per year.

This ship was chosen as a basis for this study because it is a medium-sized cargo vessel operating within coastal waters and using medium-speed marine engines. While it is not a "Laker" (operating in the freshwater Great Lakes) and has some unique features, it was considered to have typical characteristics of middle range Canadian commercial vessels.

Continuous Water Injection

CWI to the charge air is a relatively simple method of reducing NOx by up to 30%, and particulate emissions by about 25%, without engine modifications. A fine, freshwater mist is injected directly into the hot compressed air of the turbocharger outlet. A system was designed for demonstration on a B.C Ferries vessel, but there is no known system currently in continuous operation. The installed cost of the technology is about $50,000. In field tests conducted by Environment Canada, CWI achieved a 22% reduction in NOx and an average reduction in specific fuel consumption of 1%, which resulted in a net saving of approximately $143 per tonne of NOx reduced. CWI is not recommended at water-fuel ratios above 25% due to expected fuel consumption penalties.

Table 2: Summary of NOx Control Technologies

Technology	Principle	NOx Control	Particulate Control	Other Emissions	Installed Costs	Operating Costs	Supply	Major Issues
Continuous Water Injection (CWI) **($145)/tNOx**	water mist added to compressed air before cylinder; cools air, absorbs heat	10-30%	0-25%	HC, CO, SO_2 unchanged	$4-5/kW (low); low installation	minor reduction in specific fuel consumption at low levels	developing; M.A. Turbo/Engine Design; customized	concern about condensation, deposition
Fuel-Water Emulsions (FWE) **$217/tNOx**	microfine water droplets embedded in fuel droplets; explosive vapourization reduces large HCs	30-50%	medium	HC, CO reduced up to 50%	$28/kW; low capital; high installation	fuel penalties; minor part replacements	new (2 years); MAN B&W; Several vendors (RESON; SIT)	high pressure and low viscosity required; emulsion stability; 1.5% fuel penalty
Direct Water Injection (DWI) **$443/tNOx**	high-pressure water injected into cylinder separately before fuel; cools cylinder prior to combustion	40-60%	low	unknown	$36/kW (med); high capital; low installation	fuel penalties; minor part replacements	new (2 years); Wärtsilä	2.1% fuel penalty; compatibility with older engine designs
Exhaust Gas Recirculation (EGR)	cool filtered exhaust gas added to charge air; lowers temperature and increases pressure	up to 50%	very poor	unknown	2% of engine	unknown	not available	fouling, deposition, rapid corrosion
Humid Air Motor (HAM) **$206/tNOx**	compressed air humidified (saturated) by water vapour; cools air, absorbs heat	60-80%	medium	unknown	$98/kW (high); high capital; low installation	negligible	new (1 year); Pielstick; Munters	water condensation; energy requirement
Selective Catalytic Reduction (SCR) **$552/tNOx**	reduction of NOx to nitrogen and water using injected urea; oxidation of HC, CO, ammonia	up to 99%	0%	HC, CO reduced 70-90%; SO_2 unchanged	$100/kW (high) high capital & installation	high; urea cost significant	established; 1. ABB Flakt 2. Siemens 3. Haldor Topsøe	high sulphur a poison; exhaust temp > 300°C; large size creates installation problems

Fuel-Water Emulsions

FWE systems can reduce NOx formation in marine diesel engines by 30 to 50% by intimately mixing water into the fuel oil. On-board ultrasonic homogenizer systems are recommended to achieve water droplet sizes down to 1 micron. The resulting emulsion of microfine water droplets in fuel is heated to control viscosity and injected in to the engine from a modified high-pressure fuel system in the same manner as ordinary fuel oil. The systems have only recently been commercialized as an option on new MAN B&W marine engines and have not been commonly used in retrofits. A significant benefit of FWE systems is a drastic reduction of particulate emissions (smoke) and lower engine soot deposition. It has been demonstrated in smoke-sensitive Alaskan cruise routes. The estimated installed cost of FWE technology as a retrofit on the *Cabot* is about $325,000, but there is some uncertainty associated with the degree and cost of the fuel system modification required. At a water-fuel ratio of 50%, FWE can achieve a 50% reduction in NOx at a cost of approximately $217 per tonne of NOx reduced. A major portion of this cost is a 1.5% specific fuel consumption penalty, assumed from vendor test results.

Direct Water Injection

DWI technology can reduce NOx emissions from marine engines by 40 to 60%, through the injection of a very high-pressure fine water mist into the combustion chamber. DWI systems are currently a proprietary technology of Wärtsilä, one of the largest marine engine makers in the world. A unique combined fuel and water injector nozzle must be retrofitted onto each cylinder. Water injection occurs separately from (and just prior to) fuel injection in the combustion cycle, cooling the cylinder and reducing NOx formation. Reductions in particulate (smoke) emissions are minor, but the system is used to complement Wärtsilä's current smokeless, common rail fuel injection technology. The technology has only recently been adopted for large marine engines over the last couple of years. There were about 10 installations on Wärtsilä engines in the Baltic Sea in early 2000, with another 15 on order. The capital cost rate is about $30/kW and the estimated installed cost of DWI systems as a retrofit on the *Cabot* is about $413,000, assuming that no major modifications are necessary to the Pielstick engines. DWI may not be a viable technology for these specific engines due to engine design differences. At a water-fuel ratio of 50%, DWI can achieve a 50% reduction in NOx at a cost of approximately $443 per tonne of NOx reduced. The largest component of this cost is an assumed 2.1% specific fuel consumption penalty.

Exhaust Gas Recirculation

EGR technology uses engine exhaust gases that have been cooled after the turbocharger. This reduces the combustion temperature, and increases the mass flow rate and pressure to reduce NOx formation. Despite exhaust gas cleaning, particulate emissions are usually increased with the use of this technology. The technology is viable for on-road diesel engines using very low sulphur fuel, but is currently not considered applicable in the marine engine market, due to significant fouling and corrosion issues.

Humid Air Motor

The HAM system is a recent technology that uses combustion air almost entirely saturated with water vapour (humid air) in a marine diesel engine. The charge air is humidified by water vapour produced in a humidification vessel by evaporating freshwater or seawater directly into the charge air using the heat from the engine or its exhaust gases. The system was developed by Munters AB of Sweden and is only available commercially on new Pielstick engines. NOx emissions reductions of 60 to 80% have been achieved in demonstration tests. The installed costs of the HAM system for the *Cabot* likely range from $0.8 to $1.2 million, but there are virtually no operating costs. The unit cost of NOx reduction is estimated to range from about $166 to $245 per tonne of NOx reduced.

Selective Catalytic Reduction

SCR is the only technology of the six studied that controls NOx emissions in the exhaust gas after they have been generated. SCR is capable of reducing NOx emissions by up to 99% by reacting NOx with ammonia (from a urea solution) over a catalyst in the hot exhaust gases of marine engines. Hydrocarbons and carbon monoxide are also reduced significantly, but particulate matter is uncontrolled. The technology is supplied by three major vendors worldwide, and at the end of 2000, there were over 60 installations, most of which were in the Baltic Sea. The total installed cost of SCR systems for the *Cabot* is estimated at $1.2 million. A 95% reduction in NOx emissions is achievable at a cost of $552 per tonne of NOx reduced. The largest cost component in this estimate is the cost of urea required for the reaction. SCR technology may not be practical for the *Cabot* because significant retrofit changes (at an increased cost) may be required to install SCR into the existing exhaust gas piping configuration.

Cost Sensitivities

The costs of the NOx control technologies were evaluated using a discount rate of 10%, an amortization term of 23 years, and average or typical NOx reductions. Three sensitivity analyses were run on the cost data to examine the effects of varying economic assumptions and the range of NOx reduction for each technology. Table 3 shows the changes, expressed in percentages, that occur to the base case unit costs appearing in Table 1. The unit costs of NOx control technologies generally increase with shorter amortization terms (project life) and higher discount rates. HAM unit costs are particularly sensitive to discount rates because this technology has the highest capital/operating cost ratio.

Table 3: Sensitivity of NOx Control Unit Costs
(% Unit Cost Increase)

Technology	Amortization Term (Years)				Discount Rates		NOx Range	
	10y	15y	20y	25y	8%	15%	Low	High
Continuous Water Injection	9%	3%	1%	-1%	-3%	8%	47%	-24%
Fuel-Water Emulsions	18%	7%	2%	-1%	-6%	16%	25%	-17%
Direct Water Injection	11%	4%	1%	-1%	-4%	10%	25%	-17%
Humid Air Motor	44%	17%	4%	-2%	-14%	38%	17%	-13%
Selective Catalytic Reduction	13%	5%	1%	-1%	-4%	12%	6%	-4%

NOx Ranges: CWI 22%+/-7%; FWE 50%+/-10%; DWI 50%+/-10%; HAM 70%+/-10%; SCR 95%+/-5%.

The unit costs also change with the assumed NOx reduction level, since NOx reductions represent the denominator of the unit cost ratio. For technologies with lower NOx reduction levels (20-50%), such as FWE, DWI and particularly CWI, the unit costs are very sensitive to the NOx reduction achieved. In contrast, SCR unit costs do not vary significantly, because NOx reduction level are already high.

Regulatory Environment

There are two key regulatory initiatives that concern marine NOx emissions. In 1997, the International Maritime Organization set proposed NOx emissions limits for all marine engines over 130 kW. The limits are based on engine speed and are intended to achieve a 30% reduction in marine NOx emissions compared to 1992 levels. If ratification occurs as expected in 2002 or 2003, these limits will apply to new ships and any major retrofits to existing ships after January 1, 2000. Engine makers have already complied with IMO limits with their current models. The U.S. has recently developed proposed marine emissions regulations for large ships that use the proposed IMO limits.

In 1998, Sweden independently set up a voluntary system of differential port and fairway dues based on ship environmental performance to encourage Baltic Sea ship operators to control NOx and sulphur emissions. This has triggered a strong growth in NOx control technology development in the marine community. It is expected that similar systems will soon be adopted by other countries in northern Europe. Many other countries are starting to consider similar local regional control measures for marine NOx, particulate and sulphur emissions.

Conclusions

The following conclusions were drawn from the analysis in this study.

- Continuous Water Injection (CWI) to the charge air appears to be most cost-effective system for low levels (10-30%) of NOx reductions, but the low level of operating experience makes further testing a necessity. It would be best used for trimming NOx emissions to meet minimum IMO limits.
- The Fuel-Water Emulsion (FWE) system appears to be a promising, medium-cost technology for achieving medium levels (30-50%) of NOx reduction. Since FWE is reasonably simple to retrofit onto existing ships without significant structural or engine modifications, it appears to be a practical retrofit solution.
- Direct Water Injection (DWI) technology appears to be effective for medium levels of NOx reduction (40-60%), but may not be a practical technology for engine retrofits, due to its specific engine design requirements. It becomes much more cost effective on new engines.
- The relatively new Humid Air Motor (HAM), despite high initial capital costs, appears to be a practical, cost-effective method of achieving medium to high levels (60-80%) of NOx reduction. Limited operating experience suggests that it can be retrofitted in the engine room without need for new water supply, and performs well.
- The Selective Catalytic Reduction (SCR) system has the highest unit cost of the five technologies analyzed, but can achieve almost complete NOx reduction. Installation costs are a significant issue if major retrofitting is required. This technology is best suited for vessels operating in regions having very stringent environmental control programs and financial incentives.

Recommendations

The testing and demonstration programs for the different technologies should be continued and broadened to gather more practical operating and cost data.

- A small-scale HAM system should be tested in the Engine Laboratory.
- FWE systems using ultrasonic homogenizers should be tested in the Laboratory.

- A demonstration of FWE systems using pre-blended emulsions and homogenizer systems should be undertaken.
- The field demonstrations of the CWI system should be continued over a longer time period (say, one year) with longer test duration (several hours) to gather more data on specific fuel consumption effects and operating issues.
- A small-scale HAM system should be demonstrated on an appropriate vessel to gather actual operating information. Support for capital costs may be required from the federal government as well as Pielstick, who may have incentive to increase current HAM operating experience.
- A small-scale SCR system should be demonstrated on an appropriate vessel (federal government, private) having relatively few installation problems.

Two general suggestions should also be considered:

- The scope of this type of technology assessment study should be broadened to include more off-road diesel engine sources. These include locomotives and other off-road heavy-duty diesel engines used in construction and heavy industry. These studies may have to focus more on the scoping of regulatory developments and technology issues, as opposed to cost analyses.
- An inventory of marine NOx emissions should be conducted to understand the segmentation of marine NOx emissions in Canada and the implications of the proposed IMO limits on the Canadian marine sector. Currently, Canadian marine NOx emissions are calculated by the Pollution Data Branch of Environment Canada as area sources based on fuel consumption data, registered vessels and average emissions factors.

Sommaire

Introduction

L'étude a consisté à examiner les coûts directs, les avantages du point de vue de l'environnement et l'applicabilité de six technologies de réduction des émissions de NO_x conçues pour des moteurs diesel marins : injection continue d'eau dans l'air de suralimentation (CWI, *continuous water injection*), émulsions carburant-eau (FEW, *fuel-water emulsion*), injection directe d'eau (DWI, *direct water injection*), recyclage des gaz d'échappement (EGR, *exhaust gas recirculation*), humidification de l'air d'admission (HAM, *humid air motor*) et réduction catalytique sélective (SCR, *selective catalytic reduction*). Le coût et les avantages pour l'environnement de chacune des technologies ont été évalués d'après leur application hypothétique à un navire canadien, le NM *Cabot*, un porte-conteneurs roulier de 14 600 tonnes de jauge brute.

Le tableau 1 présente un résumé des coûts reliés à chacune des technologies de réduction des NO_X pour le NM *Cabot*. La technologie de recyclage des gaz d'échappement (EGR) ne figure pas au tableau, car elle ne constitue pas actuellement une option viable pour les moteurs marins. Le taux de réduction des NO_X varie de 22 % à 95 %, à un «coût unitaire» qui varie de -143 $ (économie) à 552 $.

Tableau 1 : Coût des technologies de réduction des NO_X pour le NM *Cabot*

	Coûts après installation ($)	Coûts / (économies) d'exploitation ($/an)	Coûts / (économies) annualisés* ($/an)	Réduction des NO_X (%)	Coût unitaire ($/t NO_X)
Injection continue d'eau	51 000 $	(32 000 $)	(26 000 $)	22 %	(143 $)
Émulsions carburant-eau	325 000 $	54 000 $	91 000 $	50 %	217 $
Injection directe d'eau	413 000 $	137 000 $	184 000 $	50 %	443 $
Humidification de l'air d'admission	1 048 000 $	1 500 $	120 000 $	70 %	206 $
Réduction catalytique sélective	1 156 000 $	306 000 $	436 000 $	95 %	552 $

* Les coûts annualisés comprennent les coûts d'exploitation et les coûts totaux après installation amortis à 10 % sur 23 ans.

Parmi les technologies évaluées, l'injection continue d'eau (CWI) dans l'air de suralimentation est la moins coûteuse. Dans sa configuration qui a mené au taux maximal de réduction des NO_X durant les essais officiels, la CWI est la technologie qui est associée aux coûts totaux après installation les plus faibles et elle est la seule à générer des économies de carburant. Elle affiche cependant le plus faible potentiel de réduction des NO_X (22 %). À l'opposé, la réduction catalytique sélective (SCR) s'est révélée la technologie la plus coûteuse. Elle est également la plus efficace pour réduire les NO_X (de 90 % à 99 %), mais ses coûts d'achat et d'installation sont élevés, tout comme ses coûts d'exploitation, en raison de la consommation d'urée. Quant aux systèmes d'émulsions carburant-eau (FWE) et d'humidification de l'air d'admission (HAM), ils ont entraîné des réductions moyennes des NO_X, en contrepartie de coûts modérés. Les systèmes HAM sont très coûteux à l'achat, mais leurs coûts d'exploitation sont négligeables et ils sont très écologiques. Les systèmes FWE sont relativement peu coûteux à mettre en place, mais ils occasionnent une légère augmentation de la consommation de carburant. L'injection directe d'eau (DWI) est aussi une technologie moyennement performante, mais elle est associée à des coûts d'immobilisation et d'exploitation légèrement plus élevés que les autres technologies comparables.

Navire d'application : NM *Cabot*

Un navire de référence a été désigné pour servir de point de comparaison aux fins de l'analyse coûts-avantages. Le NM *Cabot* est l'un des trois porte-conteneurs rouliers de cote arctique exploité à longueur d'année par la société Océanex, de Montréal, Québec. Le *Cabot* fait chaque semaine le trajet aller-retour entre Montréal et St. John's, Terre-Neuve. Construit en 1979, il a une jauge brute de 14 597 tonnes et est propulsé par deux moteurs V12 Pielstick PC2.5 à deux arbres qui affichent une puissance nominale de 5,8 mW chacun (11,6 mW au total). Le navire utilise du mazout intermédiaire (IFO) 180 la majorité du temps (91 %), et du diesel marin lorsqu'il est à quai (9 % du temps). Les moteurs tournent durant 6 000 heures par année, à une charge moyenne de 85 % de leur charge maximale, au cours des quelque 48 trajets hebdomadaires du navire. Ainsi, en supposant un taux d'émissions de NO_X de 14 g/kWh, on évalue à 831 tonnes par année le total des émissions de NO_X.

Ce navire a été choisi pour l'étude, parce qu'il est un navire de charge de taille moyenne, qu'il navigue le long des côtes et qu'il est propulsé par deux moteurs marins vitesse moyenne. Bien qu'il ne soit pas un «laquier» (bâtiment conçu pour naviguer dans les eaux douces des Grands Lacs) et malgré certaines caractéristiques uniques, il est considéré comme représentatif des navires marchands canadiens de catégorie moyenne.

Tableau 2 : Résumé des technologies de réduction des NO_X

Technologie	Principe	Réduction des NO_X	Réduction des particules	Autres émissions	Coût après installation	Coûts d'exploitation	Fournisseur	Principaux problèmes
Injection continue d'eau (CWI) (145 $)/t NO_X	Vapeur d'eau ajoutée à l'air comprimé en amont du cylindre; refroidit l'air, absorbe la chaleur	10 à 30 %	0 à 25 %	HC, CO, SO_2 inchangés	4 à 5 $/kW (faible); faibles coûts d'installation	Faible réduction de la consommation spécifique de carburant à de faibles rapports C/E	Développement par M.A. Turbo/Engine Design; personnalisée	Condensation, dépôts
Émulsions carburant-eau (FWE) 217 $/t NO_X	Minuscules gouttelettes d'eau enrobées dans des gouttelettes de carburant; la vaporisation explosive réduit les gros HC	30 à 50 %	Moyenne	HC, CO réduits jusqu'à 50 %	28 $/kW; faible coût d'achat, coût d'installation élevé	Augmentation de la consommation de carburant; remplacements de pièces mineurs	Nouveau (2 ans); MAN B&W; plusieurs distributeurs (RESON; SIT)	Forte pression et faible viscosité nécessaires; stabilité de l'émulsion; augmentation de la consommation de carburant de 1,5 %
Injection directe d'eau (DWI) 443 $/t NO_X	Eau injectée à haute pression dans le cylindre, avant le carburant; refroidit le cylindre avant la combustion	40 à 60 %	Faible	Inconnues	36 $/kW (moyen); coût d'achat élevé; faibles coûts d'installation	Augmentation de la consommation de carburant; remplacements de pièces mineurs	Nouveau (2 ans); Wärtsilä	Augmentation de la consommation de carburant de 2,1 %; compatibilité avec les moteurs anciens
Recyclage des gaz d'échappement (EGR)	Gaz d'échappement refroidis et filtrés ajoutés à l'air de suralimentation; réduit la température et augmente la pression	jusqu'à 50 %	Très faible	Inconnues	2 % du coût du moteur	Inconnus	Non disponible	Encrassement, dépôts, corrosion rapide
Humidification de l'air d'admission (HAM) 206 $/t NO_X	Air comprimé humidifié (saturé) par de la vapeur d'eau; refroidit l'air, absorbe la chaleur	60 à 80 %	Moyenne	Inconnues	98 $/kW (élevé); coût d'achat élevé; faibles coûts d'installation	Négligeables	Nouveau (1 an); Pielstick; Munters	Condensation d'eau; besoin d'énergie

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Tableau 2 : Résumé des technologies de réduction des NO_X (suite)

Technologie	Principe	Réduction des NO_X	Réduction des particules	Autres émissions	Coût après installation	Coûts d'exploitation	Fournisseur	Principaux problèmes
Réduction catalytique sélective (SCR) 552 $/t NO_X	Réduction des NO_X en azote et en eau par injection d'urée; oxydation des HC, CO, ammoniac	Jusqu'à 99 %	0 %	HC, CO réduits de 70 à 90 %; SO_2 inchangés	100 $/kW (élevé) coûts d'achat et d'installation élevés	Élevés; coût élevé de l'urée	Établis; 1. ABB Flakt; 2. Siemens; 3. Haldor Topsøe	Haute teneur en soufre (poison); gaz d'échappement > 300 °C; problèmes d'installation dus aux grandes dimensions du dispositif

Injection continue d'eau

La CWI est une méthode relativement simple qui permet de réduire les émissions de NO_X jusqu'à 30 % et les émissions de particules d'environ 25 %, sans avoir à modifier le moteur. Une fine vapeur d'eau est injectée directement dans l'air chaud comprimé en aval du turbocompresseur. Un système a été conçu aux fins d'une démonstration à bord d'un navire de BC Ferries, mais il ne semble exister présentement aucun système exploité en permanence. Le coût après installation de cette technologie s'élève à environ 50 000 $. Au cours d'essais en conditions réelles effectués par Environnement Canada, la CWI a mené à une réduction de 22 % des NO_X et à une réduction de 1 %, en moyenne, de la consommation spécifique de carburant, ce qui s'est traduit par des économies nettes d'environ 143 $ par tonne de NO_X «non rejetés». Il n'est pas recommandé d'aller au-delà d'un rapport carburant-eau de 25 %, en raison de l'augmentation prévisible de la consommation de carburant.

Émulsions carburant-eau

Les systèmes FWE peuvent réduire de 30 à 50 % la formation de NO_X dans les moteurs diesel marins en mélangeant intimement de l'eau au mazout. L'utilisation de systèmes embarqués d'homogénéisation par ultrasons est recommandée pour obtenir des gouttelettes d'eau de la taille d'un micron. L'émulsion eau-carburant est chauffée, ce qui limite sa viscosité, puis injectée dans le moteur de la même manière que du mazout ordinaire, par un système d'injection haute pression modifié. Commercialisés depuis peu, ces systèmes ne sont offerts qu'en option dans les nouveaux moteurs marins MAN B&W et sont encore rarement installés en rattrapage. Un avantage important des systèmes FWE est la réduction substantielle des émissions de particules (fumée) et la diminution des dépôts de suie dans le moteur. Cette technologie a fait l'objet d'une démonstration le long des côtes de l'Alaska, où on est particulièrement sensible aux rejets de fumée. Les coûts d'installation en rattrapage de la technologie FWE à bord du NM *Cabot* sont évalués à environ 325 000 $, mais l'importance et le coût des modifications à apporter au circuit d'alimentation demeurent incertains. À un rapport carburant-eau de 50 %, la réduction des NO_X peut atteindre 50 %, moyennant un coût approximatif de 217 $ par tonne. Ce coût est surtout attribuable à une augmentation de 1,5 % de la consommation de carburant, taux établi à la lumière des résultats des essais effectués par le fournisseur.

Injection directe d'eau

La technologie DWI permet de réduire de 40 à 60 % les émissions de NO_X des moteurs marins par l'injection à très haute pression de minuscules gouttelettes d'eau dans la chambre de combustion. Actuellement, Wärtsilä, l'un des plus grands fabricants de moteurs marins au monde, détient un brevet sur cette technologie. Un injecteur unique, qui sert pour le mazout et l'eau, doit être installé dans chaque cylindre du moteur. L'injection d'eau, immédiatement avant l'injection de mazout, dans le cycle de combustion, refroidit le cylindre et réduit la formation de NO_X. La réduction des émissions de particules (fumée) est faible, mais le système est utilisé en complément de la technologie de rampe commune d'injection de Wärtsilä, qui ne produit pas de fumée. La technologie est appliquée aux gros moteurs marins depuis quelques années seulement. Au début de 2000, on comptait une dizaine de systèmes installés sur des moteurs Wärtsilä exploités dans la mer Baltique, et 15 autres étaient en commande. Le coût d'achat est d'environ 30 $/kW et on évalue à environ 413 000 $ le coût d'installation en rattrapage d'un système DWI à bord du *Cabot*, en présumant qu'aucune modification majeure aux moteurs Pielstick ne serait nécessaire. Mais il n'est pas sûr que la technologie DWI soit applicable à ces moteurs, en raison de leur conception, différente de celle des moteurs Wärtsilä. À un rapport carburant-eau de 50 %, la DWI peut réduire jusqu'à 50 % les émissions de $NO_{X,}$ à un coût d'environ 443 $ par tonne. Ce coût est surtout attribuable à l'augmentation prévue de 2,1 % de la consommation de carburant.

Recyclage des gaz d'échappement

La technologie EGR brûle les gaz d'échappement du moteur qui ont été refroidis en aval du turbocompresseur. Cela réduit la température de combustion et accroît le débit massique et la pression et, ce faisant, réduit la formation de NO_X. Même si les gaz d'échappement sont plus propres, cette technologie augmente habituellement les émissions de particules. La technologie est viable pour les moteurs diesel des véhicules routiers qui utilisent du mazout à très faible teneur en soufre, mais, pour l'instant, elle n'est pas considérée applicable au créneau des moteurs marins, en raison d'importants problèmes d'encrassement et de corrosion.

Humidification de l'air d'admission

Le système HAM est une technologie récente qui consiste à alimenter un moteur diesel marin en air de combustion quasi saturé de vapeur d'eau (air humide). L'air de suralimentation est humidifié dans une enceinte d'humidification, où de la vapeur d'eau, produite par l'évaporation d'eau douce ou d'eau de mer sous l'effet de la chaleur du moteur ou de ses gaz d'échappement, est directement injectée dans l'air de suralimentation. Le système, développé par Munters AB de Suède, est seulement offert sur les nouveaux moteurs Pielstick. Une réduction des émissions de NO_X de 60 à 80 % a été atteinte au cours d'essais de démonstration. Les coûts après installation du système HAM à bord du *Cabot* devraient se situer entre 0,8 et 1,2 million de dollars, mais les coûts d'exploitation sont pratiquement nuls. Le coût unitaire de réduction des NO_X devrait varier de 166 $ à 245 $ par tonne.

Réduction catalytique sélective

La SCR est la seule technologie, parmi les six étudiées, qui réduit les émissions de NO_X dans les gaz d'échappement, c'est-à-dire «après coup». La SCR peut réduire jusqu'à 99 % les émissions de NO_X, grâce à la réduction des NO_X par l'ammoniac (d'une solution d'urée) en présence d'un catalyseur, dans les gaz d'échappement chauds des moteurs marins. Ce procédé entraîne également une réduction notable des hydrocarbures et du monoxyde de carbone, mais non des particules. Trois grands fournisseurs offrent cette technologie dans le monde et à la fin de 2000, plus de 60 navires en étaient équipés, la plupart naviguant dans la mer Baltique. On évalue à 1,2 million de dollars le coût total après installation d'un système SCR à bord du *Cabot*. Une réduction de 95 % des émissions de NO_X serait réalisable, à un coût de 552 $ par tonne. Le principal élément de coût, dans cette estimation, est celui de l'urée nécessaire à la réaction. De plus, il se peut que la technologie SCR ne convienne pas au *Cabot*, en raison des importantes modifications (et des coûts à l'avenant) que pourrait nécessiter l'installation du système, compte tenu de la configuration actuelle du circuit des gaz d'échappement.

Facteurs de sensibilité aux coûts

Le coût de chaque technologie de réduction des NO_X a été évalué en supposant un taux d'actualisation de 10 %, une période d'amortissement de 23 ans et des réductions moyennes ou typiques de NO_X. Les données de coûts ont été soumises à trois analyses de sensibilité, afin d'examiner les effets d'hypothèses économiques variables et la réduction des NO_X pour chaque technologie. Le tableau 3 présente les variations, en pourcentages, par rapport aux coûts unitaires du tableau 1. Le coût unitaire des technologies de réduction des NO_X augmente généralement avec la réduction de la période d'amortissement (durée du projet) et l'augmentation du taux d'actualisation. Le coût unitaire de la HAM est particulièrement sensible au taux d'actualisation, car c'est la technologie qui affiche le rapport coût d'achat/coût d'exploitation le plus élevé.

Tableau 3 : Sensibilité des coûts unitaires de réduction des NO_X
(% d'augmentation des coût unitaires)

Technologie	Période d'amortissement (années)				Taux d'actualisation		Fourchette de réduction des NO_X	
	10 ans	15 ans	20 ans	25 ans	8 %	15 %	Bas	Haut
Injection continue d'eau	9 %	3 %	1 %	-1 %	-3 %	8 %	47 %	-24 %
Émulsions carburant-eau	18 %	7 %	2 %	-1 %	-6 %	16 %	25 %	-17 %
Injection directe d'eau	11 %	4 %	1 %	-1 %	-4 %	10 %	25 %	-17 %
Humidification de l'air d'admission	44 %	17 %	4 %	-2 %	-14 %	38 %	17 %	-13 %
Réduction catalytique sélective	13 %	5 %	1 %	-1 %	-4 %	12 %	6 %	-4 %

Fourchettes de réduction des NO_X : CWI 22 % +/- 7 %; FWE 50 % +/- 10 %; DWI 50 % +/- 10 %; HAM 70 % +/- 10 %; SCR 95 % +/- 5 %.

Les coûts unitaires varient également en fonction des taux de réduction des NO_X supposés, puisque les réductions de NO_X représentent le dénominateur du rapport du coût unitaire. Pour les technologies associées aux plus faibles taux de réduction des NO_X (20 à 50 %), soit la FWE, la DWI et particulièrement la CWI, les coûts unitaires sont très sensibles à la réduction des NO_X obtenue. À l'inverse, dans le cas de la SCR, les coûts unitaires ne varient pas beaucoup, puisque le taux de réduction des NO_X est déjà élevé.

Cadre réglementaire

Il existe deux grandes initiatives réglementaires en ce qui concerne la réduction des émissions de NO_X des navires. En 1997, l'Organisation maritime internationale (OMI) a proposé une norme qui limite les émissions de NO_X de tous les moteurs marins de plus de 130 kW. Ces limites, qui varient en fonction de la vitesse du moteur, visent une réduction de 30 % des émissions par rapport aux chiffres de 1992. Si ce projet de norme est ratifié comme prévu en 2002 ou 2003, ces limites s'appliqueront aux nouveaux navires et aux navires existants qui feront l'objet de travaux majeurs de modernisation à compter du 1er janvier 2000. Les modèles actuels des fabricants de moteurs sont déjà conformes aux limites de l'OMI. Les États-Unis ont récemment élaboré un projet de règlement sur les émissions des grands navires, qui reprend les limites proposées par l'OMI.

En 1998, la Suède a établi un système de réduction volontaire des émissions, qui fait varier les droits de port et les droits sur les chenaux en fonction des performances environnementales des navires. Le but de ce système est d'encourager les exploitants des navires de la mer Baltique à réduire leurs émissions de NO_X et de soufre. Cette initiative est à l'origine de l'essor considérable du développement des technologies de réduction des NO_X dans le milieu maritime. On s'attend à ce que d'autres pays de l'Europe du Nord adoptent bientôt des systèmes semblables de réduction volontaire des émissions. Et de nombreux autres pays commencent à envisager des mesures locales et régionales similaires pour réduire les émissions de NO_X, de particules et de soufre des navires.

Conclusions

Les conclusions ci-après ont été tirées de l'analyse coûts-avantages.

- L'injection continue d'eau dans l'air de suralimentation (CWI) semble être le système le plus économique pour réduire par de faibles marges les émissions de NO_X (10 à 30 %), mais d'autres essais sont nécessaires, en raison du peu d'expérience que l'on a de cette technologie en service réel. Elle serait particulièrement à propos pour obtenir de faibles réductions de NO_X afin de satisfaire aux exigences minimales de l'OMI.
- Les émulsions carburant-eau (FWE) sont une technologie prometteuse et moyennement coûteuse, qui mène à des réductions moyennes des NO_X (30 à 50 %). Comme elle est assez simple à installer en rattrapage sur les navires existants, sans qu'il soit nécessaire d'apporter des modifications importantes à la structure ou au moteur, elle semble représenter une solution de rattrapage pratique.
- L'injection directe d'eau (DWI) semble efficace pour des réductions moyennes de NO_X (40 à 60 %), mais elle se révèle peu propice à une installation en rattrapage, en raison d'exigences précises auxquelles doit répondre le moteur. Son rapport coût-efficacité devient toutefois très intéressant dans le cas des nouveaux moteurs.
- La technologie d'humidification de l'air d'admission (HAM), relativement nouvelle, semble offrir un bon rapport coût-efficacité, en dépit de coûts d'immobilisation élevés. En effet, elle permet des réductions de NO_X allant de moyennes à fortes (60 à 80 %). Une expérience limitée en exploitation laisse penser qu'elle peut être installée en rattrapage sans qu'il soit nécessaire de prévoir un nouveau circuit d'alimentation en eau, et qu'elle donne ainsi un rendement satisfaisant.
- Parmi les cinq technologies étudiées, la SCR est associée au coût unitaire le plus élevé, mais elle permet d'éliminer presque totalement les NO_X. Les coûts d'installation représentent un enjeu important si des travaux majeur de modernisation sont nécessaires. C'est donc la technologie qui convient le mieux aux navires exploités dans des régions qui appliquent des programmes très rigoureux de protection de l'environnement et qui peuvent bénéficier d'incitatifs financiers.

Recommandations

Les programmes d'essai et de démonstration des différentes technologies devraient se poursuivre et être élargis pour recueillir davantage de données pratiques sur l'exploitation et les coûts de chacune.

- Essayer au banc un petit système HAM.
- Faire l'essai en laboratoire de systèmes FWE utilisant des systèmes d'homogénéisation par ultrasons.
- Organiser une démonstration de systèmes FWE utilisant des émulsions pré-mélangées et des systèmes d'homogénéisation.
- Prolonger (disons à un an) les démonstrations en service du système CWI et faire durer plus longtemps les essais (plusieurs heures) de façon à colliger davantage de données concernant les effets de la technologie sur la consommation de carburant et sur le fonctionnement du moteur.
- Organiser une démonstration d'un petit système HAM à bord d'un navire approprié afin de recueillir des données sur son fonctionnement en conditions réelles. Une aide financière pour les coûts d'immobilisation pourrait être demandée au gouvernement fédéral de même qu'à Pielstick, qui pourrait trouver son compte dans la multiplication des mises en service du système HAM.
- Organiser la démonstration d'un petit système SCR à bord d'un navire approprié (gouvernement fédéral, privé) sur lequel il serait relativement facile à installer.

Voici par ailleurs deux suggestions d'ordre général.

- La portée de ce type d'étude comparative de technologies devrait être élargie à d'autres moteurs diesel non routiers, ce qui comprend les moteurs de locomotives et les moteurs diesel d'équipements lourds utilisés dans l'industrie de la construction et l'industrie lourde. Ces études devraient être axées davantage sur les questions réglementaires et sur les enjeux technologiques que sur les analyses de coûts.
- Il y aurait lieu de réaliser un inventaire des émissions de NO_X des navires, afin de mieux comprendre la répartition par secteur des émissions de NO_X au Canada, ainsi que les conséquences des limites proposées par l'OMI sur le secteur maritime canadien. Actuellement, la Direction des données sur la pollution d'Environnement Canada établit les émissions de NO_X des navires au Canada par région, d'après les données sur la consommation de carburant, les navires immatriculés et les facteurs d'émission moyens.

CHEMINFO

Table of Contents

CHEMINFO

List of Figures

List of Tables

CHEMINFO

Glossary

BMEP	Brake mean effective pressure
CO	Carbon monoxide
CO_2	Carbon dioxide
CWI	Continuous water injection
DWI	Direct water injection
dwt	Deadweight ton
EGR	Exhaust gas recirculation
EPA	Envrionmental Protection Agency (U.S.)
FF	French franc
FMk	Finnish markka
FWE	Fuel-water emulsions
GRT	Gross rated tonnage
GVWR	Gross vehicle weight rating
GWT	Gross weight
HAM	Humid air motor
HC	Hydrocarbon
IFO	Intermediate fuel oil
IMO	International Maritime Organization
ISO	International Organization for Standardization
MCR	Maximum continuous rating
MDO	Marine diesel oil
MEPC	Marine Environmental Protection Committee
NOx	Oxides of nitrogen
PM	Particulate matter
PLC	Programmable logic controller
RoRo	Roll on, roll off
rpm	Revolutions per minute
SBT	Segregated ballast tank
SCR	Selective catalytic reduction
SEK	Swedish kroner
TDC	Transportation Development Centre
TEU	Twenty-foot equivalent unit
VOC	Volatile organic compound

1. Introduction

1.1 Background

With the advent of the International Maritime Organization's (IMO) MARPOL 73/78 Annex VI agreement to control atmospheric emissions from marine vessels, new marine NOx emissions limits have been proposed for the international shipping industry. While Annex VI has yet to be ratified, the NOx limits are designed to achieve a worldwide 30% reduction versus 1992 levels. Once in force, the IMO NOx limits will apply to all new ships (or major retrofits) built after January 1, 2000, with engines rated greater than 130 kW. In anticipation of this, all marine engine makers have made internal modifications to their designs such that all new engines meet the proposed limits. Regulations on sulphur oxides (SOx) and volatile organic compounds (VOCs) have also been proposed in Annex VI.

Existing ships needing retrofits will have to consider how to control NOx emissions to meet the proposed standards. It is generally believed that more stringent international NOx limits may occur in the long term. Also, in some world regions, such as the Baltic Sea, innovative voluntary financial NOx control measures are being set that seek greater reductions. For any of these reasons, higher reductions in NOx emissions from marine engines will then likely require some sort of additional control technology.

Canada, as a member of the IMO, is currently examining the proposed IMO NOx limits and considering the decision to ratify. Transport Canada has the role of co-ordinating Canada's IMO response. As part of the broad effort to develop improved marine environmental policies in Canada, the Transportation Development Centre (TDC), Transport Canada's R&D agency, is in the process of examining technology developments and co-ordinating efforts to facilitate their adoption for the Canadian marine sector.

Several NOx reduction technologies for marine diesel engines have been developed and commercialized recently to meet these anticipated control requirements. TDC, with the assistance of Environment Canada, has recently established an on-going laboratory testing program of emissions control technologies for marine engines. The program has recently been extended to include field demonstrations of some of the more promising technologies. So far, these programs have focused largely on technical performance issues. In order to progress further with the development of marine emissions control technology in Canada, there is now a need to examine and understand recent technology developments in the international marine community from an economic and technical perspective.

1.2 Purpose

The purpose of this study was to examine the costs and environmental benefits of five marine NOx emissions control technologies identified by Transport Canada as having good potential for future development. The technologies proposed for study included:

- Continuous water injection to the charge air (CWI);
- Fuel-water emulsions (FWE);
- Direct water injection (DWI);
- Exhaust gas recirculation (EGR); and
- Selective catalytic reduction (SCR).

Some research early in the study discovered that there was limited potential for EGR in marine applications with heavy fuel oil. To compensate for this, a sixth promising technology, the Humid Air Motor system (HAM) was identified and included in the cost-benefit analysis.

The main objective of the study was to prepare a cost and performance analysis for each technology examining the current capital, installation and on-going operating costs required to retrofit the technology onto specific existing marine engines. To standardize the analysis, a benchmark vessel was used for each technology. The intent of the cost analysis was to gather current cost information provided by technology vendors, engine makers and other suppliers to develop detailed estimates of the true costs of purchasing, installing and continuously operating the technology over the defined life of the benchmark vessel.

A second objective was to compare the performance and characteristics of the technologies to identify major issues, constraints and development potential. The assessment of environmental performance focused on NOx emissions. The technologies were compared in terms of NOx reduction potential and the cost effectiveness of the technologies. Particulate matter (PM) emissions reduction performance was also considered, since it is a major area of concern in marine air pollution.

1.3 Methodology

The methodology for this study combined several different research elements to gather a variety of information on policy development, scientific theory, technical descriptions, environmental performance, operating issues and experience, costs, suppliers and markets.

A broad literature search was conducted in the first stage of the study to gather relevant background information on most of these subject areas. The literature search focused on key trade journals, technical and policy publications and presentations, some government legislative reports and technology vendor product information. One of the most important benefits of the literature search was to use recent news articles and business directories to identify the potential technology vendors, engine makers, and international marine experts to be consulted in the field research stage. The internet was a valuable research tool to find a wide variety of this information.

The second stage of the study was to compile a comprehensive list of relevant data on the case study vessel, the M.V. *Cabot*. With the co-operation of Oceanex, the ship operator, the key information on the vessel, the engines, the fuel, water and exhaust systems, and the typical operating profile was collected and summarized for use by technology vendors. This established the key parameters and baseline operating conditions to be used in the cost analysis.

The third stage of the study involved the initial contact with technology vendors and engine makers to request technology cost information. Several vendors were selected for most technologies to provide additional breadth and increase the likelihood of response. Following initial telephone contact to establish the study context and the proper respondent, an official letter of request containing the ship information and data request was e-mailed to each vendor. The following information was requested from technology vendors and engine makers:

- Capital cost of all system equipment;
- Installation cost of system
- System operating costs
  - Fuel consumption savings
  - Consumables (chemicals, catalyst)
  - Replacement parts and frequency
  - Other operating or maintenance costs
- Assumptions used to develop the above costs
- NOx reduction potential associated with this installation (%)
- Major operating issues
- Operating experience information

In most cases, a follow-up telephone interview was made within a week to gather background data, re-direct the research or supply additional information. In some cases, the process was somewhat iterative, with occasional questions from vendors directed back to the shipowner for more details.

The response rate for the data requests was moderate. There was a strong interest in participating, and most vendors shared technical information readily, but detailed, specific cost information was harder to obtain consistently. Vendors replied in various degrees: responding only verbally in the interview, sending general product literature (brochures, reports, CDs), summarizing relevant general rule-of thumb data, or preparing specific detailed answers.

To provide additional background to the study and gather general information on the six technologies, a set of interviews was conducted with some identified marine experts and a few selected ship operators.

The final stage of the study was the development of a spreadsheet cost model to prepare cost estimates specifically for the *Cabot* and analyze the NOx reduction performance of the technologies. The cost model estimated capital equipment and installation costs along with key operating costs, such as fuel penalties or savings, consumables and maintenance. All cost quotes were converted to Canadian dollars based on foreign exchange rates as of mid-December 2000. The total installed costs were amortized at 10% over a 23-year time horizon, as specified by Transport Canada. Since the vendor response data was usually incomplete or very general, assumptions had to be made based on best available information to fill in some data gaps.

1.4 Disclaimer

The information contained in this study is intended to be used by Transport Canada and Canadian marine sector representatives as a basis of technical and economic discussion, principally to help prioritize future technology development. It is not intended to be used for competitive commercial purposes. The results are considered to be reasonably reliable to meet the purposes of this study, but there are some uncertainties inherent in the data due to the broad scope and nature of the research. A more detailed engineering study would have to be conducted on each of the technologies to assist in investment decision-making.

2. Regulations

2.1 Summary

Regulators are paying increased attention to marine NOx emissions in coastal waters. The IMO began the process of controlling NOx emissions internationally by reaching an agreement on marine air pollution limits in 1997.

This chapter examines the IMO Annex VI agreement in context of NOx and PM emissions. This background is necessary context for the study of the five NOx control technologies in this study. Some country case studies are also provided to illustrate some of the current and planned international developments regarding the control of NOx and PM emissions from marine engines.

2.2 IMO NOx Targets

The IMO has recently set NOx emissions limits for all international vessels, which are still subject to ratification. This section briefly summarizes these proposed regulations.

2.2.1 MARPOL 73/78 Annex VI

MARPOL 73/78 is the International Convention for the Prevention of Pollution from Ships, an international marine treaty adopted by the IMO in 1973 and later revised in 1978. The intent of the treaty is to reduce pollution from all marine vessel operations. The Treaty and its Annexes contain requirements to control discharges of substances such as chemicals, oil, garbage and emissions from incineration. On September 26, 1997, IMO adopted Annex VI: Regulations for the Prevention of Air Pollution from Ships. Among other provisions,[1] Annex VI sets standards covering eight areas:

Regulation 12:	Ozone-Depleting Substances (ODS);
Regulation 13:	**Nitrogen Oxides (NOx);**
Regulation 14:	Sulphur oxides (SOx);
Regulation 15:	Volatile Organic Compounds (VOC);
Regulation 16:	Shipboard Incineration;
Regulation 17:	Reception Facilities;
Regulation 18:	Fuel Oil Quality;
Regulation 19:	Requirements for Platforms and Drilling Rigs.

[1] Annex VI also provides rules on exemptions, surveys and certifications, and inspection controls.

2.2.2 NOx Limits

Uncontrolled NOx emissions rates from marine diesel engines are inversely proportional to engine speed. Within a particular class of engine, NOx emissions rates can vary considerably due to specific combustion characteristics. For example, the 1992 stand of vessels (statistical sample) used to negotiate the IMO Annex VI showed a broad range of NOx emissions rates for different engine speeds. NOx emissions rates for large, low-speed engines (<200 rpm) typically range between 15 and 29 g/kWh. For medium-speed engines at 500 rpm, NOx emissions rates range from 10 to 18 g/kWh. For smaller, high speed engines, NOx rates typically vary between 8 and 14 g/kWh. The variation in NOx emissions rates by engine speed is illustrated in Figure 1.

Annex VI Regulation 13 requires that all marine diesel engines rated above 130 kW, that are installed on new vessels or vessels undergoing major conversions after January 1, 2000, must have weighted average NOx emissions below limits defined by an equation based on rated engine speed. The rated engine speed, designated by *n*, is measured in rpm:

For large engines with $n < 130$ rpm, NOx limit = 17.0 g/kWh
For engines > 130 rpm, NOx limit = $45 \times n^{-0.2}$

The NOx limits range from 17.0 g/kWh for very large, slow-speed engines (< 130 rpm) to about 9.8 g/kWh for small, high-speed engines (>2,000 rpm). The IMO limit curve was selected to achieve an overall 30% reduction in marine NOx emissions worldwide. It is shown on the diagram on the next page. For medium-speed engines on vessels such as the M.V. *Cabot*, which is rated at 520 rpm, the NOx limit is about 12.9 g/kWh.

2.2.3 Particulate Matter

There are no IMO regulations proposed for PM. Instead of controlling PM, ports and other local jurisdictions tend to be concerned primarily over opacity limits for ship engine exhaust.

2.2.4 Certification

All new engines have to be certified according to the NOx Technical Code and delivered with an official letter of compliance. The certification process includes a NOx measurement program for each unique engine type, stamping the components that affect NOx formation and maintaining a technical file that is delivered with any new engine.

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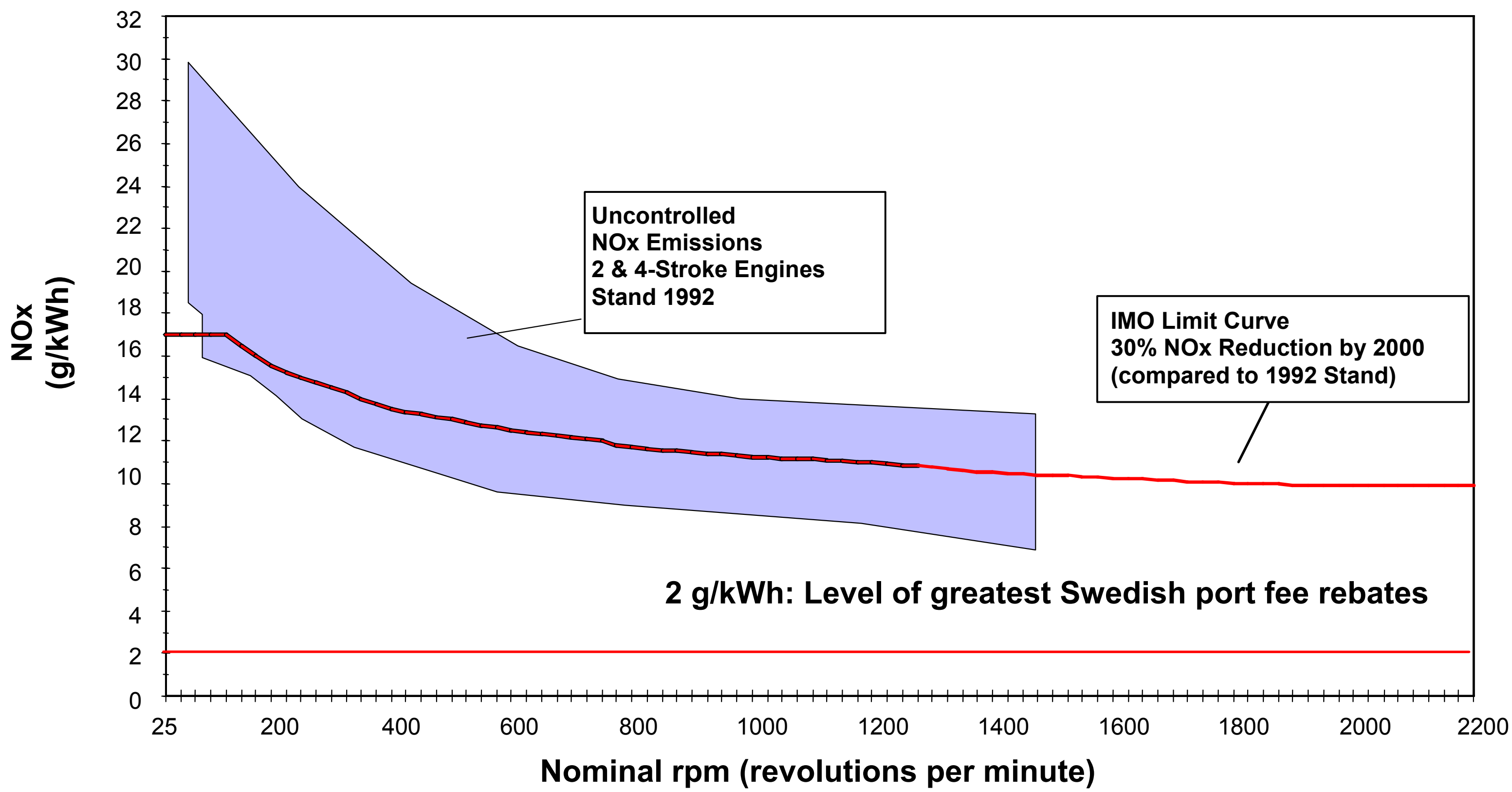

Source: IMO Marine NOx Emissions Performance based on 1992 stand; from Siemens literature, 2000.

Figure 1: Uncontrolled NOx Emissions and IMO NOx Limits

2.2.5 Ratification

The adoption of the proposed measures in Annex VI requires the ratification of a minimum of 15 countries with a combined minimum coverage of 50% of the world's shipping tonnage. Once this level of ratification has been reached, there is a one-year period before the regulations come into force. The regulations are set to apply retroactively to January 1, 2000, so all marine engine makers are currently complying with the limits for all new engine sales.

Since many countries must provide consent under the IMO constitution, it is difficult to bring about proposed regulatory changes quickly. To date, only three countries with relatively small shipping tonnage have ratified Annex VI: Sweden, Norway and most recently, Singapore. The ratification of the Annex VI measures will be required from major flag vessel nations such as Panama, Liberia, Greece and Russia before the approval requirement is reached. At present, the date of entry into force cannot be reliably estimated, but some experts believe it could be in the 2002-2005 time frame. Under the IMO ratification process, an international status review will be conducted next year to assess progress and possible revisions to the approval process if no significant progress has been made [1].

Despite the significant economic presence of the U.S., the vast majority of large marine vessels in U.S. waters are foreign-flagged vessels. Currently, an inter-agency task force in the U.S. is preparing documentation for consideration by the Senate Foreign Relations Committee, but an on-going political stalemate on foreign treaties may delay senate voting for an extended period of time [2].

Over the next few years of this decade, most experts see the IMO Annex VI being passed and becoming effective retroactive to January 1, 2000. There is also a belief that this is just a first stage in a long-term process of tighter controls on vessel emissions. The first generation of controls gets countries familiar with the regulatory and technical development processes and further controls can be developed depending on the evolution of viable control technologies.

2.3 Meeting Existing IMO NOx Limits

For most marine diesel engines, the IMO maximum limits represent a level that is about 20% or so below typical levels. IMO limits can be achieved on most marine diesel engines by making minor adjustments to the combustion process.

One of the most important basic NOx control techniques is to delay the injection timing towards the end of the compression stroke. This reduces the maximum temperature attained during the combustion, which directly reduces NOx formation. Retarded fuel injection increases fuel consumption by a few per cent, but this penalty can be offset by increasing the compression ratio. Retarded injection timing can achieve NOx reductions up to about 20%.

New engine designs have incorporated variable injection timing control systems that allow the fuel injection to be adjusted to achieve optimum conditions balancing NOx reduction with engine performance. These "common rail" systems are part of new electronic engine control systems, which allow the injection timing to be precisely controlled for optimum combustion based on multiple engine parameters, independent of speed and load.

Most manufacturers have increased the compression ratio of medium-speed engines by up to about 40%. Higher pressures change the reaction dynamics to give more rapid and complete combustion. More than 30 years ago, the brake mean effective pressures (BMEP) were typically 12-17 bar. This improved to 18-23 bar in the last 20 years and more recently, this has increased to 25-28 bar for the newest generation of engines. Superior materials and turbochargers are always used on medium-speed engines to attain these higher pressures and performance, but the designs are now approaching the technical turbocharger limits. To overcome this, manufacturers are now examining the use of two-stage, inter-cooled turbocharging combined with a charge air cooler to reduce the charge air temperature and consequent NOx formation. It is claimed that Wärtsilä is currently working on the design of a very-high pressure engine that will have approximately double the BMEP [3].

2.4 Other NOx Control Measures

There is some debate that the IMO limits do not go far enough in controlling emissions. Some countries may be considering imposing tighter measures. A U.S. delegation to the Marine Environmental Protection Committee (MEPC) claimed that NOx and hydrocarbon (HC) emissions from marine vessels contribute indirectly to climate change as precursors to the formation of ground-level ozone, a greenhouse gas. The U.S. paper called for NOx emissions to be reduced by a further 25 to 30% below the current proposed Annex VI limits.

Many northern European countries are considering setting standards beyond the proposed NOx limits. The development of local marine emissions control policies more stringent than IMO regulations provides a regulatory push for the development of NOx control technologies. However, there is a risk that uncoordinated marine regulatory development could reduce the efficiency and effectiveness of the worldwide shipping industry.

Differential charging is used by some countries to encourage environmentally friendly activity by offering a financial or other incentive to port users to operate in a particular and defined way. There are three current examples: a Swedish program for reduced port and fairway dues, the Segregated Ballast Tank (SBT) Regulations, and the Netherlands Green Award. The Swedish situation is presented as a case study.

2.4.1 Sweden

Sweden has been a world leader in setting local marine environmental standards for sulphur dioxide (SO_2) and NOx emissions. It is one of the three countries that have ratified the IMO MARPOL Annex VI. On January 1, 1998, Sweden established a schedule of fairway and port dues scaled based on the NOx emissions performance of vessels and the sulphur content of fuel used. Before this scaled fee structure was imposed, there was one standard fairway fee for all vessels, at 3.6 SEK/GRT (Swedish kroner per gross rated tonnage). In the current system, the dues for uncontrolled NOx emissions are higher than the previous fee, but fees are reduced progressively from this maximum level depending on the certified fuel sulphur content and NOx control levels in place.

The Swedish fairway fees start at 5.0 SEK/GRT for any NOx emissions rate above 11.0 g/kWh and decline linearly to a minimum of 3.4 SEK/GRT for NOx performance below 2.0 g/kWh. A rebate of 0.9 SEK/GRT is applied to all fairway dues if the fuel sulphur level is below 0.6% for passenger ferries and 1.0% for cargo ships [4]. Harbour fees are also subject to discounts that vary by major port. For example, the Stockholm harbour discounts are tiered: 0.05 SEK/GRT for NOx rates between 7 and 13 g/kWh and 0.15 SEK/GRT for levels below 7 g/kWh. Other harbours, such as Göteborg, Helsingborg and Malmö, set slight different discount schedules [5]. As an extra incentive for owners to install NOx control systems, Swedish authorities will rebate up to 40% of the capital cost over a 5-year period; the costs paid from dues collected on the vessel [6]. In setting up this system, Sweden is setting higher fees for uncontrolled NOx emissions, but essentially offering “rebates” for increasing levels of environmental controls. Dues can be reduced by up to 50% by using low-sulphur fuel and maximum NOx control technology.[2]

The Baltic Sea has been designated a SOx Emission Control Area under special provisions of Regulation 14 in the IMO MARPOL Annex VI. While the IMO international standards for sulphur content of marine fuels are proposed at 4.5%, this special designation mandates the use of fuels having a sulphur content of less than 1.5%. The European Union was active in getting the North Sea declared a SOx Emission Control Area in April 2000, with the same limitation. This designation is being considered for many other coastal/urban regions.[3] The Swedish rebates on fairway and port dues (above) are based on levels which go further than the Baltic Sea Control Area

[2] For the *Cabot* (14,600 GRT), fairway discounts could be as high as C$5,500 saving per visit.

[3] Vancouver and the St. Lawrence Seaway have been mentioned in Canada. Los Angeles and Seattle are under consdieration in the U.S.

limit. A SOx rebate is available if the ship bunker fuel has < 0.5% Sulphur for ferries and < 1% for cargo ships.

As of the end of 1999, over 1,300 ships were operating on low sulphur fuels within Swedish coastal limits. Also at that time, 11 vessels were certified in Sweden for reduced NOx emissions and reduced dues. Four of these used direct water injection technology, which achieved NOx emissions rates between 6.5 and 8.0 g/kWh.[4] The other seven used SCR systems, which achieved the lowest NOx emissions rates of between 0.5 and 1.8 g/kWh, qualifying these vessels for the maximum fee reduction. An estimated 40 more ships were being certified for NOx reductions in the year 2000. Based on increasing sales orders for SCR and DWI systems, the number of annual certifications is expected to grow in the short term. Most of these vessels are passenger ferries, which have frequent runs, but some cargo ships are starting to install controls to reduce fees as well. By the end of 2000, Swedish authorities calculate that this program will have reduced total Swedish marine NOx emissions by 40% [7].

2.4.2 Norway

Norway, another country that has ratified the IMO MARPOL Annex VI, is about to put in place a somewhat similar system that involves differential harbour fees, and other tax benefits. The Norwegian-based marine classification society Det Norske Veritas has established a special class designation for a "green" ship, which is able to achieve more than a 60% reduction below IMO target levels. Under the Norwegian system, "green" ships will qualify for enhanced fee reductions and other credits.

2.4.3 Other Differential Fee Programs

The only other known differential fee systems are the European Commission SBT Regulations and the Green Award set up by the Netherlands Directorate of Shipping and Maritime Affairs and the Port of Rotterdam Authority [8].

Although the European Commission has shown interest in differential charging, it has so far only taken action with SBTs. The SBT Regulations are the only example of a mandatory system applicable in all European Union member states. The European Commission SBT Regulations were set in 1994 to provide a reduction in port dues for tanker vessels with SBTs. However, a European Commission White Paper [9] discusses other possible Community actions for air emissions, such as the introduction of minimum fuel quality standards, differential fuel charges based on emissions and differential port and fairway charges based on emissions. Community action or legislation however is not likely to materialize in the short term. Some of the northern European countries, such as

[4] No details were available on the engine types or NOx reduction levels associated with these rates.

Finland, Germany and Denmark appear to be moving independently toward programs similar to those in Sweden [10].

The Netherlands Green Award is a voluntary program principally applied to the port of Rotterdam. It covers a wide range of environmental controls and its incentives often involve credits or discounts on port services. Because of the broader nature of this program, more resources are required to administer and monitor it compared to the other two.

2.4.4 United States

In July, 2000, the U.S. EPA signed the final rule regulating emissions from new marine diesel engines above 37 kW in power. Three different standards are proposed for different engine categories based on basic engine technologies used in marine vessels:

1) land-based non-road diesel engines (displacement per cylinder $D < 5$ L);
2) locomotive engines ($5 < D < 30$ L);
3) unique marine diesel engines ($D > 30$ L)

Category 1 and 2 engines are used for smaller vessels typically used in inland waterways and their proposed standards are based on the corresponding EPA Tier 2 standards for non-road and locomotive engines. Most larger, commercial cargo vessels use Category 3 engines. The EPA has not adopted any emissions standards for Category 3 engines, but rather has set up a voluntary certification program to encourage vessel owners to adopt the MARPOL Annex VI limits.

In a recent development, the concept of deferring the regulatory development process for Category 3 standards to external IMO limits was legally challenged and an out-of-court settlement was reached. Under U.S. laws, the U.S. EPA must now domestically develop its own proposed Category 3 standards by April 2002. The IMO MARPOL Annex VI limits may still be selected after this due process, but the U.S. may come up with different standards.

2.4.5 Alaska

The Alaska Department of Environment Conservation has set up an Alaska Cruise Ship Initiative that covers waste management, water releases and air emissions. Smoke opacity and SO_2 emissions are key issues in Alaskan ports. Emissions reduction practices such as use of lower-sulphur fuels, adjusting engine timing, and engine operating protocols are currently being used. Since Alaska is a major world cruise market in the summer, ship operators are examining control technologies on diesel engines and alternative power systems [11].

2.4.6 Other U.S. Diesel Engine Regulations

The second phase of program are proposed regulations, phased in from 2007 to 2010, to achieve on-road emissions reductions of more than 90% over levels achieved by the phase 1 reductions. These proposed rules also include clean on-road diesel fuel standards by 2006 to allow the catalytic technologies to work effectively. The proposed 2007 regulations set on-road NOx emissions limits of 0.20 g/bhp-hr (0.27 g/kWh) and PM limits of 0.01 g/bhp-hr (0.013 g/kWh).

3. Vessel Profile

3.1 Summary

This case study analysis focuses on the M.V. *Cabot*, one of three ice-class Ro/Ro container ships operated year-round by the commercial shipping company Oceanex, based in Montreal, Quebec. The *Cabot* was built in 1979 and has had one major hull modification. When full, it has a gross rated tonnage (GRT) of 14,597 and when empty, a net tonnage of 4,379. The container ship makes regular weekly round-trip runs between Montreal and St. John's, Newfoundland, sailing through the St. Lawrence River and the Gulf of St. Lawrence. The *Cabot* shares this supply route with a smaller Oceanex vessel, the M.V. *Cicero* (10,919 GRT). The third and largest Oceanex vessel, the *Sanderling* (21,849 GRT), runs between Halifax, Nova Scotia, and St. John's or Corner Brook, Newfoundland. Photographs of the *Cabot* and its engine room are included in Appendix A.

This ship was chosen as a basis for this study because it is a medium-sized cargo vessel operating within coastal waters and using medium-speed marine engines. While it is not a "Laker" (operating in the fresh-water Great Lakes) and has some unique features, it was considered to have typical characteristics of middle range Canadian commercial vessels.

Most of the information in the following profile of the case study vessel was provided by Oceanex, the ship owner. Additional information was collected from the engine manufacturer, petroleum suppliers, and other engine component (e.g. propeller and turbocharger) suppliers. The key information and assumptions that are used in the cost analysis are summarized in tables at the end of this chapter.

3.2 Propulsion System

The propulsion system for the *Cabot* consists of two main engines, each having separate controllable pitch propellers and separate exhaust systems. Auxiliary engines, water and boiler systems were not considered in this analysis.

3.2.1 Engines

The main propulsion for the *Cabot* is from 2 twin Pielstick 12 PC2.5 V "medium-speed" engines at 5.8 MW (7,800 bhp) maximum continuous rating (MCR) each. The total power rating for the propulsion system is approximately 11.6 MW. Pielstick is a marine engine company based in Paris, France, with manufacturing operations in St. Nazaire, in northwest France. It is now part of the MAN B&W Group, and currently manufactures four series of diesel engines for merchant ships ranging in size from 3.9 to 26.5 MW.

The PC2.5 series of engines is a discontinued generation of medium-speed engines (rated at 478 kW/cylinder and 520 rpm) that range from 2.9 to 8.6 MW. Pielstick no longer produces a medium-speed engine at 5.7 MW. The latest generation in this series of engines is the PC2.6 B series, designed to be about 60% more powerful per cylinder (750 kW/cylinder, 600 rpm) and ranging from 9 to 15 MW in power, too powerful for the *Cabot*'s requirements. The only equivalent-power alternative supplied by Pielstick would be the 16-valve engine in the PA6 B STC series. This is a higher-speed engine (1,050 rpm) using a sequential turbocharging system, which provides higher torque, lower fuel consumption, and lower smoke emissions.

Table 1: Pielstick Engine Line Power Ratings
(MW)

Engine Line	**Power/ cylinder**	**Number of Cylinders**						
	(kW)	**6**	**8**	**12**	**14**	**16**	**18**	**20**
PC2.5 (old)	478	2.9	3.8	**5.8**	6.7	7.7	8.6	-
PC2.6 B (new)	750			9.0	10.5	12.0	-	15.0
PA6 B STC (new)	405			4.9	-	6.5	-	8.1

Source: SEMT Pielstick

Each engine on the *Cabot* has 12 cylinders that operate on a 4-stroke cycle; 6 on each side of a V configuration. The cylinder bore is 400 mm and displacement in 460 mm. The BMEP of combustion at 520 rpm is 19 bar, which is typical of such marine diesel engines. For each engine, there are two Brown Boveri VTR 401 turbochargers mounted at the end of the exhaust gas manifolds on each side of the engine.

The two engines are positioned side by side along the centre line of the ship with a narrow service aisle between. There is a limited amount of room in the surrounding engine room area, which spans two decks. An upper deck area gives access to the cylinder heads and fuel, air and exhaust piping and turbochargers. A lower deck gives access to the crankshaft and auxiliary systems.

3.2.2 Propeller

The ship has two separate shafts, one from each engine. Kamewa Controllable Pitch propellers having four stainless steel blades (102 XF/4 type) are mounted on each shaft. The diameter of the each hub is 1 m and the diameter of the blades is 3.6 m.

3.2.3 Exhaust

The *Cabot* has two separate exhaust gas pipe systems running to separate port and starboard stacks located near the stern of the ship. One exhaust pipe system starts from the two turbochargers mounted on the end of one of the 12 V Pielstick PC2.5 engines. The two turbocharger exhaust gas outlets (D = 0.65 m) join together immediately and run in a pipe (D = 0.9 m) horizontally for about a 5 m length through a boiler feed water economizer. After a 90° upwards elbow, the vertical run is about 20 m from the engine room through two decks to the top of the stack. The stack housing is approximately 6 m above the surface deck. The exhaust pipe runs through congested structural steel work for the bottom 3 m of the stack structure, but there is ample space around the pipe over the top 3 m. There is no silencer on the system. The same exhaust configuration applies to the other engine, but in mirror image. The exhaust gas configuration is illustrated in profile and elevation diagrams in Figures 2 and 3.

The temperature of the exhaust gas before the turbocharger is in the range of 370-390°C. The economizer inlet exhaust temperature is 325°C, but this falls to about 240°C at the economizer outlet. At MCR, the exhaust gas flow rate is 3.54 t/h per cylinder. This is approximately 42 t/h for each engine exhaust pipe.

3.2.4 Water System

The *Cabot* has a main freshwater storage capacity of 400 t for crew use and general cleaning. The vessel also has a 15 t water storage tank in the engine room, which is used for general washing, and to supplement the boilers and the expansion tanks.

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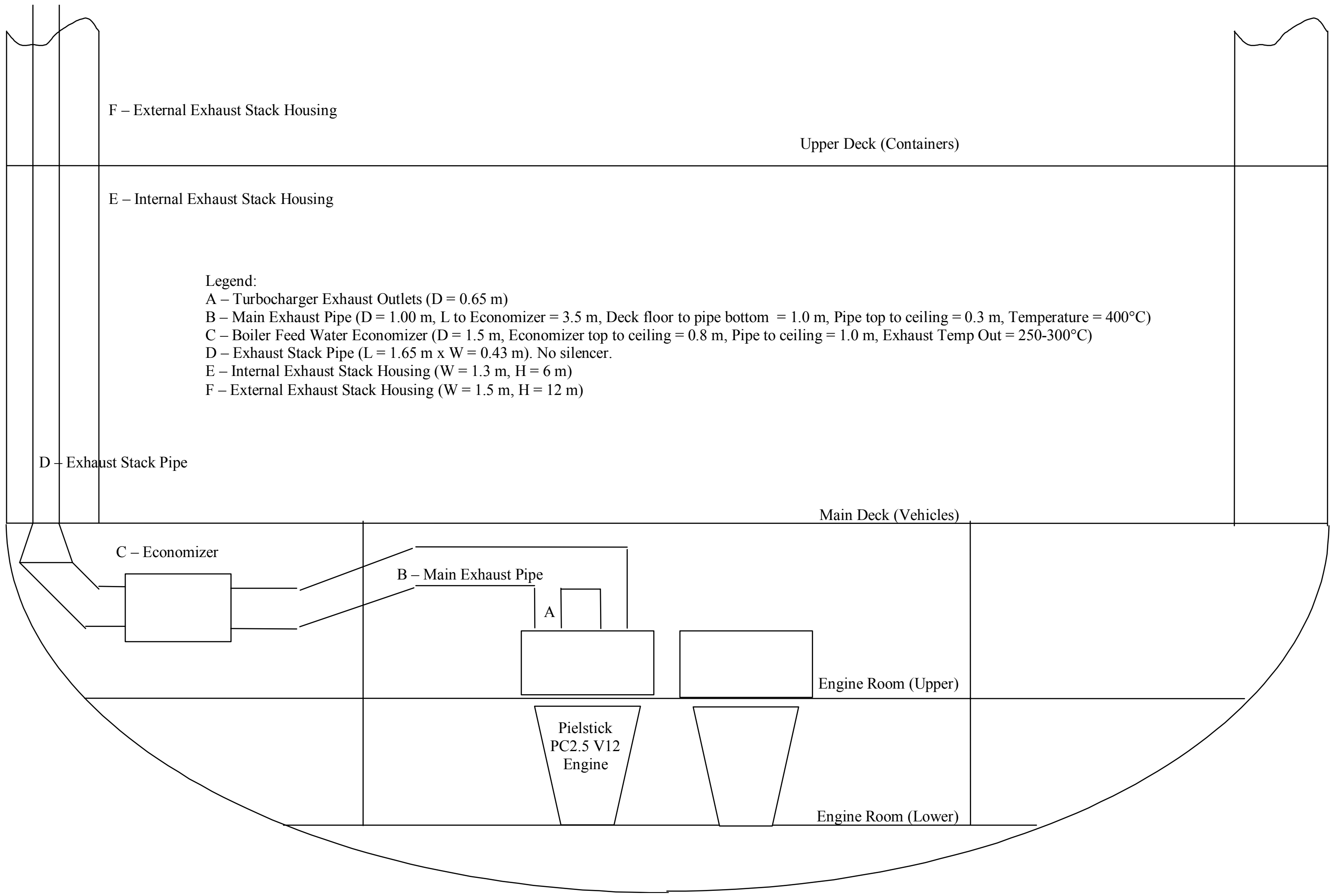

Figure 2: Cross Section of RoRo Carrier at Exhaust Pipe Line (Original)
(Approximate scale when printed – 1 in. = 2.2 m)

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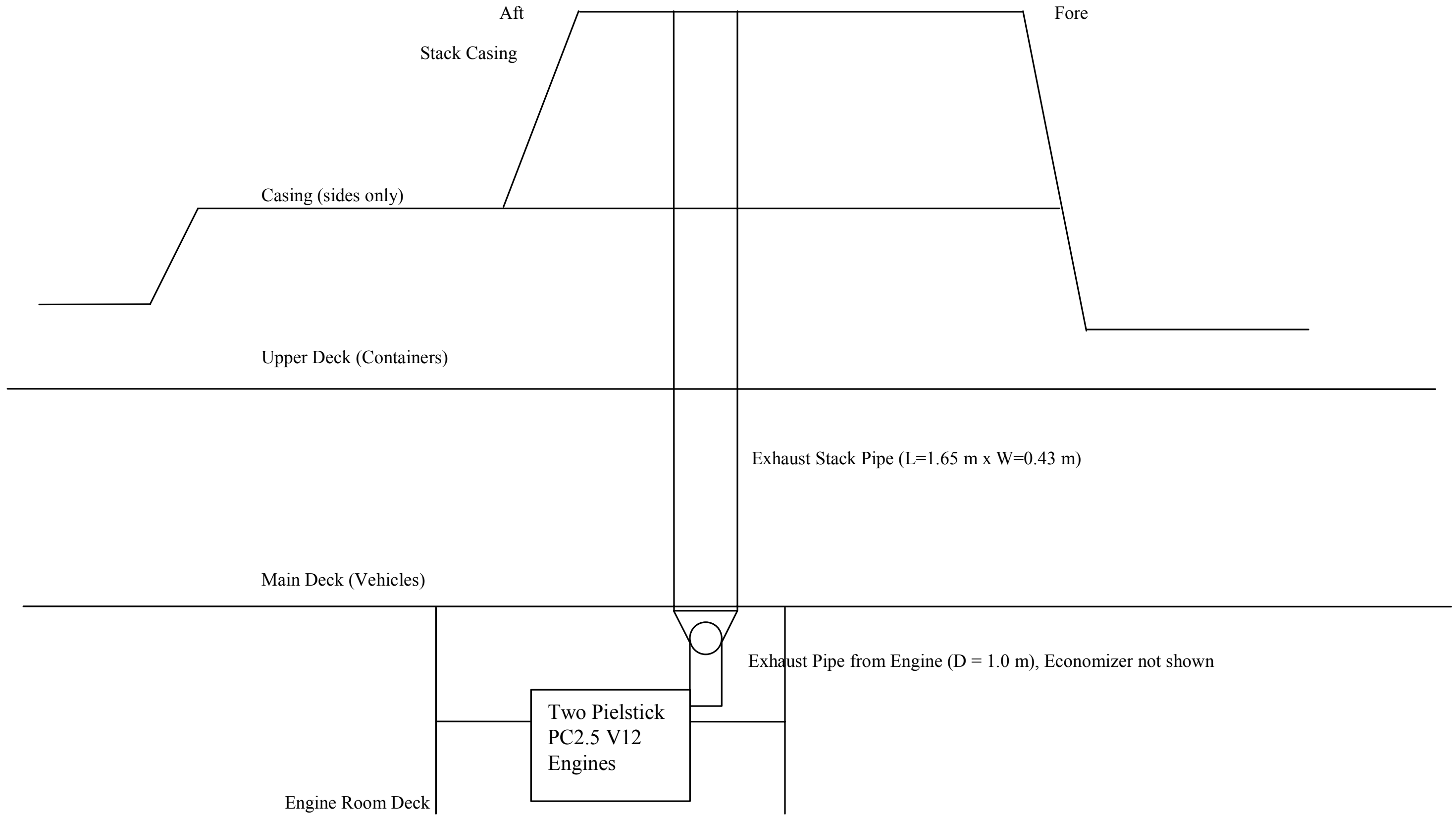

Figure 3: Elevation View of RoRo Carrier (Original)
(Approximate scale when printed – 1 in. = 4 m)

3.3 Operating Profile

The M.V. *Cabot* runs regularly in weekly round trips between Montreal, Quebec, and St. John's, Newfoundland. The outbound voyage from Montreal departs each Monday and takes approximately 60-64 hours (approx. 2½ days) of steaming time, depending on the weather and season.[5] The inbound voyage from St. John's departs each Thursday and takes roughly the same time. For this study, the total operating time for the engines is assumed to be 125 hours per trip. Over an average year, the vessel is assumed to make 48 weekly round trips, for a total engine operating time of 6,000 hours per year.

The ship has a cargo capacity of 644 twenty-foot equivalent units (TEU), but a typical voyage load is about 500 TEU (77% of capacity). The engine load range that provides the optimum fuel consumption is between 82 and 86% of the MCR.[6] The engines are usually operated at equal load levels in constant speed mode at 520 rpm. In this mode, the ship's speed is then controlled by varying the pitch of the propellers. Although capable of 18 kn, the typical average speed for voyages is about 16.5 kn.

3.3.1 Fuel

Intermediate Fuel Oil (IFO) 180 is used as the main fuel for the engines. IFO 180 is a common mid-grade of marine fuel oil, also known as "marine bunker", which is a blend of mostly heavy fuel oil (HFO) and some marine diesel oil (MDO). This fuel meets the British Standards Institute specifications of a maximum 180 cSt viscosity at 50°C and has a density of about 0.99 kg/L. The heating value of IFO is assumed to be 42 GJ/t, similar to that of HFO. The sulphur content of the IFO fuel used on the *Cabot* averages just under 1.5%. Many commercial marine operators try to use IFO 180 since it is perhaps the cheapest fuel blend that ensures reliable engine performance and meets local environmental restrictions. Many ports have maximum allowances for sulphur in fuels. For example, Toronto and Montreal fuel sulphur levels are restricted to a maximum of 1.5%.

In port areas, the engines are run on MDO alone, but this amounts to about 10% of the total fuel use for a voyage. MDO has a density of 0.84 kg/L and assumed heating value of 39 GJ/t. The typical sulphur content of MDO is about 0.5%. In contrast, on-road diesel fuel has about 0.05% sulphur. As part the next phase of diesel regulations, the U.S. EPA is preparing legislation that would bring all fuel sulphur levels down to 30 ppm, or 0.03% sulphur, by 2007.

In one round trip, the fuel consumption is approximately 200-210 t of IFO 180 and 20 t of MDO fuel. For this study, the use of 205 t of IFO is assumed per round trip. This

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[5] The total steaming time for one recent round trip was 123.25 hours.
[6] On one recent trip, the average load recorded was 9,900 kW (2 engines), which is roughly 85% of MCR.

translates into an overall fuel consumption rate of approximately 182 g/kWh. The engines are well-balanced during operations, and maintained regularly with new parts and components to achieve optimal efficiency. The engine thermal efficiency is calculated at approximately 48%,[7] which falls into the expected range of 45-50% for medium-speed engines.

3.3.2 NOx Emissions

Actual uncontrolled NOx emissions for the M.V. *Cabot* have been measured by Environment Canada in limited performance tests [12]. As mentioned in Chapter 2, the 1992 stand (sample) of ships used to develop the IMO NOx limits showed that the expected range of average NOx emissions rates for a medium-speed (520 rpm) vessel was 10-18 g/kWh [13]. Environment Canada test data shows that the *Cabot*'s NOx emissions rate ranged from 12.5 g/kWh at the highest load to 24.8 g/kWh when operating in port. It is assumed that the engine will run at its highest load for the majority of each 60 hour one-way trip and so the average emissions rate is expected to be close to the low end of this range. Based on an unscientific weighting of the various emissions levels recorded during testing, the average NOx emissions rate is assumed to be 14.0 g/kWh. This corresponds to the mid-point of the expected range. The exact level is not critical for the study, but this reasonable estimate serves as a reference point from which the NOx reduction performance of various technologies can be compared.

NOx emissions from diesel engines do not tend to increase appreciably over the life of an engine, since they are largely based on the combustion temperature-time profile. This is not the case for HC and PM emissions, which can increase due to wear or lack of maintenance. NOx measurements only need to be made once for a particular type of engine and generally apply throughout the engine life. Among different ships using the same engines and fuel, NOx emissions should be at similar levels.

[7] Based on IFO at 42 GJ/t and MDO at 39 GJ/t.

3.4 Summary

Tables 2, 3 and 4 summarize the key fuel and engine characteristics and the assumptions used for the cost analysis in this study.

Table 2: Fuel Characteristics and Assumptions

	IFO	MDO	Total/Avg
Density (kg/L)	0.993	0.84	
Heating Value (GJ/t)	41.73	38.68	
Price ($/L)	$0.177	$0.368	
Price ($/t)	$179	$438	$202
Fuel Consumption (t/trip)	205	20	225
Fuel Cost ($/trip)	$36,611	$8,757	$45,368

Note: “Trip” refers to a round trip voyage (Montreal - St. John’s - Montreal)

Table 3: Operating Characteristics and Assumptions

Engine Power Rating (2 engines, at MCR)	11,633 kW
Expected Operating Load (%MCR)	82-86%
Assumed Average Operating Load (%MCR)	85%
Trips per Year	48
NOx Emissions Rate Range (g/kWh)	10-18
Assumed NOx Emissions Rate (g/kWh)	14
IMO Limit (g/kWh)	12.9
Main Water Storage Capacity (t)	400
Auxiliary Water Storage Capacity (t)	15

Table 4: Summary of Operating Performance Assumptions

	per Trip	per Year
Average Engine Operating Time (hours)	125	6,000
Average Engine Output (MWh)	1,236	59,328
Fuel Consumption (t)	225	10,800
Fuel Energy Input (GJ)	9,328	447,756
Fuel Cost ($)	$45,368	$2,177,671
Uncontrolled NOx Emissions (t)	17	831
Fuel Consumption Rate (g/kWh)	182	182
Thermal Efficiency (%)	48%	48%

4. Continuous Water Injection to Charge Air

4.1 Summary

Continuous water injection (CWI) to the charge air is a relatively simple method of reducing NOx by up to 30% and PM emissions by about 25%, without engine modifications. A fine, freshwater mist is injected directly into the hot compressed air of the turbocharger outlet. A system was designed for demonstration on a B.C Ferries vessel, but there is no known system currently in continuous operation. The installed cost of the technology is about $50,000. In field tests conducted by Environment Canada, CWI achieved a 22% reduction in NOx and an average reduction in specific fuel consumption of 1%, which resulted in a net saving of approximately $143 per tonne of NOx reduced. CWI is not recommended at water-fuel ratios above 25% due to expected fuel consumption penalties.

4.2 Description

The information on the CWI system was provided by M.A. Turbo/Engine Design of Vancouver, the only known North American vendor of CWI technology.

4.2.1 Operating Principle

CWI uses existing freshwater from the ship to moisten and humidify the combustion air in the manifold just prior to the cylinder. A small portion of the water evaporates in the charge air, but most of the injected water remains in the form of mist (microdroplets). The moist charge air mixes with the injected fuel inside the cylinder. CWI technology can be used with most marine fuels, although the intimate mixing is enhanced with lighter fuels. The water absorbs energy released from the combustion reaction and reduces the peak flame temperature. The evaporation of water mist in the cylinder contributes significantly to the reduction in flame temperature because of the high latent heat of vapourization of water. Water vapour has a heat capacity to further absorb energy through superheating. The reduction of the flame temperature is the main factor contributing to a lower rate of NOx formation.

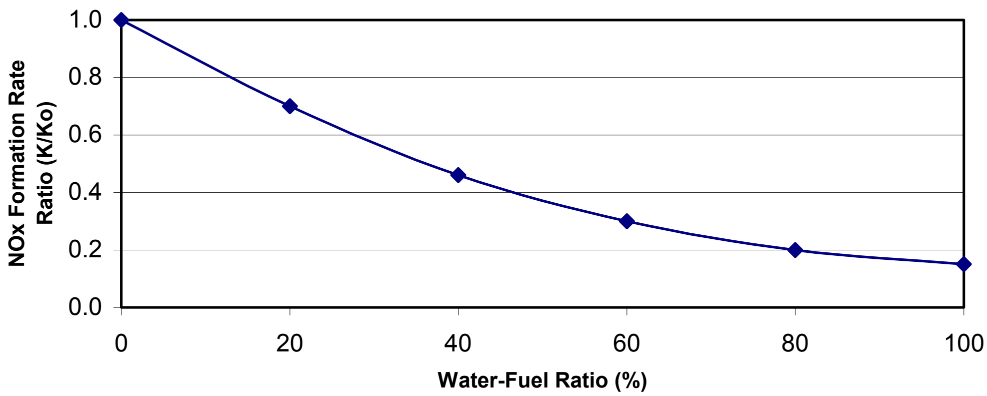


Figure 4: Theoretical NOx Reductions from Water Injection

NOx emissions reductions follow a negative exponential pattern with increasing water-fuel ratios. In Figure 4, the NOx reductions are represented by the ratio of the controlled NOx formation rate constant (K) to the uncontrolled NOx formation rate constant (K_0). The greatest NOx reductions occur at the lowest water-fuel ratios (slope of line is high) and reductions diminish at higher ratios (slope is lower). [8]

At low water-fuel ratios (below about 25%), the presence of the water acts to improve the combustion kinetics, which results in a slight decrease in specific fuel consumption below uncontrolled levels.

However, above 25% water-fuel ratio, the water content starts to interfere with the combustion process and specific fuel consumption increases. Figure 5 shows that the optimum specific fuel consumption is theoretically achieved at a water-fuel ratio of approximately 10%, and that fuel penalties start occurring above 25%.

[8] This relationship is based on the Zeldovich mechanism: $K/K_0 = \exp[-E\Delta T_c/R(Tc-\Delta T_c)]$, where the change in combustion temperature (ΔTc) is a function of water-fuel ratio (M.A Turbo/Engine Design).

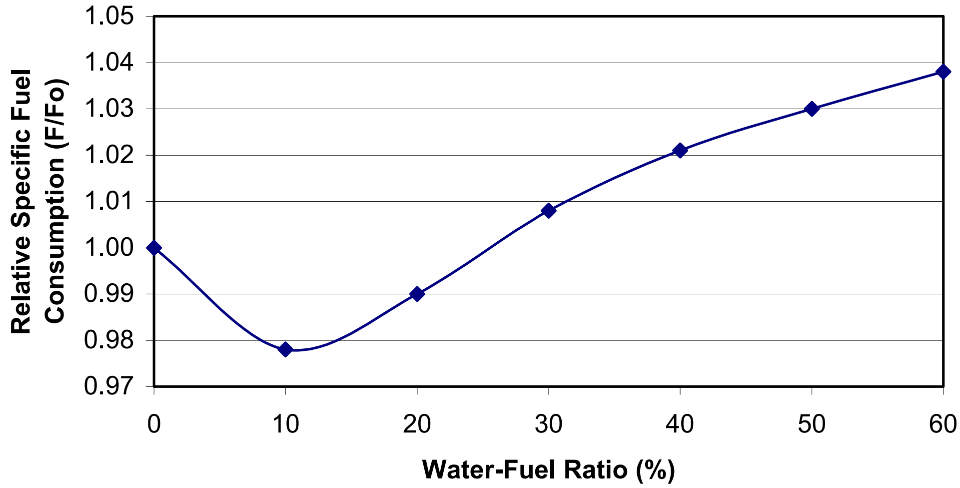
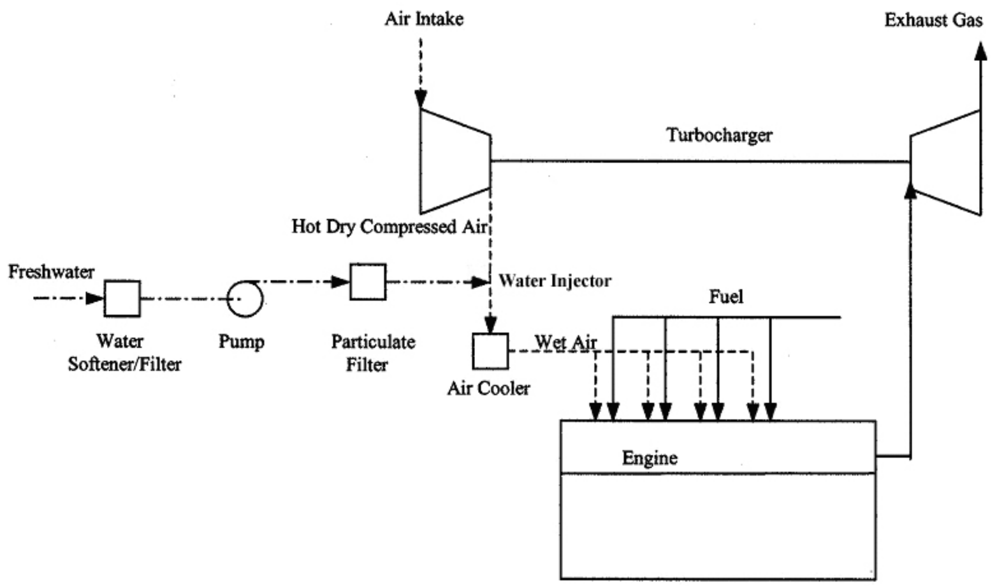


Figure 5: Fuel Consumption Effect of Water Injection

4.2.2 System Description

The CWI system consists of a water filtration and softener system, water pump, multiple fine-spray injectors, a process control system and a low-voltage power supply. The system is designed to operate at engine load levels above about 25-30% of MCR. Water is injected as a fine spray mist into the charge air manifolds directly after the turbocharger compressor on each engine at a pressure of 75 psig. The flow is controlled by solenoid valves on the water supply lines, which activate once certain threshold boost air temperature and boost air pressure levels are attained.

The ship's freshwater system is assumed to be used as a source of water. A 24 V water pump with a dedicated power unit is used to boost the water pressure from about 60 psig (standard pressure) to about 85 psig. It is designed with an internal recirculation loop. The water filtration system is designed to demineralize water and remove foreign PM. It consists first of a softener cartridge on the suction side of the pump, followed by a particulate filter cartridge on the pump discharge. These cartridges must be changed monthly for good operation. Assuming a 20% water-fuel ratio is used at standard operating conditions, the freshwater system should have the capacity to handle approximately 25 additional tonnes of water for a 2½ day, one-way trip.



Source: M.A. Turbo/Engine Design

Figure 6: CWI System Schematic Diagram

4.2.3 Size

The CWI system occupies only a small space in the engine room of a ship. The principal components (pump, water softener and particulate filter) can be fit into one module or in separate spaces. A control system cabinet is also required. Both of these would likely occupy a floor space of no more than 1 m^2. Some extended piping may be required to connect to a freshwater supply line.

4.2.4 System Performance

The CWI technology has the ability to reduce NOx and PM emissions simultaneously with fuel consumption. In theory, NOx emissions reductions are generally limited to 25% of uncontrolled levels without a fuel penalty. The technology vendor, M.A. Turbo/Engine Design, reports that the estimated NOx reduction potential is up to 30% and the estimated PM reduction is up to 25%.

Recent tests of the CWI system on a B.C Ferries vessel showed NOx reductions ranging from 11 to 22% using water-fuel ratios ranging from 15 to 40%. The tests were carried out in July 1999 and January 2000 by Environment Canada in collaboration with Transport Canada and B.C. Ferries. The CWI system was installed on the *Queen of New Westminster*, a 8,700 GWT passenger/car ferry (with a 3.4 MW Wärtsilä 9R32D engine) that runs on the Tsawwassen - Nanaimo route. Several separate water injection tests with duration ranging from 5 to 20 minutes were performed on outbound and return voyages.

The water-fuel ratio was varied and emissions performance for several compounds was measured. Under these test conditions, NOx reductions ranged from 10 to 22%. The average PM reduction during the January 2000 test was 19.8%. The levels of carbon monoxide (CO) and carbon dioxide (CO_2) were relatively unchanged. The specific fuel consumption (g/kWh) decreased by an average of approximately 1% during the short-term tests due to a slight increase in engine load with an unchanged fuel rate. This reduction level was generally observed at all water-fuel ratios tested [14].

4.2.5 Operating Issues

Since there is relatively little operating experience with CWI systems, there is limited information about the long-term effects of the system on the engine or its components. Some of the major engine manufacturers warn about potential corrosion problems that may result if water mist is allowed to condense into larger droplets in the air manifold or the air intake valves. A proper CWI system design would protect against this threat.

4.3 Costs

Capital, installation and operating cost estimates for the CWI system were provided by M.A. Turbo/Engine Design. System performance assumptions were taken from Environment Canada's official *Queen of New Westminster* test program report.

4.3.1 Key Assumptions

The key assumptions used in the cost calculations were:

- Capital cost rate of $3.50 per kW for a two-engine system;
- Installation takes 10 working days at a total cost of approximately $10,000;
- Annual consumable cost of only $800 per year;
- No other maintenance assumed;
- Water-fuel ratio of 40% (maximum during testing) but water costs negligible;
- A NOx reduction of 22% (maximum during testing);
- A 1.0% fuel consumption savings, as observed during testing.

The capital costs comprise the costs of all system components, including process controls. No component cost breakdown was provided. Installation cost was assumed on the basis of two mechanics over a period of 10 working days, plus expenses. The cost of consumables is only the monthly replacement of small softening and filtration cartridges. No other water treatment costs and no modifications to water storage tanks are assumed.

The 22% NOx reduction level was selected for the comparative analysis, since this was the highest NOx reduction that was achieved at a 40% water-fuel ratio during the Environment Canada tests. The fuel savings associated with the reduction in specific fuel consumption were assumed to be 1.0%, the average calculated for all the tests. Since changes to the water-fuel ratio theoretically result in changes to specific fuel consumption, a sensitivity analysis for different fuel-water ratios is presented following the cost summary.

No cost estimate was provided by the vendor for freshwater supply. The additional freshwater required for the CWI system was assumed to be provided from the ship's freshwater system at negligible cost. A brief water cost analysis is provided in section 4.3.4 to support this assumption. No other unusual maintenance costs were identified.

4.3.2 Cost Analysis

Assuming the above operating conditions apply, the cost of NOx reduction with CWI technology is a saving of $143 per tonne of NOx reduced.

Table 5: CWI System Costs
(Basis: M.V. *Cabot* with two 5.8 MW Pielstick engines)

Capital Cost	
Capital Cost	$41,000
Installation Cost	$10,000
Total Installed Cost	$51,000
Annualized Installed Cost ($/y)*	**$5,700**
Operating Costs	
Fuel Cost Penalty/(Savings) ($/y)	($33,000)
Cartridge Consumables ($/y)	$800
Net Operating Costs/(Savings) ($/y)	**($32,200)**
Total Annual Cost/(Savings) ($/y)	**($26,200)**
NOx Reduction	**22%**
Annual NOx Reductions (t/y)	**183**
Cost per tonne NOx reduced ($/t)	**($143)**

* Total installed costs are amortized at 10% over 23 years.

This system is a relatively low-priced method of achieving low levels of NOx reductions, along with additional fuel savings. The influence of the initial installed cost on the total system costs is relatively small, compared to the estimated fuel savings, which is the most significant cost component of the system.

4.3.3 Sensitivity of Water-Fuel Ratio

The overall cost of NOx reduction using CWI depends greatly on the specific fuel consumption achieved with the system. The above analysis was made based on a NOx reduction of 22% (achieved at a water-fuel ratio of about 40%) and an assumed average reduction in the specific fuel consumption of 1% [14]. According to the theory, increased fuel savings can be achieved using lower water-fuel ratios, but this was not observed during the field testing.

Figures 4 and 5 can be used to illustrate the sensitivity of costs to fuel consumption. If the specific fuel consumption could be reduced to the optimal 2.2% at low water-fuel ratios, the effect on annual fuel savings would make this NOx control technology more attractive with a potential savings of $438 per tonne NOx reduced. On the other hand, if higher water-fuel ratios were used, resulting in a specific fuel consumption increase of 2.0%, the unit costs of NOx control would increase to about $173 per tonne. While this is a valuable illustration of the impact of fuel savings, in practice, these theoretical fuel consumption and NOx reduction levels are unlikely to be achieved consistently.

Table 6: CWI Cost Sensitivity to Water-Fuel Ratio

Water-Fuel Ratio	**10%**	**>>40%**
Theoretical Fuel Consumption Change	-2.20%	+2.0%
Incremental Fuel Cost/(Saving) ($/y)	($72,000)	$65,000
Total Annual Cost/(Saving) ($/y)	($65,000)	$72,000
NOx Reduction	18%	50%
Annual NOx Reductions (t/y)	150	415
Cost per tonne NOx reduced ($/t)	**($438)**	**$173**

4.3.4 Sensitivity to Water Costs

There is some uncertainty about the cost of supplying the freshwater required for the CWI system. The above analysis assumes no additional cost for water. Calculations show that at a 25% water-fuel ratio, a typical water flow rate of approximately 500 L of water per operating hour is required. This translates into a requirement of about 30 t of freshwater (30 m^3 or 30,000 L) for a one-way trip between Montreal and St. John’s.

If the ship’s current freshwater system is not capable of supplying this volume at minimal cost, there are a few options available to supply the additional water. One option would be to install a freshwater storage tank in an available void space. To give flexibility to run at maximum load and higher water-fuel ratios, the tank capacity should be between 50 and 60 m^3, roughly equivalent to one half a jumbo rail tank car. Installed costs for such water tanks range from about $2 to $7 per lb. of steel used, depending on the installation difficulty, and a rough conservative estimate would be about $50,000, installed [15]. If existing tanks are available and could be converted to CWI service, the capital costs could be reduced or eliminated. Municipal water supplied at each port would be used to fill the tank. At an average price of approximately $\$1/m^3$, the cost of municipal water would be about $2,700 per year [16]. After amortizing the capital costs at 10% and 23 years, the annual costs of such a system would amount just over $8,000 per year.

A second alternative would be to install a freshwater generator dedicated to CWI water service. A rough estimate from Pielstick suggests the cost of a freshwater generator capable of supplying this volume is about $50,000 installed. Assuming energy costs are relatively low, this translates into an additional annual cost of about $6,000 per year, after amortization.

The above water supply analysis suggests that the annual costs to supply freshwater to a CWI system would not exceed $10,000 per year. If an alternative freshwater system were necessary, it would increase the annual costs and the unit costs of NOx control.

4.4 Practical Experience

The CWI System designed by M.A. Turbo/Engine Design is the first implemented technology in North America for the reduction of NOx, PM and CO emissions from the existing marine diesel engines while at the same time providing an important fuel savings. The technology has largely been installed for demonstration tests and has accumulated approximately 3,600 hours of operating experience in North America.

No other worldwide demonstrations of CWI technology were identified in the research for this study.

5. Fuel-Water Emulsions

5.1 Summary

Fuel-water emulsion (FWE) systems can reduce NOx formation in marine diesel engines by 30 to 60% by intimately mixing water into the fuel oil. The resulting dispersion of microfine water droplets in fuel is injected normally into the engine cylinders. The systems have only recently been commercialized as an option on new MAN B&W marine engines and are rarely used in retrofits. A significant benefit of FWE systems is a drastic reduction of PM emissions (smoke) and lower engine soot deposition. The estimated installed cost of FWE technology as a retrofit on the *Cabot* is about $325,000. At a water-fuel ratio of 50%, FWE can achieve a 50% reduction in NOx at a cost of approximately $217 per tonne of NOx reduced. A major portion of this cost is an assumed 1.5% specific fuel consumption penalty.

5.2 Description

The information in this section is summarized from product literature and personal interviews with MAN B&W, RESON, Pielstick, Wärtsilä and other marine experts.

5.2.1 Operating Principle

FEW is prepared by applying a strong mechanical shear force to a fuel-water mixture. FWE can reduce NOx emissions by lowering the peak temperature of the combustion process. In a typical temperature-time profile of a diesel engine combustion cycle, the temperature increases very quickly to a distinct, high-temperature peak (“spike”) during the compression stage of the cycle, when initial combustion occurs. As the reaction is completed, the temperature of the gases declines to the exhaust gas temperature. Since NOx formation is dependent on temperature and duration of combustion, the presence of water in the fuel acts to absorb the heat of combustion and can significantly reduce the temperature peak and associated NOx formation.

The effectiveness of emulsions on NOx reduction depends on the oil viscosity, the engine load, the water content and how well the water is mixed with the fuel (mean water droplet size and distribution). Most companies designing FWE claim that there is a linear relationship between NOx reductions and the water-fuel ratio: generally a 1% reduction in NOx for every 1% increase in water-fuel ratio, up to a limit of about 50%. On medium-speed engines using IFO or HFO, FWE can reduce NOx emissions levels typically to the range of 6 to 8 g/kWh [17]. (MAN B&W reports that FWE reduces NOx emissions for its 514 rpm 48/60 engine to about 6.7 g/kWh, about half the IMO NOx limit). Beyond this point, engine power drops off considerably. FWE is most effective for NOx reduction at high loads, because water emulsions produce increased ignition delays (and therefore more fuel in the combustion chamber) at lower loads.

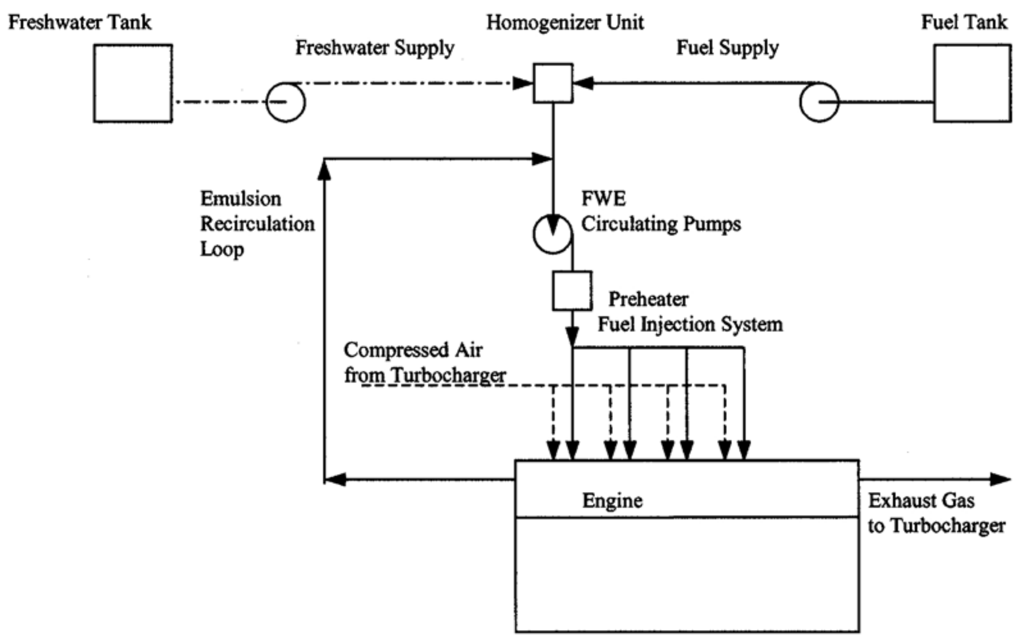
The aim in FWE is to obtain the smallest water droplets intimately mixed with the fuel in the emulsion at the microscopic level. As the emulsion is atomized, the water droplets are finely and more evenly interspersed with the fuel droplets. Using ultrasonic cavitation homogenizer systems, it is possible to produce FWE having water droplet size down to about 1 micron. This emulsion typically consists of one or two water droplets trapped inside each fuel droplet. When the fuel droplet is injected into the hot engine, the water droplets vapourize explosively, further tearing apart the long asphaltene hydrocarbon chains. This increases the surface area and allowing more complete combustion, but does not prolong the combustion duration. The water also absorbs the heat of combustion, smoothes the burn rate and lowers the maximum reaction temperature [18].

5.2.2 Equipment

There are several different variations in supplying FWE to engines. FWE can be prepared by mechanical, ultrasonic, steam injection, or pressurized choking methods. Preparation can take place on board the ship or on shore, and additives may or may not be required. Homogenizer units are most commonly mentioned on-board technology for marine diesel engines. If emulsions are prepared on the ship, a homogenizer unit is required to perform the mixing and purified water is required.

An on-board FWE system is relatively simple. It generally consists of a water storage tank and water pump, a dosing module unit, a homogenizer unit, emulsion circulating pumps, a preheater, and associated piping, meters and valves. The mixing of the water and fuel typically takes place instantaneously inside the homogenizer unit, although in some systems, a pre-mixing tank is included before the homogenizer to achieve more flow uniformity.

The purified water can be prepared on the ship through the use of a water treatment system or supplied from shore. A ship's boiler feed water treatment system may be able to supply the purified water, if there is sufficient capacity. In any case, some form of purified water storage is recommended. If the emulsions are prepared on shore, no homogenizer is required on the ship, but an on-shore unit and the existing ship fuel tanks can be used for the emulsion, assuming there is an additional 20-25% of volume capacity for the fuel emulsion.



Source: MAN B&W, RESON

Figure 7: FWE System Schematic Diagram

Fuel and water flow separately through a dosing control unit and enter the homogenizer. The homogenizer unit first creates a fine emulsion by using a shearing the fuel and water with an electrically-driven mechanical mixer, the only moving component of the system. The most common homogenizers currently employ electronic transducers to impart ultrasonic energy to the FWE to create microfine emulsions, which have a high degree of stability. Ultrasonic cavitation reduces water droplet size by almost an order of magnitude. A water-content meter installed before the engine injection controls the flows of water into the dosing unit.

5.2.3 System Size

FWE homogenizers are available in modular designed, skid mounted units that consist of several separate homogenizer tanks. A standard 4 m^3/hour unit would meet the requirements of the *Cabot* engines. This system has 4 homogenizer tanks in parallel and is about 2 m long by 1.5 m wide by 2 m high. A single unit has enough capacity to provide emulsions for both engines. A separate, wall-mounted control cabinet that contains the programmable logic controller (PLC), the motor starters, and the generators for the ultrasonic transducers is also provided.

5.2.4 System Performance

FWE produces a smoother, cleaner burning engine with less oil choke build up. NOx emissions can be reduced by up to about 50%:

> "Roughly, NOx emissions will be reduced by 1% water for each 1% water in the HFO (i.e. 50% water and 50% HFO gives a reduction of 50% NOx - this is a 33% water in emulsion mixture). However, at least 10% water must be added to see the effect [19]."

The water-fuel ratios needed to achieve this performance will vary by engine and fuel, but a reasonable average is about 50% water-fuel ratio (33% water in total emulsion).

Fine PM (soot) emissions can be reduced by at least 80% using emulsions. Using diesel fuel, a 10% fuel-water ratio can reduce PM (smoke) by 80% and the reduction level increases to over 95% with increasing fuel-water ratios. For HFO, the PM reduction effect is moderate at lower fuel-water ratios, but beyond about 50% water-fuel, PM emissions increase. HC emissions generally decrease by 30 to 50% using diesel, but may increase using the heaviest fuel oils. CO emissions are reduced from 20 to 50% using emulsions.

There is a slight fuel consumption penalty that increases with increasing water-fuel ratios. For diesel, as the fuel-water ratio increases from 25 to 50%, the specific fuel consumption increases from 0.5% to 1.0%. For HFO at typical operation, the penalty is slightly higher; approximately 1.5% at a 50% water /fuel ratio.[9]

5.2.5 Operating Issues

In a typical marine fuel supply system, the operating pressure is usually too low to accommodate the addition of water. At typical fuel system operating temperatures, the water has a tendency to vapourize and cause pump cavitation. In order to prevent this, a closed, high-pressure fuel emulsion circulation system is usually recommended. The fuel temperature is limited to 100°C and water temperature is limited to 90°C. In MAN B&W's fuel-water emulsion systems, the homogenizer is situated on the low-pressure side (for better mechanical mixing) before the high pressure pumps.

The existing fuel pumps may not be able to supply the pressure and increased volume required to pump (and recirculate) the fuel-water emulsion. FWE systems can significantly increase the volumetric flow rate through the fuel system. For example, a FWE system operating at a 50% water-fuel ratio would require the capacity of the fuel pumps to accommodate a 50% increase in flow. Most new fuel pumps are designed to

[9] RESON FWE performance test results (emissions and fuel consumption).

have a capacity about 30% higher than the MCR rate, but as they age, pump capacity declines. If typical engine operation is 85% MCR, there may be enough extra pumping capacity, but flexibility may be constrained. It may be necessary to replace the fuel pumps with higher capacity models for use with a fuel-water emulsion system. Larger diameter fuel pipes may also be necessary. The higher capacity fuel pumps also impose a greater load on the engine camshaft, and retrofits to the engine may be necessary to minimize longer-term maintenance problems.

The addition of water in microfine droplets to oil increases the viscosity logarithmically. For example, the viscosity of an HFO increases by a factor of 2.0-2.5 with an emulsion having a 50% water-fuel ratio. An emulsion preheater, installed after the homogenizer, is usually necessary to reduce the emulsion viscosity to a level of 10-15 cSt typically required for combustion.

The stability of fuel-water emulsions over time is an important factor when considering the design of this NOx reduction technology. After any mechanical shear force is applied to emulsify a fuel-water mixture, there is a tendency for both phases to re-coalesce, due to molecular surface tension forces. This tendency increases with time but decreases as the fuel viscosity increases. For systems in which the emulsification takes place immediately before injection to a marine engine, no additive is generally required. Low-viscosity gas oils, such as on-road or off-road diesel used in heavy duty vehicles, require emulsification additives to maintain the emulsion. However, emulsions of the heavier fuels typically used in marine engines maintain stability and do not require additives. These include MDO, light fuel oil (LFO), IFO blends and HFO. If an FWE is prepared on shore and stored in the ship's fuel tank for a voyage, additives are probably not required. However, to operate on the safe side, MAN B&W recommends that if the FWE of MDO is to be stored for more than one day, then additives should be used.

5.3 Costs

Capital, installation and operating cost estimates for FWE systems were obtained from MAN B&W, RESON and Pielstick. Cost submissions were either too general or incomplete and a cost model was developed using data from all three responses.

5.3.1 Key Assumptions

The key cost assumptions used in the calculations for the M.V. *Cabot* are:

- A maximum NOx reduction of 50% achieved at a water-fuel ratio of 50%.
- Maximum water flow rate of 1.3 m^3/h; emulsion flow rate of 3.8 m^3/h (at MCR);
- Capital cost of equipment of $125,000, based on standard 4 m^3/h homogenizer unit;
- Installation, fuel system and engine modification costs of $200,000;
- Fuel penalty of 1.5%;
- Additional water costs negligible;
- Replacement of transducers (US$3,000/unit) once a year;
- No other maintenance assumed.

The maximum NOx reduction reported in the literature in practical applications is 50%. The cost analysis is based on achieving this maximum level. This sets the maximum water-fuel ratio and allows sizing of the homogenizer system. A single RESON EM 7185 Modular Ultrasonic Homogenizer unit (four homogenizers with total capacity of 4 m^3/h) at a list price of US$66,000 ($102,000) was assumed to meet the needs of the *Cabot*. With additional piping and control systems and delivery, this price was assumed to be $125,000. This was felt to be a reasonable level, since a rough MAN B&W total capital cost estimate was about 15% lower than this and a Pielstick estimate was about 50% higher.

The installation cost estimate of $200,000 selected for use in the analysis was a rough midpoint of different estimates received from MAN B&W, RESON, and Pielstick. The RESON installation cost of $4,000 was almost negligible, since it only assumed a simple two-day installation of basic components with no system modifications. An installation cost estimate of $90,000 was calculated based on a general MAN B&W rule of thumb of US$20,000 to 40,000 per system. The details were not specified, but this would likely include some piping, water and fuel system modifications. The Pielstick installation cost estimate was the highest at about $300,000, since it considered comprehensive modifications and some new capital components not include in their capital cost estimate. The modifications included an unspecified water system changes, an additional mixing tank, new fuel and water pumps, high pressure circulating pumps (up to 6 bar), larger higher-pressure piping, and engine modifications (e.g. camshaft, gaskets). Since there is considerable uncertainty about the degree of retrofit required, a cost of $200,000 was considered a reasonable compromise from the various estimates.

A specific fuel consumption fuel penalty of 1.5% was assumed for the IFO used on the *Cabot*, based on RESON test results of FWE systems on Deutz engines.

For this analysis, the costs for the additional water are assumed to be negligible for simplicity and to permit cross-technology comparison, since it is assumed that the ship's

400 t water storage and system could handle the extra water demand. The ultrasonic transducers have a typical life of one to two years and need to be replaced periodically at a cost of about US$3000 per set. A one-year replacement frequency is assumed. Since the system produces a clean operation, no other maintenance costs are assumed.

5.3.2 Cost Analysis

Using the above cost and operating condition assumptions, the cost of NOx reduction from FWE systems is $217 per tonne of NOx reduced. A $325,000 initial investment in capital and installation is required.

Table 7: FWE System Costs
(Basis: M.V. *Cabot* with two 5.8 MW Pielstick engines)

Capital Cost	
Capital Cost	$125,000
Installation Cost	$200,000
Total Installed Cost	$325,000
Annualized Installed Capital Cost ($/y)*	**$37,000**
Operating Costs	
Fuel Cost Penalty/(Savings) ($/y)	$49,000
Maintenance	$5,000
Net Operating Costs/(Savings) ($/y)	**$54,000**
Total Annual Cost/(Savings) ($/y)	**$91,000**
NOx Reduction	**50%**
Annual NOx Reductions (t/y)	**415**
Cost per tonne NOx reduced ($/t)	**$217**

* Total installed costs are amortized at 10% over 23 years.

While the basic equipment capital cost and on-going operating costs appear to be relatively low at first glance, FWE systems have higher costs due to minor fuel penalties and installation issues. The fuel penalty of 1.5% yields the largest cost component in the analysis. The requirement for a larger-capacity, high-pressure fuel supply system and its potential impacts on the engine also add significantly to the cost.

If an additional (separate) water system were required dedicated only to the FWE system, rough cost estimate shows that it might increase the annual costs by $10,000 to $20,000 per year, or about 10%. The annual costs estimated for an 60 m^3 tank filled with purchased water, a freshwater system, or a reverse osmosis system, all with water treatment filters and softeners, are roughly comparable within this range.

5.4 Practical Experience

MAN B&W, one of the largest manufacturers of marine diesel engines, now offers ship operators FWE systems on a new line of "Invisible Smoke" (IS series) of medium-speed diesel engines. Its 48/60IS and 58/64IS engines, manufactured in Augsburg, Germany, have been redesigned and use 15% water mixed into the fuel to reduce smoke emissions to below the visibility limit across the load range [17]. These systems have been installed on two Norwegian Cruise Lines vessels for slow steaming operation in Alaskan waters: the *Norwegian Sky* and *Norwegian Wind*. In mid-2000, MAN B&W delivered six 48/60IS engines using FWE systems for a series of RoRo paper carriers for Nordic Forest, operating in the Baltic Sea. NOx reductions can be reduced further, by increasing the water-fuel ratio.

MAN B&W does not offer FWE systems as retrofits to existing engines. The MAN B&W Group also includes SEMT Pielstick as an separate operating company. Pielstick reports that it has tested FWE systems for Pielstick engines, but there have been no commercial sales to marine or power plant installations.

RESON reports that homogenizer systems have been installed on two Holland America cruise ships (*Ryndam* and one other) to process oil sludge. The systems are effective in eliminating oil sludge, but are operated manually and require close attention by operators.

RESON GmbH is a world leading company in ultrasonic technology used in underwater and industrial systems. RESON has marketed homogenizer systems for over 20 years and has been an official supplier of modular ultrasonic homogenizer systems to MAN B&W for the last two years. In addition, it has recently tested its homogenizer systems on marine engines with Deutz, Wärtsilä, and Pielstick. A RESON manager believes that there are a few other smaller suppliers of homogenizer systems. There may be many different small designers and manufacturers of homogenizer systems, but most would tend to be mechanically based systems. These are initially effective, but the quality of emulsions can degrade over time with the wear and tear on the mechanical components. Some other companies identified in this market include Martek and Hamworthy [20].

6. Direct Water Injection

6.1 Summary

Direct water injection (DWI) technology can reduce NOx emissions from marine engines by 40 to 60%, through the injection of a high-pressurized fine water mist into the combustion chamber. Reductions in PM (smoke) emissions also occur. Water injection occurs separately from (and just prior to) fuel injection in the combustion cycle, cooling the cylinder and reducing NOx formation. DWI systems are currently a proprietary technology of Wärtsilä, one of the largest marine engine makers in the world. The technology has only recently been adopted for large marine engines (1-2 years) and there were about 10 installations on Wärtsilä engines in the Baltic Sea in early 2000 with another 15 on order. The estimated installed cost of DWI systems as a retrofit on the *Cabot* is about $413,000, assuming that the no major modifications are necessary to the Pielstick engines. DWI may not be a viable technology for these specific engines due to engine design differences. At a water-fuel ratio of 50%, DWI can achieve a 50% reduction in NOx at a cost of approximately $443 per tonne of NOx reduced. The largest component of this cost is an assumed 2.1% specific fuel consumption penalty.

6.2 Description

All the information in this section was provided by Wärtsilä from product literature, cost responses and a personal interview. Supporting information was provided by published literature.

6.2.1 Operating Principle

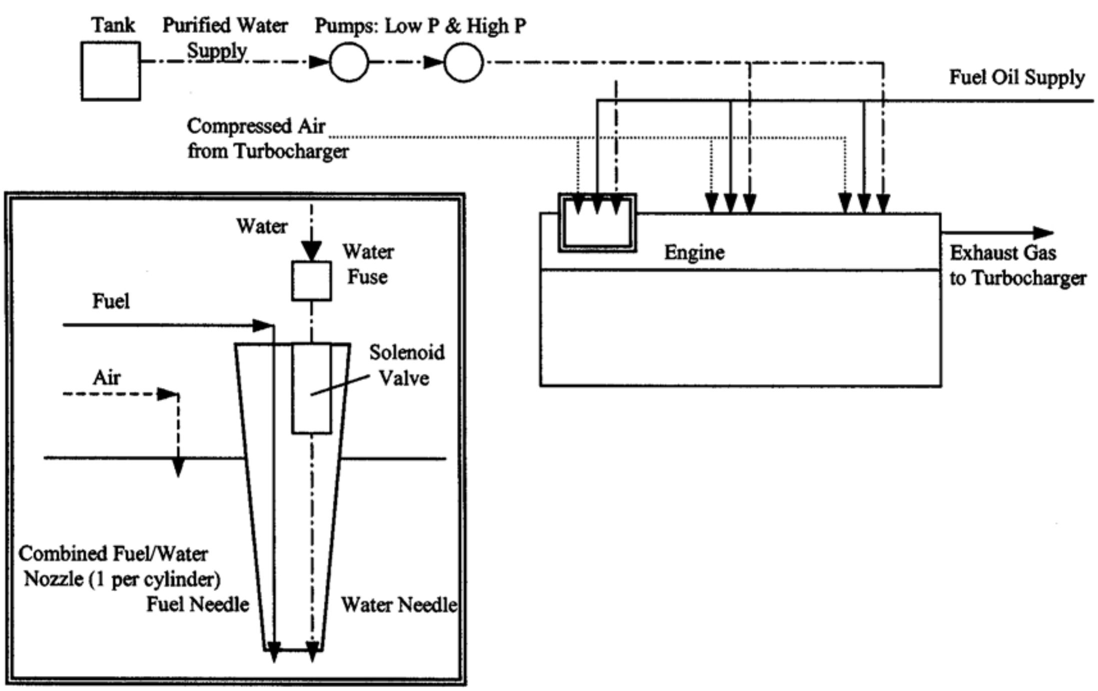
DWI technology uses clean water injected independently into the marine engine combustion chamber close to the injected fuel to reduce NOx formation. The system employs a uniquely designed combined fuel-water injection valve and nozzle mounted on each cylinder of the engine. Each nozzle has two separate needles for fuel and water, which are controlled separately. The water to fuel ratio usually ranges from 40 to 70% and this can reduce NOx emissions by up to about 50 to 60%. Therefore, on medium-speed engines using IFO or HFO, DWI produces NOx emissions levels typically in the range of 5 to 7 g/kWh [21].

Like any other of the water-fuel technologies, DWI reduces NOx by lowering the initial temperature of the fuel combustion. In the injection sequence, water injection occurs before the fuel injection, resulting in a cooler combustion chamber prior to fuel combustion. The system is designed to operate at high water injection pressures (210 to 500 bar depending on the engine) to properly atomize the water stream after injection. The water injection stops before the fuel injection, so that the fuel ignition and combustion process is not compromised. The NOx reduction effect increases in a roughly linear relationship with increasing water-fuel ratios.

6.2.2 Equipment

Wärtsilä is the only known marine engine maker offering this technology for NOx control on its new Vasa 32, W32, and W46 engines. These Wärtsilä engines feature specially-designed cylinder heads, which incorporate the combined fuel-water nozzles of the DWI system. The cylinder head castings are quite thick and use a special stainless steel alloy for high strength and rigidity. The pistons and piston tops are also designed with high strength alloys to withstand the physical erosive force of the water injection.

The DWI system consists of two central water pump modules (low-pressure and high-pressure), a control unit, a set of combined fuel-water injection nozzles (one for each cylinder) and associated piping and wiring.



Source: Wärtsilä NSD

Figure 8: DWI Schematic Diagram

Water must be supplied to the low-pressure pump module from the ship's freshwater system or from dedicated water tankage. At the 50% water-fuel ratios typically used for maximum NOx control, the water capacity required for a one way trip of the *Cabot* would be about 60-70 m^3.

The low-pressure pump is used to boost water pressure to 3.5 bar and ensures stable water flow rates to the high-pressure pumps. Filters are installed prior to the low-pressure pump to ensure that the freshwater is free of particulate. The high-pressure pump boosts pressure as high as 500 bar and feeds all the combined fuel-water injectors. Both pumps are contained in modules consisting of motor, pump, piping, and electrical controls.

The combined fuel-water injectors are cylindrical in shape and fitted into holes drilled into the cylinder head. The nozzles have two separate needles at the bottom that are controlled separately. Water injection is activated by an attached solenoid valve. A water flow fuse is a small safety device installed prior to each injector. It acts to shut off water flow to the engine if the water needles in the injector get stuck, or in the event of excessive water flow or water leakage. The water system is independent of the fuel system, and if water shutoff is necessary, engine operation will not be affected. The injectors experience wear at the high operating pressures and must be replaced after about 6,000 operating hours (once a year).

Water injection timing and duration are controlled electronically by the central control unit, which receives its input from the engine output. NOx reduction can be optimized for different operating conditions, using a computer and is efficient above 40% load.

6.2.3 System Size

The DWI system can be installed in the engine room of a ship, since the only large components are the low- and high-pressure pump modules. These modules are roughly the same size and are relatively compact (1 m x 1 m x 1.7 m, L/W/H). All the other components (injectors, fuses, piping) are installed directly on the engines.

6.2.4 System Performance

The DWI system is capable of achieving NOx reductions of between 40 and 60%, depending on water-fuel ratios and engine loads. DWI reduces PM emissions, but the magnitude of the effect was not identified. DWI may not have the same effect on smoke as FWE. The water acts more as a passive thermal sink and may not have the same physical explosive force that is present in FWE. The principal control of smoke in engines using DWI is through electronic and independent fuel injection control.

6.2.5 Operating Issues

There has been some debate in the industry about the tendency of DWI technology to produce smoke at low speed and low load levels. For example, after extensive testing, MAN B&W rejected DWI technology on its engines due to unacceptable increased smoke levels, especially at low loads for slow steaming [22].

Wärtsilä claims that smoke is not a significant issue with DWI. It cites the example of the success of its engines in the cruise ship market, especially in Alaskan waterways in the summer season, the most environmentally sensitive market. Wärtsilä reports that not a single Wärtsilä W46 engine (the most commonly used engine on cruise ships) has ever had a smoke fine from the Alaska Department of Environment Conservation [23]. (A US$50,000 fine is laid against any smoke violation exceeding 0.2 on the Ringelman scale.)

Wärtsilä has recently developed the "Enviro-Engine", which combines smoke control with a 50% NOx reduction. This new engine design incorporates DWI in the design along with a "common rail" fuel-water injection control technology. The common rail system produces no smoke by permitting independent control of fuel and water injection to each cylinder. In older engine designs, a single fuel pump would be used and the fuel and water injection rates would be dependent on the engine speed, due to mechanical linkage. The common rail system uses one small, high-pressure fuel pump for every two cylinders in the engine. Each fuel pump is controlled by an independent electronic injection control system, which is programmed to adjust fuel and water injection rates at lower loads for complete smoke control.

DWI was selected as the preferred NOx control technology by Wärtsilä due to the superior control of water-fuel ratios and its minimal effects on the long-term reliability of the engine and its auxiliary systems. Wärtsilä tested FWE systems, but had concerns about potential corrosion and operating problems in the fuel injection system. Evidence from FWE testing suggested corrosion could be a problem over the long term. Also, some pump cavitation was observed at higher emulsion temperatures, which affected pump efficiency and increased risk of component erosion. Wärtsilä has also tested HAM technology in a cooperative venture with Munters, the developers of the HAM system. However, the HAM system did not give the desired results; the issue appeared to involve the presence of water droplets in the charge air, which did not meet Wärtsilä's design standards [23].

The Wärtsilä Technology Group reports that it does not believe it is possible to retrofit Pielstick engines effectively with its DWI technology. The DWI injectors were developed for use on the newest generation of Wärtsilä engines, which use premium high-strength material and operate at about 25 bar BMEP. Wärtsilä claims that the very high fuel injection pressures (500 bar) used by its DWI system are incompatible with the design of Pielstick PC2.5 engines. According to Wärtsilä, these Pielstick engines are based on an "older engine design", which uses materials which that withstand these high injection pressures. The key issues appear to be that there is no room on the existing cylinder heads to incorporate the combined fuel-water injectors and the cast cylinder head, and that piston and engine materials are not of sufficient rigidity and strength to withstand the high injection pressures. If a retrofit on the Pielstick engines on the *Cabot* were possible, it would have to be done during a scheduled turnaround. Wärtsilä claims that its Technology Group would have to be involved and that the pulled cylinder heads would likely have to be sent to its maintenance facility for the high-tolerance rework required.

6.3 Costs

All cost information used for this analysis was provided by Wärtsilä, the only supplier of DWI technology. The cost information was based on existing retrofit experience on Wärtsilä engines only.

6.3.1 Key Assumptions

The key cost assumptions used in the calculations for the M.V. *Cabot* are:

- Capital cost rate of US$20 per kW for a two engine system;
- Installation costs of 15% of capital;
- Overall operating cost rate of US$2.00 per MWh;
- Fuel penalty of 2.1%;
- Injector nozzles (US$250 each) replaced each year
- No additional water cost;
- NOx reduction of 50% achieved with a 50% water-fuel ratio.

The capital cost rate is a general rate used in Wärtsilä literature. It comprises the component costs of the DWI system, including the two water pump modules, all fuel injectors, and control unit. This rate agrees closely with capital cost estimates provided for the DWI installation on the *Silja Symphony* and *Silja Serenade* in 1999. The installation costs are assumed to be 15% of the capital rate and represent the costs of system assembly and connection. This rate was selected such that the total installed cost agreed with the installed cost rate reported by Silja Line. The cost of the engine overhaul is not included in the estimate, since it is assumed that this is a scheduled sunk cost.

The operating cost estimates provided by Wärtsilä were unspecific. The general rule of thumb was that total operating costs were "in the region of US$1.50 to 3.00 per MWh of output", most of which was "water and increased fuel consumption". The fuel penalty varies with the water-fuel ratio: a 30% water-fuel ratio produces a 1.0-1.5% penalty and a

60% ratio produces a penalty of 2-3%. A fuel penalty of 2.1% was assumed for a 50% water-fuel ratio based on a scaling of the above estimates. The cost of annual injector replacements was calculated directly as $9,300 per year based on a replacing 24 injectors (1 per cylinder) once a year at a cost of US$250 each. Water costs were assumed to be negligible, to be consistent with the cost analyses of the other “water” technologies. Since the total of these estimated itemized operating costs was below the expected total operating cost range of US$1.50 to 3.00/MWh, the minimum total operating cost rate of US$1.50 per MWh was chosen. An unidentified “other operating costs” category (accounting for all maintenance, parts, etc.) was assumed to account for the difference.

6.3.2 Cost Analysis

Using the above assumptions and operating conditions, the cost of NOx control using DWI systems for the *Cabot* is $443 per tonne of NOx reduced. The total installed cost is approximately $413,000 and operating costs are estimated at about $137,000 per year.

Table 8: DWI System Costs

(Basis: M.V. *Cabot* with two 5.8 MW Pielstick engines)

Capital Cost	
Capital Cost	$359,000
Installation Cost	$54,000
Total Installed Cost	$413,000
Annualized Installed Capital Cost ($/y)*	**$47,000**
Operating Costs	
Fuel Cost Penalty/(Savings) ($/y)	$68,700
Replacement Parts ($/y)	$9,300
Other Operating Costs	$59,000
Net Operating Costs/(Savings) ($/y)	**$137,000**
Total Annual Cost/(Savings) ($/y)	**$184,000**
NOx Reduction	**50%**
Annual NOx Reductions (t/y)	**415**
Cost per tonne NOx reduced ($/t)	**$443**

* Total installed costs are amortized at 10% over 23 years.

In the analysis above, the annual operating costs appear to be most significant, while initial installed costs are modest. The fuel consumption penalty is the largest cost component. Variations in the water-fuel ratio do not have a large impact on the unit cost of NOx reduction. Using a 60% ratio increases NOx reduction, but also fuel penalty, with a resulting unit cost that is about $20 per tonne lower.

There is some uncertainty over the magnitude of the on-going operating costs. First, the fuel consumption penalty may be overstated or even non-existent. There is some anecdotal evidence from Wärtsilä that DWI may not cause such fuel penalties for certain vessels. Second, the other operating and maintenance costs are based only on rough cost estimates and may not materialize in a properly designed and. tuned system. On the other hand, a DWI retrofit on engines that cannot withstand the high injection pressures or the eroding force of water may require some continuous maintenance attention.

The final installation costs are also uncertain, since the compatibility of the engines with DWI will determine the ultimate retrofit effort required. The assumption that DWI can be retrofitted onto the Pielstick engines without any major engine modifications is a critical one. This may be appropriate for commercial Wärtsilä marine engines of the same size, but the installation cost may be understated for retrofits on other engines.

The cost of water was handled in the same way as for FWE systems, since the same volume and quality of water is required. If an additional (separate) water system were required dedicated only to the DWI system, the costs would be similar to FWE: the annual costs of between $10,000 to $20,000 per year, or about 10% of total annual costs. The annual costs estimated for an 60 m^3 tank filled with purchased water, a freshwater system, or a reverse osmosis system, all with water treatment filters and softeners, are roughly comparable within this range.

6.4 Practical Experience

Over the last seven years, Wärtsilä has spent a total of 2,000 hours testing DWI technology on a total of 16 commercial marine vessels in the Baltic Sea. Wärtsilä NSD Corporation, a division of Metra Corporation, is the world's leading supplier of cruise ship propulsion machinery, and the only marine engine maker that has adopted this technology.

The first installation of DWI technology was in 1993 on the *Aurora af Helsingborg*, which runs between Denmark and Sweden. This vessel uses one 2.4 MW Wärtsilä 6R32 engine. A selective catalytic reduction (SCR) system was tested at the same time on this vessel. By 1995, Wärtsilä reached an agreement with Silja Line to retrofit the engines on the passenger ship *Silja Symphony* and its sister vessel *Silja Serenade,* based in Stockholm. This was a DWI technology advancement, since each vessel has four main 8.1 MW Wärtsilä 9L46 engines, much larger than the original test vessel. DWI has been installed on the Silja Line fleet. In 1998, Wärtsilä secured its first production orders for new medium-speed engines equipped with DWI as its selected NOx control option for new marine diesel engines. The first delivery of these orders occurred in January 1999 to the *Mistral*, a RoRo forest products carrier. A total of seven of these carriers, chartered by Transfennica for Godby Shipping, have now been fitted with new Wärtsilä engines with DWI. In 1999, Wärtsilä had a total of 15 DWI system orders, mostly for ships in the Baltic Sea. The year 2000 figure was not available, but was expected to be higher than 1999. Table 9 summarizes Wärtsilä's 10 DWI installations as of early 2000.

Table 9: Wärtsilä DWI Installations
(early 2000)

Vessel	Operator	Engine Model	Power Rating (MW)
Aurora af Helsingborg	Scandlines	6R32	2.4
Silja Symphony	Silja Line	9L46	4 x 8.1
Silja Serenade	Silja Line	9L46	4 x 8.1
Mistral	Transfennica	12V46C	12.6
Miranda	Transfennica	12V46C	12.6
Friedrich Russ	Transfennica	12V46C	12.6
Elisabeth Russ	Transfennica	12V46C	12.6
Seagard	Transfennica	16V46B	15.6
Caroline Russ	Transfennica	16V46B	15.6
Pauline Russ	Transfennica	16V46B	15.6

Source: Wärtsilä

Some of the new cruise ships delivered in the period from late 1999 to 2000 also now have DWI technology installed along with a common rail fuel injection system. Since Wärtsilä provides most new engines to the cruise ship market, most new orders have the new DWI technology installed at the ship works.

Mitsubishi is reported to have conducted trials on a variation of DWI called stratified fuel-water injection. The system uses a single injector with two inputs (fuel and water). An injection cycle starts with a pilot injection of fuel, followed by water, fuel, water again and finally fuel. By this method, water is essentially inserted intermittently into the fuel stream and no extra machining is necessary for retrofitting. The system was tested for a year on a 5,000 dwt vessel with a 6UEC52 engine and NOx reductions of 50% have been reported without increased wear [24].

7. Exhaust Gas Recirculation

7.1 Summary

Exhaust gas recirculation (EGR) technology uses engine exhaust gases that have been cooled after the turbocharger. This reduces the combustion temperature and increases the mass flow rate and pressure to reduce NOx formation. Despite exhaust gas cleaning, PM emissions are usually increased with the use of this technology. The technology is viable for on-road diesel engines using very low sulphur fuel, but is currently not considered applicable in the marine engine market, due to significant fouling and corrosion issues.

7.2 Description

In an EGR system, exhaust gases from the engine pass through the turbocharger, releasing energy to compress the incoming combustion air. The temperature and pressure of the gases are reduced considerably. A portion of the exhaust gases is recirculated back and is added to the compressed air before the cylinder. Particulate filters are used to remove entrained solids prior to mixture with the combustion air. The exhaust slipstream flow is carefully controlled to adjust for engine load changes. The lower temperature of the exhaust gases contributes to a cooler combustion. The increased mass flow increases the combustion pressure and dilutes the oxygen content. All these effects contribute to lower NOx formation.

EGR technology has been used successfully for several years in on-road light-duty diesel (passenger) vehicles, burning relatively clean (<0.1% sulphur) diesel fuel. EGR technology is spreading through into truck and bus engines in order to meet new emissions standards for trucks. The U.S. EPA has promulgated emissions standards for heavy-duty vehicles (i.e. diesel trucks and buses) that set a limit of 4 g NOx per brake-horsepower (or 5.3 g/kWh) starting in the year 2004. European trucks have to meet the Euro 3 standards, which were set in October 2000.

7.3 System Performance

When EGR was tested on marine engines, NOx reduction performance was actually quite good, achieving levels close to 50% reduction. However, PM emissions and opacity levels increased substantially, despite gas cleaning. The net effects of the increased PM, opacity and the associated fouling, corrosion and surface wear more than offset the NOx reduction benefits. EGR has been dismissed as a potential technology by all major marine engine makers.

7.4 Operating Issues

The recirculated gas creates fouling of the cylinder and components, and contributes to accelerated corrosion. These effects drastically increase the surface wear of important engine components such as cylinder liners and piston rings. The operating life of engines is reduced and reliability is affected very quickly.

The MAN B&W experience with testing EGR technology on marine engines has been characterized as “disastrous.” In recent bench test studies, MAN B&W tested EGR technology on two different types of engines using two fuels. A six-cylinder engine 40/54 engine was tested using gas oil considered to be relatively “clean” of sulphur. After only a 20-hour operating period, fouling and component wear were evident and the test was discontinued. Similar tests were carried out on two one-cylinder engines using a blended HFO with much higher sulphur content. In these tests, despite the installation of filters and water scrubbers to clean the recirculated exhaust gas, massive fouling and corrosion was observed, also after 20 hours of operation.

Significant component wear was observed in both tests on piston rings, cylinder liners and valve heads after only a short time. In the tests using HFO on the one-cylinder engine, valve surfaces were reduced by 50% over a 50-hour running period. In addition, corrosion was observed on the turbocharger compressor wheels and the surfaces of the charge air coolers.

The PM deposition and fouling problem also contributes to a contamination of the lubricating oil, which only accelerates the engine wear.

The presence of sulphur in the fuel is a major problem with EGR. The exhaust gas contains SO_2, which can further oxidize to the trioxide, and form sulphuric acid in the presence of water. This tends to occur at lower temperatures that are seen after the turbocharger and especially when mixing with the relatively cool charge air. A MAN B&W marine engine specialist claims that some Japanese technical papers published several years ago attributed the wear problems from EGR mainly to corrosion from the presence of sulphuric acid in the blow-by gas.

The other contributing factor is the quality of the fuel. PM formation is enhanced with heavier fuel oils, due to the incomplete combustion of high molecular weight hydrocarbons (e.g. asphaltenes) and the presence of inorganics, including heavy metals. Fine particulates ($PM_{2.5}$) are also formed in diesel combustion due to the reaction of SO_2 with nitrogen compounds to form inorganic sulphates and nitrates. Filtration and scrubbing systems are somewhat effective in removing larger PM, but most of the fine particulate behaves like a gas and cannot be easily removed from the system.

7.5 Cost

Costs for EGR systems on marine diesel engines have not been developed by engine makers.

Since EGR has been considered as a viable technology for heavy-duty diesel engine burning clean (low-sulphur) fuels, there has been some cost estimation work done by the U.S. EPA for two separate regulations:

- New Emission Standards for Heavy-Duty Diesel Engines Used in Trucks and Buses (Final Rule published October 1997)
- Emission Standards for 2004 and Later Model Year Heavy-Duty Highway Vehicles and Engines (Final Rule published October 6, 2000)

The U.S. EPA estimated that the increase in purchase price of engines designed with EGR in the heaviest vehicle segment (Vehicle Class 8, GVWR>33,000 lb.) of heavy-duty diesel vehicles is US$439. This is about 2% higher than the baseline average purchase price of US$21,700 for unmodified engines in this segment [25].

7.6 Practical Experience

Most of the major marine engine manufacturers have tested EGR in bench scale tests with smaller engines. In addition to MAN B&W mentioned above, Wärtsilä and Pielstick are known to have tested and dismissed EGR.

8. Humid Air Motor

8.1 Summary

The Humid Air Motor (HAM) system is a recent technology that uses combustion air almost entirely saturated with water vapour (humid air) in a marine diesel engine. The charge air is humidified by water vapour produced in a humidification vessel by evaporating freshwater or seawater directly into the charge air using the heat from the engine or its exhaust gases. The system was developed by Munters AB of Sweden and is only available commercially on new Pielstick engines. NOx emissions reductions of 60 to 80% have been achieved in demonstration tests. The installed costs of the HAM system for the *Cabot* likely range from $0.8 to $1.2 million, but there are virtually no operating costs. The unit cost of NOx reduction is estimated to range from about $166 to $245 per tonne NOx reduced.

8.2 Description

Much of the information in this section is summarized from various Munters and Pielstick publications and interviews [26, 27, 28].

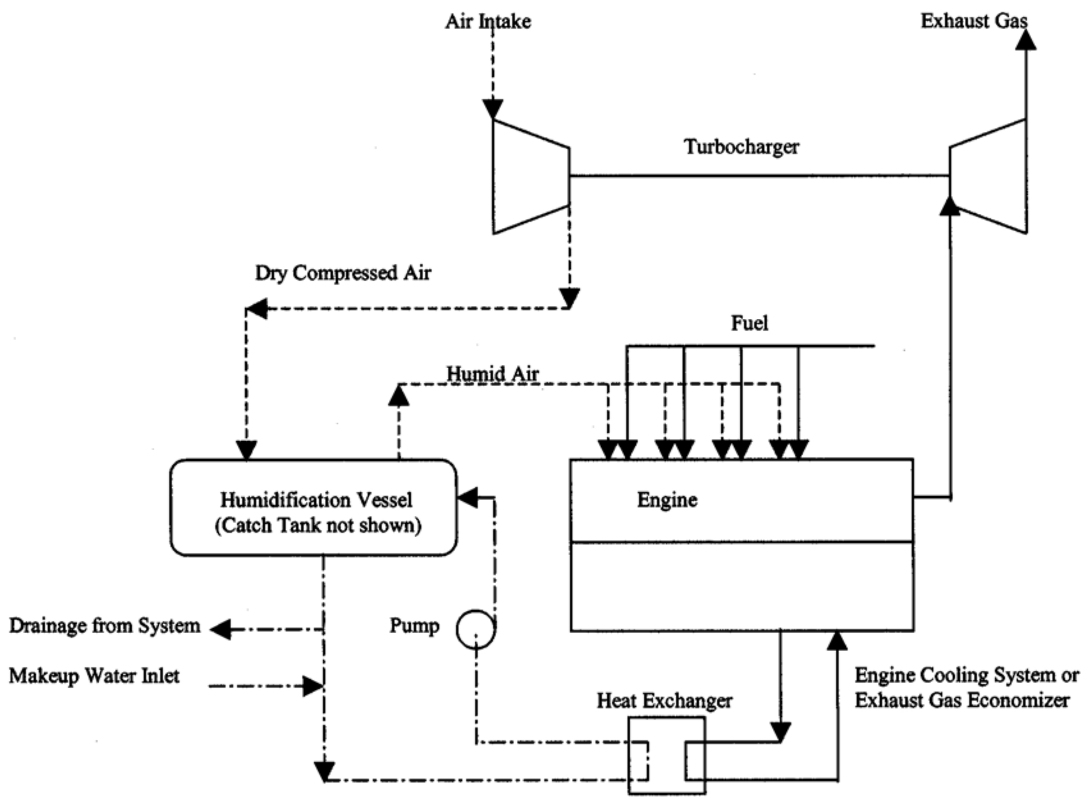
8.2.1 Operating Principle

The HAM system is based on the same general principle of the other technologies that add water to the combustion chamber: the presence of water reduces NOx formation in the cylinder. The key difference is that the water is completely evaporated into the combustion air and mixed thoroughly prior to the cylinders. After contacting with water in the humidification vessel, the relative humidity of the combustion air is close to 100% saturation.

The presence of water vapour acts to change the thermodynamic properties of the combustion air. The evaporation of water from liquid to vapour is an energy-consuming process that reduces the temperature of the compressed air. The HAM system can be used to replace the turbocharger intercooler. It is capable of reducing typical charge air temperatures to 70°C versus 50°C for conventional intercoolers [28]. The saturated humid air has almost twice the heat capacity of dry air. This allows more of the initial heat generated in the compression cycle to be absorbed, reducing NOx formation. The presence of water vapour also dilutes the combustion air. Since the concentration of oxygen in the cylinder is reduced, there is lower excess oxygen and a reduced tendency for NOx formation. Another advantage of using water vapour is that it is mixed completely in the saturated air, producing no local “hot spots” in the cylinder. This contributes to a uniform combustion process.

8.2.2 System Description

The key components of the HAM system are a humidification vessel, a heat exchanger and a recirculating water system, as shown in Figure 9.



Source: SEMT Pielstick, Munters

Figure 9: HAM System Schematic Diagram

Hot compressed air from the turbocharger outlet is directly contacted with hot water at its boiling point in the humidification vessel. Through water evaporation, the air is saturated at close to 100% relative humidity and is then charged directly to the engine air manifold for combustion. This long, narrow pressure vessel, also known as a humidification tower or “HAM unit”, is the largest component of the system at up to 4 m in length and 1 to 2 m in diameter for large engines. It can be installed horizontally or vertically, depending on available space around the engines. A separate catch tank is included with the vessel to receive water drained periodically from the system. In vertically oriented vessels, the catch tank is integrated with the vessel but in horizontal installations, the catch tank is installed separately below the vessel for natural drainage.

The water is heated in a heat exchanger that extracts heat from either the engine jacket cooling water system or an exhaust pan (economizer). The engine cooling system is used as the heat source more often in smaller engines, while the exhaust gas economizer is typically used in larger engines.

A charge pump recirculates the water in a continuous loop through the vessel and the heat exchanger. Only a small portion of the hot water is evaporated upon contact with the charge air. The water vapour rate ranges from about 1.5 to 3.0 times the specific fuel consumption, depending on the desired humidity level and NOx reduction. In order to ensure a good evaporation, only 5 to 10% of the total circulating water volume is evaporated in the vessel. The circulation system is self-regulating through its control system, such that variations of charge air temperature and pressure due to engine load changes are accommodated.

Freshwater or seawater can be used for water makeup, since the evaporated water is free of minerals. The system has been tested successfully in water with up to 30% salt content. The vessel is equipped with an automatic bleed-off system (controlled by a conductivity sensor) to maintain acceptable mineral levels in the circulating water. A portion of the water is drained off from the vessel to a catch tank periodically to purge minerals from the system. In some regions with high water hardness, such as the Baltic Sea, an inexpensive water treatment additive may be required to control calcium and magnesium deposition.

8.2.3 System Size

There are five key components for a HAM system: a horizontal humidification vessel, a circulating module (pump and catch tank), heat exchanger, filling module and a control cabinet. Piping and electrical connections are added in installation. A HAM system designed for installation on 2 PC2.5 engines would have the dimensions shown in Table 10.

Table 10: HAM System Components

	Number	Length	Width	Height
Humidification Vessel	2	3.74	1.2D	1.2D
Circulating Module	2	1.6	0.75	1.8
Heat Exchanger	2	0.7	0.5	1.1
Filling Module	1	1.6	0.75	1.4
Control Cabinet	1	1.2	0.4	2.0

Source: SEMT Pielstick

The two horizontal humidification vessels are the largest components in the system and present the most difficulty for retrofit installation. On the limited number of existing and planned HAM installations on large-scale marine engines (detailed in section 9.4), these vessels are mounted near the ceiling of the engine room underneath the maintenance trolley beam. There are no existing installations where the HAM vessels are mounted outside the engine room.

8.2.4 System Performance

Lab tests and demonstrations have shown that NOx reductions in HAM systems can range from about 60 to 80%, depending on the absolute humidity achieved in the charge air. For example, a 60 to 70% reduction can be achieved at humidity levels of around 50 g H_2O/kg dry air, while reductions of close to 80% can be achieved at humidity levels above about 90 g H_2O/kg dry air. Demonstration tests suggest that there is relatively little effect on CO and HC emissions, but some reduction in fine particulate matter has been observed due to the cleaner engine and exhaust turbine surfaces. Currently, there is not enough information available to conclude whether specific fuel consumption is affected positively or negatively. Pielstick reports that operators have detected no significant changes to engine performance and suggests that since the HAM system increases the maximum combustion pressure, there may even be a slight increase in engine efficiency.

8.2.5 Operating Issues

The pressure drop in the charge air system due to the humidification vessel is not a significant problem, but the system should be installed close to the engine to minimize the length and number of angles of the charge air piping. Since the humid air is almost completely saturated with water, the vessel outlet pipe and charge air manifold must be well insulated to prevent a significant temperature drop, which might create condensation and possible corrosion issues. Wärtsilä reports that the possible formation of water droplets in the humid charge air is a concern. The HAM system is started up simultaneously with the engine, but ideally should be stopped about 15 minutes before engine shutdown to dry up the system.

The HAM system requires energy from the engine or exhaust gases to evaporate the water. For large engines, the presence of a HAM system using exhaust gas heat will likely reduce the thermal energy available in the economizer for the ship's existing steam system. Pielstick reports that the HAM system may be less appropriate for cruise ships, where the demands on the steam systems are high.

8.3 Costs

Costs estimates for the HAM system have been obtained separately from Pielstick and Munters. Since the technology is relatively new, the cost estimates have the uncertainty associated with "one-off" systems, and there is some discrepancy between the capital cost estimates.

8.3.1 Key Assumptions

The key assumptions for the two different cost estimates (Pielstick and Munters) in the cost analysis are as follows:

- Two capital cost estimates obtained: an installed capital cost rate of 520 FF/kW (French francs per kilowatt) (Pielstick) and a capital cost quote per engine of $250,000 (fob works, 12-order minimum, Munters). The cost for two delivered systems is assumed to be 25% higher.
- Installation cost per system of 300,000 FF (Pielstick) or $95,000 to 125,000 (Munters). A midpoint cost of $110,000 was selected for the Munters cost estimate.
- Chemical additive consumption of US$2/day (Pielstick) or "no greater than $1,500 per year" (Munters).
- No change in specific fuel consumption or maintenance
- 70% NOx reduction selected for analysis, based on midpoint of range.
- Vapour rate approximately 2.0 times specific fuel consumption

Pielstick did not provide a specific HAM capital cost estimate for the *Cabot* engines. Instead, it provided a cost analysis that uses only a general installed cost rate of 520 FF/kW. This estimate was made in early 1999 at a fairly early stage of HAM technology development when HAM systems were only installed on small engines and before the first large-scale engine installation. This rate may be overstated now due to learning curve experience and economies of scale on capital and installation costs for larger, multiple engine systems. The Munters cost estimate of $250,000 per system for a 5.8 MW engine is a current estimate, but was based on a minimum order of 12 systems. This cost was increased by 25% to account for delivery and a two-system production run.

Rough installation costs were provided by each company, based on the experience of one existing marine HAM installation. The installation costs assume sufficient space in the engine room with no major changes required. Both HAM cost estimates assume that salt water is used as the water source and there are therefore no water storage or treatment costs. The only operating costs are chemical additives used for hardness control. The limited operating information suggests that there is no observable fuel consumption penalty and no additional maintenance required.

Since HAM NOx reductions can vary from 60 to 80%, depending on the humidity level achieved, a midpoint of 70% reduction was selected for this analysis. This is consistent with the assumption used by Pielstick for its HAM cost analysis presentations.

8.3.2 Cost Analysis

The cost of NOx reduction using HAM likely ranges from $166 to $245 per tonne of NOx reduced. An average cost of $206 per tonne was selected for comparative analysis. Total installed costs may range from $0.8 million to 1.2 million. Operating costs are negligible.

Table 11: HAM System Costs

(Basis: M.V. *Cabot* with two 5.8 MW Pielstick engines)

	Pielstick	Munters	Average
Capital Cost			
Capital Cost	$1,129,000	$624,000	$876,000
Installation Cost	$124,000	$220,000	$172,000
Total Installed Cost	$1,253,000	$844,000	$1,048,000
Annualized Installed Capital Cost ($/y)*	**$141,000**	**$95,000**	**$118,000**
Operating Costs			
Fuel Cost Penalty/(Savings) ($/y)	$0	$0	$0
Chemical Consumption	$1,500	$1,500	$1,500
Maintenance	$0	$0	$0
Net Operating Costs/(Savings) ($/y)	**$1,500**	**$1,500**	**$1,500**
Total Annual Cost/(Savings) ($/y)	**$143,000**	**$97,000**	**$120,000**
NOx Reduction	**70%**	**70%**	**70%**
Annual NOx Reductions (t/y)	**581**	**581**	**$581**
Cost per tonne NOx reduced ($/t)	**$245**	**$166**	**$206**

* Total installed costs are amortized at 10% over 23 years.

The Munters capital cost estimate is about 55% of the calculated Pielstick capital cost estimate. While the Munters estimate is more specific and current, it is for components only and may be understated since additional turbocharger rebalancing and modifications to the charge air manifold material may be necessary. These additional modification costs are assumed in the Pielstick estimate. Despite the differences, the capital cost of the system components is the largest cost element, since there are virtually no operating costs. The installation costs for two HAM systems, although somewhat uncertain, are not insignificant, ranging from about $0.1 million to $0.2 million.

8.4 Practical Experience

Munters AB of Sweden first developed the HAM system in 1997 through tests at Scania's engine laboratory in Södertälje, Sweden. In tests conducted on an unmodified 320 kW, 14 L V8 Scania engine, NOx reduction ranged from 62 to 74%. The first HAM system to be installed on an operating vessel was later that year on a Norwegian pilot boat operating in the Baltic Sea. The system was installed on one main 6-cylinder, 11 L Scania engine and used filtered sea water having a salt content of 4 to 6%. As of February 2000, this system had accumulated approximately 1,200 operating hours and tests have shown no deposits on the cylinder liner and the cylinder head. The operating crew starts and stops the system simultaneously with the engine and reports no operating problems. A second HAM installation was made on the same type of engine (Scania 6-cylinder, 11 L), one of four main engines on a small ferry in the Baltic. This system has had about 1,800 hours of operating experience as of February 2000.

In 1997, Munters and Pielstick established a cooperative research venture to develop the technology for larger engines. In 1998, a prototype HAM system was tested on a 3-cylinder, 1.6 MW test bench Pielstick PC2.6 engine.[10] Tests were conducted at various humidity levels, charge air temperatures, and load levels. Some test conditions included the use of HFO and water with salt concentration of up to 30%. NOx reductions ranging from about 60% up to 81% were achieved, depending mainly on the humidity level. There no real change in CO or HC emissions or specific fuel consumption. In 1999, a second series of tests was conducted on a higher load engine (Pielstick PC2.6 B600 rated at 735 kW/cylinder) and similar results were achieved.

The first installation of a HAM system on a large-scale engine was in August 1999 on the Viking Lines M/S *Mariella*, a large passenger/car ferry operating on the Stockholm-Helsinki route. The *Mariella* is one of seven vessels in the Viking Lines fleet. The system was installed on a 6.0 MW Pielstick 12 PC2.6 engine, one of four main engines on the vessel. The humidification vessel (3.8 m L x 1.2 m D) was installed horizontally suspended from the ceiling of the engine room. The installation was completed during normal operation of the vessel and no down time was required. The system has achieved NOx reductions of about 70% in operation during the last year, with no operating

[10] This PC2.6 engine is rated at 540 kW/cylinder, the same as the M.V. *Cabot*.

problems. Viking Line reports that the engine has cleaner operation with the HAM system, and this can potentially increase the time between maintenance periods. An inspection of the ABB-model turbocharger on the engine with the HAM system revealed a relatively clean turbine having minimal and smooth carbon deposits. The effect of the HAM system on fuel consumption is currently unknown due to difficulties with accurate engine load measurements, but Pielstick believes the effect is neutral to positive.

After considering the competing NOx reduction alternatives, Viking Lines approved the installation of HAM systems for the three remaining engines on the *Mariella* starting in October 2000. The three new HAM systems were expected to be operational at the end of 2000. SCR suppliers were reported to be offering substantial capital discounts to entice Viking to install their systems, but the high operating cost of SCR systems (due to urea consumption) was a concern.

Viking Line is now planning to install HAM systems on three more vessels in its fleet starting in early 2001: first the *Amorella* (Stockholm-Turku), then the *Isabella* (Stockholm-Turku) and *Gabriella* (Stockholm-Helsinki). The engine room in the *Amorella* has less available space than the *Mariella* and some retrofitting may be necessary to accommodate the humidification vessels.

Pielstick is currently the only engine manufacturer offering HAM systems as an option on its new generation of PC engines, in cooperation with Munters. In addition to marine engine application, Pielstick also reports the recent installation of HAM systems on stationary diesel engines used in two electric power plants in France and Corsica. Munters is continuing to develop smaller and more modular HAM systems, with capacity for higher charge air humidity levels.

9. Selective Catalytic Reduction

9.1 Summary

Selective catalytic reduction (SCR) is the only technology of the six studied that controls NOx emissions in the exhaust gas after they have been generated. SCR is capable of reducing NOx emissions by up to 99% by reacting NOx with ammonia (from a urea solution) over a catalyst in the hot exhaust gases of marine engines. Inert nitrogen and water are produced in the reaction. HC and CO are also reduced significantly, but PM and SOx are uncontrolled. The technology is supplied by three major vendors worldwide and at the end of 2000, there were over 60 installations, most of which were in the Baltic Sea. The total installed cost of SCR systems for the *Cabot* is estimated at $1.2 million. A 95% reduction in NOx emissions is achievable at a cost of $552 per tonne of NOx reduced. The largest cost component in this estimate is the cost of urea required for the reaction. SCR technology may not be practical for the *Cabot* because significant retrofit changes (at an increased cost) may be required to install SCR into the existing exhaust configuration.

9.2 Description

The information in this section was summarized from ABB Flakt and Siemens product literature and personal interviews.

9.2.1 Operating Principle

SCR is a technology in which NO and NO_2 emissions in the hot exhaust gas are reacted (reduced) with an amine-based compound over a vanadium-based catalyst and converted to inert nitrogen (N_2) gas and water vapour (H_2O).[11] The use of SCR technology has no effect on the operation of the engine, since the reactions occur after the combustion process. The technology is used in many different fuel combustion applications, including electric power generation (fossil-fuel, combined cycle, co-generation), incineration, industrial boilers and process heaters, and various transport modes (passenger vehicles, trucks, locomotives, and marine vessels).

In land-based SCR applications, ammonia (NH_3) is usually selected as the amine-based reactant, but for marine systems, a 35-40% solution of urea [$CO(NH_2)_2$] in de-ionized

[11] The term "selective" is used since the amine-based reactant selectively reduces only NO and NO_2. Non-selective catalytic reduction (NSCR) processes typically use methane as the reducing agent and can also reduce CO_2 and nitrous oxide (N_2O) emissions.

water is typically used for safe handling and toxic risk reasons. Once the urea solution is vapourized in the hot exhaust gases, it immediately decays to ammonia and CO_2 and the following two reduction reactions convert the NOx to nitrogen and water:

$$4NO + 4NH_3 + O_2 \text{ ----------> } 4N_2 + 6H_2O$$
$$6NO_2 + 8NH_3 \text{ ----------> } 7N_2 + 12H_2O$$

The NOx reduction rate can easily be varied to meet different air pollution regulations by adjusting the urea injection rate between 0 and 100%. A trace amount of ammonia is produced as a by-product of the urea decomposition. This can cause undesirable odour and present a safety hazard. A complete SCR system usually includes an oxidation catalyst after the SCR catalyst to control HC, CO and the trace ammonia emissions from the system. There are no waste products involved with the combined SCR and oxidation process. The system does not control PM, since filters would put an undesired back pressure on the exhaust system. SO_2 emissions are not controlled and may be oxidized to the trioxide form (SO_3).

9.2.2 Equipment

A urea-based SCR system consists of the following components:

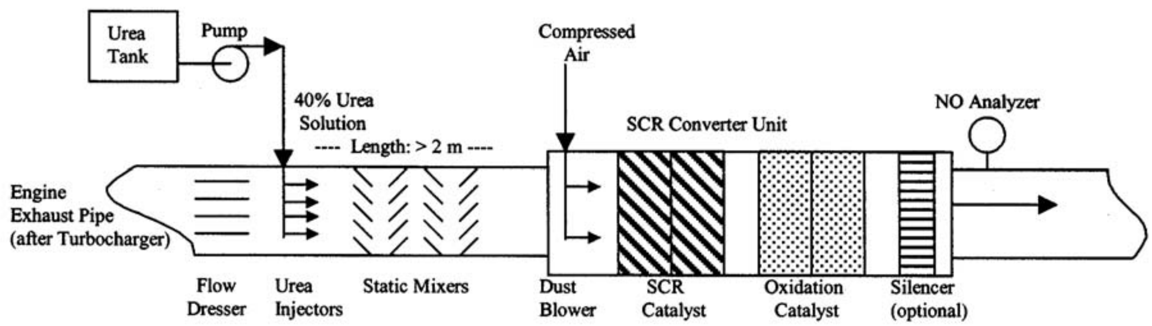
- catalytic converter unit (including two catalysts and dust blowing system);
- urea injector and static mixer elements;
- control/metering and injection system for urea solution;
- urea service pump;
- urea tankage;
- NOx analyzer after SCR for feedback control; and
- additional process instrumentation and piping.

The SCR and oxidation catalyst layers consist of ceramic monoliths/blocks packed side by side in multiple layers inside the converter casing. The SCR catalyst is always located upstream from the oxidization catalyst. The different layers of catalyst material are placed on elastically mounted shelves within the converter. The catalyst blocks usually have narrow square or honeycomb channels. The SCR catalyst is typically composed of a porous titanium oxide and fibre matrix on which vanadium oxide is coated. The open area is typically >65% thus providing an extremely large contact surface. The catalysts are selected to suppress ammonia slip to below 10 ppm across the engine load range.

A 40% urea solution (specific weight: 1.112 kg/L at 20°C) is typically used in marine SCR systems. Urea is a solid commodity chemical principally used as fertilizer. It can be prepared into a 40% solution easily by most chemical distributors. Although the solution has a distinct odour, it is safe to handle, non-toxic and will not decompose to ammonia at ambient temperatures. A free-standing urea tank with vent and filling system is required.

Urea is somewhat corrosive on copper alloys, so storage tank protection should be used. The recommended material is steel coated with a protective epoxy coating, stainless steel or plastic. The urea solution consumption is generally within 6 to 10% (by volume) of the fuel consumption, depending mainly on the desired NOx reduction versus uncontrolled levels.

The urea solution must vapourize and dissociate to ammonia before the SCR catalyst. For proper injection, vaporization and mixing of the urea solution, an injection and mixing section is arranged after the turbocharger, but at least 2 m upstream of the SCR converter. The section includes an exhaust flow dresser (to make exhaust flow linear), a fitting for the urea injector and downstream static mixer elements. Urea is supplied by the service pump system via a control valve to the multiple injector system. The injection of urea into the exhaust duct is augmented by pressurized injection air, supplied by a compressor system, in order to atomize the urea solution and to purge the injector from urea solution after injection shut off. Downstream from the injection section, static mixers are fitted into the exhaust piping to produce a homogenous gas flow before the SCR converter unit.



Source: Siemens, ABB

Figure 10: SCR Schematic Diagram

The control/metering unit regulates the urea injection flow to suit the different engine load conditions according to a pre-set injection curve. It receives load and rpm signals from the engine, or a NOx signal from the optional NOx analyzer. The NOx analyzer instrumentation is used for trend adjustments of the injection curve.

A blowing system is necessary in catalytic converters to prevent the buildup of fine PM. Calcium sulphate (a fine, white gypsum powder) can be formed in the engine exhaust from trace amounts of calcium present in the fuel and lubricating oils and sulphur in the fuel. This can occur in any marine diesel engine, with or without SCR systems. Calcium sulphate will deposit on the front of the catalysts, blocking the pores and reducing activity. An automated dust-blowing system uses short, regular bursts of compressed air from fixed lances mounted inside the converter to remove fine particulate buildup. Dust blowing duration and intervals are adjustable via the control panel.

9.2.3 System Size

The urea tank required for an SCR system on the *Cabot* would have to have a capacity of approximately 10 m^3 for a one-way voyage. Since urea solution may not be easily available from chemical distributors in St. John's, it is more prudent to design the urea tank at twice this capacity (20 m^3) for a round-trip voyage.

Two SCR converter units would be required for the engine exhausts on the *Cabot*. Converter units can be mounted horizontally or vertically in the exhaust piping, but require approximately 2 m in axial length (or height). Each converter unit requires approximately 4.0 m^2 of cross-sectional area to handle the exhaust gas flow. This can be accommodated as a 2.0 m by 2.0 m square area or a 1.5 m by 2.7 m rectangular area, due to the modular form of the catalyst sections. In addition, about 6 m of exhaust piping length must be available to insert the injection section (2.5 m) and mixing section (3.5 m) after the turbochargers and before the installed converter unit. The injection/mixing section replaces the exhaust pipe, but is roughly the same diameter.

9.2.4 System Performance

SCR systems are designed to reduce NOx emissions to nitrogen and water, and oxidize HC and CO to CO_2 and water. NOx emissions reduction levels typically range from 85 to 99%, depending on the amount of urea used. Usually, the local NOx emissions limits or the highest port fee rebates determine the degree of NOx reduction. The oxidizer catalyst achieves HC reduction levels of between 70% and 90% and CO reductions of 50 to 90%, making the exhaust free of typical diesel odour and substantially reducing the human health risk. Ammonia emissions (ammonia "slip") are usually controlled to less than 3 ppm by the oxidizer unit. SCR converter units are often equipped with integrated silencer sections for total noise reductions of 30 to 35 dB. In some installations, SCR units replace a ship's silencer units in the stack, if the temperature is high enough.

9.2.5 Operating Issues

As a rule of thumb, the SCR reaction temperature should be ideally above about 300°C to maintain catalyst life. This is due to the possible formation and condensation of wet PM due to fuel quality. As the viscosity and the sulphur level of the fuel increase, the recommended operating temperature must rise. Increased sulphur, if allowed to deposit, acts a poison to the vanadium oxide catalyst.

The fuel oil quality, the exhaust gas temperature, engine design and conditions are important factors for the formation of wet PM. Wet PM, such as condensable HC present in exhaust gases of heavier fuel oils, may cause reduced catalyst activity by blocking active catalyst sites and increase back pressure. If problems arise with wet PM accumulation on the catalysts, it will be necessary, at least temporarily, to increase the exhaust gas temperature.

SCR systems must work above the minimum temperatures shown in Table 12 for fuels with different sulphur levels.

Table 12: Exhaust Gas Temperatures for Urea SCR Systems

Fuel type	Diesel Oil	Marine Diesel Oil	Heavy Fuel Oil	Heavy Fuel Oil
Sulphur content	<0.1%	<0.25%	<1%	<5%
Minimum temperature	270°C	280°C	290°C	300°C

Source: Siemens

SCR systems can be retrofitted onto the exhaust systems of existing ships, but space and system constraints may increase the difficulty of installation. New exhaust piping may have to be added through alternative routes to meet the SCR space requirements. Exhaust gas boilers or economizers should be located downstream of SCR units, since they typically reduce exhaust temperatures lower than 250°C. Depending on the configuration of a ship's exhaust system, this may mean that economizers or boilers close to the engines would have to be relocated.

The exhaust gas composition and temperature varies from time to time, depending on the condition of the engine, ambient conditions, engine load and the amount of foreign substances introduced into the combustion chambers via impurities in the fuel and lubricating oil or the combustion air. The content of ash, sulphur, phosphorus and arsenic in the fuel particularly influences the lifetime of the catalysts. The addition of used lubricating oil to the fuel oil should be avoided, since it usually contains many heavy metals. Depending on the operating conditions, type of catalyst, and the design safety margin, the performance of the catalysts can be reduced over time. However, under ideal conditions, an SCR converter system can be operated as long as 60,000 hours (typically 10 years) before replacement of spent catalyst is required.

9.3 Costs

Cost information for SCR systems was obtained from two major SCR vendors, ABB Flakt and Siemens. In addition, two engine makers, Wärtsilä and Pielstick, supplied general estimates, which were used as points of comparison. Several of the cost elements provided by the engine makers were based on rules of thumb provided by the two vendors.

9.3.1 Key Assumptions

The key assumptions used in the SCR cost calculations for the M.V. *Cabot* are:

- Capital cost rate of US$30 per kW for a two engine system;
- Installed cost rate of US$64/kW;
- No fuel penalty;
- Average consumption of urea solution (40%) of 17.0 L/MWh;
- Average urea cost of $0.19/L for 40% solution;
- Average catalyst and maintenance cost rate of $1.87/MWh;
- Average NOx reduction of 95% achieved.

The capital cost rate of US$30/kW was averaged from two different ABB capital cost estimates. The first estimate was an actual price range of US$300,000 – $350,000, quoted for a complete SCR system sized for the *Cabot*. The high end of the range was selected to be conservative. The second estimate was from an earlier interview with ABB's environmental manager, who estimated the capital cost rate for a complete system to be 300,000 SEK/MW. The two estimates are within 2% of each other and the average is equivalent to US$30/kW. This was used to calculate the capital cost of equipment for the *Cabot* at $547,000. The capital cost estimate includes the converter units, urea tank, pump, injector and mixing sections.

The installed cost (capital + installation) rate of US$64 per kW was averaged from two installed cost rate estimates, one from ABB and one from Siemens. The ABB installed cost estimate for two SCR systems sized for the *Cabot* was given as US$650,000 – $800,000. The higher value of US$800,000 (US$68/kW) was selected to reflect anticipated installation difficulties (see below). No specific cost quote was received from Siemens, but in an interview, a typical current installed cost rate range of US$40 – $60 per kW was provided, which has been observed during the year 2000. Again, the higher value of US$60/kW was selected for the same reason. The average of US$64/kW was used to produce the total installed cost of $1.16 million. The installation cost was calculated by difference.

Based on a review of the *Cabot* exhaust system drawings, the installation of SCR systems on the *Cabot* will require a difficult reconfiguration of the ship's exhaust system. The ship's boiler economizers are located on the exhaust directly after the turbochargers (about 3 m downstream). The exhaust gas temperature at the turbocharger outlet is 325°C but only 240°C at the economizer outlet, which is too low for an SCR to operate effectively. This prevents an SCR from simply being installed in the vertical exhaust stack casing, as is commonly done in some retrofitted ships with stack-mounted economizers or boilers. The economizers would have to be relocated to a position on the stack that is downstream of the SCR converter unit. One suggested alternative was to install the injection and mixing section vertically in the casing at the main deck level, the SCR unit vertically in the casing at the upper deck level and the economizer placed on top of the SCR. Another alternative was to install the injection and mixing section horizontally in the engine room, the SCR vertically in the casing at the main deck level and the economizer on top of the SCR.

Further difficulties are presented since there may be some space constraints in the stack casing, making it more difficult to install and a vertical SCR converter unit. If the economizers cannot be moved, a new exhaust gas pipe bypass may need to be installed to route the hot gases to a deck-mounted SCR unit and then returned to the economizer. In any event, the costs to install SCR systems on the *Cabot* are uncertain, but will likely be on the high side, due to the existing exhaust gas configuration. SCR installations typically take no more than two weeks in drydock, but more time may be required for the *Cabot*.

The urea consumption rate is assumed to be an average of 17.0 L of a 40% solution per MWh, based on published ABB and Siemens rates. ABB's urea consumption rates range from 13 to 20 L/MWh and Siemens rates range from 15 to 20 L/MWh. The midpoints of each of these ranges were selected and averaged. The price of urea solution was estimated at $0.19/L, based on a current price range of US$0.10 – $0.15 per L, as reported by Siemens in 2000 [6].

The on-going catalyst replacement and maintenance cost rate was determined to be $1.87/MWh, based on averaging operating cost estimates from ABB and Siemens. ABB estimated that these costs were 1 SEK per gram of NOx reduced, which converts to $2.11/MWh for the *Cabot* at a 95% reduction rate. Siemens did not estimate catalyst and maintenance costs directly, but reported that total operating costs (including urea) ranged from US$2.80 to $3.70 per MWh. Once urea costs are removed, Siemens implied catalyst and maintenance costs are calculated to be $1.64/MWh. These two values were averaged.

The ABB and Siemens literature reports NOx reductions of 90 to 99%, using the urea rates stated above. Since the midpoints of the urea rates were selected for the analysis, the midpoint of the NOx performance range (95%) is also selected.

9.3.2 Cost Analysis

Using the above assumptions and operating conditions, the cost of NOx reduction using SCR systems is estimated to be $552 per tonne of NOx reduced. The total installed cost for the *Cabot* is estimated to be $1.2 million. Annual operating costs are estimated to be about $0.3 million per year.

Table 13: SCR System Costs

(Basis: M.V. *Cabot* with two 5.8 MW Pielstick engines)

Capital Cost	
Capital Cost	$547,000
Installation Cost	$609,000
Total Installed Cost	$1,156,000
Annualized Capital Cost ($/y)*	**$130,000**
Operating Costs	
Fuel Cost Penalty/(Savings) ($/y)	
Urea Consumption	$195,000
Catalyst & Maintenance	$111,000
Net Operating Costs/(Savings) ($/y)	**$306,000**
Total Annual Cost/(Savings) ($/y)	**$436,000**
NOx Reduction	**95%**
Annual NOx Reductions (t/y)	**789**
Cost per tonne NOx reduced ($/t)	**$552**

* Total installed costs are amortized at 10% over 23 years

The overall costs of SCR systems are heavily influenced by the cost of urea consumption, which is the largest cost element in the above analysis. It outweighs the annual impact of the total installed cost. The initial capital cost is relatively high, since such large components must be installed. Installation costs, although somewhat uncertain due to a difficult retrofit situation, are also high. However, the very high NOx reductions that can be achieved (95%) balance these high costs, such that the cost per tonne is not truly excessive.

Even though there is some uncertainty about the installation costs, a sensitivity analysis shows that the estimate still provides a reasonable cost benchmark for SCR systems. If the installation costs were to double to $1.2 million due to major problems, the total annual costs and the cost per tonne of NOx would be increased by only 16%.

9.4 Practical Experience

As of the end of 2000, there were over 60 ships worldwide that have SCR systems installed to control NOx emissions. This number will increase by about 10 to 20% in 2001. Most of these vessels run in northern Europe, and particularly the Baltic Sea, where stringent environmental performance-based port fees and fairway dues are in place in Sweden and being developed in other Baltic countries. Most of the existing installations have occurred in the past three years since the 1998 introduction of the Swedish fees rebate system. The highest possible fee rebates are available to ships having NOx emissions lower than 2 g/kWh, and SCR systems are the only NOx reduction technology that can achieve these levels. There is also a program to assist vessel owners with the capital costs of SCR systems. The ships with SCR systems are mostly commercial container and RoRo cargo vessels, although some RoPax (passenger/car) vessels have started to install the systems recently. Table 14 provides some examples of existing SCR installations.

There are only a few SCR installations outside of Europe. ABB reports that there are only five ships known to have SCR systems in the U.S. Four of these are steel carriers that operate only in San Francisco Bay and the fifth is a dredging vessel operating off Santa Barbara, California. In the Far East, there have been SCR tests and demonstrations, but no permanent installations.

There are three major suppliers of SCR systems to the commercial marine market: ABB Flakt, Siemens, and Haldor-Topsøe. ABB Flakt, based in Sweden, is the leading supplier of marine SCR systems, with an estimated 44% of the installations. ABB has no catalyst manufacturing, but develops the catalyst specifications based on customer needs and purchases its catalyst under contract. Siemens, based in Germany, has approximately 35 to 40% of the installations, and Haldor-Topsøe of Denmark has the small remainder. Both Siemens and Haldor-Topsøe are integrated into catalyst manufacturing.

ABB installed the first marine engine SCR system in 1992 on the Scandlines passenger ferry *Aurora*, which operates in the Baltic Sea. The ship burns relatively clean (low-sulphur) fuel and the system has been running effectively for over 60,000 operating hours.

Table 14: Examples of Siemens SCR Installations
(early 2000)

Operator	Vessel	Engine Application	Fuel	Engine Maker	Engine Size (MW)
Silja Line	*Europa*	4 main	HFO	MAN B&W	4 x 7.95
Fosen Trafikklag	*Hertug Skule* (N)	1 main	Diesel MDO	Bergen Diesel	0.92
Gotland Rederi	*Thielvar* (S)	4 main 2 aux.	Diesel MDO	Wärtsilä	4 x 3.72 2 x 1.24
Gotland Rederi	*Visby* (S)	4 main 3 aux.	Diesel MDO	MAN B&W (2-st) Wärtsilä	4 x 5.20 3 x 1.44
Gotland Rederi	Fast Ferry (S)	4 main 3 aux.	Diesel MDO	Ruston Diesel (Alsthom)	4 x 7.00 3 x 0.54
Gotland Rederi	1600 LM RoPax 1 (S)	4 main 3 aux.	HFO	Wärtsilä	4 x 12.6 3 x 1.53
Gotland Rederi	1600 LM RoPax 2 (S)	4 main 3 aux.	HFO	Wärtsilä	4 x 12.6 3 x 1.53
Na	MS *Baltic 2*	1 main	HFO	MAN B&W	3.36
Na	MS *Baltic 3*	1 main	HFO	MAN B&W	3.36
Na	MS *Baltic 4*	1 main	HFO	MAN B&W	3.36
Roerd Braren	MS *Timbus* (S)	1 main 1 aux.	HFO MDO	MaK	3.84 0.54
Roerd Braren	MS *Forester* (S)	1 main 2 aux.	HFO MDO	MaK	3.84 0.24
Roered Braren	MS *Cellus* (S)	1 main 1 aux.	HFO MDO	MaK	3.84 0.54
SEA PARTNER	MS *Ortviken* (S)	2 main 3 aux.	HFO MDO	MaK	2 x 4.05 3 x 0.61
TT-Line	*Nils Dacke* (D)	1 main	Diesel MDO	MaK	4.50
United Shipping	na (S)	1 main	HFO	Wärtsilä	5.40
Viking Line	*Gabriella* (SF)	1 genset	Diesel MDO	Wärtsilä	2.00
Birka	*Birka Princess*	4 main 3 aux.	HFO MDO	Wärtsilä	4 x 4.50 2 x 2.25 1 x 1.50

Table 15: Examples of ABB Fläkt SCR Installations
(early 2000)

Vessel	Operator	Engine Maker	Engine Size (MW)
Aurora	Scandlines	Wärtsilä	2.46
Scandica	SNMA	Hedemora Scania	2 x 1.30 4 x 0.25
RN 23	Royal Navy	Paxman	1.30
Atle	SNMA	Pielstick Wärtsilä Wärtsilä	5 x 3.68 4 x 0.66 0.35
Fincclipper	FG-shipping	Sulzer Sulzer	4 x 5.80 1 x 1.16
Finneagle	FG-shipping	Sulzer Sulzer	4 x 5.80 1.16
Constructor	Coflexip Inc.	Nohab	2 x 2.65
Spaarneborg	Wagenborg	Sulzer Wärtsilä	10.92 2 x 0.92
Schieborg	Wagenborg	Sulzer Wärtsilä	10.92 2 x 0.92
Slingeborg	Wagenborg	Sulzer Wärtsilä	10.92 2 x 0.92
Stena Brittanica	Stena RoRo	Sulzer Sulzer	4 x 6.00 3 x 1.16
Stena Hollandica	Stena RoRo	Sulzer Sulzer	4 x 6.00 3 x 1.16
Tor Viking	B&N Viking	MaK MaK Caterpillar	2 x 3.84 3 x 2.88 2 x 0.53
Balder Viking	B&N Viking	MaK MaK Caterpillar	2 x 3.84 3 x 2.88 2 x 0.53
Vidar Viking	B&N Viking	MaK MaK Caterpillar	2 x 3.84 3 x 2.88 2 x 0.53
Anke Ehler	Ehler	MaK Caterpillar	6.10 2 x 0.53
Elisabeth	Holwerda	MaK Caterpillar	6.10 2 x 0.53
Dalsland	Holwerda	MaK Caterpillar	6.10 2 x 0.53
Mikal With	Egil Ulvan	MaK	1.14

10. NOx Control Case Studies for Selected Shipping Lines

10.1 Introduction

To provide additional context to the study, case studies on NOx controls are presented based on interviews and literature on selected segments of the marine industry.

10.2 Cruise Ships

To date, there has been relatively little control of NOx emissions among the world's cruise ships. Most of the environmental pressure on cruise ships has been on controlling smoke emissions (opacity limits), wastewater treatment, and solid waste disposal, which are major issues for host ports and waterways in natural environments.

There are approximately 125 cruise ships operating in the world operated by over 25 different cruise lines.[12] The two major cruise ship operators in the world are Carnival Corp. and Royal Caribbean Cruises, which together control perhaps 40% of the world's major cruise ships. Other large operators include Princess Cruises, Norwegian Coastal Voyage, and Norwegian Cruise Lines. The world's major cruise regions are Alaska (summer), the Caribbean (winter) and Europe.

Most cruise ships use Wärtsilä engines for their propulsion systems. Wärtsilä engines have approximately 80% of the cruise line market with MAN B&W having most of the remainder. As of the year 2000, all new cruise ships must have engines that meet the IMO NOx limits, but current engine designs can be modified to meet these limits without additional external NOx control technologies. Most cruise ships in the world are built in shipyards in Italy and France.

Carnival Corp., a Florida-based cruise line company, is planning to use DWI technology on some of its existing cruise ship engines for smoke and NOx reduction. Carnival runs Carnival Cruise Lines (the world's largest in terms of passengers), Holland America Line, Windstar Cruises, and Cunard Lines. In total, Carnival and its subsidiaries operate about 30 ships in Alaska, the Caribbean, and Europe. These ships can be easily retrofitted with DWI because they all have Wärtsilä engines. Carnival also has a working agreement with Wärtsilä to develop a smokeless diesel-electric propulsion system for its new cruise ships by 2001. The new system will use Wärtsilä's common rail design incorporating

[12] Cruise Lines International Association (CLIA)

DWI. All new cruise ships for the various Carnival lines will have DWI systems installed and some ships in current production may also be retrofitted.

Royal Caribbean Cruises Corp. has two cruise line subsidiaries – Royal Caribbean International and Celebrity Cruises – that operate 15 and 6 ships, respectively. To date, Royal Caribbean has been working with MAN B&W on smoke reduction and NOx control solutions, but no NOx control technologies have been installed. Royal Caribbean reports that its ships have never been fined for smoke violations in Alaskan waters due to their low-smoke engines.

Princess Cruise Lines, based in Los Angeles, currently operates a fleet of 10 cruise ships. All have Wärtsilä engines and the company reports that it is looking into DWI technology for its engines. Princess was able to reduce smoke and NOx emissions on some of its Alaskan ships by changing the fuel injectors on some of the diesel engines to improve the spray pattern. These changes will soon be made on the whole fleet.

According to Wärtsilä, Carnival has taken the biggest initiative to date to study the control of NOx emissions with the DWI technology. The first sales of the DWI option for new cruise ship engines were made in 2000, but only on a small portion of orders. While all other cruise lines are also studying the NOx issue, the relatively recent Carnival developments are the most significant initiatives to date. The only known NOx control alternative used on cruise ships is FWE systems, which have been installed on two Norwegian Cruise Lines vessels that operate in Alaskan waters.

10.3 Ferry Lines

Ferry lines are concerned about smoke and NOx emissions because of their frequent operation near major urban centres. One Canadian, one Swedish and two Finnish ferry lines are briefly profiled in this section.

10.3.1 B.C. Ferries

Since 1999, B.C Ferries has started to test NOx control technologies on its vessels. CWI was tested in early and mid 2000 aboard the *Queen of New Westminster*. The developer of the CWI technology approached B.C. Ferries to test the technology in 1999. The tests showed some promising NOx reductions at a low cost, but there are concerns about the long-term effect on the engines. Some of the issues included unreliable atomization of the water leading to water buildup in the air manifold, concerns over the injection timing, and uncertainty about the long-term effect of deposits on valves and pistons. B.C. Ferries is interested in continuing testing of the technology for longer periods on smaller, older vessels.

FWE systems are being considered for testing on a smaller vessel in cooperation with a local fuel distributor. At this year's conference of the Society of Naval Architects and Marine Engineers in Vancouver, it was reported that Wärtsilä presented a proposal to B.C. Ferries about the use of DWI technology [29].

10.3.2 Viking Line

Viking Line, a Finnish company, is one of two major ferry companies operating in the Baltic Sea It runs seven car-carrying passenger ships between cities in Sweden, Finland and Latvia. Viking uses only low-sulphur fuel in order to reduce SOx emissions. This allows a 0.9 SEK/GRT discount on port fees.

Viking has adjusted its engines to run the minimum possible quantity of NOx without external controls. Viking is noted for the first installation of a HAM system in the world on the M/S *Mariella*. Viking has now committed to install HAM systems on three more ferries in the near future. In addition to HAM systems, an SCR system has been installed on a 2 MW genset engine on the M/S *Gabriella*.

10.3.3 Silja Line

Silja Line, a Finnish-based ship operator, is the leading passenger ferry company in the Baltic Sea with a fleet of six passenger/car ferries. As of the end of 2000, Silja had installed DWI and SCR systems on the main engines of three of its largest ships. A smaller, fourth ferry is about to be retrofitted with SCR systems. Silja was the world's first major passenger ferry line to receive an ISO 14001 certification in 1999. Silja's fleet NOx reduction target is a 75% reduction from 1995 levels by the year 2003 [30].

In 1999, DWI was installed on the main engines of the *Silja Symphony* and *Silja Serenade*, twin-sister ferries that run daily on the Helsinki – Stockholm route. Each vessel has four main Wärtsilä 9L46 engines rated at about 8 MW each. The auxiliary engines on these two ships have had small SCR systems in place and operating trouble-free since 1995.

The DWI systems were installed sequentially while the ships were in service, due to the flexibility of having four main engines. One engine could be safely brought off-line while the other three remained in operation. The retrofits involved installing the common-rail fuel system, water control pumps and fuses; modifying the cylinder heads by drilling ports for the combined fuel-water injectors; modifying the piston tops; and installing additional piping. The capital costs of the DWI system were estimated to fall between 1.1 and 1.3 million FMk ($250,000 - $300,000) for each engine. This level is very close to Wärtsilä's reported rule of thumb of US$20/kW. The installation of DWI was scheduled to coincide with regular engine overhaul work as part of a long-term service agreement with Wärtsilä. As a result, the direct installation cost for DWI alone was not quantified, but was relatively low. The factors contributing to the decision to use DWI on these engines were relatively lower costs versus SCR, ease of installation, ample engine room space for the control cabinet and availability of water.

The DWI systems have operated well, after some initial start-up difficulties. The NOx reduction varies with water ratios and engine loads, but for a typical 75 to 80% running load, a 60% NOx reduction is achieved using a 60% water-fuel ratio. NOx rates now typically range from 5 to 6 g/kWh, down from uncontrolled rates of 15 g/kWh. Silja acknowledges that in theory, there is a slight fuel penalty associated with use of DWI, but on a statistical basis, there has been no significant change to fuel consumption observed in operation over the last year.

In January 2000, large SCR systems were installed on the main engine exhausts of the *Silja Europa*, a passenger/car ferry operating daily on the Turku – Stockholm route. The ship has four MAN B&W 6L58/64 engines, each of which is rated at about 7.95 MW. The systems were installed on the *Europa* during an 11-day dry dock visit, as part of a scheduled turnaround. This duration was considered very fast, compared to some SCR installations that have lasted as long as four to five weeks. No significant structural redesign was necessary, since it was relatively easy to access the exhaust casing from the ship's car deck. The capital cost of the four systems was about 10 million FMk and total installed cost was 17 million FMk ($1 million per engine).

Although there were some problems during startup, the SCR systems on the *Europa* have operated smoothly for the past year. They achieve an average NOx reduction of 95%, down to NOx levels of 1.1 g/kWh. Since the engines operate on HFO with a sulphur content of less than 0.5%, the *Europa* qualifies for the full Swedish port fee rebates of 2.5 SEK/GRT, and the SCR system is expected to have a payback of about 2.5 years.

In January 2001, SCR systems will be installed on the main engine exhausts of the *Silja Festival*, a ferry about half the size of the *Europa*, which runs on the same route. The other ships in the Silja fleet are the *Silja Finnjet*, a fast ferry powered by gas turbine engines, and the small *Wasa Queen*.

10.3.4 Birka Cruises

Birka Cruises is a Swedish-based company that operates four vessels in the Baltic Sea. Its flagship, the *Birka Princess*, recently had SCR systems retrofitted for its four main engines and three auxiliary engines, all of which are Wärtsilä models. The four main engines are Wärtsilä 12V32D engines, each of which is rated at 4.5 MW. Two of the auxiliary engines are 6R32 engines (2.25 MW each) and the third is a 4R32 (1.5 MW). The SCR systems were installed in the engine stack. The waste heat boilers had to be repositioned downstream of the SCR systems since there was no room to install SCR converter units between the turbochargers and the boilers. The ship has engine silencers, which were not affected in the retrofit. The total installed cost of the retrofit was US$780,000. The system was installed since the port fees rebates will generate sufficient return to make the project economically viable. The ship burns HFO with low-sulphur levels, qualifying it for discounts and eliminating any SCR risk.

10.4 Cargo shipping

NOx control technologies such as SCR and DWI have been installed on several cargo ships operating in northern Europe. Many of these are RoRo container ships and paper or forest product carriers. Transfennica is one example of a ship operator that has committed to DWI technology for some of its new ships.

10.4.1 Transfennica

Transfennica is a Finnish-based commercial shipping company that operates scheduled services between Finland and main European trading ports. It operates a fleet of about 20 RoRo vessels, 14 of which are new ships. The company has responded to stricter environmental demands in Swedish ports by introducing DWI to cut NOx emissions from the engines in its latest generation of vessels. This important project has been successfully carried out together with Wärtsilä NSD. Altogether, seven Wärtsilä 46 engines were ordered with DWI technology, the first production orders of this technology for medium-speed engines. Transfennica is also considering retrofitting existing engines with DWI technology.

In 1997, Transfennica was one of the first commercial marine operators to be awarded an international ISO 14001 environmental certificate. The company’s environmental program integrates environmental issues with the ISO 9002 quality management system.

11. Conclusions

The following conclusions were drawn from the analysis in this study.

- Continuous Water Injection (CWI) to the charge air appears to be most cost-effective system for low levels (10-30%) of NOx reductions, but the low level of operating experience makes further testing a necessity. It would be best used for trimming NOx emissions to meet minimum IMO limits.
- The Fuel-Water Emulsion (FWE) system appears to be a promising, medium-cost technology for achieving medium levels (30-50%) of NOx reduction. Since FWE is reasonably simple to retrofit onto existing ships without significant structural or engine modifications, it appears to be a practical retrofit solution.
- Direct Water Injection (DWI) technology appears to be effective for medium levels of NOx reduction (40-60%), but may not be a practical technology for engine retrofits, due to its specific engine design requirements. It becomes much more cost effective on new engines.
- The relatively new Humid Air Motor (HAM), despite high initial capital costs, appears to be a practical, cost-effective method of achieving medium to high levels (60-80%) of NOx reduction. Limited operating experience suggests that it can be retrofitted in the engine room without need for new water supply, and performs well.
- The Selective Catalytic Reduction (SCR) system has the highest unit cost of the five technologies analyzed, but can achieve almost complete NOx reduction. Installation costs are a significant issue if major retrofitting is required. This technology is best suited for vessels operating in regions having very stringent environmental control programs and financial incentives.

12. Recommendations

The testing and demonstration programs for the different technologies should be continued and broadened to gather more practical operating and cost data.

- A small-scale HAM system should be tested in the Engine Laboratory.
- FWE systems using ultrasonic homogenizers should be tested in the Laboratory.
- A demonstration of FWE systems using pre-blended emulsions and homogenizer systems should be undertaken.
- The field demonstrations of the CWI system should be continued over a longer time period (say, one year) with longer test duration (several hours) to gather more data on specific fuel consumption effects and operating issues.
- A small-scale HAM system should be demonstrated on an appropriate vessel to gather actual operating information. Support for capital costs may be required from the federal government as well as Pielstick, who may have incentive to increase current HAM operating experience.
- A small-scale SCR system should be demonstrated on an appropriate vessel (federal government, private) having relatively few installation problems.

Two general suggestions should also be considered:

- The scope of this type of technology assessment study should be broadened to include more off-road diesel engine sources. These include locomotives and other off-road heavy-duty diesel engines used in construction and heavy industry. These studies may have to focus more on the scoping of regulatory developments and technology issues, as opposed to cost analyses.
- An inventory of marine NOx emissions should be conducted to understand the segmentation of marine NOx emissions in Canada and the implications of the proposed IMO limits on the Canadian marine sector. Currently, Canadian marine NOx emissions are calculated by the Pollution Data Branch of Environment Canada as area sources based on fuel consumption data, registered vessels and average emissions factors.

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Appendix A: Ship Photographs

M.V. *Cabot* RoRo Container Ship

M.V. *Cabot* RoRo Container Ship

M.V. *Cabot* Engine Room (upper level, forward)

M.V. *Cabot* Engine Room (lower level)


M.V. *Cabot* Engine Room (upper level, aft starboard)


M.V. *Cabot* Engine Room (upper level, aft port)