MARTOB

On Board Treatment of Ballast Water (Technologies Development and Applications) and Application of Low-sulphur Marine Fuel

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1 Introduction

1.1 Background

The major pollutants released into the atmosphere by fossil fuel combustion are carbon dioxide (CO_2), carbon monoxide (CO), particulates, hydrocarbons, nitrogen oxides (NO_x) and sulphur oxides (SO_x). NO_x and SO_x contribute to acidification of water, soil depletion, forest damage and detrimental health effects. SO_x mainly consist of sulphur dioxide (SO_2) and sulphur trioxide(SO3) which are formed by the oxidation of fuel bound sulphur during the combustion process. The emission of SO_x from an engine or boiler is therefore a function of the sulphur content of fuel oil used and, hence, can only be reduced by removing the sulphur present in the fuel or by removing the SO_x content from the exhaust gas.

The reduction in land based SO_x emission levels through proposed and existing environmental legislation has resulted in a relative increase of emission levels from ships, the reason attention has moved towards the marine industry over the last decade. Shipping being a global industry, to achieve emissions reduction from ships, legislation need to be proposed through an international governing body such as the IMO or through regional governments prohibiting such emissions in their territorial waters.

With Annex VI of MARPOL 73/78 still awaiting ratification, the European Commission is preparing a community strategy to include marine heavy fuels in the "Sulphur in liquid fuels" directives of 1999/32/EC. To meet such legislation there is a need to develop compliance procedures, keeping in mind its effectiveness and ease of policing whilst considering the global trading pattern of ships. Conforming to current and future legislation not only has additional cost implications in the form of manufacturing and operational costs but also costs incurred to demonstrate compliance.

1.2 The project

The work described in the report has been undertaken in the MARTOB workpackage 5 under Directorate-General for Energy and Transport Contract no. GRD1/2000/25383- SI2.316038 as a part of the "Competitive and Sustainable Growth" programme. Input to the work has been provided in joint partnership by:

MARINTEK
Wallenius Wilhelmsen
Shell Marine Products
MAN B&W Diesel A/S
University of Newcastle upon Tyne
The Norwegian Shipowners' Association
Fueltech

The present world bunker market is based on the balance of supply and demand within the framework of requested fuel qualities. A change in the framework will affect this balance, and the applicability of forthcoming regulations of sulphur content of the fuel will depend on the supply side being able to meet the new demand with regards to crude quality and refinery infrastructure. The objective for the work in MARTOB has been to assess the commercial, technical and operational impact of a sulphur cap on marine bunker fuel in European waters. The project hopes that the outcome will help to facilitate the introduction of an important sulphur emission abatement measure without unintentional distortion of competition in the shipping market.

Detailed information regarding the MARTOB project is found on the project web site www.marinetech.ncl.ac.uk/research/martob/.

1.3 The Challenge

In November 2002 the European Commission adopted a new European Union strategy to reduce atmospheric emissions from seagoing ships (EC, 2002). This includes a proposal for modifying directive 99/32/EC on the sulphur content on liquid fuels so as to extend its scope to include heavy bunker fuel oils, as well as proposals for the introduction of economic incentives.

The aims of the measures expected that the Commission will highlight are:

1. To reduce the overall emissions in the so-called SECAs (SO_x Emission Control Areas - the North and Baltic Seas) as well as in all EU port areas.
2. To establish a regulatory regime with which all seagoing ships will be able to comply by using only two different fuels.
3. To ensure that fuels complying with EU standards will be available in all EU ports.

Among the means for achieving these aims are the following, all of which are to be written into directive 1999/32:

- Member states bordering on the SECAs of the North and Baltic Seas must ensure that only marine fuels with a sulphur content of less than 1.5 per cent are used in their territorial waters, and possibly also, if applicable, in their exclusive economic zones. This shall apply to all vessels of all flags, either from the date of the MARPOL Annex VI coming into force or from January 1, 2005, whichever is the earlier.
- Only fuels with less than 0.2 per cent sulphur may be used in inland waterways and EU port areas. (It is suggested that the latter should be defined as extending from the “outer limit of territorial sea to the quayside.”)
- By 2005 member states must ensure that all marine gas oil sold in their territories shall have less than 0.2 per cent sulphur. (A change in the definition of gas oils is suggested, so as to exclude the so-called DMB and DMC grades.)

The driving force behind new regulations related to the sulphur content in fuels consumed by ships, is the increasing relative emission of sulphur oxides from shipping in Europe if nothing is done. Assuming no change of the present marine fuel qualities and abatement measures being implemented on land sources, it has been predicted that shipping related sulphur emissions will represent two third of the total sulphur emissions in Europe in 2010

The IMO MARPOL Convention, Annex VI, sets a maximum limit for sulphur content of 4.5 % for marine fuels allowed used onboard ships. Annex VI also defines Sulphur Emission Control Areas (SOxECAs) to be areas with special requirements to use of *low sulphur* marine fuels where the max sulphur limit is 1,5%. The Baltic Sea was designated a SOxECA in the original protocol. In MARPOL Annex V, Regulation 5 IMO included the English Channel to be part of the North Sea as a special area. The SOxECAs in Europe are defined as in table Table 1.

Table 1: North Sea and the English Channel as defined in MARPOL

Geographical area	***Defined by***
North Sea	North Sea: The North Sea area means the North Sea proper including seas therein with the boundary between: i) the North Sea southwards of latitude 62^0 N and eastwards of longitude 4^0 W; ii) the Skagerak, the southern limit, of which is determined of the Skaw by latitude 57^0 44,8' N; and iii) the English Channel and its approaches eastwards of longitude 5^0 W and northwards of latitude 48^0 30' N.
Baltic Sea	The Baltic Sea means the Baltic Sea proper with the Gulf of Bothnia and the Gulf of Finland and the entrance to the Baltic Sea bounded by the parallel of the Skaw in Skagerrak at 57^0 44,8' N.

The fuel qualities proposed in the 1999/32 Amendment (Table 3) is connected to its use within geographical location in European waters and to ship types/ ship movements. The European Commission use the IMO defined SOxECAs for geographical regulations as well as requirement for low sulphur fuel. However, in addition to the SOxECA regulations the 1999/32 Amendment propose that all passenger ships operating on regular services to or from any Community port shall use low sulphur fuel not exceeding 1.5 % sulphur. This shall apply to vessels of all flags. Further the Amendment propose a maximum sulphur content of 0.2 % for fuel used by ships at berth in Community ports and on inland waterways.

The regulation of European low sulphur fuel qualities and respective European geographical area are summarized in Table 2.

The European Commission will regulate fuels for use in Europe and make marine fuels with sulphur content limits available according to the requirements in the proposed amendment. The Commission defines fuel grades according to the sulphur content in the fuel in three levels, as indicated in Table 3.

Table 2: Fuel qualities allowed by ship types/ movements in different European waters.

Geographical area	*Ship Type/ Ship Movement*	*Fuel Quality accepted/ required to use*
At berth	All	Quality 1 (< 0,2% sulphur)
Baltic Sea and North Sea	All	Quality 2 (< 1,5% sulphur) or less
All European waters	Cruise/ Passenger vessels on regular service inside European Waters	
European waters except for the Baltic Sea and North Sea	All ships except Cruise/ Passenger vessels on regular service in European Waters	Quality 3 (1,5% - 4,5% sulphur) or less

Table 3: Fuels in Directive 1999/ 32 according to Qualities with respect to sulphur content.

EU Directive	*Limit of sulphur content in fuel*
Quality 1	< 0,2%
Quality 2	< 1,5%
Quality 3	1,5% - 4,5%

ISO 8217 gives quality criteria for marine fuels, including content of sulphur. Table 3 – 6 present a comparison on sulphur content requirements between the ISO 8217 and the proposed low sulphur regulation requirements.

Table 4: Marine Gas Oils (MGO) – Quality 1 fuels (see Table 3)

ISO 8217 Standard Fuel grades	*Sulphur Requirement in Europe*	*ISO 8217 Sulphur limit*
DMX	<0,2%	<1,0%
DMA	<0,2%	<1,5%

We need to emphasise ISO 8217 DMX fuel is a special quality meant for use in life-boat engines and emergency generators, and is not accepted for use in ships due to its low flash point (below 60 ^{o}C). Therefore the only Quality 1 fuel allowed to use according to new EU regulations is the ISO 8217 DMA fuel quality.

Table 5: Marine Diesel Oil (MDO) – Quality 2 fuels (see Table 3)

ISO 8217 Standard Fuel grades	*Sulphur Requirement in Europe*	*ISO 8217 Sulphur limit*
DMB	<1,5%	<2,0%
DMC	<1,5%	<2,0%

Table 6: Low Sulphur Heavy Fuel Oils – Quality 2 fuels (see Table 3)

ISO 8217 Standard Fuel grades	Sulphur Requirement in Europe	ISO 8217 Sulphur limit
RMA - RMC	<1,5%	<3,5%
RMD15	<1,5%	<4,0%
RML55 – RME25	<1,5%	<5,0%

Table 7: High Sulphur Heavy Fuel Oils – Quality 3 fuels (see Table 3)

ISO 8217 Standard Fuel grades	Sulphur Requirement in Europe	ISO 8217 Sulphur limit
RMA - RMC	<4,5%	<3,5%
RMD15	<4,5%	<4,0%
RML55 – RME25	<4,5%	<5,0%

Based on the fact that the required fuel qualities are not readily available today in large quantities, the challenge for the ship operator may be summarised to be to:

1. Obtain and use the right fuel quality at the right time and place
2. Change fuel quality, if required, with no technical or operational problems
3. Verify own compliance with new regulation

2 Future availability of low sulphur fuel qualities

2.1 The international marine bunker market

With 95% of world international trade transported by ship, the fortunes of the shipping industry are strongly linked to world trade. Marine fuels account for about 20% of total fuel oil demand, so the development of this market has important implications for refining industry.

Growth will continue in future, but increasing demand for bulk and general cargo trade will most probably be balanced by increased efficiency by tankers as newer, more efficient double-hulled vessels replace single-hulled vessels. Depending on world economic growth, energy use by marine transport is expected to grow by around 1.5 % per year until 2020, with higher growth rates in gas oil bunkers compared to fuel oil because of sulphur restrictions, particularly for coastal voyages.

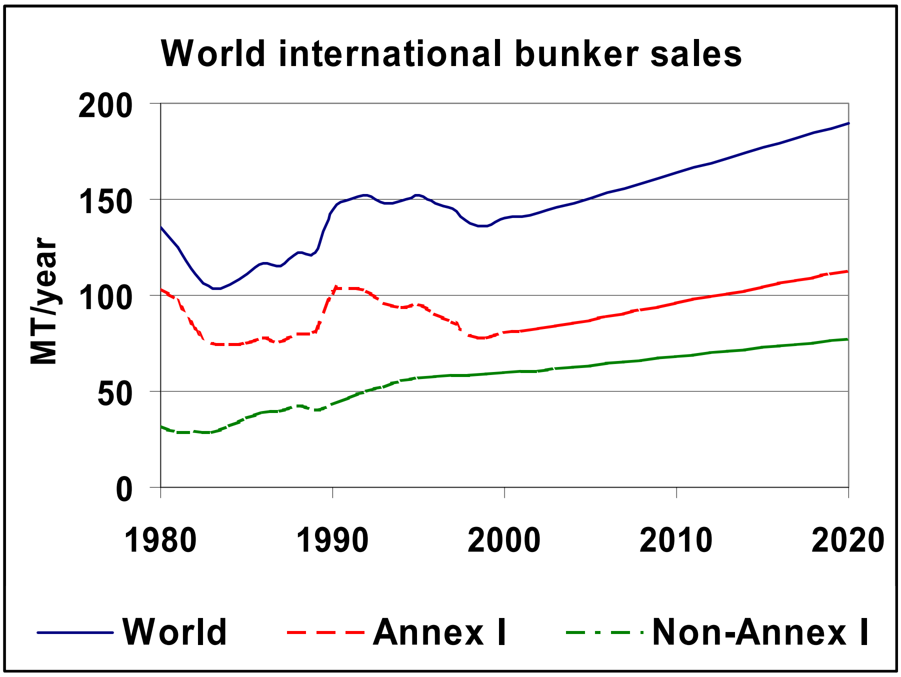


Figure 1 - Development of world international bunker sales divided by Kyoto Protocol Parties (Source EIA, 2002)

As shown by Figure 1 and Figure 2, the world consumption of international bunker fuel is expected to continue to increase the next decade. The world total consumption of bunker is obviously significantly higher than indicated in figure 1, as sales to domestic consumption is not included in the figure. In order to establish a consistent understanding of the fuel consumption on a regional level, international bunker and domestic bunker fuel sale figures needs to be combined, a task which represents a challenge due to inconsistent reporting on marine bunker sales.

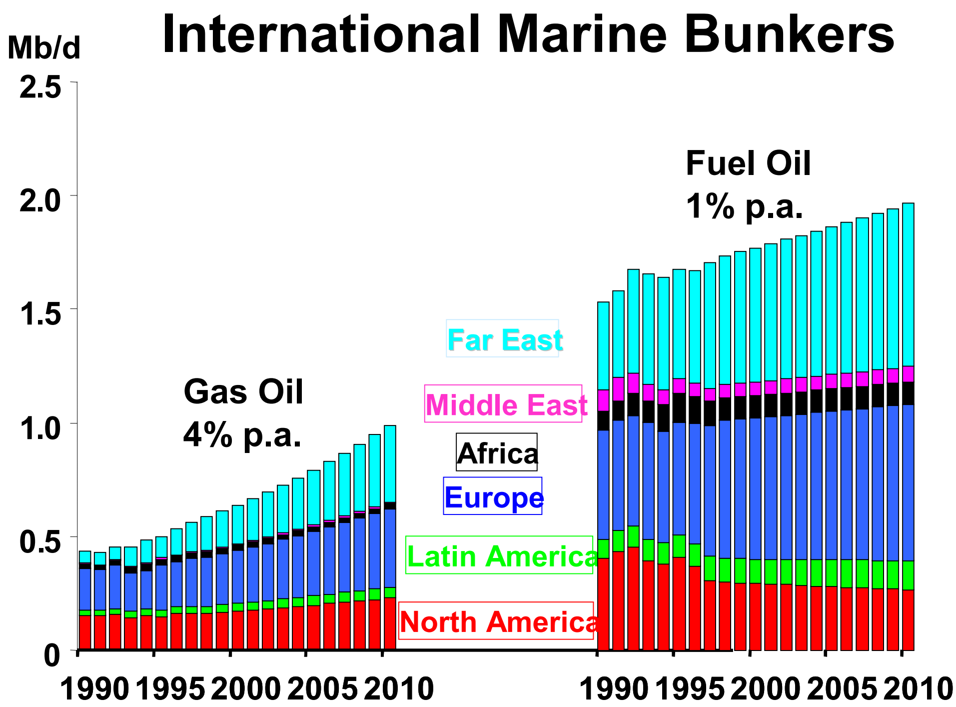


Figure 2 - Regional developments of international bunker sales (Concawe, 2002), (Shell, 2000)

2.2 The European marine bunker market

Several assessments have been made recently to try to quantify the marine bunkers consumption in Europe. As seen from Table 8 the various studies does not provide consistent results, and this is to some extent due to different approach to the task, and how international/domestic sale and consumption have been considered.

Table 8 - Estimated sale and consumption of marine bunker fuel in Europe

Study performed by	Reference year	Total million tonnes
Bunker consumption		
BMT[1]	2001	33,5
ENTEC[2]	2000	49,5
Bunker sales		
BMT[1]	2001	40,6
Beicip-Franlab[3]	2000	43,6

[1] Source (BMT, 2000).
[2] Source (ENTEC, 2002) Fuel consumption is not presented in the study, but has been calculated based on the applied emission factor 3179 kg CO_2 per tonnes fuel consumed
[3] Source (Beicip-Franlab, 2002), Including 1999 figures for EU Accession countries

The most significant conclusion drawn from the comparison of different studies is that a significant uncertainty still exists with respect to the consumed volume of marine fuel oil in European waters. As a consequence of this it will be equally uncertain what effect new legislation will have on this market.

Based on sale figures collected in workshops arranged in connection with the MARTOB project, the sales in Europe of marine fuel oil have been estimated to be approximately 42.1 million tonnes (2001 figure). This figure does not include distillates, hence the figures found by Beicip-Franlab seems to be closest, but still somewhat low as this figure includes distillate sales.

With respect to low sulphur fuel oil (not including MDO/MGO) with a sulphur content below 1.5%, the European supply has been estimated to be approximately 6.5 million tonnes, where the marine share represents less than 1 million tonnes annually.

Most inland consumption is moving to low sulphur fuel oil or natural gas. The IMO has proposed a reduction in the global maximum sulphur level in marine bunker fuel from 5% to 4.5%, which compares with the current global typical range in the order 2.8-3.5%, with only 0.02% of fuels used world-wide in shipping at a sulphur content over 4.5% and with the world average at 2.7%.

The proposed introduction of SO_x Emission Control Areas (SECA's), within which the sulphur content of fuel used on ships will be limited to 1.5% is expected to have a major impact on the supply side of the market. The Baltic and North Seas have been proposed as initial SECA's. Ratification by IMO members is not expected before 2005. More immediate are plans by the EU to impose sulphur limits on fuel oil used within EU territorial waters, probably set at 1.5% maximum. In either case, the provision of adequate quantities of segregated low sulphur bunkers does not currently exist.

2.3 Augmenting low sulphur fuel oil supply

The options available to a refinery for increasing Low Sulphur Fuel Oil Supply to the bunker market are:

- Re-blending from the current HSFO market
- Switch to a lower sulphur crude diet
- Invest in Residue Desulphurisation (RDS)
- Redirect the low sulphur fuel oil destined for inland markets

2.3.1 Re-blending from the current HSFO market

A limited supply of lower sulphur content HFO could be available by re-blending current HSFO with MDO, or other components. This option presents a risk for producing unstable LSFO bunkers. Dilution of a thermally cracked residue with too high concentration of a paraffinic diluent ("cutter-stock") such as gas oil could result in an unstable fuel. It is consequently necessary to ensure that the aromaticity of any diluent is high enough to keep the asphaltenes dispersed. The addition of catalytically cracked cycle oils is one way of doing this, and so providing an adequate stability reserve.

Assuming properly done blending (right components from selected grades, and in correct order), the Beicip-Franlab report suggests that around 4 MT of 1.5% S bunkers could be available in North Europe and about 0.7 MT in the south, as indicated below. The sulphur content of the remaining HSFO would increase to about 3.4 wt% in the North and 3.2 wt% in the South. Those figures and those for 1% S HFO case are presented in the table below.

Table 9 - Potential low sulphur bunker production by re-blending

POTENTIAL LSFO BUNKER PRODUCTION BY RE-BLENDING		
HFO Bunkers Sulphur Cont. wt%	**Atlantic/NEW/Other (MT)**	**Mediterranean (MT)**
<1.0	1.2	0.4
<1.5	4.0	0.7

This option may cover a small part of the market today, in SECA's (Sulphur Emission Control Areas) like the Baltic and North Sea where max. Sulphur 1.5% is required. But in general terms this represents a non-significant option, as it is not giving a viable solution in this problem. However, we need to be cautious as uncontrolled blending with feedstocks available in the market may give huge problems to the shipping due to unstable products. Stability is one of the critical parameters for handling fuel oil on board the vessels.

2.3.2 Switch to a lower sulphur crude diet

If we consider three different crude oils, Brent blend, Iranian Heavy and Arabian light, it is evident that there is a clear diversity in quality and yield, which will affect the refineries processing and output.

Table 10 – Crude oil data and typical output quality

Crude oil Analysis	**Arabia light (Saudi Arabia)**	**Iranian heavy (Iran)**	**Brent blend(UK)**
Density at 15C	0.860	0.872	0.830
Sulphur content %	1.90	1.89	0.35
Residue yield %	44.5	47.0	35.7
Atmospheric distillation			
(Residue) Density at 15C	0.959	0.972	0.923
(Residue) Sulphur Cont. %	3.28	3.02	0.78

Refineries will be constrained by their capability to handle more than a certain amount of a particular type of crude. This will depend on the configuration of the refinery to cope with the volumes of products created by crude processing and the constraints within which the refinery is allowed to operate, particularly in respect to environmental emissions.

2.3.3 Invest in Residue Desulphurisation (RDS)

Refinery processes for desulphurisation of HSFO are likely to be very expensive with each plant costing well in excess of $200 mln. At such levels, it is highly unlikely that the refining industry would be prepared to consider investments to support a low sulphur bunker business, without confidence in a significant and sustainable price increase for this higher quality product. It is very difficult to indicate what the additional investment cost will be, but according the source "*Costs and benefits of controlling SO2 emissions from Ships in the North Sea and Seas to the West of Britain, May 1998, page 26*" (ICC, 1998), we will have following additional cost increase in manufacturing cost:

Table 11 – Estimated price premium on low sulphur fuel oil

Bunker Sulphur Content	Additional cost of producing low S bunker fuel compared with current high S bunker fuels (US$/t)*
2.0% Mass	35-50
1.5% Mass	45-70
1.0% Mass	55-85
0.5% Mass	65-95

The above figures are much in line with the figures provided by BMT[2] and Beicip-Franlab (Beicip-Franlab, 2002).

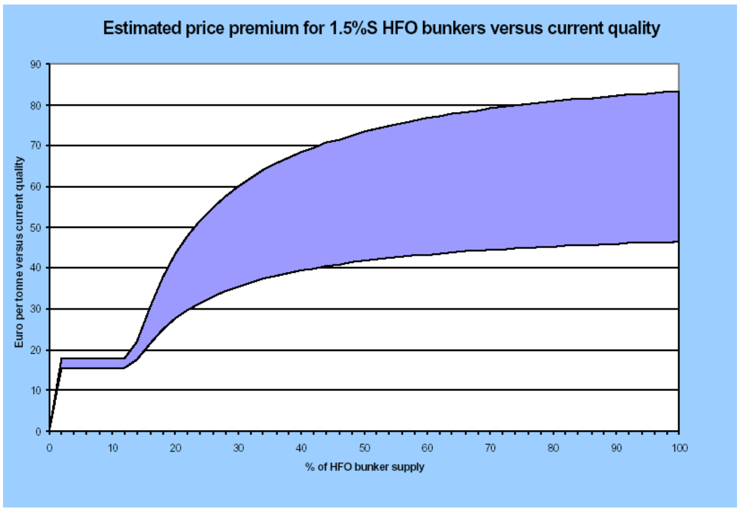


Figure 3 - Estimate of price premium for low sulphur fuel oil (from Beicip-Franlab, 2002)

2.3.4 Redirect the low sulphur fuel oil destined for inland markets

The enforcement of the directive 1999/32/EC from January 1st 2003, will represent a significant increasing demand for LSFO 1% S max. and the contrary for HSFO. This will represent, on the base of the forecast for 2005 a deficit of about 8-10 MT LSFO, and a surplus of 12 MT for HSFO. This unbalance will be more significant for the Southern and Mediterranean refineries. In N.W.E and Nordic countries is being today produced a significant amount of LSFO, mainly diverted to the local ferry segment as bunkers, and exported to counties where they need LSFO for the utilities. This volume is already allocated, and if shipping wants this product they will have to bid it away from the inland market.

Main producers of LSFO are the refineries in Scandinavia, where the logistics for using North Sea crude are favourable. However the volume of this LSFO gone to the bunker market is linked up to long term contracts with the ferry companies, and hence not available for open spot bunker market. Therefore it is unlikely that the refiners there will ever put this product on the open market. As far as 1% avails are concerned the fact that 1% has blown out from a negative Low sulphur to High sulphur to +13-15usd/te suggests that the market believes it will become tight next year as the new legislation comes in. Key factors will be Portugal and Spain who rely on fuel oil when hydroelectricity is scarce. France is unlikely to change their demand. Italy is already mainly 1% and as they have moved over to gas but this has substituted it's HSFO demand not LSFO demand and if anything ENEL has increased its imports. Greece is the other big unknown as they burn vast amounts of HSFO.

2.4 Feasibility of increased low sulphur fuel oil supply

If tighter sulphur specifications are introduced for bunkers, this will reduce the capability of refineries to support the bunker market. The capability of the oil refining industry to produce more low sulphur fuel oil for both the inland and the bunkers market is limited through a combination of factors such as the availability of low sulphur crudes and the configuration of the refineries to cope with the different product volumes associated with high and low sulphur crudes.

The oil industry is unlikely to consider the bunkers market as a particularly attractive market within which to make substantial investments to convert high sulphur components into low sulphur fuel. In Figure 4 the position of the marine bunker market relative to the major oil markets are indicated. As indicated by the figure, bunker only represents approximately 5% of the European oil market in a situation where stricter requirements are expected in several sectors.

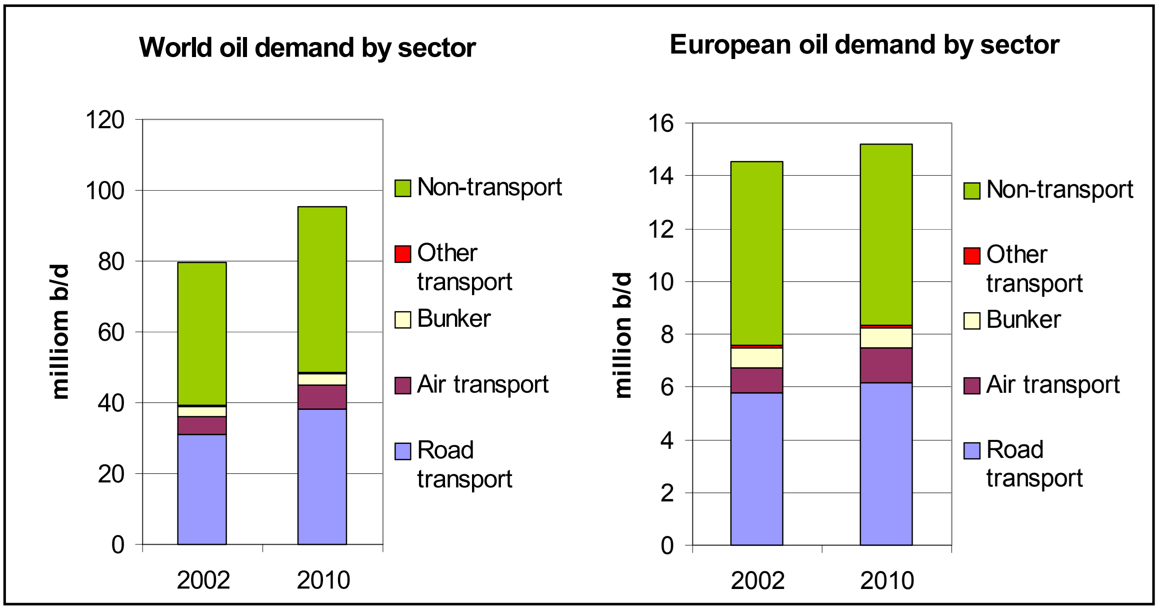


Figure 4 - Demand of oil by sector (Source EIA, 2001)

If the sulphur control areas were to be introduced including all consumption with fuel with maximum 1.5% sulphur, two options occur:

1. Operators would need to switch to distillates, and the distillate market redirected/increased to meet the increasing demand.
2. The availability of low sulphur fuel oil must increase. This would either imply increasing refinery output of these qualities, or redirect present LSFO market shares presently held by land-based consumers.

Due to the arguments above, it is considered most feasible in the short term to switch to distillates, and in the longer run changes are required in the present refinery structure to be able to supply a significant larger amount of LSFO.

The introduction of the Directive 1999/32/EC from January 1st, 2003 will limit the sulphur content of inland fuel oil to a maximum of 1%. This will create a disposal issue for the oil refining industry for high sulphur fuel oil components.

An alternative outlet for high sulphur fuel oil is the bunker market. However, if tighter sulphur specifications are introduced for bunkers, this will reduce the capability of refineries to support the bunker market.

The capability of the oil refining industry to produce more low sulphur fuel oil for both the inland and the bunkers market is limited through a combination of factors such as the availability of low sulphur crudes and the configuration of the refineries to cope with the different product volumes associated with high and low sulphur crudes.

The oil industry is unlikely to consider the bunkers market as a particularly attractive market within which to make substantial investments to convert high sulphur components into low sulphur fuel.

The required use of low sulphur (1.5%) bunkers within EU territorial waters, with even tighter sulphur specifications (0.2%) within port areas will present a major challenge for the marine business in terms of segregation of fuels both in ship and shore tankage and delivery systems.

More work needs to be done to quantify the impact of the above changes in respect to the ability of the refining industry to meet the changing demand, and to assess the overall cost impact on the business. This should take account of work currently being undertaken by Concawe into the impact on the European oil industry resulting from the introduction of lower sulphur specifications for both inland and marine fuels.

3 Future demand of low sulphur fuel qualities

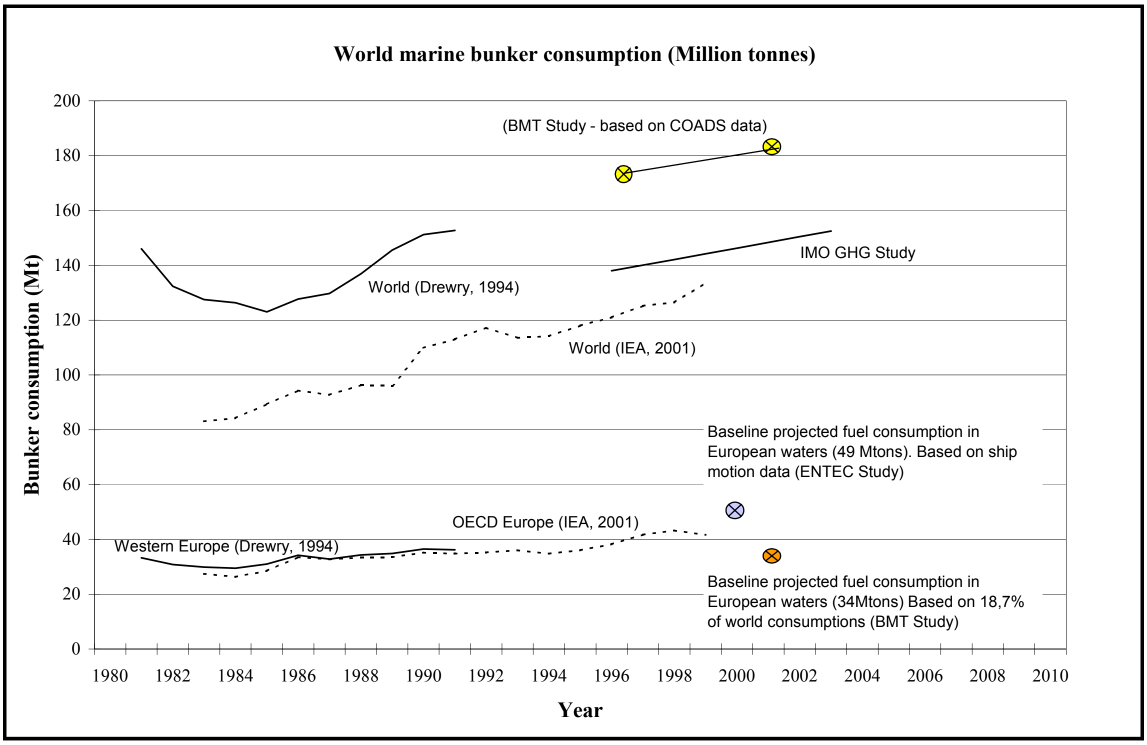
Several independent studies have been performed to assess the emissions from fuel consumption in shipping. The different studies vary in extent and scope, and the results are varying. In this work is was intended to base the work on the study performed by BMT in 2000 (BMT, 2000), but due to the release of a new study by ENTEC (ENTEC, 2002) after commencement of the project, it was considered necessary to provide a summary of comparison of different studies. The main reason for this is that the results vary significantly. In the comparison work performed only the major European studies over the last 10 years were considered.

In addition to assessment of the emission inventories presented, fuel market surveys were also been compared. In order to have confidence in a bottom up analysis of emissions, where consumption and emissions are calculated based on fleet and ship movement data, a minimum of correlation must be found to the reported sales data for fuel in the same region.

It is clear when considering and comparing various studies related to emissions from shipping and marine fuel consumption, that one definite conclusion is that the estimates of world and European marine fuel consumption are uncertain. Major sources of uncertainty are:

- Alternative area definitions as basis for study
- Inconsistent use of definition of the segments considered
- Alternative choices of lower size of vessels included
- Uncertainties related to reported data
- Alternative mix in the summary of all bunker consumption versus bunker for international trade and/or domestic trade.

A summary of some estimates of marine fuel consumption is provided in Figure 5. World total consumption of marine fuel including all domestic consumption has not been established, but estimates performed indicate an annual consumption in the region 230-270 million tones (represents estimates for different reference years 1999-2002).



Sources: (Drewry, 1994), (IEA, 2001), (IMO, 2000), BMT, 2000), (ENTEC, 2002), IEA figures calculated from CO_2 emissions.

Figure 5 – Estimates of fuel consumption in Europe and in international shipping

With respect to estimated consumption related to international trade (i.e. world total consumption excluding all domestic activity), these estimates appear more accurate as dominating sale figures are relatively reliable. Estimates for fuel consumption related to international sea borne transport indicate an annual consumption in the range 146-170 million tonnes assuming base year 2000. Comprehensive Ocean-Atmosphere Data Set (COADS) as provided in the BMT study indicate that 'European' waters were found to be the location for an average of 18.7% of global ship observations. Combining the COADS data on share of ship operations in European waters and the estimated fuel consumption related to international suborned trade, international trade represents an annual consumption in European waters in the range of 27-32 million tonnes.

Combining this with the conclusion from the ENTEC study (30% of European ship movements domestic), the total annual marine bunker consumption in Europe should be in the range 39-46 million tonnes.

The ENTEC report concluded that the annual consumption in European waters were 49.5 million tonnes in 2000. This includes 1.3 million tonnes consumed by the fisheries and including a geographic area extending very far west in the Atlantic Ocean.

Based on a consideration of sales data (which corresponds fairly well), the expectancy that marine bunker fuel is exported from Europe (sale estimated to approximately 51

MT in WP5.1 report), and the fact that ENTEC is operating with a large geographic area, it is considered reasonable to assume that the annual consumption is found in the region 39-46 million tonnes (2000 as reference year).

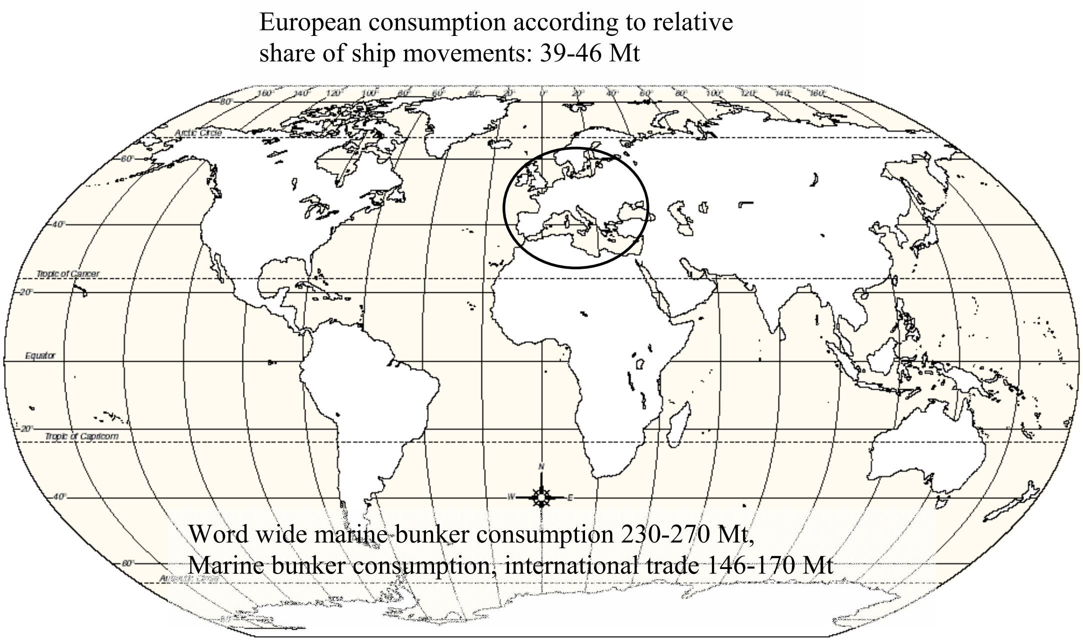


Figure 6 – Annual marine bunker consumption estimates (2000 estimates)

As seen in Figure 6 the established estimate would imply that the marine bunker consumption in Europe represent approximately 18% of the world total marine fuel consumption, and this corresponds well with the COADS data.

Forecasting the future demand for marine bunker and in particular low sulphur grades in Europe based on the estimates presented above represents a significant challenge. As the estimates represent a relatively large interval, and the annual change in demand has historically been moderate, a forecast would not change the interval for several years ahead.

The classical forecasting methodology has been based on extrapolation of the future. The shipping market has been extremely volatile the recent years due to a series of political and financial events (Asian economic crisis, September 11th, unstable situation in middle east). This is easily seen by trade statistics and statistics for the sea-borne trade.

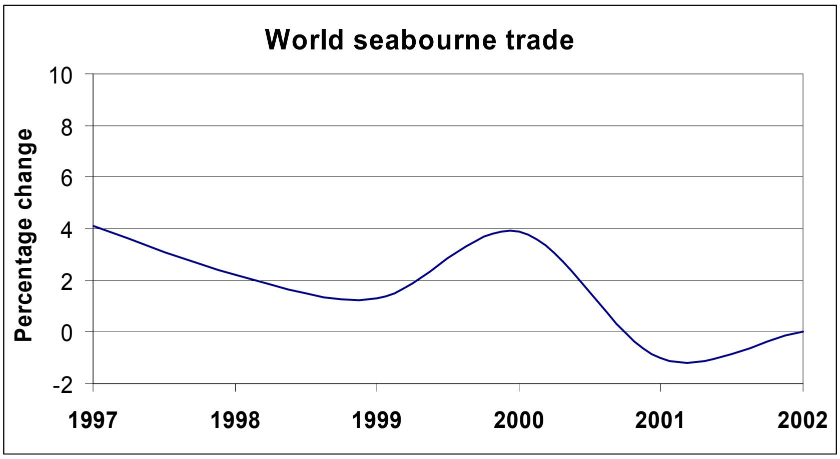


Figure 7 - Annual change in world sea-borne trade, 1997–2001 (Goods loaded, source: UNCTAD, 2001, UNCTAD, 2002)

World sea-borne trade (goods loaded) contracted after 15 consecutive years of annual increases reaching 5.83 billion tons. The annual growth rate was negative – 1 per cent compared to the 3.9 per cent increase of 2000. Forecasts for 2002 indicated that annual growth rates would probably be positive but modest. Due to this combined with an expanding fleet, total maritime activities measured in ton-miles and the productivity of the world fleet also decreased in 2001.

The IMO GHG Study (IMO, 2000) presented a methodology for forecasting marine bunker fuel consumption based on the combination of predicted fleet growth, and the historic relationship between world economic growth and growth in sea-borne trade. The same approach applied for this study indicates an estimated growth of marine bunker consumption in European waters as presented in Figure 8. The forecast is indicated together with IEA historical date, and represents an average annual growth of 1.5% after 2000.

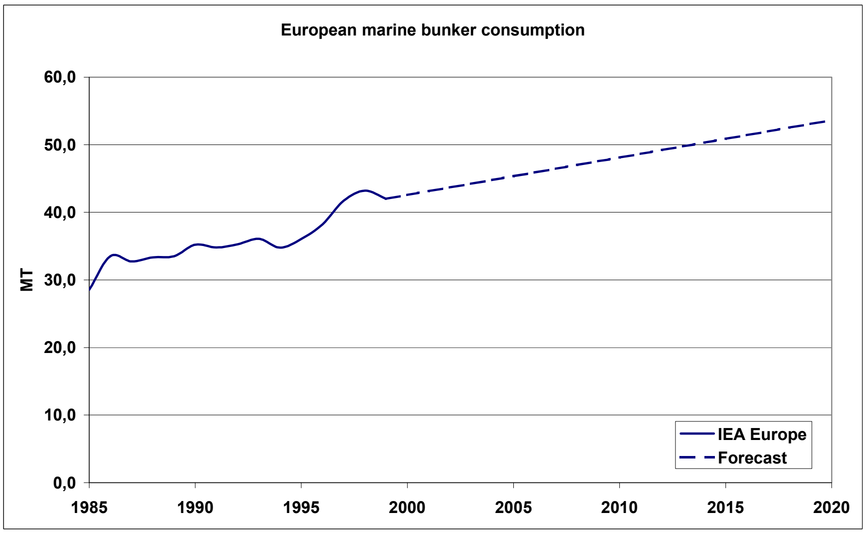


Figure 8 – Estimated growth of marine bunker consumption in European waters.

This scenario implies that the marine bunker consumption in Europe will increase from the present level of 39-46 MT to 50-57 MT in 2020. This is in line with the ENTEC study, which has used the same growth rate to estimate future demand, but overall values are lower as the ENTEC study estimated a higher value for consumption in 2000.

ENTEC concludes that the marine fuel consumption for the North Sea/Baltic will represent 12.9 MT in 2000. Projected to 2005/2006, scheduled time for the implementation of the SOxECA, the actual consumption amounts to about 14 MT. As mentioned above these figures might be slightly overestimated. On the other hand, the actual low sulphur fuel demand on establishing the SOxECA would most likely be considerably higher than the net consumption inside the control border. Many coastal vessels have routes with frequent pass of the boarder, making the change over procedures time consuming and burdensome, many vessels also lack the facility to store and handle several fuel qualities. This is confirmed from the results from the end user Questionnaire performed by this project, where ship operators among other things are questioned about fuel selection/operation within the new legislation.
Furthermore, several operators of trans-ocean vessels express intention to operate continuously on low sulphur fuel under the new regime, either due to lack of capability to cope with dual bunker fuel solutions for their existing ships, of company policy reasons etc. Also various operational aspects, time lag from actual change over to clean low sulphur at the engine inlet is obtained etc., imply a resulting low sulphur demand in excess of the net consume inside the SOxECA.

The Directive 1999/32 amendment introduces a 1.5 % sulphur limit for marine fuels used by passenger vessels on regular services to or from any EU Community port, also outside the SOxECA, enforced from 2007. From the included definition of "passenger ships" and "regular services" goes forth that the main part will constitute fixed route ferries. From the ENTEC study it can be derived that ferries amounts to about 14 % of the total fuel consumption in European waters. Assuming the same relative consumption by ferries inside the SOxECA as for the total in European waters, indicate that ferries outside the SOxECA, but within European constitute for in excess of 10 % of the total, or about 5 MT.

From the above, and taking into consideration that the ENTEC results most likely slightly overestimate fuel consumption, it can be concluded that the actual fuel consumption within the SOxECA and by passenger vessels on regular services in EU waters is in the range 17 –19 MT by year 2007. The future low sulphur fuel demand will probably far exceed these figures, much dependent on among others price differentiation between actual products, ship owners attitudes, retrofit of fuel system arrangements, control regime etc. A quantity well above 20 MT is seen as a realistic demand in 2007. These figures are a significantly higher in magnitude compared to the quantities of low sulphur bunker fuel available in to-days marine bunker market, as stated above (LSHFO supply less than 1 MT).

The capability of the oil refining industry to produce more low sulphur fuel for the marine market is limited through the combination of factors such as the availability of low sulphur crudes and the configuration of the refineries to cope with the different product volumes associated with high and low sulphur crudes. The oil industry is unlikely to consider the marine bunker market as a particularly attractive market within which to make substantial investments to convert high sulphur components into low sulphur fuel. A conclusion from the combined work considering the demand and supply side is that more work need to be done to quantify the impact of the actual changes in respect to the ability of the refining industry to meet the changing demand. This will require direct input and cooperation from the fuel oil industry to improve the demand estimates, and to assess the overall cost impact on the business.

4 On-board implementation of new sulphur regulations

On-board implementation of the coming new requirements to sulphur content in marine bunker fuel will represent a new challenge for shipowners, making it necessary to re-consider:

- Bunkering strategy
- Ship design for newbuilding
- Fuel and engine operation
- Optimisation of fuel system configuration

4.1 The options

4.1.1 Fuel system

The effect of the proposed sulphur regulations is highly influenced by the fuel system design and arrangements. The fuel oil systems are structured by means of tanks, pumps, heaters, pipes, valves, centrifuges, etc. for the different fuel processing before the final combustion inside an engine or boiler.

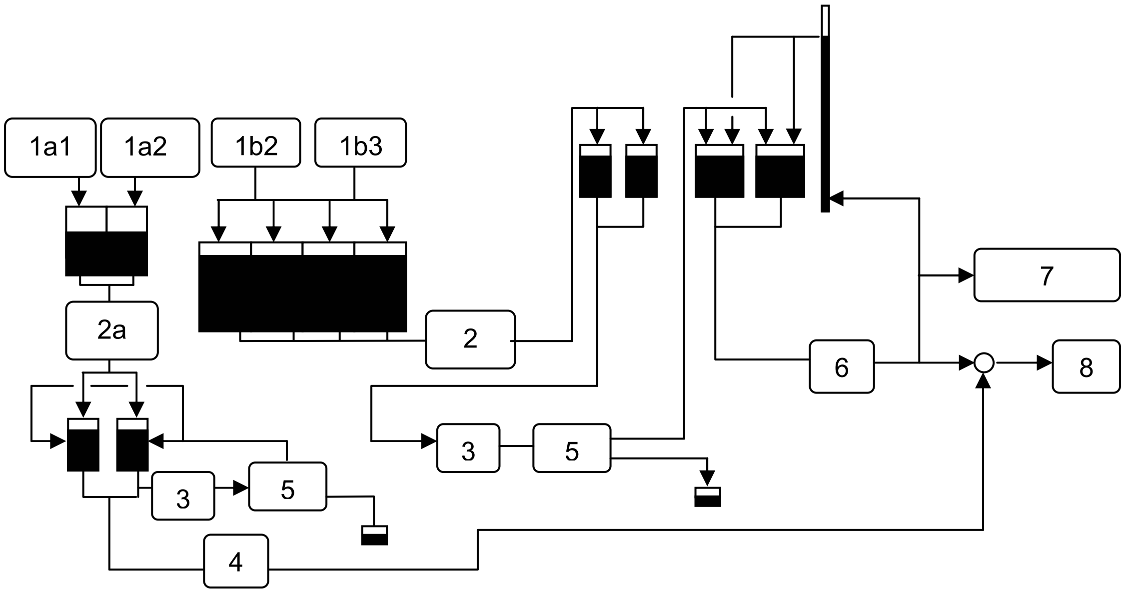
The fuel systems onboard vessels today may consist of:

- Storage system
- Transfer system
- Pre treatment/ Purifying system
- Supply system for combustion
- Drain system

In the figures below components as pumps, pipes, valves, filters, vents, heaters etc. necessary to transfer, heat, centrifuge and filtrate the fuel are not included. Instead simplified overview models with fuel tanks, process blocks and flow lines are applied to describe the different fuel systems. All systems described are relevant for both heavy fuel oil and diesel oil. In case of heavy fuel oil systems, components for heating and heat tracing are introduced to keep the heavy fuel viscosity sufficiently low (pump-able/ flow-able), these components are not usually part of a MDO system.

The illustration in Figure 9 shows a possible layout of a fuel oil system with full segregation for two fuel qualities in storage, settling and service tanks, except for the involved piping arrangement. This system will lead to some mixing of fuel in pipes and components, but possible coagulated volumes are small and possible to handle in fuel centrifuges and filters.

The difference between the complex fuel system as indicated in Figure 9 and typical fuel system lay-out found in many existing ships are illustrated by Table 12 and Figure 10.



1a1. Quality 1 gas oil supply.
1a2. Quality 2 diesel oil supply.
1b2. Quality 2 HFO supply.
1b3. Quality 3 HFO supply.
2. Pumping to settling tank
2a Pumping to combined settling & service tanks
3. Pumping to centrifuging
4. Pumping to consumption
5. Centrifuging, removal of sludge and water
6. Pumping – circulation of fuel for fuel consumers
7. Fuel consumers used under ship movement
8. Fuel consumers used while at berth

Figure 9 - Multiple fuels treated onboard vessel with tank segregation

Three typical variations of the fuel system as shown in Figure 9 will typically be found:

FO A) MDO + HFO:
One bunkering, centrifuging and supply system for MDO, and one for HFO. Often several separate bunker tanks (heated) are available in the ship, enabling use of different bunker oil. Systems are merged before the pressurizing (supply) stage on the engine circulating system. Auxiliary engines are fed from the joined systems, i.e. they burn the same fuel as the main engine. This configuratrion is typically referred to as the “Unifuel” concept. It is possible to run auxiliary engines on separate fuel, i.e. by closing off the line from the HFO system to the auxiliary engines. Auxiliary engines run on MDO/MGO or the same fuel as the main engine.

FO B) MDO + 2 HFO types:
One bunkering and settling system for each type of HFO. Possibly with additional bunker tanks. The HFO system is common from settling tanks onwards, i.e. it is identical to system A, but with an additional bunker and settling tank for alternate HFO types. This option implicates both “Unifuel” and separate fuel alternative.

FO C) MDO – 2 separate HFO:
One bunkering, centrifuging and supply system for each type of HFO. Two completely separate HFO systems up to the joining point before the supply pumps pressurizing the engine circulating system. Unifuel or separate fuel.

Table 12 - Additional FO system equipment

	Additional equipment
FO A)	Base case – no additionally – reference Figure 10.
FO B)	• Possibly an additional bunkering system for the additional bunker tank • Possibly enhanced bunker heating system to accommodate different fuel characteristics (pumping temperature, flash point, viscosity, etc.) • Possibly additional bunker tank(s) • One additional transfer pump to settling tank • One additional settling tank
FO C)	• All of those associated with FO B) • Possibly an additional set of fuel oil centrifuges • Possibly an additional centrifuge room including sludge tank, etc. • Additional service (Day) tank • Piping and instrumentation according to standard

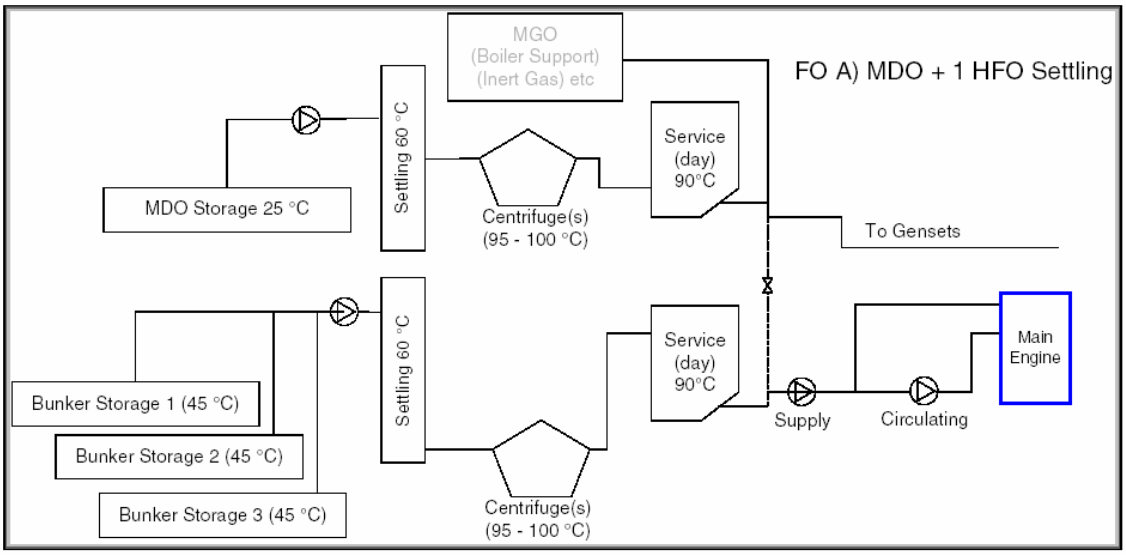


Figure 10 – Typical schematic lay-out of simple fuel oil system

4.1.2 Lubrication

As demonstrated in theory by the tribology of cylinder lubrication, and also supported by service experience, it is important to maintain a balance between the fuel sulphur content and the base number of the oil lubricating the cylinder liner. In this way, the influx of alkalinity to the combustion space can be balanced with the sulphur content of the fuel.

Combined with engine design factors, this balance must be controlled to ensure a small amount of corrosion in the cylinder liner(s). This is known as controlled corrosive wear – which is a desired situation. Due to a number of other factors influencing cylinder lubrication – fuel/lube oil performance, chemical, mechanical and thermal aspects of lubrication – the base number/fuel sulphur balance in itself is generally a prerequisite, but never a guarantee for satisfactory cylinder lubrication.

The engine running duration very much influence the need for a balanced BN/S ratio, and it is a general rule that the longer the duration, the more important is the BN/S balance. Owing to the diversified fuel oil system designs in service and being implemented, it could be an idea to handle/run on at least two different cylinder lube oils. The use of electronic lubricators seems promising in the effort to maintain a balanced BN/S ratio. Multiple cylinder lube oil systems is another possibility, maybe in combination with electronic lubricators for optimal flexibility.

For engines operating on heavy residual fuel oil, a cylinder oil with a viscosity of SAE 50 and BN of about 70 is normally recommended. In most cases, the high BN cylinder lubricant will also be satisfactory during temporary operation on diesel oil/gas oil. In general, changing the cylinder oil type to correspond to the fuel type used (i.e. bunker fuel or diesel oil/gas oil) is considered relevant only in cases where operation on the respective fuel type is to exceed 10 hours.

The object is not only to be able to physically handle various fuel types. The task is to maintain proper engine running, in a balance between cylinder lubrication and HFO type. Accordingly, considerations similar to those given for the fuel system apply to the cylinder lube oil system. Again, there are several cylinder lube oil system constellations that could be implemented to allow various degrees of adaptation to any specific bunker oil sulphur content:

- CLO A) One single cylinder oil system:
  This option represents a conventional system with ability to handle one cylinder lube oil type at a time, i.e. running with a fixed Base Number. Feed rate can be manually controlled and is seldom adjusted.
- CLO B) One single cylinder oil system equipped with electronic lubricators.
  This option also represents a system with ability to handle one cylinder lube oil type at a time, i.e. running with a fixed Base Number. The electronic lubricator (very much) eases adjustment of feed rate and, hereby, alkalinity influx.
- CLO C) Two cylinder lube oil systems:
  This option requires basically two cylinder lube oil storage, service and supply

systems. Systems joined before engine flange via a changeover valve. This provides the ability to handle two different cylinder lube oils, such as a conventional BN oil type (usually BN 70) and maybe a low-BN oil type (e.g. BN 50 or BN 40).

- CLO D) As CLO C) but possibly equipped with a mixing station:
  In this option, BN 40 and BN 70 could be mixed in steps to achieve stepwise regulation of the cylinder lubricant BN (stepwise between BN 40 and 70).
- CLO E) Two cylinder lube oil systems equipped with electronic lubricators:
  Same as option C, but easy cylinder feed rate adjustment enables implementation of different sulphur handles according to different Base Number oils.

In general, the complexity of the cylinder lube oil system increases A through E, but not as much as the similar increase for the fuel oil systems, simply because the fuel oil system is more extensive (more components) in the first place. Three basic parameters should be sought balanced in the configuration and co-agency of the fuel oil and cylinder lubrication systems:

- Fuel oil incompatibility
- Fuel changeover frequency
- Combustion chamber lubrication and Acid/Base balance

The MARTOB project cannot alone conclude decisively on these issues, but only outline possible solutions and not recommend one in particular. Future service experience will demonstrate the necessity. A close watch on engine condition should be observed in connection with more frequent changeover between varying HFO sulphur contents.

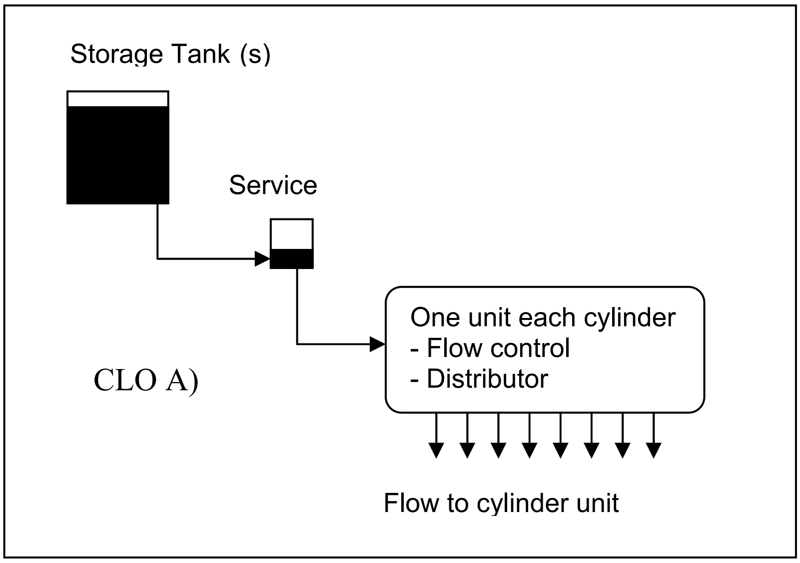


Figure 11 – Standard cylinder oil system

Table 13 – Fuel and cylinder lube oil system configuration matrix

	FO A)	FO B)	FO C)
CLO A) 1 CLO syst.	Inflexible fuel change over (-) Risk of fuel incompatibility (-) Req. fuel mixing equipment (-) Non optimised Acid/Base balance for prolonged running (-) Genset LO/FO mismatch (-) Low cost (+) Simplicity (+)	Less inflexible fuel change-over (-) Risk of fuel incompatibility (-) Non optimised Acid/Base balance for prolonged running (-) Genset LO/FO mismatch (-) Req. fuel mixing equipment (-) Low cost (+) Simplicity (+)	Flexible fuel change-over (+) Flexibility in fuel use (+) Reduced risk of fuel incompatibility (+) Non-optimised Acid/Base balance for prolonged running (-) Genset LO/FO mismatch (-) Higher cost (-) Relatively complex FO syst. (-)
CLO B) 1 CLO syst. + Electronic lubricator	Inflexible fuel change over (-) Risk of fuel incompatibility (-) Req. fuel mixing equipment (-) Good Acid/Base balance above 2% S (+) Genset LO/FO mismatch - Unifuel (-) Relatively low cost (+) Simplicity (+)	Less inflexible fuel change-over (-) Risk of fuel incompatibility (-) Good Acid/Base balance above 2% S (+) Genset LO/FO mismatch (-) Req. fuel mixing equipment (-) Relatively low cost (+) Simplicity (+)	Flexible fuel change-over (+) Flexibility in fuel use (+) Reduced risk of fuel incompatibility (+) Good Acid/Base balance above 2% S (+) Genset LO/FO mismatch (-) High cost (-) Relatively complex FO syst. (-)
CLO C) 2 CLO syst	Inflexible fuel change over (-) Risk of fuel incompatibility (-) Req. fuel mixing equipment (-) Good Acid/Base balance for two fuels (+) Genset LO/FO mismatch - Unifuel (-) Relatively low cost (+) Simplicity (+)	Less inflexible fuel change-over (-) Risk of fuel incompatibility (-) Good Acid/Base balance for two fuels (+) Genset LO/FO mismatch (-) Req. fuel mixing equipment (-) Relatively low cost (+) Reduced simplicity (-)	Flexible fuel change-over (+) Flexibility in fuel use (+) Reduced risk of fuel incompatibility (+) Good Acid/Base balance for two fuels (+) Genset LO/FO mismatch (-) Relatively high cost (-) Relatively complex system (-)
CLO D) 2 CLO syst + Mixing tank	Inflexible fuel change over (-) Risk of fuel incompatibility (-) Req. fuel mixing equipment (-) Good Acid/Base balance range of fuels (+) Genset LO/FO mismatch - Unifuel (-) Relatively low cost (+) Relatively complex LO syst. (-)	Less inflexible fuel change-over (-) Risk of fuel incompatibility (-) Good Acid/Base balance range of fuels (+) Genset LO/FO mismatch (-) Req. fuel mixing equipment (-) Relatively high cost (-) Relatively complex LO syst. (-)	Flexible fuel change-over (+) Flexibility in fuel use (+) Reduced risk of fuel incompatibility (+) Good Acid/Base balance range of fuels (+) Genset LO/FO mismatch (-) High cost (-) Complex system (-)
CLO E) 2 CLO + Electronic lubricator	Inflexible fuel change-over (-) Risk of fuel incompatibility (-) Req. fuel mixing equipment (-) Very good Acid/Base balance all fuels (+) Genset LO/FO mismatch - unifuel (-) Relatively low cost (+) Relatively complex LO syst. (-)	Less inflexible fuel change-over (-) Risk of fuel incompatibility (-) Very good Acid/Base balance all fuels (+) Genset LO/FO mismatch (-) Req. fuel mixing equipment (-) Relatively low cost (+) Reduced simplicity (-)	Flexible fuel change-over (+) Flexibility in fuel use (+) Reduced risk of fuel incompatibility (+) Good Acid/Base balance All fuels (+) Genset LO/FO mismatch (-) High cost (-) Complex system (-)

4.1.3 Operation

The operational options related to fuel management, according to new regulatory proposals, are shown in Table 2.

Table 2: Fuel qualities allowed by ship types/ movements in different European waters.

Geographical area	*Ship Type/ Ship Movement*	*Fuel Quality accepted*
At berth	All	Quality 1 (< 0,2% sulphur)
Baltic Sea and North Sea	All	Quality 2 (< 1,5% sulphur) or less
All European waters	Cruise/ Passenger vessels regular inside European Waters	
European waters except for the Baltic Sea and North Sea	All ships except Cruise/ Passenger vessels on regular services to or from EU port	Quality 3 (1,5% - 4,5% sulphur)

Table 14: Fuels in Directive 1999/ 32 related to fuels in ISO 8217 specification.

EU Directive	*ISO 8217*	*EU sulphur limit to ISO 8217 fuels*
Quality 1	MGO: DMA	< 0,2%
Quality 2	MDO: DMA and DMB HFO: All Categories	< 1,5%
Quality 3	HFO: All Categories	1,5% - 4,5%

For the typical trading patterns in Northern Europe, the implication are different for different trades:

- European coastal vessels
  The most natural choice will be to have a continuous operation on low sulphur products (LSHFO, MDO)
- Inter Continental trade
  Based on the response from a questionnaire to a number of ship owners, most would prefer to operate on high sulphur HFO outside SOxECA and low sulphur HFO inside.
- Inter European/US trade Dependent
  for these trades, the optimal choice will be closely related to number of roundtrips, port calls etc.

For vessels operating all or most of the time inside a SOxECA, a monofuel operation on a selected low sulphur fuel quality will be the natural choice, with limited operational consequence.

Dependant of the fuel systems tank layout there will be different procedures to obtain correct sulphur values of the fuel entering the combustion chambers. If the vessel is equipped with single settling and service tanks, sufficient flushing time must be ensured. In MARPOL Annex VI Regulation 14 (6) following requirement is given:

"*Those ships using separate fuel oils to comply with paragraph (4)(a) of this regulation shall allow sufficient time for the fuel oil service system to be fully flushed of all fuels exceeding 1.5% m/ m sulphur content prior to entry into SOx Emission Control Area. The volume of low sulphur fuel oils (less than or equal to 1.5% sulphur* *content) in each tank as well as the date, time, and position of the ship when any fuel-changeover operation is completed, shall be recorded in such log-book as prescribed by the Administration.*“

Outside an SOxECA area the fuel qualities are not regulated and is free to choose for the ship operator on economical considerations. As indicated by the answers to a questionnaire to shipowners (part of the project work), and used as an assumption in the study, most owners would prefer to operate on ordinary HFO outside the SOxECA.

A normal solution regarding fuel on board is storage tanks for ME/AE/boiler operation which normally is HFO, and additionally MDO storage for use on special occasions, prior to engine maintenance or lengthy harbour stays. The proposed at berth regulations require use of MGO with sulphur content below 0.2 % while at berth, this imply either that the existing MDO storage and service system no is shifted to hold MGO, or the ship will need a further set of fuel settling and service tanks.

For those not choosing a monofuel option, a number of options how to operate to meet the 1.5 % sulphur requirement will be available when arriving to the SOxECA area. The most likely alternative fuels/pre-treatment options will be:

1. Fuel change over to MGO operation on SOxECA border. No or little impact on fuel distribution in storage tanks.
2. Fuel change over to MDO operation on SOxECA border. One additional fuel quality stored on board, need to store and treat both MDO and MGO.
3. Fuel change over to LSHFO operation on SOxECA border. Ship prepared with duplicate set of settling/service tanks which simplifies and fuel transfer and reduces operational risk while changing fuel. LSHFO will occupy parts of storage capacity.
4. Fuel change over to LSHFO approaching SOxECA border. One additional fuel quality stored on board. Procedure involves draining of settling tank to storage tank and fill with LSHFO. Level in service tank should be low initial to fuel transfer to reduce response time of sulphur drop in fuel mix. LSHFO will occupy parts of storage capacity.

A proposal for a duplicate fuel system arrangement is presented in Figure 9. It is proposed to use the same processing components for both heavy fuel oil qualities, HSHFO and LSHFO. The figure also shows duplicate light fuel oil system for MGO and MDO.

The two most important features to address in connection with the handling of multiple fuel types on board are fuel incompatibility issues and fuel change-over procedures.
Fuel oils are produced on the basis of widely varying crude oils and refinery processes. Due to incompatibility, such fuels can occasionally tend to be unstable when mixed, for which reason mixing on board should be avoided to the widest possible extent. Unstable fuel mixtures could settle into an inhomogeneous blend that could and has been known to clog filters and centrifuges, etc. A mixture of

incompatible fuels in the tanks can result in rather large amounts of sludge being taken out by the centrifuges or even lead to centrifuge blocking.

Re-circulating the contents of the tank through the centrifuge can counteract in-homogeneity in the service tank. This will have to be carried out at the expense of the benefits derived from a low centrifuge flow rate.

Various fuel change-over procedures exist, mainly owing to different engine designs. Independent of fuel type, most engine manufacturers recommend a preferred fuel viscosity at injection. This is partly because viscosity influences the pressure drop across the fuel injector tip or nozzle and, thereby, also the atomisation and spray pattern, etc. Another purpose is to keep even working conditions for the fuel oil injection equipment on the engine. Since the temperature of the fuel determines fuel viscosity, changing fuel type often means changing injection temperature.

The purpose of the change-over procedure is to avoid a too rapid and too large change in fuel oil temperature and, thereby, protect the fuel injection equipment on the engine. Usually, the high fuel oil injection pressure requires very narrow tolerances in the fuel injection equipment. This means that an uneven thermal expansion of the equipment could cause seizure, e.g. of the plunger and barrel. Typically, uneven thermal expansion may result from a thermal shock coming from a too large and too rapid change in fuel oil temperature.

With respect to detailed change-over procedures, these should normally be available from the engine manufacturer

Example: MAN B&W recommended change over procedure; change over from Heavy fuel oil to Diesel oil during running:

To protect the fuel oil injection equipment against temperature surges, which may cause scuffing with the risk of sticking of the fuel valves and of the fuel pump plungers and suction valves, the change-over to diesel oil is performed as follows (manually):

- *Preheat the diesel oil in the service tank to about 50 °C, if possible.*
- *Cut off the steam supply to the fuel oil pre-heater and heat tracing.*
- *Reduce the engine load to ¾ of MCR load.*
- *Change to diesel oil when the temperature of the heavy oil in the pre-heater has dropped to about 25 °C above the temperature in the diesel oil service tank, however, not below 75 °C.*

Note: If, after the change-over, the temperature (at the pre-heater) suddenly drops considerably, the transition must be moderated by supplying a little steam to the pre-heater, which now contains diesel oil.

A fuel system was modelled as shown in Figure 12 and used in combination with case studies to assess the operational aspects of change-over for vessels operating only partially inside a SOxECA. As initial sulphur content of the HFO in all tanks, the typical world wide average value of 2.7% was chosen. In order to ensure that a limit of 1.5% should be reached, the sulphur content of fuel into the tank was set to 1.45%.

A typical relationship between sizes of settling and day tanks and fuel consumption was chosen (tanks with a capacity of 24 hours of fuel consumption).

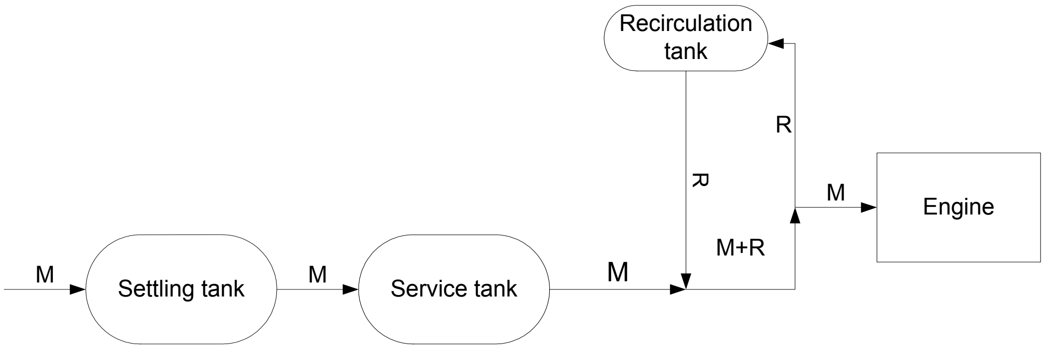


Figure 12 - Simulation model of a Fuel Tank System

If both tanks contain conventional HFO with a sulphur content of 2.7%, the time to reach a level below 1.5% in the service tank will depend on the initial level in both tanks at the time of switch over from supply of HFO to LSHFO to the settling tank. If both tanks are full at the time of switch over, it will take 120 hours, or 5 days, from switch over until fuel with a sulphur content below 1.5% reaches the engines. During this period it will take 3 of the 5 days to dilute the sulphur level in the settling tank from 2.7 to 1.5%.

Some of the results from the simulations are presented in Table 15 below. As seen from the table the time to switch over from HFO to LSHFO at the engine is very sensitive to the initial level in the two different tanks. If the tank level in both the settling and service tank is down to a 25% level of filling prior to switch over, the time is reduced from 120 hours to 30 hours.

Table 15: Time [hours] to reach 1.5 % sulphur content in fuel to the engine[1)].

		Initial level in service tank at switch over			
		100 %	75 %	50 %	25 %
Initial level settling tank at switch over	100 %	120	106	94	84
	75 %	106	90	76	65
	50 %	94	76	60	47
	25 %	84	65	47	30

[1)] Excluding time needed to reach the wanted initial tank level when reducing from full tank

The operational impact of the calculations is shown in Figure 13. For a vessel operating at 14 knots, the ship would have to perform the change over almost 1700 nautical miles from the SOxECA border to be certain that the fuel to the engines are below 1.5% upon crossing the border. With a speed of 20 knots, the equivalent distance from the SOxECA border would be 2400 nautical miles. As an extreme example this would imply that a container vessel would need to perform the change over just after leaving the East Coast of US heading for Northern Europe.

The results indicated in Table 15 does not include the time the supply to the settling tank has to be closed to allow the level in the tanks to be lowered. In an operational procedure, the change over procedure applying the principle of reducing the tank level in the service tank prior to dilution (actual change over initiated) will have to take also this time into account. This would imply that a time optimal procedure would commence by closing the supply from the settling tank to the service tank. Then the settling tank should be drained and filled with LSHFO. The dilution in the service tank should then be performed with a constant low level in the service tank, and only after a prescribed period of time should the tank level in the service tank again be increased.

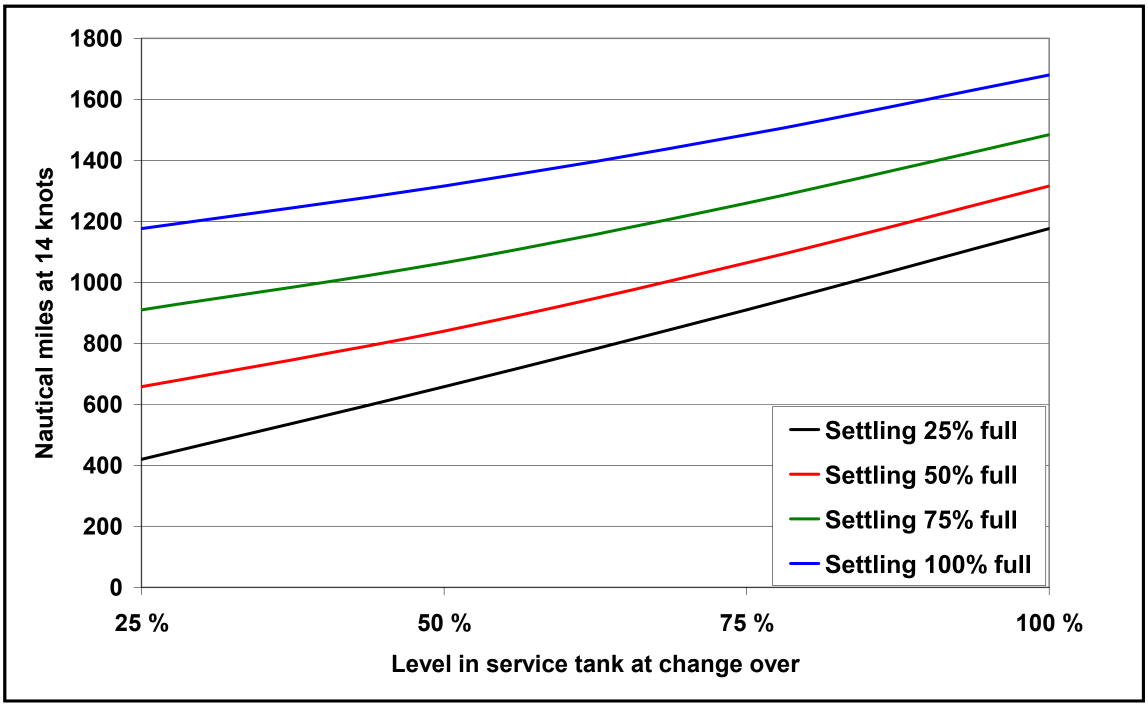


Figure 13 - Necessary distance from SOxECA for fuel change over with common HFO fuel system

4.2 Technical constraints

Within the scope of the work an assessment has been done, in view of the proposed maximum 1.5% S in fuel in SECA zones, to consider:

- The experience gained in connection with two-stroke and four-stroke diesel engine plants operating on low-sulphur fuel.
- Possible technical implications for the ship and engine auxiliary systems, arising from operation on low-sulphur (heavy) fuel oil.
- The present standard of fuel and lube oil systems used in connection with two-stroke and four-stroke marine diesel engines.
- Suggest solutions and evaluate the possibilities for the application.

Based on diesel engine design, theory of tribology and service experience the possibilities of applying multiple fuel and/or lube oil systems has evaluated based on assessment of the variety op options as indicated above. In service experience case studies were analysed as a part of the work.

First, it is essential to acknowledge that no two fuel oils are alike, and that by introducing different blends of fuels to achieve lower sulphur content can result in a fuel that is not performing satisfactorily. The blending process must therefore be considered in such case, and blending standards or directions be made.

Secondly, the sulphur in the fuel oil is resulting in sulphuric acid causing the most predominant corrosion in a cylinder liner, and a balance between cylinder lube oil BN and fuel sulphur maintaining some controlled corrosion is usually beneficial. This being the rule, deviations exist in both directions. Short term running with a balanced BN/S ratio has resulted in poor cylinder conditions, while good cylinder condition has occasionally been maintained, even under long term running, with an unbalanced BN/S ratio. The BN/S balance is not the only parameter influencing the cylinder condition. Both the fuel and cylinder lube oil performance influence the cylinder condition, as well as engine design parameters. However, the main rule of balanced BN/S ratio stands, i.e. the longer the running duration, the more important it is.

Owing to the diversified fuel oil system designs in service and being implemented, it could be an idea to handle/run on at least two different cylinder lube oils. The use of electronic lubricators seems promising in the effort to maintain a balanced BN/S ratio. Multiple cylinder lube oil systems is another possibility, maybe in combination with electronic lubricators for optimal flexibility.

Principal dual fuel system alternatives have been laid out. The possibility of abandoning the unifuel concept for certain ship types has been mentioned. The fuel change-over procedures for diesel engines running two and four stroke cycles have been outlined.

The time required for changing completely from one fuel to another fuel containing less than 1.5% S can be very long – well above 100 hours. In most of the calculated cases (see below for details), the change-over period is considerably longer than the period used for dimensioning the fuel oil system's settling and/or service tanks up to three or five times longer.

Depending on the vessel type and trading pattern in and outside the SECA zones, this might/might not induce a requirement for multiple (dual) fuel and lube oil systems. The major issues involved are:

- Fuel oil incompatibility
- Fuel change-over issues
- Base number – sulphur balance: Acid/Alkalinity
- Duration of fuel change-over – the 'Sulphur Battery'

The MARTOB project cannot conclude decisively on every aspect of these issues, but only outline possible solutions and not recommend one in particular. Future service experience will demonstrate the necessity. A close watch on engine condition should be observed in connection with more frequent change-over between varying HFO sulphur contents.

As has been apparent from service experience, and a result of the multitude of factors influencing engine running and combustion chamber tribology, it is not possible to recommend any specific auxiliary system configuration for a given combination of fuel sulphur content and cylinder lube oil. In addition, the application feasibility of such systems depends on market specific details, trading patterns, etc. that was not possible to address within the scope of the MARTOB project. Instead, the various possibilities, and various configurations has been outlined along with the advantages and disadvantages they may posses.

It should be noted and anticipated that experienced engine room designers and ship yards will probably invest some effort in commercialising engine room design, in order to be able to most effectively cope with the challenges of multiple fuel and cylinder lubricant systems. In that case, deviations from the concepts outlined here will probably occur.

4.3 Operational impact

The MARTOB Task 5.2 report "Future availability of LSHFO" indicates that there will be a problem to supply sufficient LSHFO according to the demand for the fuel as a result of introduction of the new regulations. Answers to the questionnaire also show that several ship owners plan to use LSHFO also outside SOxECA. If a noticeably part of the trans ocean fleet will use LSHFO on a continuous basis, the demand situation could be critical. Passenger ships on regular services to or from EU ports will always have to use LSHFO quality from 1st July 2007. Oil tankers consume fairly large quantities of fuel during un-loading, cargo pumps are normally steam driven from ship's steam boilers. Daily consumption for a VLCC during un-loading might reach close to 100 tons. But the biggest additional consumption of gas oil compared today will come from auxiliary engines earlier using heavy fuel oil at berth.

A tight supply situation for LSHFO might involve re-blending of current HSHFO with low sulphur products, MDO or other components. This option presents a risk for producing unstable LSHFO bunkers. Dilution of a thermally cracked residue with too high concentration of a paraffinic diluent such as gas oil could result in an unstable fuel. It is consequently necessary to ensure that the aromaticity of any diluent is high enough to keep the asphaltenes dispersed. The addition of catalytically cracked cycle oils is one way of doing this, and so providing an adequate stability reserve. Reduced stability reserve means that even small changes in external conditions will bring about instability. Two fuels, each stable within themselves, may prove to be incompatible when mixed. The mechanism of incompatibility is similar to that of stability and depends on the chemistry of the blended fuels.

Important for the recognition of the results in this report is the Questionnaire developed in the project, and distributed in collaboration with ECSA and the Norwegian Shipowners' Association. Close to thirty ship operators returned the Questionnaire, together forming a representative volume for most sectors of domestic and international shipping. The answers to the Questionnaire have been applied as basis for assumptions made during the work. Answers to the questionnaire show that many ship owners/ operators find that their fuel systems are not adequately arranged to handle dual fuel operation for main or auxiliary engines.

For ships continuing their mono fuel operation within the new legislation, the SOxECA border regulation will represent few consequences. Regarding continuous operation on low sulphur fuel, the MARTOB project has assessed experience from two vessels with several years operation on such products.

The fuel is one of the most significant aspects of environmental impact defined in Wallenius Wilhelmsen's extensive environmental programme. As a part of that programme the Wallenius Lines owned PCTC (Pure Car and Truck Carrier) TURANDOT has been running on Marine Diesel Oil, MDO, from January 1998 until December 2001. The bunker specification was DMB quality but with a Sulphur content of less than 1%. By this the SO_2 emissions were reduced by 75% compared to the sister vessel TITUS operating on HFO 380 cSt. This is in line with the company's long term target to reduce SO_2 emissions by operating on fuel containing less than 1.5% S by the end of 2003. Fuel consumption was reduced by at least 5% thanks to the higher heat value and less heating of fuel tanks.

Findings from the work onboard indicate that savings from fully utilized MDO operation corresponds to an price difference of about 20 USD/tonne compared to ordinary 380cST HFO. The most important savings are from crew reduction, fairway fees and cylinder oil consumption. Due to regulations regarding safety crew, the crew reduction is not utilized on TURANDOT. The savings in work could also be used to reduce the cost of external services, e.g. onboard trucks, hydraulics and electric motors.

Problems with sludge have occurred two times. This might be because the DMB quality of MDO is an intermediate product that is normally not delivered in such large quantities as when bunkering TURANDOT.

A test with RMG 35 fuel with a sulphur content of less than 1% was not successful. It was impossible to process the fuel in the separator and consequently not possible to use for running the engine. This was probably due to the fact it was a blended product. The bunkering was made in December 2002 and resulted in big problems onboard. In spite the fact that the product fulfilled the RMG 35 standard it was not possible to use as fuel.

The proposed amendment to Dir. 1999/32 states that at berth there will be prohibited to use fuel with a content of sulphur above 0.2%. This will require vessels to carry gas oil, a quality not normally used onboard. Trans-ocean vessels might experience problems purchasing such low sulphur gas oil in international ports, hence it might be necessary to await entering European port. As some vessels are not allowed to carry out bunkering operations while loading or discharging, this will delay the loading operations. If the vessels have to change over to MGO at berth or in the harbour area there are increased risks for black outs. A black out is of course much more critical if the vessel is under manoeuvring in harbour and not at berth.

Trunk engines designed for HFO will more frequent operate on MGO. Experience must be collected to ensure that safe operation is obtained.

The case studies from dual fuel operation reveal that no firm general conclusion on best practice can be made with respect to change in operational procedures for dual fuel operation. The main reasons for this are that the trading pattern of the vessel, and the space available for fuel system modifications will heavily influence the operator's decision.

The optimal solution from an operational point of view, considering both safety and extent of new operational procedures, is to have dual fuel storage and fuel pre-treatment systems for high and low sulphur fuel qualities.
For ships in inter continental trade, change over from HSHFO to LSHFO is a viable option due to few visits each year to the SOxECA. Long hauls and few visits will

provide a sufficient time window to properly plan and execute change over from HSHFO to LSHFO, without significantly increasing the risk for stop of engines.

For ships with more frequent visits in the SOxECA, change over between HSHFO and LSHFO is not recommended unless the ship has two separate fuel pre-treatment systems, due to the complicated change over operational procedures and increased risk for stop of engines.

The study is not able to establish general cost estimates on the economic impact for any ship operating in a SOxECA, although case study results are presented. In the work it is however provided presentations on how a ship owner may estimate and consider best solution with respect to economic impact of new regulations.

Two important areas of further work have been identified from the case studies:

- More experience feedback should be collected on dual fuel operation to gain increased knowledge on potential safety and operational problems experienced with change over between HFO and LSHFO.
- Operational procedures should be carefully established and approved by administrations for those who will operate on more than one fuel quality and with change over between different fuel qualities upon entering a SOxECA.

5 Verification of compliance

The existing compliance procedure of documentary evidence, stating the sulphur content of fuel oil supplied, laid down in regulation 18 of Annex VI, MARPOL 73/78, may be falsified because there are significant financial benefits in the use of poor quality high sulphur fuels. Hence, there will be every possibility that a ship entering European waters could be using high sulphur fuel oil instead low sulphur. However, the procedure uses information that forms a part of the existing bunkering process and therefore has the minimal cost implications.

Any compliance procedure developed should be based on the trading pattern of ships and its ease of policing. This then governs the type of procedure or technology used and its effectiveness. The most effective procedure to ensure compliance would be to control at source as applied by the Sulphur in Liquid Fuels Directive, 99/32/EC, with the responsibility of the member state to prohibit the sale of fuel oil with sulphur content higher then the set limits. However, shipping being a global industry with ships trading within and outside European waters the procedure will only be effective in reducing European sulphur emissions by 40%.

For ships entering European waters on a regular basis, it may be made mandatory to fit sulphur in fuel or SO_x measuring equipment. Such instruments can be used not only to demonstrate compliance with legislation but also be used as a part of an emissions trading scheme. In this case the measuring equipment also needs to be linked with a time record of the ships position.

A review of the existing sulphur in fuel measurement technology has shown that most of the detection techniques are through combustion of a small quantity of fuel (oxidative techniques) and needs a sample of fuel to be extracted from the system for a test to be completed. This can be avoided by fitting an X-Ray Fluorescence (XRF) on line measuring instrument upstream of the inlet to the engine. However, the cost of such instrument is approximately £40,000 with additional costs for calibration and on going maintenance by an expert technician. The analysers capable of measuring SO_x in the exhaust gas can be divided into extractive and non-extractive system, the former being permanently installed in a remote location analysing gas samples extracted from the uptake with capability of measuring emissions from multiple engines, and the latter carrying out in-situ analysis without extraction. The analysers are of the UV fluorescence type using a zinc ray lamp as the UV source.

The use of the Automatic Identification System (AIS) which is a ship broadcasting system that operates on the VHF maritime band to transmit and receive ship specific information could be used to transmit bunker related information during the ships transit through European waters. The method is simple in the sense that it is utilising an existing system to transmit additional information and has minimal cost implications. However, the accuracy of the system is dependent on the estimation of predicted fuel consumption.

The measurement of sulphur content from engine efficiency relies on on-line measurement of engine efficiency from standard engine parameters, measurement of water in fuel, engine fuel oil consumption and fuel density. The disadvantage in this approach is that continuous measurement of cylinder peak pressure is required and the online measurement of density at the fuel oil flow meter. The cylinder oil drain analysis and fuel/exhaust gas sample collection procedures would both be labour intensive and the analysis of samples potentially very expensive. Remote sensing was seen to be a very desirable method for verifying compliance with legislation, as it does not involve the ship operator in anyway. However, the cost of such remote sensing instrument and its associated equipment would be expensive.

6 Conclusions and recommendations

1. Several assessments have been made recently to try to quantify the marine bunkers consumption in Europe, BMT, Entec, Beicip-Franlab etc. The various studies do not provide consistent results, and this is to some extent due to different approach to the task, and how international/domestic sale and consumption have been considered. The most significant conclusion drawn from the comparison is that a significant uncertainty still exists with respect to the consumed volume of marine fuel oil in European waters. As a consequence of this it will be equally uncertain what effect new legislation will have on this market.

2. Based on sale figures collected in workshops arranged in connection with the MARTOB project, the sales in Europe of marine fuel oil have been estimated to be approximately 42.1 million tonnes (2001 figure). This figure does not include distillates, hence the figures found by Beicip-Franlab seems to be closest, but still somewhat low as this figure includes distillate sales.

3. Based on the MARTOB analysis is concluded that the fuel consumption within the SOxECA and by passenger vessels on regular services in EU waters is in the range 17 –19 MT by year 2007. The future low sulphur fuel demand will probably far exceed these figures. A quantity well above 20 MT is seen as a realistic demand in 2007.

4. Present European supply of low sulphur fuel oil with sulphur content below 1.5% (not including MDO/MGO) has been estimated to be approximately 6.5 million tonnes, where the marine share represents less than 1 million tonnes annually. These figures are significantly smaller in magnitude compared to the concluded demand.

5. The provision of adequate quantities of segregated low sulphur bunker does not currently exist. On short term part of the shipping operators might need to switch to distillates, and the distillate market redirected/increased to meet the increasing demand.

6. The options available to a refinery for increasing Low Sulphur Fuel Oil Supply to the bunker market are:
   - Re-blending from the current HSFO market
   - Switch to a lower sulphur crude diet
   - Invest in Residue Desulphurisation (RDS)
   - Redirect the low sulphur fuel oil destined for inland markets

7. A limited supply of lower sulphur content HFO could be available by re-blending current HSFO with MDO, or other components. This option presents a risk for producing unstable LSFO bunkers. Dilution of a thermally cracked residue with too high concentration of a paraffinic diluent (“cutter-stock”) such as gas oil could result in an unstable fuel. It is consequently necessary to

ensure that the aromaticity of any diluent is high enough to keep the asphaltenes dispersed. The addition of catalytically cracked cycle oils is one way of doing this, and so providing an adequate stability reserve.

8. If the tight supply should result in reduced stability for parts of the LSHFO products, the shipping industry will face more frequent operational problems, clogging of fuel separators and filters, fuel coagulation and heavy sludge formation. This also involves increased chance for incompatibility with other fuel qualities during changeover operations.

9. Assuming properly done blending (right components from selected grades, and in correct order), the Beicip-Franlab report suggests that around 4 MT of 1.5% S bunkers could be available in North Europe and about 0.7 MT in the south, as indicated below.

10. It is difficult to predict what the future cost for low sulphur fuel will be, but sources considered by this work indicate additional cost of producing low sulphur fuel in the range 45-70 USD/t for 1.5 % sulphur to 65-95 USD/t for 0.5 % sulphur content. This study has not been able to contradict these projections.

11. The required use of low sulphur (1.5%) bunkers within EU territorial waters, with even tighter sulphur specifications (0.2%) within port areas will present a major challenge for the marine business in terms of segregation of fuels both in ship and shore tankage and delivery systems.

12. Engine manufacturers recommend a preferred fuel viscosity at injection, and since the temperature of the fuel determines fuel viscosity, changing fuel type also mean changing injection temperature. Controlled conditions during changeover between two different fuel qualities are of vital importance to avoid too rapid and too large change in fuel oil temperature and, thereby. protect the fuel injection equipment on the engines. The high fuel oil injection pressure requires very narrow tolerances in the fuel injection equipment. An uneven thermal expansion of the equipment could cause seizure, e.g. of plunger and barrel.

13. Of engine tribology reasons the sulphur content of the fuel must be balanced with the Base Number of the engine lubricant. For engines operating on heavy residual fuel oil, a cylinder oil with a viscosity of SAE 50 and BN of about 70 is normally recommended. In most cases, the high BN cylinder lubricant will also be satisfactory during temporary operation on diesel oil/gas oil. In general, changing the cylinder oil type to correspond to the fuel used is considered relevant only in cases where operation on the respective fuel type is to exceed 10 hours.

14. For vessels operating all or most of the time inside a SOxECA, a monofuel operation on a selected low sulphur fuel quality will be the natural choice, with limited operational consequences. Regarding continuous operation on

low sulphur fuel, the MARTOB project has assessed experience from two vessels with several years of operation on such products. Based on the cases assessed, continuous operation on low sulphur qualities does not represent a significant technical/operational challenge, but fuel cost increase is higher than savings related to maintenance, operation etc.

15. Case studies from operation based on change between different fuel qualities (HS and LS), reveal that no firm general conclusion on best practice can be made with respect to amendment of operational procedures in such cases. The main reasons for this are that the trading pattern of the vessel, and the space available for fuel system modifications will heavily influence the operator's decision.

16. Dependant of the fuel system tank layout there will be different procedures to obtain correct sulphur values of the fuel entering the engine. If the vessel is equipped with single settling and service tanks, sufficient flushing time must be ensured. The time required for changing from a high sulphur fuel to another containing less than 1.5 % S could be very long – well above 100 hours.

17. The optimal solution from an operational point of view, considering both safety and extent of new operation procedures, is to have dual fuel storage and fuel pre-treatment systems for high and low sulphur fuel qualities. For ships in inter continental trade, change over from HSHFO to LSHFO is a viable option due to few visits each year to the SOxECA. Long hauls and few visits will provide sufficient time window to properly plan and execute change over from HSHFO to LSHFO, without significantly increasing the risk for stop of engines.

18. For ships with more frequent visits in the SOxECA, change over between HSHFO and LSHFO is not recommended unless the ship has two separate fuel pre-treatment systems, due to the complicated change over operational procedures and increased risk for stop of engines.

19. The study is not able to establish general cost estimates on the economic impact for any ship operating in a SOxECA. The economic impact, from a ship operator perspective, will vary between different trading patterns and ship designs etc. Ship owners are in general recommended to assess own need for low sulpher fuel operation and bunkering strategy, and to perform a fleet assessment of alternative options to comply with the new regulation. Included in a fleet assessment would be economical evaluation of impact of investment in equipment versus impact of revised operational procedures.

20. The proposed amendment to Dir. 1999/32 states that at berth there will be prohibited to use fuel with a content of sulphur above 0.2%. This will require vessels to carry gas oil, a quality not normally used onboard. Trans-ocean vessels might experience problems purchasing such low sulphur gas oil in international ports, hence it might be necessary to await entering European port. As some vessels are not allowed to carry out bunkering operations while

loading or discharging, this will delay the loading operations. If the vessels have to change over to MGO at berth or in the harbour area (e.g. diesel electric power plants, auxiliary machinery) there are increased risks for black outs. A black out is of course much more critical if the vessel is under manoeuvring in restricted waters, hence change over to MGO should be limited to at berth condition.

21. Some depending on fuel system layout, changeover operation between different fuel types or qualities always involve increased risk levels for engine stop, due to un-proper procedures, faulty operation, incompatibility between the actual fuels with heavy coagulation as consequence etc. Due to this fact, changeover operations should be avoided in restricted waters, and always be performed in open sea or at berth after manoeuvring is finished/started.

22. To allow the shipping operators adequate time and opportunity for adoption to the new sulphur regulations, the maritime administrations should in due time prescribe the involved requirements to system arrangements and expected framework for control regime (routines for fuel sampling, logbook recordings etc.).

23. The practice to maintain documentary evidence of fuel oil quality standards laid down under regulation 18 of Annex VI of MARPOL 73/78 must be firmly adhered to so that a legally sound method can be documented for follow up of non-compliance vessels. Due to the possibilities of falsification of documentary evidence and samples, and also the cost and labour associated with undertaking a high percentage of investigation calls for additional verification procedures. These additional verification procedures should be designed to allow identification of possible non-compliance warranting a more detailed default investigation. Based on studies conducted in this work it was found that the AIS and remote sensing provide the most promising solution and it is recommended that further study should be conducted.

24. Three important areas of further work have been identified from the case studies:

    - More work needs to be done to quantify the impact and ability for the refining industry to meet the changing demand in fuel qualities, and to assess the overall cost impact on the business. This should take account of work currently being undertaken by Concawe into the impact on the European oil industry resulting from the introduction of lower sulphur specifications for both inland and marine fuels.

    - More experience feedback should be demonstrated on dual fuel operation to gain increased knowledge on potential safety and operational problems experienced with change over between HFO and LSHFO/MDO/MGO.

- Operational procedures should be carefully established for those who will operate on more than one fuel quality and with change over between different fuel qualities upon entering a SOxECA. Further work must be undertaken to clarify requirements for monitoring, documentation and verification of compliance defined as acceptable for any administration enforcing the new sulphur regulations.

7 References

Beicip-Franlab, 2002; Advice on the cost to fuel producers and price premia likely to result from a reduction in the level of sulphur in marine fuels marketed in the EU, Beicip-Franlab Study C.1/01/2002, April 2002.

BMT, 2000; Study on the economic, legal, environmental and practical implications of a European Union system to reduce ship emissions of SO2 and NOx, BMT Murray Fenton Edon Liddiard Vince Limited, report 3623, August 2000.

Clarkson, 2002; Shipping market outlook, Clarkson Research Studies, 2002.

CONCAWE, 2002; Communication with CONCAWE, 2002

Drewry, 1994; Marine bunker fuels : markets, economics and technical developments, Drewry Shipping Consultants, 1994.

EC, 2002; A European Union strategy to reduce atmospheric emissions from seagoing ships, COMMISSION OF THE EUROPEAN COMMUNITIES, COM(2002) 595 final, Brussels, November 2002.

EIA, 2001; World Energy Outlook 2001, Energy Information Administration, March 2001.

Entec, 2002; Quantification of emissions from ships associated with ship movements between ports in the European Community, ENTEC UK Limited, July 2002.

EMEP, 2000; Effects of international shipping on European pollution levels, J.E. Johnson, L. Tarrason and J. Bartnicki, The Norwegian Meteorological Institute research Report No.41, EMEP/MSC-W Note 5/2000, July 2000.

EPA, 1999; In-Use Marine Fuel, United States Environmental Protection Agency, report EPA420-R-99-027, August 1999.

Eurostat, 2002; Maritime transport of goods and passengers 1997-2000, Eurostat, Statistics in Focus, Transport Theme 7/2002.

ICC, 1998; Costs and benefits of controlling sulphur dioxide emissions from ships in the North Sea and seas to the west of Britain. IC Consultants, 1998 (H. M. ApSimon co-ordinator)

IEA, 2000; World energy outlook 2000, International Energy Agency, ISBN 92 64 18513 5, Paris 2000

IEA, 2001; International Energy Outlook 2001, International Energy Agency, Paris 2000

IMO, 2000; Study on Greenhouse gas emissions from ships, MARINTEK report MT00 A23-038, Trondheim, Norway, March 2000.

IMO, 2000; Sulphur monitoring 2001, IMO MEPC 48/INF.4, Submission to IMO MEPC48 by the Netherlands, 2002.

Koehler, 2002; Worldwide NOx emissions from merchant shipping, Horst W. Koehler, MAN B&W Diesel, 24th Annual Marine Propulsion conference 2002, The Motor ship, 10-11 April 2002, Copenhagen Denmark

Kågeson, P. (1999). Economic instruments for reducing emissions from sea transport. Air pollution and climate series No. 11. The Swedish NGO Secretariat on Acid Rain, Göteborg, Sweden. (www.acidrain.org)

LR, 1999; Marine Exhaust Emissions Quantification Study – Mediterranean Sea, Lloyds Register of Shipping, Report 99/EE/044, December 1999.

LR, 1995; Marine Exhaust Emission Research Programme, Lloyds Register of Shipping, 1995

G. Reynolds, Ø. Endresen; Ship emission and discharge inventories, International Conference on Marine Science and Technology for Environmental Sustainability, conference proceedings ENSUS 2002, University of Newcastle upon Tyne, 2002.

Shell, 2000; Internal Shell Strategy Division, International Marine Bunkers Analysis, 2000

UNCTAD, 2001; Review of maritime transport 2001, United Nations conference on trade and development, UNCTAD/RMT/2001.

UNCTAD, 2002; Review of maritime transport 2002, United Nations conference on trade and development, UNCTAD/RMT/2002

UNFCCC, 1999; Emissions resulting from fuel used for international transportation, Note FCCC/SBSTA/1999/INF.4, May 1999.