

## **Measures to Reduce Emissions of VOCs during Loading and Unloading of Ships in the EU**

---

A report produced for the European Commission,  
Directorate General - Environment

Howard J Rudd & Nikolas A Hill



---

August 2001

<b>Title</b>	Measures to Reduce Emissions of VOCs during Loading and Unloading of Ships in the EU
<b>Customer</b>	European Commission - Directorate General Environment
<b>Customer reference</b>	B4-3040/99/116755/MAR/D3
<b>File reference</b>	
<b>Report number</b>	AEAT/ENV/R/0469
<b>Report status</b>	Issue 2

AEA Technology Environment  
 E6 Culham  
 Abingdon  
 Oxfordshire  
 OX14 3ED  
 Telephone 01235 463391  
 Facsimile 01235 463001

AEA Technology is the trading name of AEA Technology plc  
 AEA Technology is certified to BS EN ISO9001:(1994)

	<b>Name</b>	<b>Signature</b>	<b>Date</b>
<b>Reviewed by</b>	A Jim Poll		
<b>Approved by</b>	Howard J Rudd		

# Executive Summary

## *Background*

1. This report has been prepared by AEA Technology Environment for Directorate General - Environment of the European Commission under contract B4-3040/99/116755/MAR/D3 - "Measures to reduce emissions of VOCs during loading and unloading of ships".
2. Directive 94/63/EC introduced Community measures to control the emissions of volatile organic compounds arising from the storage of gasoline and its subsequent distribution to service stations. It is well known that VOC emissions contribute to the formation of photochemical oxidants such as ozone which in high concentrations can impair human health and damage vegetation and materials. In addition, some VOC emissions from gasoline are classified as toxic, carcinogenic or teratogenic.
3. The Directive explicitly excludes the loading/unloading of ships. However, Article 9 of the Directive invited the Commission to look at extending the scope to include vapour control and recovery systems for loading installations and ships. The study has been undertaken to support this obligation. Its objective is to identify and assess the costs and effectiveness of measures to reduce VOC emissions from the loading and unloading of ships' tanks in the EU.
4. This report describes the information obtained, analyses its implications for marine vapour emission control in the EU and makes recommendations for future courses of action.

## *Products*

5. The main volatile products loaded in bulk are gasoline, other petroleum products (such as diesel and kerosene), organic chemicals and crude oil. The exact quantities loaded are subject to considerable uncertainty, but it has been estimated that approximately 50 to 60 million tonnes of petroleum based products (excluding crude oil) are loaded onto ships annually in the EU. Gasoline accounts for some 36 to 50 million tonnes of this total. VOC emissions from the loading of petroleum product (excluding crude oil) are approximately 9 kilotonnes representing approximately 0.07% of all VOCs emitted in the EU.
6. In addition, approximately 114 million tonnes of crude oil are loaded in the EU though the majority of this takes place in the United Kingdom (101.3 million tonnes, 81% onshore, 19% off-shore). A further 129 million tonnes (43% onshore, 57% off-shore) is loaded annually in Norway. Crude loading has been estimated to result in 114 kilotonnes of VOCs which represent approximately 0.8% of all VOC emissions in the EU.

## ***Ships***

7. Ships that carry bulk liquid cargoes can be classified according to whether they carry chemicals, products (including petroleum products, such as gasoline, kerosene, gas oil etc) or crude oil. Some ships are classified as capable of carrying both (crude/products carriers). Irrespective of the type of cargo being carried, the ship will be divided into a number of cargo and ballast tanks.
8. There are possibly over 1,200 ships carrying bulk liquid chemicals and refined products in European waters out of a global fleet of about 9,000 vessels. Industry sources estimate that about 600 of these call at European ports and terminals to load gasoline. About 300 specialise purely in carrying chemicals. The ships range in size from a few hundred tonnes to about 60,000 tonnes.
9. In terms of the mass of material loaded, ships less than 20,000 DWT account for 80% of the gasoline loaded at EU terminals. This is because the smaller ships tend to operate in domestic coastal trade whereas larger ships tend to operate internationally, often on transatlantic routes or even farther afield. The latter consequently load and unload less frequently.
10. There is a global fleet consisting of 1,260 vessels carrying solely crude oil, and all of these could load at some time in Europe. These crude carriers are generally larger than product carriers and can range in size up to more than 200,000 dead weight tonnes (DWT) and are usually dedicated to the crude trade. One company in Norway and one company in the UK are currently installing vapour recovery systems at their North Sea crude loading terminals at Hound Point and Sture.

## ***Terminals & Floating Production, Storage and Offtake vessels (FPSOs)***

11. There are approximately 80 terminals in the EU loading gasoline or other products and chemicals. Their size distribution is approximately:

<b>throughput in 1999 (kt)</b>	<b>No of terminals</b>
0-10	2
10-100	25
100-1,000	42
>1,000	10

of these, it is likely that the larger terminals load mainly gasoline and the smaller ones mainly other petroleum products and chemicals.

12. In Europe crude oil loading is almost totally confined to the North Sea, Scotland and Norway with a small amount of trans-shipment taking place in some Northern European ports such as Rotterdam.
13. In Europe, crude oil is extracted from under the North Sea and transferred ashore (to either the UK or Norway) either by pipeline or by shuttle tanker. Shuttle tankers are used for some fixed platforms and for all floating production, storage and offtake (FPSO) vessels. These are ships that function as production facilities. When an FPSO is taking

on oil from a well, there will be loading emissions from its own tanks as they are filled. About 30% of the UK's crude oil production and 70% of Norway's is loaded offshore.

### ***VOC Emissions***

14. Ship-derived emissions of VOCs come from loading, unloading, ballasting and transportation. While VOCs emitted during transportation may form a significant proportion of total VOC emissions from ships this is an operational matter on which it would not be appropriate for the European Community to regulate. Emissions during ballast water loading are believed to be small [Concawe, 2000b]. Also, Regulation 13 of the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78) requires new crude carriers of greater than 20,000 DWT, new product carriers of greater than 30,000 DWT and existing crude or product carriers of greater than 40,000 DWT to have segregated ballast tanks dedicated to ballast water only. This should eliminate VOC emissions from ballasting altogether.
15. During the unloading of a ship's tank air or inert gas is drawn into the tank as the liquid level inside drops. This cannot lead to an emission of VOC to the atmosphere because while the liquid level is falling the pressure inside the tank will always be slightly below atmospheric pressure and there will be a net inflow of air into the tank. The only circumstance in which an emission could occur is if inert gas is pumped into the tank at an excessive rate during unloading, but that would be an example of bad practice and should not occur in well managed operations.
16. In addition to this, the unloading of a ships tank is always accompanied by the loading of a shore-side tank. However, the use of floating roofs on shoreside tanks is becoming increasingly common, so emission from this source is unlikely and decreasing.
17. Consequently this report focuses on VOCs emitted during the loading of tanks. These result from the displacement of vapour present in the empty tank before loading commences, and from evaporation from the cargo being loaded. The rate of emission depends on many factors, the most important being:
  - Nature of previous cargo
  - Nature of current cargo
  - Temperature
  - Loading rate
  - Turbulence in the vapour space
  - Sea conditions (for offshore loading)
  - Time since unloading of previous cargo
  - Design of ship

### ***VOC Abatement Techniques***

18. There are a number of commercially available technologies for treating VOC emissions from ship loading. These include reducing volatility, vapour balancing, thermal oxidation, absorption, adsorption, membrane separation and cryogenic condensation.

Reducing volatility and vapour balancing have practical difficulties and are not considered as viable options at present (see 7.1 and 7.2 for more details).

19. **Combustion (thermal oxidation)** is a method commonly employed in the USA for controlling VOC emissions from ship and barge loading. There are many different systems for combusting VOC-laden air ranging in sophistication from simple enclosed flares to catalytic oxidisers with internal heat recovery. For marine applications, however, the simple enclosed flare is currently the preferred option. Thermal oxidation has negative implications in terms of safety and combustion emissions, especially CO<sub>2</sub>. Safety can be improved by using flame/detonation arrestors, inerting, enrichment or dilution and suitable management procedures. Combustion emissions can be minimised by energy recovery, although this is difficult for most marine terminals as they are often a long way from the nearest user of process heat.
20. **Absorption in chilled liquid:** The vapour from the tank loading operation is fed into the bottom of a packed column where it passes upward countercurrent to and in contact with a downward flow of chilled liquid absorbent. Hydrocarbons from the air/vapour liquid dissolve in the absorbent and are thereby removed from the air/vapour mixture. The residual air then passes out of the top of the column and is vented to the atmosphere. The absorbent liquid is regenerated in a stripping column after which it is re-chilled and fed to the absorber.
21. **Adsorption:** The air/vapour mixture passes through a bed of activated carbon. Organic molecules are adsorbed onto the carbon and permanent gases such as air or CO<sub>2</sub> pass through the bed and are vented to the atmosphere. The bed gradually becomes saturated and eventually a breakthrough point is reached where adsorption ceases and the vapour passes straight through the bed without being adsorbed. Before this happens, the bed is regenerated either by steam stripping or by vacuum. To achieve continuous operation two beds are usually used in which one bed is operating in adsorption mode while the other is being regenerated. The efficiency of this technique varies between 95% and 99% depending on the mass of carbon in the beds, the nature of the adsorbent material used and the degree of regeneration achieved. The adsorption of hydrocarbons onto activated carbon is exothermic. If the process is not properly controlled hot spots can develop within the bed. This is more likely to occur if the gas being treated contains air rather than inert gas. The adsorption of oxygenated compounds is more exothermic than that of pure hydrocarbons.
22. **Membranes:** This technique uses a semi-permeable membrane to separate organic vapours from air/vapour mixtures. The membrane is more permeable to organic compounds than to inorganic gases. The air vapour mixture passes over one side of the membrane whilst a vacuum is maintained on the other. Organic molecules selectively migrate through the membrane where they are removed by a vacuum pump.
23. **Cryogenic condensation** involves passing the vent gas through a condenser cooled by liquid nitrogen. This is because low temperatures are needed to reach sufficiently low VOC concentrations at the exit of the condenser. The technique is widely used in the pharmaceutical industry. For processes that use inert blanketing with nitrogen that is delivered in liquid form this can be a very cost effective option as it makes use of the cold temperatures associated with liquid nitrogen that would otherwise be lost. However, it is

rare for ships to be inerted with nitrogen, and where this is done, the nitrogen is usually made using an on site generator rather than by evaporating liquid. It is possible that ship vent-gas will have a higher humidity than that normally encountered in pharmaceutical and batch chemical processes where this technique is most commonly used. This will cause problems with increased fouling rates of the condensers. The particulate matter from the inert gas generators may also cause problems.

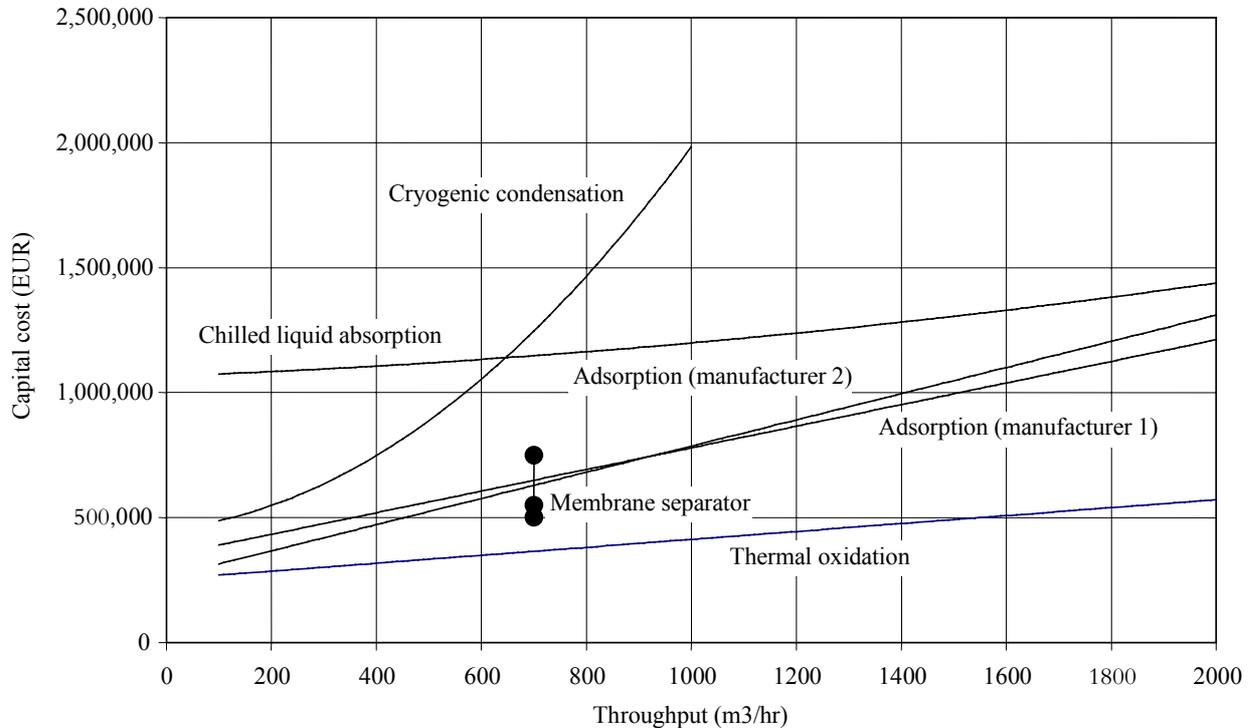
### ***Costs & Cost Effectiveness of Emission reduction***

#### ***Gasoline loading***

24. The cost of abating VOC emissions associated with the loading of gasoline onto ships consists of two separate parts. The first is the cost of installing the appropriate ship-based equipment and the second element is the cost for the shore-based vapour recovery equipment.
25. The cost of equipping a ship to enable it to transfer vapour to shore side facilities depends on whether or not the ship is:
  - currently equipped with an existing vapour collection system
  - capable of closed loading
  - equipped with an inert gas system that can be modified to collect vapours during loading operations.
26. Assuming a 5 year period for the modification of the existing ship carrier fleet and a 3% annual rate of ship replacement, the costs associated with undertaking the appropriate modifications to ships has been estimated at approximately €2,000 per tonne of VOC abated.
27. There is likely to be a wide variation in the costs of the shore-based facilities as these vary significantly according to the geography of the site. A pipeline is needed to transfer the vapour from the loading arm ship to the vapour treatment plant. The cost of the piping will depend mainly on the distance to be covered and the loading rate (which determines the pipe diameter). The distance from the berth to the treatment plant is the main factor determining the cost and this is likely to be highly site specific. Depending on the nature of the site, this distance could vary from a few hundred metres to several kilometres. Generally, suppliers estimate that on average, the piping system costs about the same as the treatment plant where the distance from the berth is short.
28. As well as piping, the following items are also required:
  - booster fans
  - detonation arrestors (are particularly expensive items and are essential where a combustion process is used as the treatment method)
  - support fuel injection (for combustion processes)
  - monitoring instrumentation
  - utilities
29. Equipment suppliers and other sources indicate that the capital and installation costs of the pipeline and associated booster pumps, detonation arrestors etc. can vary between the cost

of the control equipment up to about five times the cost of the treatment plant depending upon the distance of the plant from the berth. Experience in the USA has shown that on average the treatment plant costs 24% of the total project (DJ Woods, quoted on page 23 of [Jeffery, 1998]).

30. The graph below plots the capital cost against throughput for each of the abatement technologies described above.



31. The operating costs of the technologies consist of components which are independent of throughput. These include maintenance, and variable components such as the need for support fuel for incineration; electricity for fans, pumps, instrumentation and control systems and liquid nitrogen for cryogenic condensation.

32. There are a number of technologies being trialled in the offshore oil industry to reduce emissions of VOCs from the offshore loading of crude oil:

- Absorption of VOC in crude oil
- Condensation of VOC using refrigeration and pressurisation and use as fuel
- Hydrocarbon blanketing of FPSO cargo tanks and recovered VOC back to the process.
- Vapour balancing between FPSO and shuttle tanker.

33. The size of abatement plant required is determined by the maximum loading rate of the ship rather than by the throughput of the terminal. To calculate the cost effectiveness we make the following assumptions:

- Each product terminal (independent of terminal throughput) will need one vapour recovery unit of 2,000m<sup>3</sup>/h capacity

- Each crude terminal (independent of terminal throughput) will need one vapour recovery unit of 15,000m<sup>3</sup>/h capacity
34. Cost curves for VOC emissions abatement in many industrial sectors have been calculated by the International Institute for Applied Systems Analysis (IIASA). These have been used in conjunction with integrated assessment models to develop cost-optimal strategies for the reduction of NO<sub>x</sub>, SO<sub>x</sub>, NH<sub>3</sub> and VOC emissions in the EU and the UN ECE regions. The cost curves have been used to compare the cost-effectiveness of VOC abatement measures required to meet particular national emission ceilings and the measures identified in this study in relation to the VOC emissions associated with the loading of petroleum products onto ships.
  35. The European Commission has adopted a proposal for a Directive that would set national emission ceilings (NECs) for SO<sub>x</sub>, NO<sub>x</sub>, NH<sub>3</sub> and VOC emissions in order to achieve a given level of environmental improvement in relation to the problems of acidification, eutrophication and ground-level ozone. The marginal costs of the last measure required for the attainment of the national VOC emissions ceilings in the Commission's original proposal vary between €60 to €4,300 per tonne of VOC abated (where the highest values in those geographic areas where VOC control is most effective in abating the formation of ground level ozone). The costs for all but two countries (UK & Belgium) are less than €3,000 per tonne of VOC abated.
  36. In the negotiations following the adoption of this proposal by the Commission, the Council has agreed and published its common position containing a different and less stringent set of national emission ceilings. The marginal costs of the last measure required for the attainment of the national VOC emissions ceilings in the Council's Common Position are in the range €-18 to €1,746 per tonne where the costs for all but 3 countries in the EU being less than €500 per tonne of VOC abated. This is less than the cost per tonne abated (≈€2,000/tonne) needed to upgrade the ships. Consequently, if the Common Position Emission Ceilings are used, then abatement of these sources is cost effective nowhere in the EU.
  37. Terminals loading chemicals and other petroleum products are always much more expensive than with the most expensive measures required to meet the even the Commission proposal NECD targets for all throughputs likely to be attained in practice.

### ***On-shore and off-shore crude oil loading***

37. For off-shore loading, the costs associated with the modification of Floating Production, Storage & Offtake vessels (FPSOs) and shuttle tankers have been estimated as being in the range €400-4,000 and €1,000-5,000 per tonne of VOC abated respectively, depending on what assumptions are made for the lifetime of North Sea oil reserves.
38. The cost per tonne abated for equipping FPSOs and Shuttle tankers depends on the assumed expected lifetime of North Sea oil reserves. Our cost estimates are based on ranges of costs. For FPSOs the lower end of the range varies from approximately to €400 per tonne for an expected lifetime of 15 years to approximately €700 per tonne for a lifetime of 5 years. The upper end of the range varies from approximately to €2,200 per

tonne for an expected lifetime of 15 years to approximately €4,000 per tonne for a lifetime of 5 years.

39. For shuttle tankers the corresponding figures are lower: €1,000 per tonne for a lifetime of 15 years to €1,800 per tonne for a lifetime of 5 years. The upper end of the range varies from approximately to €2,800 per tonne for an expected lifetime of 15 years to approximately €5,000 per tonne for a lifetime of 5 years.
38. The majority of VOCs emitted during the loading of crude oil are associated with operations in the North Sea. The geographic location of the emissions means that it would be preferable to assess the impact on ozone in ambient air before proceeding with measures for their abatement.

### ***Other petroleum products & organic chemicals***

40. Other petroleum products and organic chemicals generally have lower vapour pressures than gasoline and are generally shipped in smaller quantities. For these reasons it is unlikely that the marginal costs of vapour treatment for these operations will be cost-effective in comparison to controls on the loading of gasoline and to measures in other sectors in the European economy.

### ***Safety Standards***

39. If it is decided to proceed with the introduction of measures to abate emissions of VOCs associated with the loading of petroleum products and/or crude oil onto ships, then it is recommended that the European Commission, via CEN, develop safety standards to minimise the risk of incidents involving marine vapour emission control facilities. This should take as its starting point the IMO Marine Safety Committee (MSC) Circular No 585, “Standards for Vapour Emission Control Systems”.

### ***Conclusion***

40. The emissions resulting from the ship-loading of gasoline and crude oil in the EU represent 0.07% and 0.8% respectively of all VOCs emitted annually in the EU. In general, the costs per tonne abated of measures on ship-loading are higher than the most expensive measures that Member States are likely to implement in order to comply with national emission ceilings for VOCs arising from new Community legislation. In light of this relatively small potential for reduction in VOC emissions and relatively poor cost effectiveness, it would appear that measures in other sectors of the European economy would be more effective in reducing VOC emissions than measures applied to the ship-loading of gasoline, crude oil and other petrol and chemical products. Emissions from crude oil loading offer the greatest potential for reduction, but since these are concentrated in the North Sea it would be preferable to assess the impact on ozone in ambient air before considering measures for their abatement.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Industry Overview - Petroleum Products</b>	<b>2</b>
	2.1 PORTS & TERMINALS	2
	2.2 SHIPS	2
	2.3 CARGOES	4
<b>3</b>	<b>Crude oil</b>	<b>5</b>
<b>4</b>	<b>Emissions</b>	<b>5</b>
	4.1 EMISSION SOURCE	5
	4.2 EMISSION FACTORS	7
	4.3 CRUDE OIL	12
<b>5</b>	<b>Emissions in the EU</b>	<b>13</b>
	5.1 PORTS AND TERMINALS IN THE EU	13
<b>6</b>	<b>Emission Abatement</b>	<b>16</b>
	6.1 GENERAL CONSIDERATIONS	16
<b>7</b>	<b>Measures</b>	<b>20</b>
	7.1 REDUCING VOLATILITY	21
	7.2 VAPOUR BALANCING	21
	7.3 THERMAL OXIDATION	22
	7.4 ABSORPTION	25
	7.5 ADSORPTION	27
	7.6 MEMBRANE SEPARATION	29
	7.7 CRYOGENIC CONDENSATION	31
	7.8 FPSOs AND SHUTTLE TANKERS	32
<b>8</b>	<b>Cost Analysis</b>	<b>33</b>
	8.1 COST PER TONNE ABATED	33
	8.2 SHIPS VAPOUR COLLECTION SYSTEMS	38
	8.3 FPSOs AND SHUTTLE TANKERS	39

<b>9</b>	<b>Cost Effectiveness Comparisons</b>	<b>41</b>
<b>10</b>	<b>Safety Standards</b>	<b>48</b>
	10.2 HAZARDS NOT IDENTIFIED IN MSC CIRCULAR 585	53
	10.3 CONCLUSIONS AND RECOMMENDATIONS	53
<b>11</b>	<b>Legislation</b>	<b>55</b>
	11.1 USA	55
	11.2 NORWAY	57
<b>12</b>	<b>Conclusions &amp; Recommendations</b>	<b>58</b>
	12.1 GASOLINE LOADING	59
	12.2 OTHER PETROLEUM PRODUCTS AND ORGANIC CHEMICALS	59
	12.3 ONSHORE CRUDE LOADING	59
	12.4 OFFSHORE CRUDE LOADING	59
	12.5 SHIPS	60
<b>13</b>	<b>References</b>	<b>60</b>

## **Appendices**

APPENDIX 1	INFORMATION ON EUROPEAN PORTS
------------	-------------------------------

# 1 Introduction

This report has been prepared by AEA Technology Environment for Directorate General - Environment of the European Commission under contract B4-3040/99/116755/MAR/D3 - "Measures to reduce emissions of VOCs during loading and unloading of ships".

Directive 94/63/EC introduced Community measures to control the emissions of volatile organic compounds arising from the storage of gasoline and its subsequent distribution to service stations. The Directive explicitly excludes the loading/unloading of ships. However, Article 9 of the Directive invited the Commission to look at extending the scope to include vapour control and recovery systems for loading installations and ships.

The study has been undertaken to support this obligation and has two main objectives, which are:

1. To identify and to assess the costs and effectiveness of all potentially relevant Community measures in relation to controlling emissions of VOCs from sea-going ships during loading and unloading in ports. These should be compared with measures that appear in the cost effectiveness studies underpinning the proposals for an Ozone Daughter Directive and the National Emissions Ceilings Directive.
2. To identify the most appropriate measures to reduce VOC emissions from the loading and unloading of ships, taking into account all relevant factors. These will include cost, abatement efficiency, compatibility with international safety standards, increased emissions of other pollutants such as NO<sub>x</sub>, CO<sub>2</sub>, range of VOC emitting products to be covered, size of ships and terminals to be covered, legal aspects etc.

To achieve these objectives we have collected information from a number of sources including national and international statistics, equipment manufacturers and industry representatives.

This report describes the information obtained, analyses its implications for marine vapour emission control in the EU and makes recommendations for future courses of action. It does not consider VOC emissions during transportation.

## Acknowledgements

AEA Technology would particularly like to thank the following people and organisations for supplying information and expertise:

The Concawe VOC emissions ad-hoc working group  
UKOOA work group on VOC emissions  
Fina Antwerp Olefins  
The Chemical Industries Association Marpol Annex 6 working group  
Martyn Lyons of Simon Storage  
Simon Shipley of John Zink Ltd  
Denis Hoesch of Aluminium Rheinfelden

Morten Reimer Hansen of Cool Sorption A/S  
 Beate Raabe of the International Association of Oil & Gas Producers  
 Richard Smith of McTay Engineering  
 Graham Raywood of BOC Cryoclean  
 Les White of Les White Associates Ltd

## 2 Industry Overview - Petroleum Products

### 2.1 PORTS & TERMINALS

In this study we are interested in the emissions of VOCs from the loading of seagoing ships in EU ports and terminals. The exact number of ports and terminals where the loading of volatile cargoes takes place is somewhat uncertain. We have identified the most important ones, which are listed in Appendix 1 but there are undoubtedly smaller ones, especially those connected to storage terminals that may handle small quantities of specialised products.

There are approximately 80 terminals in the EU loading gasoline or other products and chemicals. Their size distribution is approximately:

throughput in 1999 (kt)	No of terminals
0-10	2
10-100	25
100-1,000	42
>1,000	10

of these, it is likely that the larger terminals load mainly gasoline and the smaller ones mainly other petroleum products and chemicals.

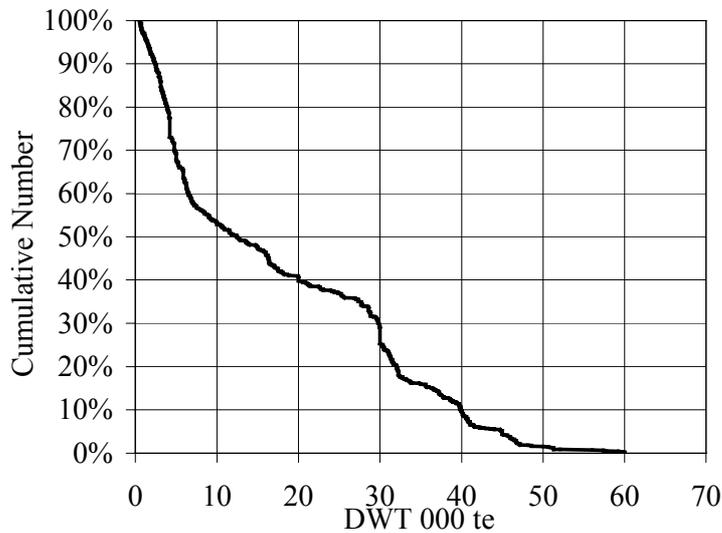
### 2.2 SHIPS

Ships that carry bulk liquid cargoes can be classified according to whether they carry chemicals, products (including petroleum products, such as gasoline, kerosene, gas oil etc) or crude oil. Some ships are capable of carrying both crude and products. Irrespective of the type of cargo being carried, the ship will be divided into a number of cargo and ballast tanks.

#### 2.2.1 Product carriers

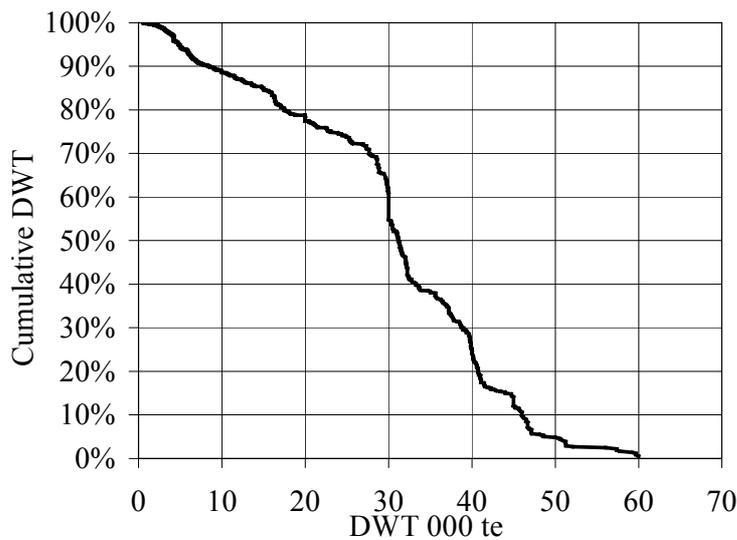
There are possibly over 1,200 ships carrying bulk liquid products in European waters. Industry contacts estimate that about 600 of these call at European ports and terminals to load gasoline. About 300 specialise purely in carrying chemicals. The ships range in size from a few hundred tonnes to about 60,000 tonnes. Figure 1 below shows the size distribution of the European product carrier fleet. The information from which this graph was constructed was supplied by a major oil and chemicals company using data from the Lloyds Register.

**Figure 1 - Product carrier fleet - % of total number of ships  $\geq$  specified deadweight tonnes (DWT)**



shows that approximately 54% of the ships are greater than or equal to 10,000 deadweight tonnes (DWT) or over in size, which means that 46% of the fleet is less than this size. However, when this analysis is carried out in terms of capacity rather than numbers of ships, a different picture emerges. Figure 2 shows a plot of cumulative DWT as a percentage of the total DWT for the fleet, as a function of size of ship. This shows that approximately 89% of the capacity is in ships of 10,000 DWT or greater, which means that approximately 11% of the capacity is in ships of less than 10,000 DWT.

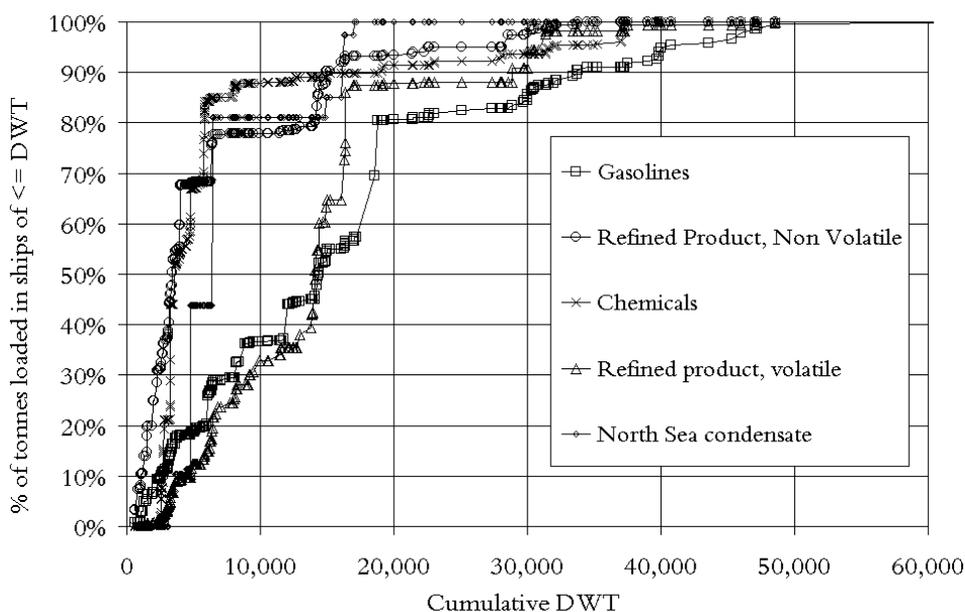
**Figure 2 - Product carrier fleet, % of total DWT  $\geq$  specified DWT**



A similar distribution holds true for the Product/Crude carriers, although the size of these tend to be larger. 90% of product-crude carriers are greater than equal to 10,000 DWT and in terms of capacity, 99% of the capacity is in vessels  $\geq$  10,000 DWT.

However, many of the smaller vessels tend to load and unload more frequently because they are predominantly engaged in domestic coastal trades where the distances are relatively short. The larger ships tend to be mostly involved in international trade, often transatlantic or further afield. Consequently, they load and unload less frequently. Figure 3 below shows data supplied by the industry showing loadings as a function of size of ship. This indicates that for gasoline 80% of the tonnage loaded is into ships less than 20,000 DWT and for other products it is greater than this.

**Figure 3 - Amount loaded as a function of size of ship at a sample of European refineries and terminals**



**2.2.2 Crude carriers**

World wide, the majority of crude oil loading takes place in the Middle East where, apparently, VOC emissions are not perceived to be a problem. In Europe crude oil loading is almost totally confined to the North Sea, Scotland and Norway with a small amount of trans-shipment taking place in some Northern European ports such as Rotterdam.

**2.3 CARGOES**

Excluding crude oil, gasoline is the largest cargo loaded in the EU. The relative volumes loaded are given in Section 4.2.1 below.

**Table 1 - common bulk organic cargoes**

Petroleum Fractions	Chemicals	
gasoline	benzene	glycols
kerosene	cumene	ketones
naphtha	esters	methanol
aliphatic hydrocarbon solvents	ethanol	xylenes
aromatic hydrocarbon solvents	ethylbenzene	styrene
acrylates	ethylene dichloride	toluene

Many of these compounds have low vapour pressures and their loading is unlikely to lead to significant emissions.

## 3 Crude oil

Crude oil is by far the largest organic liquid loaded in Europe. Nearly all of this loading takes place in the UK and Norway. There is, however, a small amount of crude oil transhipped (ie imported and re-exported) in continental European ports, mainly Rotterdam and Antwerp.

The pattern of movement of crude oil is different from that of petroleum products and bulk organic chemicals. These are manufactured in refineries and petrochemical plants and loaded into ships for transfer to overseas customers, whereas much of the gasoline produced is shipped to domestic terminals for transfer to road tankers for retail delivery.

In Europe, crude oil is extracted from under the North Sea and transferred ashore (to either the UK or Norway) either by pipeline or by shuttle tanker. Shuttle tankers are used for some fixed platforms and for all floating production, storage and off-take (FPSO) vessels. These are ships that function as drilling platforms. When an FPSO is taking on oil from a well, there will be loading emissions from its own tanks as they are filled.

The use of shuttle tankers has the potential to lead to multiple loading emissions. The shuttle tanker is first loaded offshore and then unloads into a shoreside tank at an onshore terminal. This oil will then be loaded either into a ship again or transferred by pipeline to a refinery.

About 30% of the UK's crude oil production and 70% of Norway's is loaded offshore.

## 4 Emissions

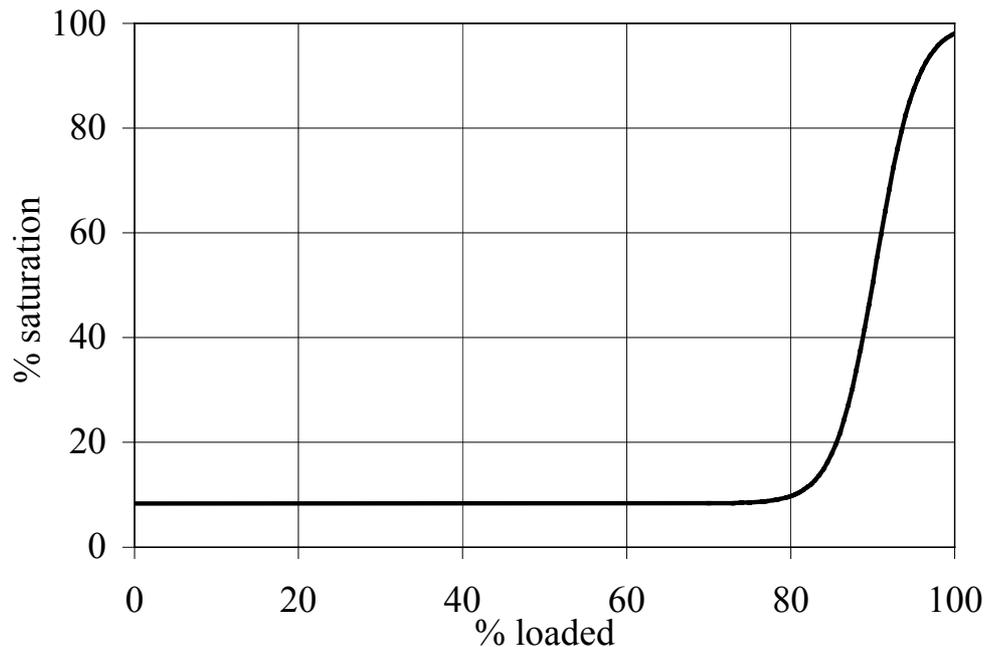
### 4.1 EMISSION SOURCE

When a tank is full the liquid level usually comes to within about 30 cm of the deck. After undergoing a sea voyage this space is fully saturated with vapour. On unloading, the liquid level slowly falls and the space is taken up by air or inert gas. When a new cargo is added the liquid level rises again, displacing the air-vapour mixture from the tank and leading to an emission of VOCs to the atmosphere.

After unloading, the concentration of vapour in the tank is not uniform, but decreases with increasing height from a maximum at the liquid surface. This is because of a combination of density stratification, where the denser vapour tends to remain at the bottom of the space, and advective and diffusive mixing, which tends to make the concentration more uniform.

Consequently, the gas that is vented from the tank on loading tends to be very lean at the start of the loading operation and very rich at the end, with a more or less sharp transition between the two at some point in the operation. This can cause a problem for abatement technology, especially combustion systems where support fuel is needed during the initial phase. Figure 4 below shows a typical concentration profile of the vent gas as a function of the amount of liquid loaded into the tank.

**Figure 4 - concentration of hydrocarbon in vent gas as a function of % loaded (Courtesy John Zink Ltd)**



This curve is purely schematic and in practice the profile can be expected to differ significantly from one loading to another. The rate of emission depends on many factors, the most important being:

- Nature of previous cargo
- Nature of current cargo
- Temperature
- Loading rate
- Turbulence in the vapour space
- Sea conditions (for offshore loading)
- Time since unloading of previous cargo
- Design of ship

Experimental studies offshore have shown that the emission rate can vary widely from one loading operation to another even under apparently identical loading conditions. In particular, movement of the ship can make a large difference to the emission rate and when the water is choppy the emission will be greater. This is especially important for offshore loading where wave heights can be much greater than in relatively calm ports and harbours.

It is becoming increasingly common for ship loading to be carried out under so-called "closed loading" conditions in which all hatches and sampling ports are closed during the loading operation. Conversion to closed loading requires the installation of vent lines and cargo tank level measurement and alarm systems. Vessels capable of closed loading have either individual tank vents or a vapour collection header and a high-level common discharge vent. Sometimes the individual tank vent line or the common vapour header may be connected to the shore side for venting through a stack. Closed loading is done to protect personnel from exposure. It does not lead to a reduction in emissions.

## 4.2 EMISSION FACTORS

The United States Environmental Protection Agency (USEPA) Compilation of Air Pollutant Emission Factors, AP-42, estimates tank loading emissions as a fraction, *S*, of a theoretical maximum emission calculated using the ideal gas law and the assumption that the air/vapour mixture in the vapour space is well mixed and in equilibrium with the liquid. That is:

$$E = S \frac{M_w p_v m_l}{10^3 RT \rho_l} \quad (1)$$

where *E* is the emission in tonnes, *M<sub>w</sub>* is the molecular weight of the vapour, *p<sub>v</sub>* is the vapour pressure of the cargo in Pa, *m<sub>l</sub>* is the mass of liquid loaded in tonnes, *R* is the gas constant in J/(mol.K), *T* is the absolute temperature in K and *ρ<sub>l</sub>* is the density of the liquid in kg/m<sup>3</sup>. *S* is an experimentally determined dimensionless constant that the USEPA calls a "saturation factor". Table 2 lists these factors recommended by the USEPA. Table 2 also lists saturation factors for truck and rail car loading for comparison. The *S* factor for ship loading is lower than for the other transport modes.

**Table 2 - Saturation factors for tank loading**

<b>Cargo Carrier</b>	<b>Mode of Operation</b>	<b>S Factor</b>
Marine vessels	Submerged loading: ships	0.2
	Submerged loading: barges	0.5
Tank trucks and rail tank cars	Submerged loading of a clean cargo tank	0.50
	Submerged loading: dedicated normal service	0.60
	Submerged loading: dedicated vapour balance service	1.00
	Splash loading of a clean cargo tank	1.45
	Splash loading: dedicated normal service	1.45
	Splash loading: dedicated vapour balance service	1.00

The emission profile depicted in Figure 4 in Section 4.1 above would represent an *S*-factor of 0.175, which is about the same as the USEPA *S* factor for submerged loading of ships quoted in Table 2 above.

The vapour pressure of a pure liquid varies from one substance to another but for any particular substance is a function only of the temperature. Table 3 below lists the vapour pressures of some of the more common high volume organic chemicals, together with the emission factor, *F*, calculated using the USEPA formula (Equation (1) above) for a temperature of 15°C.

**Table 3 - vapour pressures of common high volume organic chemicals at 15°C**

compound	Vapour pressure (kPa)	Emission Factor (kg/te)
acetone	19.6	0.13
benzene	7.84	0.071
cumene	0.166	0.0023
cyclohexane	8.13	0.079
ethanol	4.32	0.023
ethyl acetate	7.82	0.080
ethylbenzene	0.71	0.0088
ethylene glycol	0.00718	0.000052
MEK	7.82	0.065
methanol	9.84	0.037
m-xylene	0.602	0.0074
o-xylene	0.474	0.0058
p-xylene	0.638	0.0078
styrene	0	0.0053
toluene	2.21	0.024
pentane	46.5	0.39
hexane	12.8	0.13
cyclohexanone	$3.70 \times 10^{-5}$	$4.2 \times 10^{-7}$
cyclohexanol	$7.58 \times 10^{-6}$	$8.7 \times 10^{-8}$

Many of the organic compounds transported in volume by ship are complex mixtures such as gasoline, kerosene, naphtha and crude oil. Not only are they mixtures, but their composition varies from one batch to another. Consequently, their vapour pressures are difficult to estimate.

### Gasoline

The vapour pressure of a mixture is much more difficult to define than that of a pure substance. This is because some components are more volatile than others and evaporate more rapidly. Consequently, when the liquid evaporates its composition changes. The pressure exerted by the vapour in the tank space will therefore depend on the size of the vapour space itself, as well as on the temperature and initial composition of the liquid.

To avoid these difficulties, the petroleum industry uses a parameter called the Reid vapour pressure (RVP). This is defined by the procedure used to measure it - the liquid is shaken in a chamber of specified dimensions and the increase in pressure measured using an attached gauge. The RVP procedure is carried out at a specific temperature (37.8°C) and thus RVP is independent of temperature.

The relationship between RVP and the actual pressure of the vapour above a liquid in a tank (usually called the “true” vapour pressure or TVP) is not simple. The Institute of Petroleum in the UK recommends the following relationship should be used for emission estimation:

$$p_T = k p_R 10^{[a p_R T + b T + c p_R + d]} \quad (2)$$

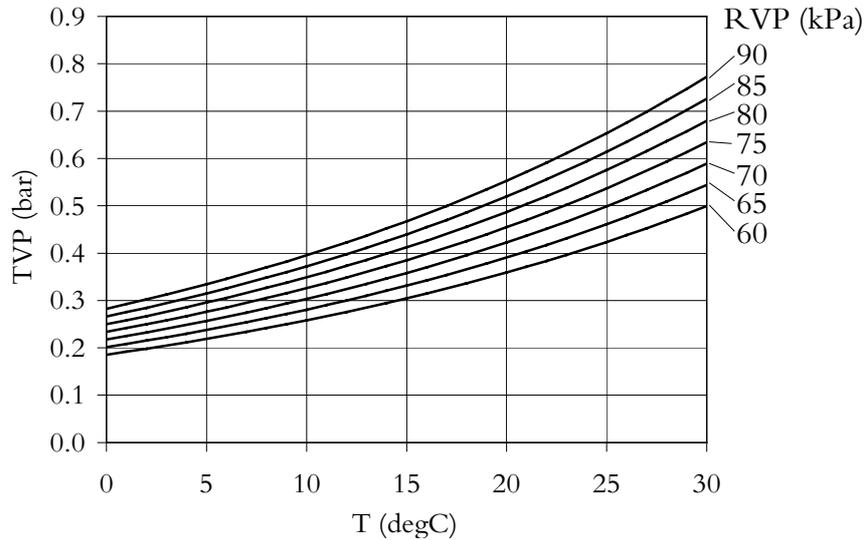
where  $p_T$  is the “true” vapour pressure in bar,  $p_R$  is the Reid vapour pressure in kPa,  $T$  is the product temperature (in °C) and  $k$ ,  $a$ ,  $b$ ,  $c$  and  $d$  are constants.

For gasoline, the recommended constants are:

k	0.01
a	$7.047 \times 10^{-6}$
b	0.01392
c	$2.311 \times 10^{-4}$
d	-0.5236

The RVP of gasoline is typically in the range 60 to 95 kPa, depending on the time of year. In the EU gasoline volatility is legislated to have a maximum of 60 kPa during the summer months. Figure 5 below shows the relationship between TVP and RVP graphically.

**Figure 5 - TVP of gasoline as a function of temperature and RVP**



Gasolines with different RVP have different average molecular weights. This is because lower molecular weight compounds are more volatile, so reducing the proportion of lower molecular weight components lowers the RVP. AP42 (Table 7.1-2) lists the average molecular weight of the vapours of three different RVP gasolines. These are:

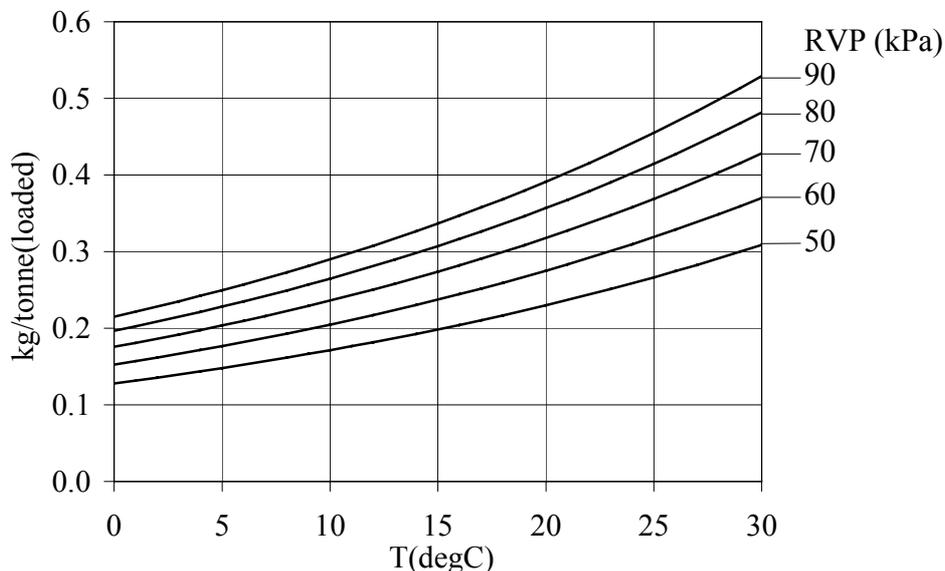
RVP (psi)	RVP (kPa)	M <sub>w</sub> (vap)
13	89.6	62
10	68.9	66
7	48.3	68

Within this range, the molecular weight as a function of RVP (in kPa) can be fitted to a simple quadratic equation.

$$M_w = -0.0023RVP^2 + 0.1758RVP + 64.942 \tag{1}$$

Using these three relationships, we can derive the emission factor as a function of RVP and temperature. Figure 6 below shows this graphically.

**Figure 6 - Emission factor for gasoline loading**



As has been mentioned already, the volatility of gasoline marketed in the EU must not exceed 60 kPa (or 70 kPa, depending on the region) during the summer months, but in winter it can be higher. The current most stringent RVP standard in the world is in California where the maximum allowable RVP is 48.3 kPa. In the 1994 Associated Octel European Gasoline Survey, RVP was found to vary between 54 and 94 kPa.

Ambient temperatures in Europe can vary widely between different parts of the continent and different times of the year. For the purpose of estimating an emission factor, we assume that the average temperatures are those shown in Table 4. Similarly, we propose to assume that the average RVPs of gasoline in Europe is as given in Table 5. From these assumptions, using the relationship illustrated graphically in Figure 6, we calculate the emission factors shown in Table 6.

**Table 4 - assumed average temperatures**

	Winter	Summer
Northern Europe	3	15
Southern Europe	10	25

**Table 5 - assumed average gasoline RVPs**

	Winter	Summer
Northern Europe	90 kPa	60 kPa
Southern Europe	60 kPa	50 kPa

**Table 6 - calculated emission factors for gasoline loading**

	Winter	Summer
Northern Europe	0.235	0.237
Southern Europe	0.205	0.266

These numbers are all rather similar, and we propose to take the average of these, 0.24 kg(emitted)/tonne(loaded), as the emission factor for gasoline loading throughput Europe. It is, of course, possible that winter gasoline is shipped during summer and that summer gasoline is shipped during winter. However, information to the level of detail needed to take this into account is not available.

### **Other Petroleum Products**

Few data are available on the vapour pressures of other petroleum products such as white spirit, kerosene and naphtha. Although RVP is part of the specification of gasoline, it is not included among the set of parameters that are used to specify other petroleum products. This is because firstly RVP is not required to assess the suitability for end use and secondly evaporative emissions have not been an issue, except for their use as solvents in, for example in paints, where atmospheric emissions do not depend on vapour pressure.

It is accepted, however, that the vapour pressures of kerosene, jet fuel, white spirit and diesel fuel are much less than that of gasoline. Indeed, they are often referred to in industry as “not-volatile”. For the purposes of this study we assume that the emission factor for these substances is 0.001 kg/te.

Apart from the above-mentioned products, there are also considerable quantities of “naphtha” shipped. The term “naphtha” usually means a cut from the crude column between gasoline and kerosene, in the boiling range 80 to 170°C. Consequently we assume its emission factor is halfway between that of gasoline (0.24 kg/te) and kerosene (0.001 kg/te) ie 0.12 kg/te.

#### **4.2.1 Overall factor for petroleum products**

Table 7 on page 12 below lists data supplied by the UK Petroleum Industry Association (UKPIA), Independent Tank Storage Association (ITSA) and the Chemical Industries Association (CIA) on the quantities of different materials loaded into ships in the UK. Similar information is not, to the best of our knowledge, available for other countries. Consequently, we assume that this breakdown also holds for other EU countries. Also included are emission factors for the different products and an average weighted according to the tonnages of each product.

**Table 7 - relative proportions of products loaded in UK**

<b>Material</b>	<b>% of total</b>	<b>Emission Factor (kg/te)</b>	<b>POCP</b>	<b>POCP weighted emission factor (kg of gasoline equiv-alent/te loaded)<sup>1</sup></b>
gasolines	69.41%	0.24	60	0.24
kerosene	14.45%	0.001	64	0.0011
naphtha	4.47%	0.12		0.12
aromatics	2.37%	0.05	95.4	0.08
others	2.87%	0.038		0.04
alcohols	1.90%	0.02	34.3	0.011
esters	0.93%	0.08	17.1	0.02
styrene	0.69%	0.01	14.2	0.0024
cumene	0.64%	0.0023	50	0.0019
methanol	0.56%	0.04	13.1	0.0087
gas condensate	0.24%	0.05		0.05
ethylbenzene	0.22%	0.01	73	0.012
C9's	0.22%	0.001		0.001
aliphatic solvents	0.22%	0.05	36.8	0.031
acrylates	0.20%	0.04		0.040
benzene	0.15%	0 <sup>2</sup>	21.8	0.00
industrial spirit	0.13%	0.05		0.050
ketones	0.09%	0.07	42	0.049
solvent naphtha	0.07%	0.15		0.15
toluene	0.06%	0.02	63.7	0.021
white spirit	0.05%	0.05		0.050
ketone alcohol	0.03%	2.50E-07		2.50E-07
para xylene	0.03%	0.01	101	0.017
ethanol	0.01%	0.02	38.6	0.013
	<b>Average:</b>	<b>0.18</b>		<b>0.18</b>

### 4.3 CRUDE OIL

The offshore oil industry has carried out extensive research work on the emission factor for offshore loading of crude oil. The emission factor is very variable and individual sources can differ considerably from one another. The United Kingdom Offshore Operators Association (UKOOA) recommends an emission factor of 1kg of VOC per tonne of oil loaded. We propose to use this as emission factor for both onshore and offshore loading of crude oil.

<sup>1</sup> If no POCP is available, the emission factor is assumed to be the same as the unweighted emission afctor.

<sup>2</sup> Assumed to be zero because loading is already subject to controls

## 5 Emissions in the EU

### 5.1 PORTS AND TERMINALS IN THE EU

There are around 80 terminals in the EU involved in the loading of volatile cargoes. There are many others that only import cargoes and so are not involved in loading.

Appendix 1 lists detailed data for amounts loaded in the EU by port. These have been derived either from data supplied by Lloyds Maritime Information Services Ltd (LMIS) or, in a small number of cases, from information obtained via the World Wide Web. The addresses of the web sites from which these data were obtained are also listed in Appendix 1.

LMIS provided data from its APEX (Analysis of Petroleum Exports) database. Lloyd's of London Publishers (LLP), LMIS's parent company, have a team of 1,000 agents in the world's major shipping ports who daily report shipping data to LLP. The Agents record each vessel's name, LR number, date of arrival, date of departure and its last and next port of call. From the vessel's name and LR number, the vessels characteristics are then added from Lloyd's Register's 'Vessel Characteristic Database.' Once these data have been put into the LLP 'Movements Database,' APEX extracts all tankers over 10,000 DWT, and analyses the actual movements. Depending on the vessel's size and its previous, current and next port of call it is possible to determine where the vessel has loaded, where it will discharge and what type of cargo it is carrying. Charter fixture information, where available, is also used to enhance the analysed data. The total database holds about 28,000 movements. APEX does not analyse ships that are only involved in domestic trade. The data are for 1999.

The information from LMIS is subject to three important sources of error. Firstly, only ships greater than 10,000 DWT are included in the figures, secondly the data are derived by assuming that all ships are loaded to their full capacity and thirdly vessels involved in domestic trade only are ignored.

It is apparent from Figure 2 that approximately 11% of product carrier capacity is in ships of less than 10,000 DWT. Virtually no crude carriers, however, are less than 10,000 DWT. Consequently, this size cut-off is expected to lead to under reporting by approximately 11% for products and 0% for crude.

The assumption that all ships are loaded to their full capacity is unlikely to be valid and data supplied by the oil industry indicate that a load of approximately 60% of DWT capacity is about average. This does not necessarily mean that the ship is 40% empty when it sails from its loading port, however.

Comparison of the LMIS data with data published on ports own web sites, where available, indicates that the former often under report the amounts loaded and unloaded. This may be because the LMIS database ignores vessels involved in purely domestic trade. However, many ports load into both seagoing ships and inland barges, and the web sites may report total loading volumes.

Table 8 below lists EU VOC emissions by country between 1990 and 1997. [data from <http://warehouse.eea.eu.int>, data set CLRTAP]

**Table 8 - EU VOC emissions by country, 1990 - 1997, kte/y**

	1990	1991	1992	1993	1994	1995	1996	1997
<b>Austria</b>	351	323	296	284	274	270	261	253
<b>Belgium</b>	358	355	354	345	336	324	324	324
<b>Denmark</b>	178	183	177	169	167	161	136	137
<b>Finland</b>	209	204	200	195	191	186	173	174
<b>France</b>	2,404	2,340	2,329	2,197	2,705	2,620	2,570	2,570
<b>Germany</b>	3,195	2,781	2,535	2,306	2,169	1,981	1,877	1,807
<b>Greece</b>	373	378	379	381	389	397	409	409
<b>Ireland</b>	197	200	199	202	175	176	103	105
<b>Italy</b>	2,213	2,293	2,338	2,344	2,349	2,368	2,368	2,368
<b>Luxembourg</b>	20	20	20	19	19	18	18	18
<b>Netherlands</b>	502	462	438	405	389	365	362	340
<b>Portugal</b>	640	652	668	672	690	691	691	691
<b>Spain</b>	1,134	1,187	1,207	1,196	1,120	1,120	1,120	1,120
<b>Sweden</b>	526	513	499	486	473	459	446	417
<b>United Kingdom</b>	2,552	2,497	2,398	2,293	2,237	2,121	2,046	1,954
<b>TOTAL</b>	<b>14,852</b>	<b>14,388</b>	<b>14,037</b>	<b>13,494</b>	<b>13,683</b>	<b>13,257</b>	<b>12,904</b>	<b>12,687</b>

Table 9 below lists amounts of petroleum products and organic chemicals loaded in EU countries and emissions calculated from them. A list of the ports from within each country where the loading took place is reproduced in Appendix 1.

**Table 9 - emission estimates for VOCs from ship loading petroleum products and organic chemicals in EU countries in 1999**

Country	Amount Loaded (te)	Emission Factor (kg/te)	Emission (te)	Corinair 1997 (te)	E as % of Corinair
<b>Belgium</b>	7,020,294	0.18	1,264	324,000	0.39%
<b>Denmark</b>	812,270	0.18	146	137,000	0.11%
<b>Finland</b>	607,840	0.18	109	174,000	0.06%
<b>France</b>	11,336,398	0.18	2,041	2,570,000	0.08%
<b>Germany</b>	1,663,053	0.18	299	1,807,000	0.02%
<b>Greece</b>	556,873	0.18	100	409,000	0.02%
<b>Italy</b>	8,268,472	0.18	1,488	2,368,000	0.06%
<b>Netherlands</b>	9,743,229	0.18	1,754	340,000	0.52%
<b>Portugal</b>	754,646	0.18	136	691,000	0.02%
<b>Spain</b>	1,817,398	0.18	327	1,120,000	0.03%
<b>Sweden</b>	999,636	0.18	180	417,000	0.04%
<b>U.K.</b>	4,542,453	0.18	818	1,954,000	0.04%
<b>Grand Total</b>	<b>51,001,606</b>		<b>8,662</b>	<b>12,311,000</b>	<b>0.07%</b>

[Concawe, 2000a] report 47 Mte of gasoline loaded in the EU. Assuming the mix of products is the same as that shown in Table 7 on page 12 above, this would imply a somewhat larger total tonnage loaded than that shown here (47 Mte/69% = 68 Mte compared with the 51 Mte shown here). The origin of this discrepancy is probably due to errors in the tonnages reported and in the assumption that the mix of products is the same for the whole of Europe as it is in the UK.

### 5.1.1 Crude Oil

Table 10 below lists amounts of crude oil loaded in EU countries + Norway.

**Table 10 - crude oil loading in EU + Norway 1999(data from LMIS)**

Country	amount loaded (te)	Emission (te) <sup>3</sup>
Norway Onshore	55,726,372	55,700
Norway Offshore	73,551,853	73,500
U.K. Onshore	81,978,488	81,900
UK Offshore	19,351,958	19,400
Netherlands	4,322,997	4,320
Denmark	4,165,103	4,170
Belgium	2,454,804	2,460
Germany	957,566	958
France	264,560	265
Sweden	123,963	124
Italy	50,000	50
<b>TOTAL</b>	<b>242,947,664</b>	<b>243,000</b>

According to the UK's National Atmospheric Emissions Inventory (NAEI), emissions of VOC from onshore and offshore loading of crude oil were, in 1998

**Table 11 - Emissions of VOC from crude oil loading in UK 1998 (NAEI)**

Operation	kte/y (1998)
Offshore Loading	44.12
Onshore loading	98.13

UK and Norway are not the only countries listed in Table 10 above as loading crude oil. Of the others, Denmark has a major oil terminal (Fredericia) taking crude oil by pipeline from the North Sea. Italy, Belgium and the Netherlands are listed because trans-shipment of oil (ie import and re-export) takes place at Antwerp, Rotterdam and a small number of other locations in Europe. France and Germany have a small amount of domestic oil production. No information is available about crude oil loading in Spain Portugal and Italy. These are small quantities and are possibly trans-shipments.

The EU-15 countries have been covered in detail, but the accession countries have not. There are currently thirteen accession countries: Bulgaria, Cyprus, the Czech Republic, Estonia,

<sup>3</sup> Calculated using an emission factor of 1kg/tonne loaded and rounding to three significant figures.

Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia and Turkey. Of these, Bulgaria, Cyprus, Estonia, Latvia, Lithuania, Malta, Poland, Romania and Turkey border the sea. Appendix 1 also discusses terminals in the Accession Countries.

The costs of installing marine vapour emission controls are unlikely to differ between accession and member countries

## 6 Emission Abatement

### 6.1 GENERAL CONSIDERATIONS

Reducing ship-loading emissions requires capital investment in three categories:

1. modifications to the ships
2. pipeline systems to transfer the vapour from the ship to the treatment plant
3. vapour treatment plant

#### 6.1.1 Ships

The cost of equipping a ship to enable it to transfer vapour to shore side facilities depends on whether or not the ship is:

- currently equipped with an existing vapour collection system
- capable of closed loading
- equipped with an inert gas system

A small number of ships are already equipped with vapour transfer pipework because they carry hazardous cargoes for which vapour treatment is necessary - eg benzene. Such ships will not need any further modification to enable them to transfer vapour ashore for treatment.

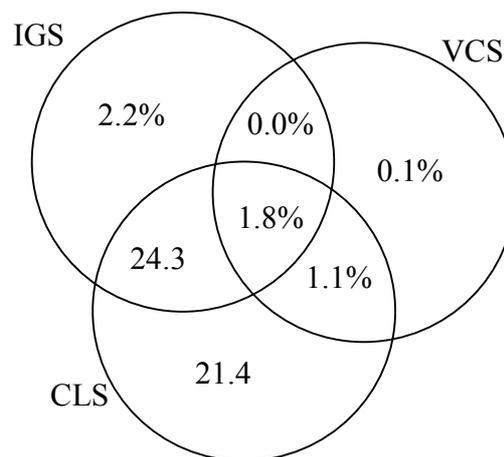
Ships that are capable of closed loading - in which all hatches and sampling ports are closed during the loading operation - have either individual tank vents or a vapour collection header connected to a high-level discharge vent. Some of the latter type of ships are also capable of transferring the vapour to the shore-side to be vented without further modification.

An increasing proportion of the tankship fleet is equipped with inert gas systems. The gas comes from either a stand-alone combustion plant or from the ships engines. It is common for the combustion gas to be scrubbed using a liquid scrubber before being fed into the tank. Despite this, ships' inert gas usually contains fine suspended particles. These can cause problems for vapour control technologies by depositing inside pipeline, valves and detonation arrestors eventually leading to fouling problems. They can also contaminate absorbent fluids, and recovered hydrocarbon.

Approximately 3% of the fleet of tankships (excluding crude carriers) probably operating in European waters are known to have an existing vapour collection system. 48.6% to be

capable of closed loading and 28.3% have inert gas systems. 25.9% have both closed loading capability and inert gas systems. Figure 7 shows these proportions graphically and also indicates the proportions that have more than one system installed. These numbers represent the proportion of ships that are known to have these systems in place. The actual proportions may be higher than these.

**Figure 7 - proportion of the European tankship fleet known to be equipped with inert gas systems (IGS), closed loading capability (CLS) and vapour collection systems (VCS)**



Once a ship is fitted with a vapour collection system, then the issue arises of its compatibility with shore side vapour handling systems. This is mainly a function of the size and design of the connection fittings used. However, such interfacial incompatibility problems could be overcome with the use of suitable adapters.

For most ships fitted with IG systems, the installed inert gas headers can, with minor modification, be used as vapour collection headers ([Benkert et al, 1987] page 84). The cost of installing a vapour collection system for a ship fitted with an inert gas system is estimated to be in the range 100,000 to 150,000 DFL<sub>1995</sub> ([Jeffery, 1998] page 23) (50,000 to 75,000 EUR<sub>2000</sub>). The cost of installing a vapour header when there is no IGS in place is reported to be approximately 275,000 EUR [Concawe, 2000a]. For comparison, contacts in the oil industry indicate that the approximate cost of a new Very Large Crude Carrier (VLCC) is about 80 MUSD (=80MEUR)<sup>4</sup> and a mid size ship (30 k DWT) is about 30 MUSD (=30MEUR). Typical annual operating cost for a VLCC is approximately 9,000 USD/day (=9,000 EUR/day) inclusive of maintenance, manning, etc. Dry-docking is done about every 2.5 years. For a VLCC it costs about 1 to 1.5 million USD, including cleaning, painting, surveys, engine repairs etc.

In Norway, Statoil are currently trialling a shipboard VOC recovery system on a shuttle tanker that condenses released vapours and uses them as fuel for the ships engines. They also claim that this fuel is cleaner than the heavy oil traditionally burned in ships' engines.

<sup>4</sup> In 2000, the value of 1 USD was: average (366 days): 1.08500 EUR, high: 1.21520 EUR and low: 0.95980 EUR. We have therefore taken the USD and the EUR as being approximately equal in value in 2000.

## 6.1.2 Loading facilities

The shoreside facilities at a loading berth include a moveable arm that connects to flanges on the ship in order to transfer liquid to and from the ship's tank. To enable vapour to be returned to shore, the loading arm can be modified with the addition of a vapour return line. Alternatively, a separate arm can be used to collect vapour.

**Figure 8 - typical loading arms without vapour return facility**



**Figure 9 - Loading arms with vapour return facility**



**Figure 10 - close-up of vapour return facility**



### 6.1.3 Pipeline systems

To transfer the vapour from the loading arm to the vapour treatment plant a pipeline is needed. The cost of the piping will depend mainly on the distance to be covered and the loading rate (which determines the pipe diameter). The distance from the berth to the treatment plant is the main factor determining the cost and this will be highly site specific. Depending on the nature of the site, this distance could vary from a few tens of metres to several kilometres. Generally, suppliers estimate that on average, the piping system costs about the same as the treatment plant where the distance to the berth is short. As well as piping, the following items are also required:

- booster fans
- detonation arrestors
- support fuel injection (for combustion processes)
- monitoring instrumentation

Detonation arrestors are particularly expensive items and are essential to meet IMO standards. Where a combustion process is used as the treatment method, the vapour in the transfer line from the ship has to be enriched, inerted or diluted to ensure the vapour concentration is outside its flammable range.

Equipment suppliers and other sources indicate that the capital and installation costs of the pipeline and associated booster pumps, detonation arrestors, etc., can vary between approximately the same as the cost of the control equipment up to about five times the cost of the vapour treatment plant depending on the distance of the plant from the berth. Experience in the USA has shown that the treatment plant on average costs 24% of the total project (DJ Woods quoted on page 23 of [Jeffery, 1998])

### 6.1.4 Treatment plant

The main factor influencing the cost of vapour treatment plant is the installed capacity, expressed in terms of maximum flow rate ( $\text{m}^3/\text{hour}$ ). The flow rate of vapour expelled from a tank being loaded is approximately the same as the loading rate of the cargo into the tank, although vapour evolution due to evaporation can add up to 10% to the total flow. The loading rate for non-static generative cargoes is determined by the physical ability of the vessel's tank structure, vent and cargo piping systems to withstand the loading pressures. For gasoline loading the flow rate of vent gas can be in the range 600 to 3,800  $\text{m}^3/\text{hr}$  and for crude loading can be in excess of 20,000  $\text{m}^3/\text{hr}$

During the course of a year many vessels, of different capacities, will call at a terminal. The maximum flow rate will be determined by the number of ships being loaded simultaneously and the number of loading arms used per ship as well as by the capacity of the ships.

## 7 Measures

This report considers a number of measures for limiting VOC emissions. These are:

- Reducing volatility
- Vapour balancing
- Thermal Oxidation
- Absorption
- Adsorption
- Membrane Separation
- Cryogenic condensation

Of these, reducing volatility and vapour balancing are only considered briefly.

The costs quoted in this report have been derived from a number of sources, mainly from equipment suppliers and existing published reports. These costs are purely indicative. The cost of building an item of equipment on any particular site is likely to differ, possibly substantially, from the figures quoted in this report. The cost of a particular piece of equipment at a particular site depends on a large number of site-specific factors such as availability of space, local regulatory regime, distance from the loading berth to the abatement plant and so on. They should not, therefore, be used by site operators for budgeting expenditure.

In most cases cost information has been supplied for a number of throughputs. These throughputs are those of the vapour treatment plant and are in units of  $\text{m}^3/\text{hr}$  of air vapour mixture fed to the plant. The vapour flow rate to the abatement plant is determined by the maximum rate at which a ship can be loaded, which in turn is determined by the ability of the vessels to withstand pressures generated by loading. It is not, therefore, simply related to the annual throughput, in tonnes of product, handled by the terminal.

To simplify the calculations we have derived, for each type of treatment process, a simple relationship between capital cost and throughput by fitting a simple curve through the data points. Wherever possible, a linear relation was used, and if this did not fit well a quadratic function. These relations are plotted in Figure 15 below.

To calculate the cost per tonne abated, we have assumed that a terminal loading products will require a single abatement plant with a vapour flow rate of  $2,000 \text{ m}^3/\text{hr}$  and that a crude loading terminal will require a plant with a flow rate of  $15,000 \text{ m}^3/\text{hr}$ , irrespective of the tonnages of material handled by the terminal.

Most of the quotations refer to the design and construction of the vapour control unit itself, including mechanical fabrication, cabling, instrumentation and control systems but excluding civil engineering, ground preparation and provision of site utility services. It has been estimated ([Jeffery, 1998] page 23) that civil work represents about 6% of the total cost. This means, therefore, that the cost must be inflated by 6.4% to take account of the necessary civil engineering work.

The costs have been quoted in a number of different currencies for a number of different years. We have converted these to year 2000 Euros (EUR<sub>2000</sub>) to enable comparison and facilitate cost effectiveness analysis. The procedure adopted to do this is to firstly convert the price in the original currency to year 2000 using the GDP deflator and then to convert to Euros using an appropriate exchange rate. The exchange rates used are listed in Table 12 below.

**Table 12 - exchange rates  
used for currency  
conversions in this report**

<b>Conversion</b>	<b>Rate</b>
USD → EUR	1.0850
GBP → EUR	1.6425
DKK → EUR	0.1432
AUD → EUR	0.6302
NLG → EUR	0.4538

The rates used are interbank rates (rates for cash and credit card transactions tend to be 2% to 4% higher) and are averaged over the whole of the year. Fortunately, the cost quotes obtained in this study have mostly been at year 2000 prices, and so inflation/deflation has not been needed in most cases.

## 7.1 REDUCING VOLATILITY

The simplest way to reduce emissions would be to reduce the volatility of the cargoes. However, in most cases this is not feasible. For pure substances (such as bulk organic chemicals) the vapour pressure cannot be changed. For gasoline, however, it can be reduced by changing the composition of the fuel to include more higher molecular weight compounds and fewer lower molecular weight ones.

Gasoline volatility characteristics recently changed due to the impact of the new EU Fuels Directive 98/70/EC. This specifies that from January 2000 the vapour pressure of all gasoline sold in EU must not exceed 60 kPa (depending on the region) during the summer months. Gasoline RVP was previously typically in the range 70 to 90 kPa depending on location and time of year.

For crude oil it may be possible to reduce the volatility by removing volatile components before loading, for example by heating the oil in a heat exchanger and separating the evolved vapour. This could then be stored and transported in pressure vessels in the manner of LPG. This technology is not yet, however, even at the research stage. A lot of research, design and feasibility work would be required before its suitability could be assessed.

## 7.2 VAPOUR BALANCING

Vapour balancing is the next simplest way of reducing emissions. However, there are a number of reasons why it is not a practical option for loading at coastal terminals. These are:

- Many shore-side tanks are fitted with floating roofs and so do not have a vapour space to collect the vapour from the ship's tank as it is displaced.

- The displaced vapour from the ship may contain contaminants from a previous cargo and fine particulate from on-board inert gas generators. In some cases these may be incompatible with the material to be stored in the shore tank.
- The ship and the shore tank may be at different temperatures, leading to a mismatch between the volumes of vapour displaced and liquid loaded. If the ship's tank is colder than the shore tank, the vapour displaced into the shore tank will expand as it warms up leading to a higher pressure inside the tank and subsequent emissions.

For these reasons, vapour balancing is not usually considered as an option for marine vapours. However, the technique has been used for offshore loading, for example on the Schiehallion FPSO, where some or all of these considerations may not apply.

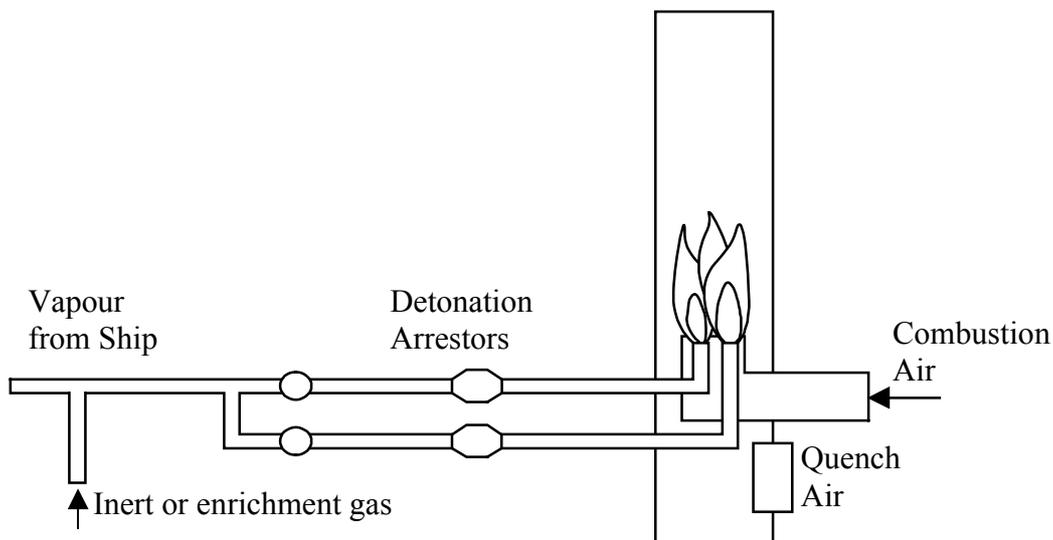
## 7.3 THERMAL OXIDATION

### 7.3.1 Process description

There are many different systems for combusting VOC laden air ranging in sophistication from simple enclosed flares to catalytic oxidisers with internal heat recovery. For marine applications, however, the simple enclosed flare is currently the preferred option. Thermal oxidation has a number of issues associated with it, namely safety and combustion emissions ( $\text{CO}_2$ ,  $\text{NO}_x$ ,  $\text{SO}_x$  etc). The former can be mitigated by the use of flame/detonation arrestors, inert gas or enrichment systems and suitable management procedures. The latter can be addressed by energy recovery, although this is difficult for most marine terminals as they are often a long way from the nearest user of process heat.

Figure 11 below shows a typical marine vapour combustion system. This consists of one to three burners at the base of a stack.

**Figure 11 typical marine vapour combustion system**



### Support Fuel

Because of the emission profile shown in Figure 4 above, the combustor requires support fuel for the first 90% of the load. The addition of support fuel is usually controlled by an on-line oxygen monitor.

## 7.3.2 Emission reduction potential

We assume that a simple combustion system such as an enclosed flare will remove hydrocarbons with an efficiency of 99%.

### 7.3.3 Costs

#### 7.3.3.1 Capital Cost

Discussions with equipment suppliers indicate that the capital cost, in year 2000 US Dollars, of this type of combustion technology is given by:

$$\text{Cost}(\text{USD}_{2000}) = 125 \times R (\text{m}^3/\text{h}) + 200000 \quad (2)$$

where R is the maximum loading rate. These costs are for equipment installed in the US. In a European context, the supplier estimates that the costs could be up to 10% to 15% higher, although in southern Europe they may be lower. Converting to Euros, inflating by 10% to take into account the European situation and by 6.4% to take into account civil work, the cost becomes:

$$\boxed{\text{Cost}(\text{EUR}_{2000}) = 158.7 \times R (\text{m}^3/\text{h}) + 254000} \quad (3)$$

### Exclusions

This cost includes a dock safety module, vapour blower unit, vapour combustion unit and a knock out vessel. It excludes civil engineering and provision of utility infrastructure such as LPG support fuel control systems, storage & supply.

#### 7.3.3.2 Operating Cost

The main cost elements for operating this type of plant are:

- power for fans & pumps
- support fuel
- operational staff
- maintenance

Discussions with the manufacturer indicate that the operating cost (excluding support fuel) for a plant of this nature is in the range 5,000 to 6,000 GBP<sub>2000</sub>/year (8,200 to 9,900 EUR<sub>2000</sub>).

### Support Fuel

Enrichment gas (usually methane, propane or butane) is added to maintain the concentration above 170% of the upper flammable limit (UFL). For methane this means a concentration of 25.5% by volume of total hydrocarbon in the vent gas. This is done for safety reasons as well as to support combustion during the lean phase of the discharge. The percent by volume of organic vapour in the vent gas, averaged over the whole loading operation, is equal to  $\frac{Sp_v}{P_{atm}}$

where  $p_v$  is the vapour pressure of the liquid being loaded and  $p_{atm}$  is atmospheric pressure and  $S$  is the USEPA “saturation factor” (= 0.2). To  $1\text{ m}^3$  of vent gas, therefore, must be added a volume of methane sufficient to bring the concentration up to 25.5% by volume. This

volume of fuel is therefore  $\left(25.5\% - \frac{Sp_v}{p_{atm}}\right) / (100\% - 25.5\%)$ . For gasoline, with a true

vapour pressure of 0.3 bar, this would mean that  $0.26\text{ m}^3$  of methane would need to be added to each  $1\text{ m}^3$  of gas vented from the ship’s tank. For less volatile cargoes, the amount would be correspondingly greater.

$0.26\text{ m}^3$  of methane weighs 0.165 kg and contains 0.132 kg of carbon which when burned produces 0.483 kg of carbon dioxide.  $1\text{ m}^3$  of vent gas results from the loading of approximately 0.7 tonne of liquid with emission factor of 0.24kg/te(loaded). It therefore contains  $0.24 \times 0.7 = 0.17$  kg of gasoline vapour.

Natural gas has a gross calorific value of  $10.86\text{ kWh/m}^3$ , and so  $0.26\text{ m}^3$  has an energy content of 2.8 kWh. The average price of gas in Europe in 1998 [DUKES, 2000] was 0.0125 EUR/kWh and so the cost of support fuel for  $1\text{ m}^3$  of vent gas is 0.035 EUR or 0.05 EUR per tonne of liquid loaded.

#### 7.3.4 Safety Implications

Marine terminals contain large quantities of highly flammable liquids in shoreside tanks and pipelines. During ship loading, the vapour being transferred from the ship to the abatement plant is also highly flammable. The main safety hazards associated with thermal oxidation are fire and explosion. These can be reduced using flame/detonation arrestors, inert gas or enrichment systems and suitable management procedures.

In the absence of an ignition source a safety incident leading to a release of vapour would merely lead to a VOC emission but in the presence of an ignition source (such as a combustion plant) could lead to an explosion.

#### 7.3.5 Effect on other pollutants

Combustion of organic compounds produces carbon dioxide, which is the main contributor to global warming. Because support fuel is used, the amount of carbon released is greater than the carbon content of the vapour being oxidised. If the vapour being combusted contains sulphur, then oxides of sulphur will be emitted.

Burning 1 kg of liquid gasoline produces 3.14 kg of  $\text{CO}_2$  (0.855kg as carbon<sup>5</sup>). Burning gasoline vapour will emit less than this because the vapour has a lower average molecular weight than does the liquid and therefore has a higher hydrogen to carbon ratio. However, an emission factor for the vapour is unavailable and so the emission factor for the liquid has been used instead. Burning  $1\text{ m}^3$  of vent gas therefore produces  $3.14 \times 0.17 = 0.534$  kg of  $\text{CO}_2$  from the vapour itself and 0.483 kg from the support fuel totalling approximately 1 kg of  $\text{CO}_2$  (as  $\text{CO}_2$ ) per  $\text{m}^3$  of gas incinerated. This is equivalent to  $1/0.7 = 1.42\text{ kg}(\text{CO}_2)/\text{te}(\text{loaded})$ .

---

<sup>5</sup> G Salway, personal communication

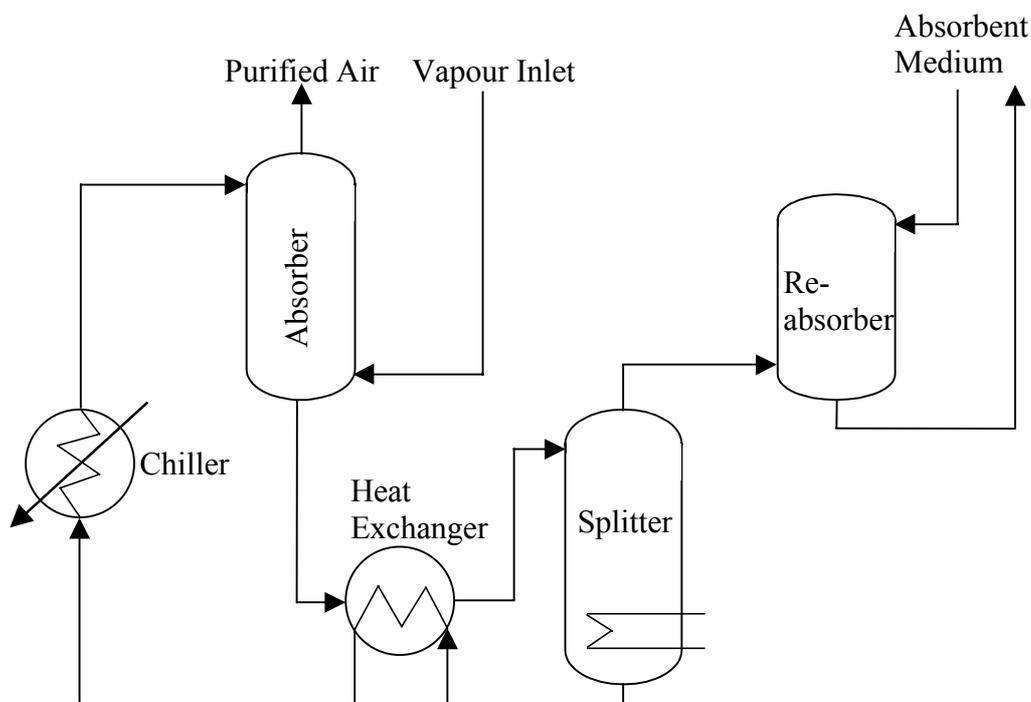
However, the extra CO<sub>2</sub> produced by the combustion of the vapour and support fuel must be offset against the fact that a simple enclosed flare has a lower fan power requirement than other abatement techniques such as absorption and adsorption. This is because the equipment imposes a smaller pressure drop which requires less power to overcome. This means that less CO<sub>2</sub> will be emitted at power stations due to the consumption of electricity. However, the direct comparison of power consumption of different techniques has not been attempted due to the unavailability of data.

## 7.4 ABSORPTION

### 7.4.1 Process description

Absorption of the vapours in a chilled low-boiling organic liquid is a common method of recovering VOCs from road tanker loading. The technology has been developed by Cool Sorption A/S of Denmark and is illustrated schematically in Figure 12 below.

**Figure 12 - Cooled liquid absorption (courtesy Cool Sorption A/S)**



The vapour from the tank loading operation is fed into the bottom of a packed column where it passes upward countercurrent to and in contact with a downward flow of chilled liquid absorbent. Hydrocarbon from the air/vapour liquid dissolves in the absorbent thereby removing it from the air/vapour mixture. The residual air then passes out of the top of the column and is vented to atmosphere. The absorbent liquid is regenerated in a stripping column after which it is re-chilled and fed to the absorber.

With this system it is necessary to inject methanol into the system to prevent moisture in the vent gas being treated freezing at the refrigerated temperatures.

Cool Sorption market several variations on the theme of chilled liquid absorption, including a system in which a chilled liquid absorption operation is used to recover vapour from the regeneration stage of a carbon adsorption system (Carbon Vacuum–Regenerated Adsorption Process - CVA) and a two stage absorption process in which the first stage is at higher than atmospheric pressure (Cold Liquid Pressure Absorption - CLPA).

#### 7.4.2 Emission reduction potential

The efficiency of an absorption column depends on the nature of the absorbent liquid and the height of the column. The absorbent is usually a low boiling hydrocarbon liquid and this, even at chilled temperatures, will have a finite vapour pressure itself. The efficiency is greater at higher VOC concentrations.

#### 7.4.3 Costs

Information supplied by the manufacturer indicates that the capital cost approximates to the relation:

$$\text{Cost}(\text{DKK}_{2000}) = 0.351 \times R(\text{m}^3/\text{h})^2 + 519.41 \times R(\text{m}^3/\text{h}) + 7 \times 10^6 \quad (4)$$

Converting to Euros and inflating by 6.4% to take into account civil engineering costs gives:

$$\text{Cost}(\text{EUR}_{2000}) = 0.0535 \times R(\text{m}^3/\text{h})^2 + 79.13 \times R(\text{m}^3/\text{h}) + 1.066 \times 10^6 \quad (5)$$

These costs include delivery and site assembly of the vapour recovery unit, commissioning and training of operators, but exclude civil engineering and provision of utility infrastructure.

#### Operating cost

The plant uses about 500 to 1,000kW of electricity, depending on plant size. This is the major item of operating cost. Electricity prices vary across Europe. In 1998, the latest year for which data are available, typical prices for industrial users in the EU ranged from 0.0325 to 0.0940 EUR/kWh with the average being 0.0583 EUR/kWh. Table 13 lists these costs for individual countries.

**Table 13 - Industrial electricity prices in the EU, 1998 (DUKES 2000)**

Country	EUR/kWh
Austria	0.0777
Belgium	0.0539
Denmark	0.0677
Finland	0.0498
France	0.0463
Germany	0.0667
Greece	0.0493
Ireland	0.0590
Italy	0.0940
Netherlands	0.0619
Portugal	0.0930
Spain	0.0583

Country	EUR/kWh
Sweden	0.0325
UK	0.0644

During operation of the equipment, therefore, the electricity cost will be  $500\text{kW} \times 0.0583\text{EUR/kWh} = 29\text{EUR/hr}$ . For a  $700\text{ m}^3/\text{hr}$  plant this equates to  $0.0416\text{ EUR/m}^3$  or  $0.059\text{ EUR/tonne}$  of liquid loaded, assuming a liquid density of  $0.7\text{ te/m}^3$ .

Maintenance costs are estimated to be approximately  $6,300\text{ EUR}_{2000}/\text{year}$

#### 7.4.4 Safety Implications

This technique does not involve any ignition sources as part of its operation and the adsorption column is operated at below ambient temperature. Consequently the risk of fire or explosion in the absorption column itself must be considered low. However, the regeneration of the adsorbent does involve the distillation of a flammable liquid and the normal safety risks associated with that operation would be encountered. Methanol is used as an “antifreeze” and the storage of this flammable liquid can pose risks.

#### 7.4.5 Effect on other pollutants

This process has quite a high consumption of electrical energy for refrigeration and pumping, and also consumes heat energy (most likely in the form of steam) for regenerating the absorbent liquid. Consequently, its operation will lead to increased  $\text{CO}_2$  emissions from power stations and site boiler houses. The process can also produce contaminated waste water that needs to be disposed of.

### 7.5 ADSORPTION

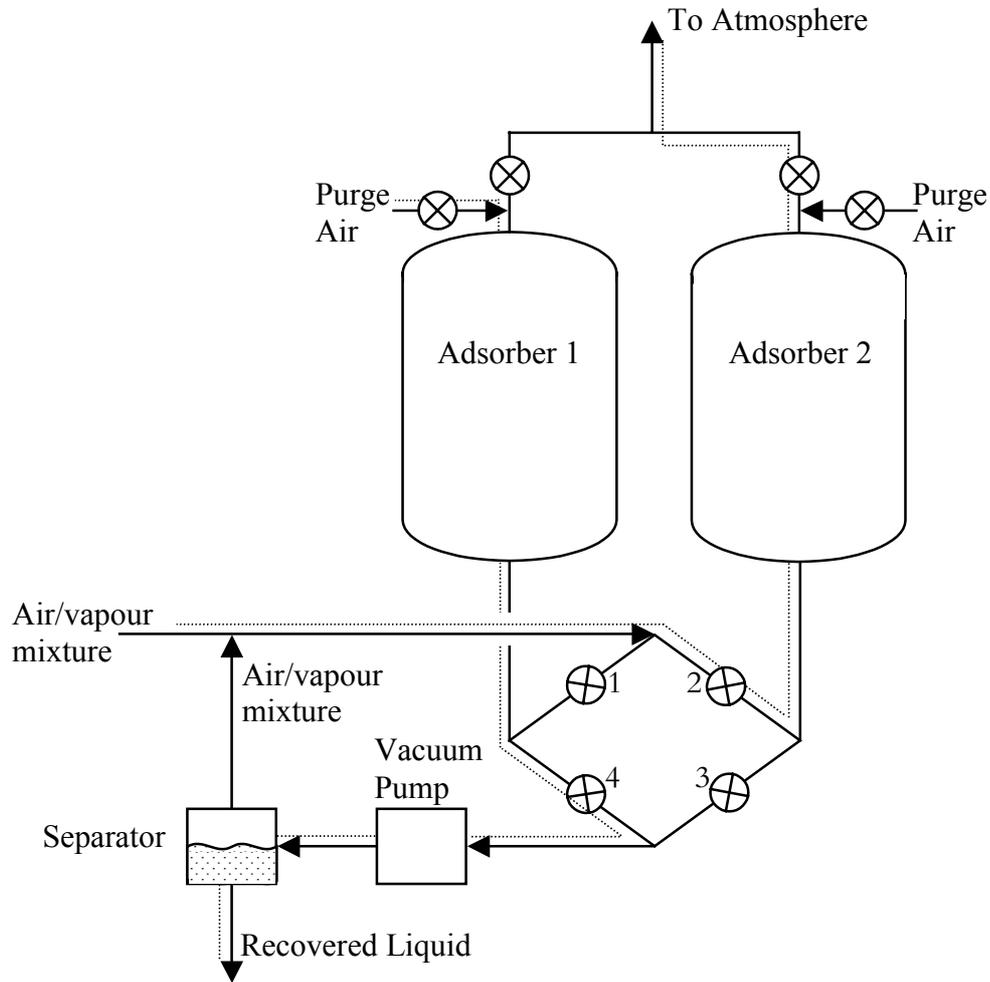
#### 7.5.1 Process description

The air/vapour mixture passes through a bed of activated carbon. Organic molecules are adsorbed onto the carbon and permanent gases such as air or  $\text{CO}_2$  pass through the bed and are vented to atmosphere. The bed gradually becomes saturated and eventually a breakthrough point is reached where adsorption ceases and vapour passes straight through the bed without being adsorbed. Before this happens, the bed is regenerated either by steam stripping or by vacuum.

To achieve continuous operation two beds are usually used in which one bed is operating in adsorption mode while the other being regenerated. Figure 13 below shows a schematic diagram of a typical configuration. In this design the beds are regenerated by pulling a vacuum on them with the admission of a small amount of purge air.

The presence of sulphur in the gas being treated can cause problems with carbon beds. If such problems are encountered, the use of a front-end scrubber or a sacrificial carbon bed may be necessary.

**Figure 13 - typical activated carbon adsorption system.**



The dotted line indicates the flow path when adsorber 2 is adsorbing and adsorber 1 is being regenerated. Valves 1 and 3 are closed while valves 2 and 4 are open. When adsorber 1 is adsorbing and adsorber 2 is being regenerated the valves 2 and 4 are closed while valves 1 and 3 are open.

### 7.5.2 Emission reduction potential

The efficiency of this technique varies between 95% and 99% depending on the height of the beds, the nature of the adsorbent material used and the degree of regeneration achieved.

### 7.5.3 Costs

Data supplied by a manufacturer indicates that the cost of this type of plant as a function of throughput, R, roughly follows the relation:

$$\text{Cost}(\text{USD}_{2000}) = 375 \times R(\text{m}^3/\text{h}) + 300000 \quad (6)$$

These costs include a dock safety module, vapour blower unit, vapour recovery unit and a knock out vessel. They exclude civil engineering and provision of utility infrastructure.

Converting to Euros and inflating by 6.4% to take into account civil engineering costs gives:

$$\text{Cost}(\text{EUR}_{2000}) = 432.8 \times R(\text{m}^3/\text{h}) + 346000 \quad (7)$$

Operating costs are reported to be in the range 10,000 to 15,000 GBP<sub>2000</sub>/year (16,500 to 24,600 EUR<sub>2000</sub>)

Data supplied by another manufacturer indicates a capital cost as a function of vapour throughput as:

$$\text{Cost}(\text{GBP}_{2000}) = 300 \times R(\text{m}^3/\text{h}) + 150000 \quad (8)$$

Converting to Euros and inflating by 6.4% to take into account civil engineering costs gives:

$$\text{Cost}(\text{EUR}_{2000}) = 524 \times R(\text{m}^3/\text{h}) + 262000 \quad (9)$$

This manufacturer indicates that annual operational cost of the equipment will be in the range 15,000 to 25,000 GBP<sub>2000</sub>. (24,600 to 41,000 EUR<sub>2000</sub>)

#### 7.5.4 Safety Implications

The adsorption of hydrocarbons onto activated carbon is exothermic. If the process is not properly controlled hot spots can develop within the bed. This is more likely to occur if the gas being treated contains air rather than inert gas. The adsorption of certain compounds eg aldehydes or ketones, is more exothermic than that of pure hydrocarbons.

#### 7.5.5 Effect on other pollutants

The operation of this equipment will lead to a small increase in CO<sub>2</sub> emissions from power stations due to the use of electricity for pumping. Apart from that there will be no effect on emissions of other pollutants.

### 7.6 MEMBRANE SEPARATION

#### 7.6.1 Process description

Aluminium Rheinfelden GmbH of Rheinfelden Germany markets the Vaconocore system that uses a semi-permeable membrane to separate organic vapours from air/vapour mixtures. The membrane is more permeable to organic compounds than it is to inorganic gases. The air vapour mixture passes over one side of the membrane whilst a vacuum is maintained on the other. Organic molecules selectively migrate through the membrane where they are removed by a vacuum pump. Figure 14 below shows a schematic diagram of a typical membrane plant.

#### 7.6.2 Emission reduction potential

The membrane VRU can be sized according to the required emission limit. If the plant is sized to achieve a stack concentration limit of 35g(HC)/m<sup>3</sup> and the inlet stack concentration is 10 wt% then the efficiency is 70% (1m<sup>3</sup> of air weighs approximately 1.2kg at 15°C and 10% of this is 120g). A plant sized to achieve a concentration limit of 10g(HC)/m<sup>3</sup> would be 90%

efficient and one designed to meet the German TA Luft standard of 150 mg/m<sup>3</sup> would be 99.8% efficient.

### 7.6.3 Costs

The manufacturer has given the following table of costs:

#### Capital Costs

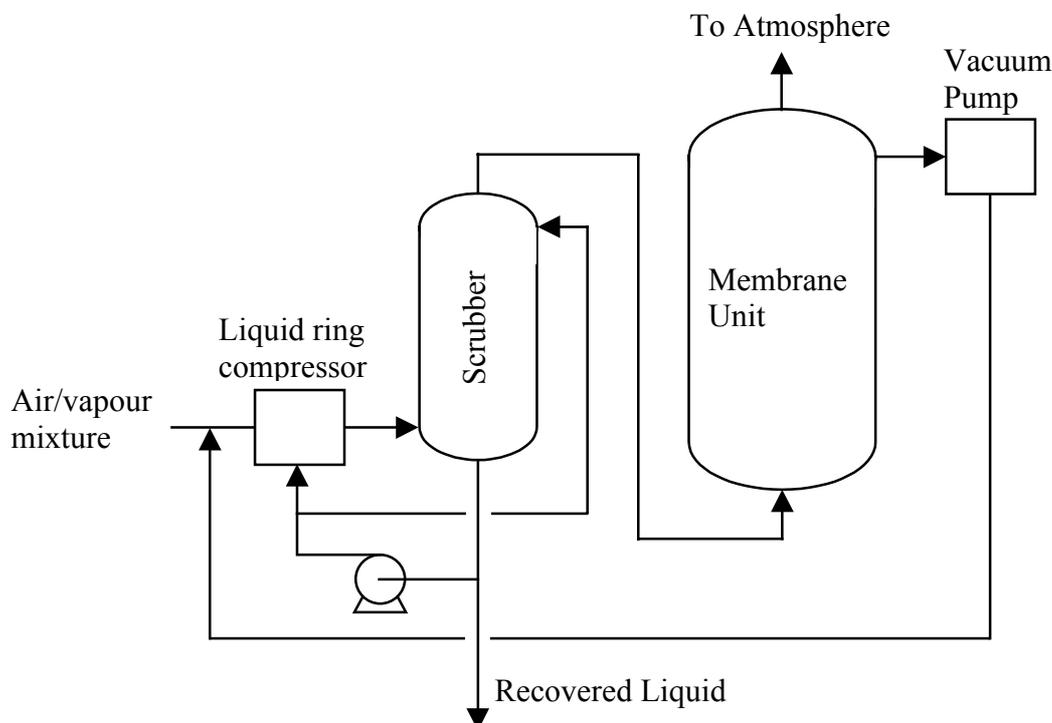
Flow Rate (m <sup>3</sup> /hr)	Stack Conc (g/m <sup>3</sup> )	Cost (EUR <sub>2000</sub> )
700	35	500,000
700	10	550,000
700	0.15	750,000

These costs exclude:

#### Operational Costs

The manufacturer estimates that the operating cost is in the range 5,000 to 10,000 EUR<sub>2000</sub> per year. However, these do not include power. A membrane unit has a liquid ring compressor and a vacuum pump that can have quite high power consumption.

**Figure 14 - membrane system for removing organic vapours from air/vapour mixtures.**



### 7.6.4 Safety Implications

This technology leads to the enrichment of the inlet gas, and this can have safety benefits due to the potential for making the inlet gas too rich to support combustion.

### 7.6.5 Effect on other pollutants

As with most of the other vapour recovery technologies, this consumes electrical energy for pumps and fans, and so leads to indirect emissions of CO<sub>2</sub>.

## 7.7 CRYOGENIC CONDENSATION

### 7.7.1 Process description

Cryogenic condensation involves passing the vent gas through a liquid nitrogen cooled condenser. Such low temperatures are needed to reach sufficiently low VOC concentrations at the exit of the condenser. The technique is widely used in the pharmaceutical industry. For processes that use inert blanketing with nitrogen that is delivered in liquid form it can be a very cost effective option as it makes use of the cold that is present in the nitrogen that would otherwise be lost. However, it is rare for ships to be inerted with nitrogen, and where this is done, it is usually made using an on site generator rather than by evaporating liquid.

A typical system will usually have two condensers operating in a “one on, one off” configuration similar to that employed in carbon bed adsorption systems. This is to enable the defrosting of the offline condenser. Organic material and water freezes on the heat exchanger surfaces reducing the heat transfer rate. Consequently the condenser has to be periodically de-frosted.

It is possible that ship vent-gas will have a higher humidity than that normally encountered in pharmaceutical and batch chemical processes where this technique is most commonly used. This could cause problems with increased fouling rates of the condensers. Also, the particulate matter from the inert gas generators may possibly cause problems.

### 7.7.2 Emission reduction potential

This technique is capable of achieving efficiencies of greater than 99%, depending on the concentration of VOC in the inlet gas.

### 7.7.3 Costs

Information provided by the manufacturer indicates that, the indicative capital cost of a cryogenic condensation plant can be fitted to the relation:

$$\text{Cost}(\text{GBP}_{2000}) = 0.758 \times R(\text{m}^3/\text{h})^2 + 117 \times R(\text{m}^3/\text{h}) + 260000 \quad (10)$$

Converting to Euros and inflating by 6.4% to take into account civil engineering costs gives:

$$\text{Cost}(\text{EUR}_{2000}) = 1.324 \times R(\text{m}^3/\text{h})^2 + 204.4 \times R(\text{m}^3/\text{h}) + 454000 \quad (11)$$

The main item of operating cost is the liquid nitrogen supply. The cost of liquid nitrogen is approximated by the relation:

$$\text{Cost}(\text{GBP}_{2000}/\text{hr}) = 0.0186 \times R(\text{m}^3/\text{h}) + 5 \quad (12)$$

or 
$$\text{Cost}(\text{EUR}_{2000}/\text{hr}) = 0.0305 \times R(\text{m}^3/\text{h}) + 8.21 \quad (13)$$

dividing by the throughput and a density of 0.7 gives a cost per tonne of liquid loaded:

$$\text{Cost}(\text{EUR}_{2000}/\text{te}) = 0.0435 + \frac{11.73}{R(\text{te/h})} \quad (14)$$

For loading rates of interest in this study the last term is approximately equal to 0.01 and so  $\text{Cost}(\text{EUR}_{2000}/\text{te}) \approx 0.05$

The other main item of operating cost is electrical power, which is typically in the range 3 kW to 15 kW depending on plant size. This is negligible in terms of cost per tonne loaded.

#### 7.7.4 Safety Implications

This technique has a low risk of fire or explosion.

#### 7.7.5 Effect on other pollutants

The plant has a low energy consumption if the energy used to generate the liquid nitrogen is not included. This can be a valid assumption if there is an existing nitrogen supply on site that is generated by evaporating liquid. The VRU can then be used to evaporate the liquid which would otherwise be evaporated by other means anyway. However, this way of producing nitrogen gas is becoming less common because of its high energy requirements.

If an existing supply of liquid nitrogen cannot be used in this way, or if an existing liquid nitrogen supply is diverted from some other cooling duty, then a great deal of energy would be involved in the production of the liquid N<sub>2</sub>. This would lead to indirect emissions of power station pollutants, principally CO<sub>2</sub>.

### 7.8 FPSOs AND SHUTTLE TANKERS

There are a number of technologies being trialled in the offshore oil industry to reduce emissions of VOCs from offshore loading. Table 14 below lists cost information provided by the United Kingdom Offshore Operators Association (UKOOA). It is difficult to retrofit an FPSO vessel because to do so would involve bringing it ashore. However, as these vessels are essentially floating production facilities any time spent ashore would involve a considerable loss of production. Recovery plant for FPSOs and offshore terminals are being trialled.

**Table 14 - cost information provided by UKOOA for VOC emission reduction from FPSOs and shuttle tankers.**

Method	Power Requirement	Cost for FPSO	Cost for Shuttle Tanker (M GBP)
Absorption of VOC in crude oil	2MW <sup>1</sup>	2.0 - 3.0	5.0 - 7.0
Condensation of VOC using refrigeration and pressurisation and use as fuel	3MW <sup>1</sup>	6.0 - 8.0	10.0 - 15.0
Hydrocarbon blanketing of FPSO cargo tanks and recovered VOC back to the process	0.1 MW	1.5 - 2.5	not applicable
Vapour balancing between FPSO and shuttle tanker	0.01MW	2.0 - 2.5	0.6

<sup>1</sup> - to provide this amount of power the ship may need extra generating capacity.

According to UKOOA, operating costs in the offshore industry are typically estimated to be 7% of capital cost per year and recovery rates achieved are typically in the range 50% to 70%.

Oil production in the North Sea is expected to decline in future years and this may have an impact on the cost effectiveness of vapour emission control for this source sector. See Section 8.3 below for a fuller discussion of this issue.

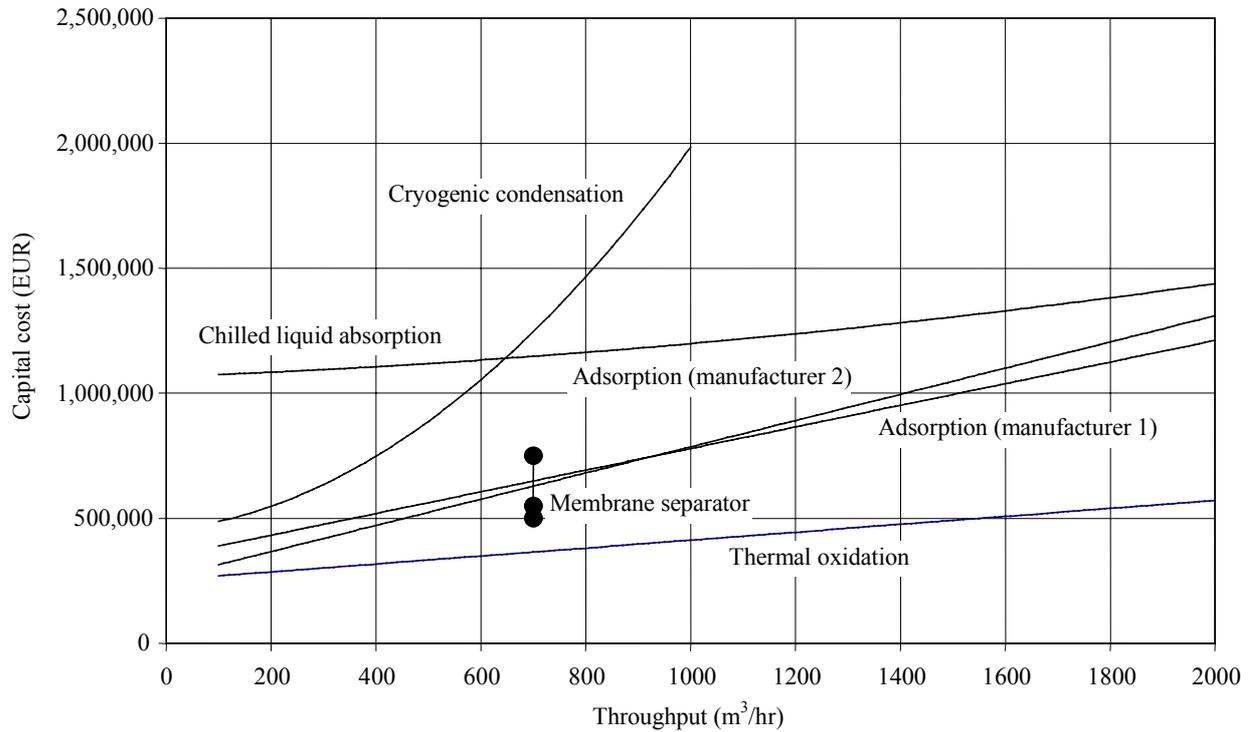
## 8 Cost Analysis

### 8.1 COST PER TONNE ABATED

#### 8.1.1 Capital costs

Figure 15 below illustrates graphically the capital cost versus throughput relationships derived above.

**Figure 15 - Capital costs of abatement technologies**



**Pipelines costs**

Equipment suppliers and other sources indicate that the cost of the pipeline and associated booster pumps, detonation arrestors etc can vary between about the same as the control equipment up to about five times the cost of the VRU plant depending on the distance of the VRU from the berth.

**8.1.2 Operating costs**

The operating costs of the technologies consist of a component that is independent of throughput, which is in the range 5,000 to 40,000 EUR/year, and a variable component, support fuel for incineration and liquid nitrogen for cryogenic condensation.

**Table 15 - variable cost (EUR/te(loader))**

Technique	Cost element	Cost (EUR/te loaded)
Thermal oxidation	Support fuel	0.05
Chilled liquid absorption	Electric power	0.059
Cryogenic condensation	Liquid nitrogen	0.05

These are all roughly equal to 0.05 EUR/te loaded. For the different categories of liquid this equates to:

**Table 16 - variable cost (EUR/te(abated))**

Cargo	Variable Cost (EUR/te(abated))
Gasoline	208
Other petroleum products and chemicals	5,000
Crude	50

### 8.1.3 Annualisation of capital costs

To compare the cost of an emission reduction measure with its resulting benefit, it is necessary to combine the capital and operating costs into single overall annual cost. The EEA Guidelines for defining and documenting data on costs of possible environmental protection measures [EEA, 1999] recommends that a discounted cash flow technique be used, specifically:

*Total annual cost* = the *present value* of the total cost stream (*investment expenditure* plus *net operating and maintenance costs*)  $\times$  *capital recovery factor*.

The capital recovery factor, A, is given by:

$$A = \left[ \frac{r(1+r)^n}{(1+r)^n - 1} \right] \quad (1)$$

where r is the discount rate (assumed to be 6% in this study) and n is the lifetime of the plant in years (assumed to be 20 years). This formula is derived by equating the capital cost of the equipment with the present value of n equal annual payments made in successive years, the first payment being made at the end of year 1. This annual payment is the annualised capital cost.

If the annual operating and maintenance costs are expected to remain constant in real terms over the useful lifetime of the pollution control equipment, then the total annual cost of the equipment may be determined by first computing the annual capital cost of the equipment using the capital recovery factor, and then adding to this the annual operating and maintenance costs. This approach has been adopted in this study. When n = 20 and r = 6%, A = 0.0872

**Table 17 - Calculation of annualised cost (EUR)  
[not including variable cost in Table 16 above]**

	Products Terminal		Crude Terminal	
	2,000 m <sup>3</sup> /hr		15,000 m <sup>3</sup> /hr	
	lower	upper	lower	upper
Capital Cost (EUR)	1.20E+06	1.40E+06	8.00E+06	1.50E+07
Transfer Pipeline System & Infrastructure	1.50E+06	4.80E+06	1.20E+07	6.00E+07
Total Capex	2.50E+06	6.00E+06	2.00E+07	7.50E+07
Annualised Capital Cost	2.18E+05	5.23E+05	1.74E+06	6.54E+06
Annual Operating Cost	1.00E+04	4.00E+04	1.00E+04	4.00E+04
Total Annualised Cost	2.28E+05	5.63E+05	1.75E+06	6.58E+06

Product loading terminals range in size from about 100,000 tonnes per year to about 2,500,000 with at least one being as big as 5,000,000 tonnes/year. The size of abatement plant needed is determined by the maximum loading rate of the ship rather than by the throughput of the terminal. To calculate the cost effectiveness we make the following assumptions:

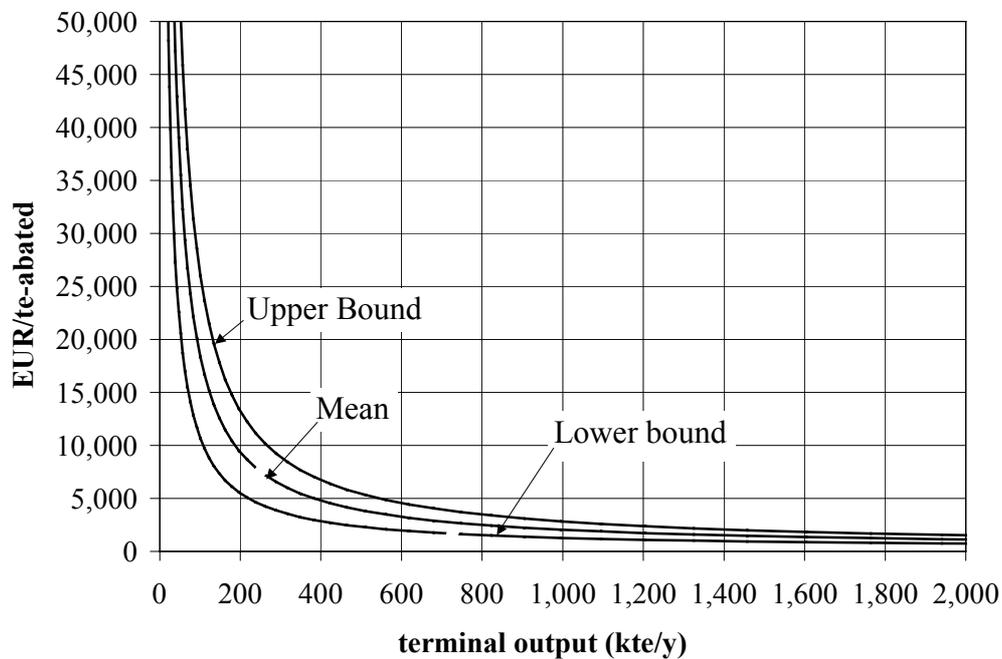
- Each product terminal will need one vapour recovery unit of 2,000m<sup>3</sup>/h capacity
- Each crude terminal will need one vapour recovery unit of 15,000m<sup>3</sup>/h capacity
- These requirements are independent of terminal throughput

The annualised cost of a 2,000m<sup>3</sup>/h plant is in the range 228,000 to 563,000 EUR/year  
 The annualised cost of a 15,000m<sup>3</sup>/h plant is in the range 1,750,000 to 6,580,000 EUR/year

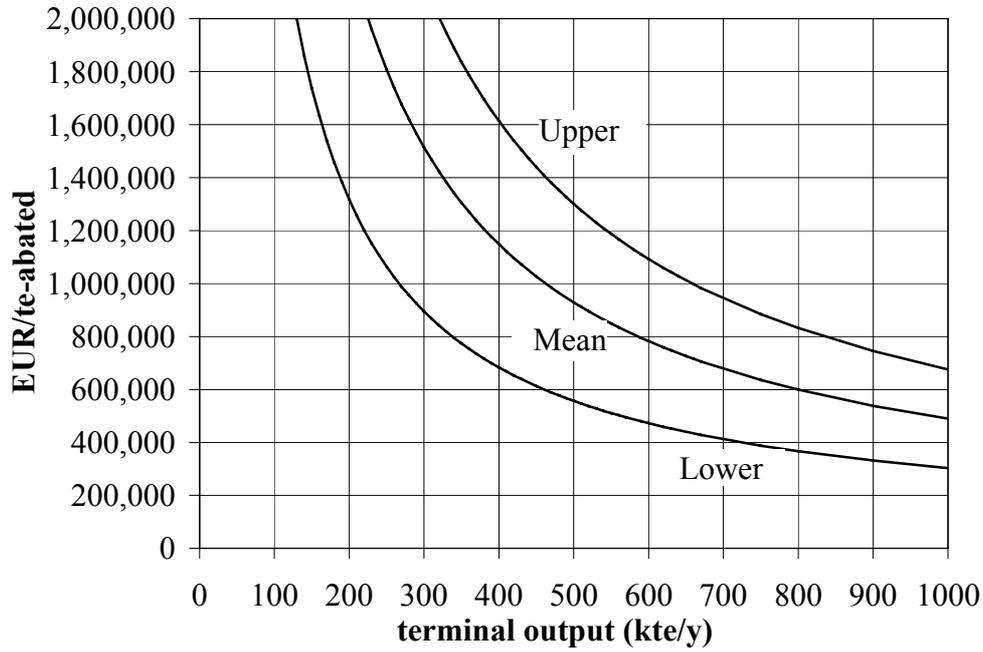
These costs do not include the variable cost of 0.05 EUR/tonne loaded. This variable cost is taken into account by converting to cost per tonne abated and adding it to the cost per tonne abated calculated from the annualised cost as a function of throughput. The graphs in Figures 16, 17 and 18 below include this.

The wide variation in cost is because the single most important factor in determining the cost of a vapour recovery system is the geography of the site. Figure 18 shows this relationship for crude oil loading.

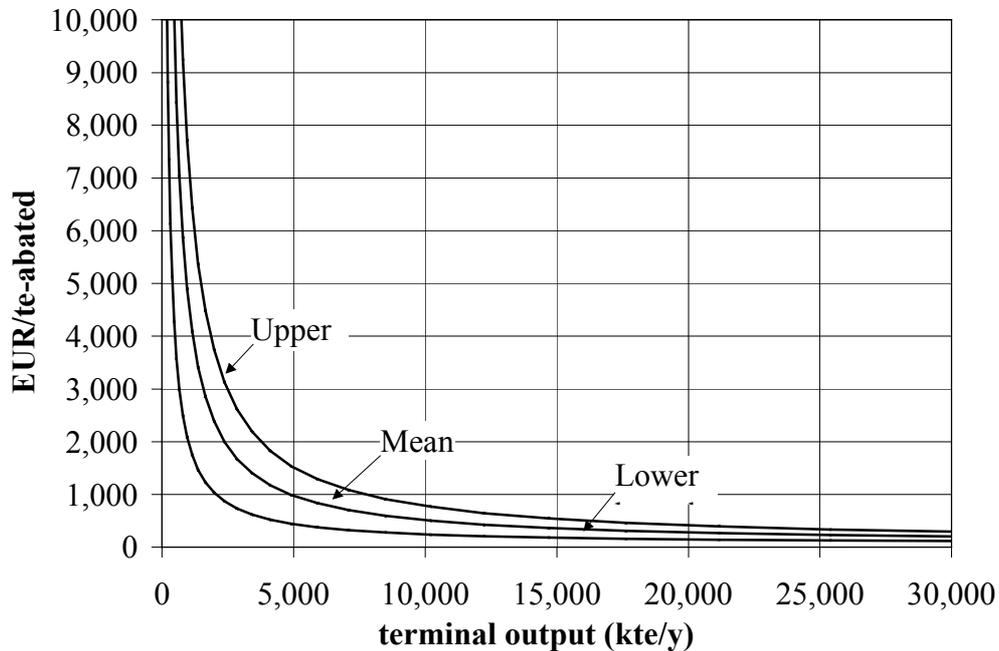
**Figure 16 - cost per tonne abated for gasoline loading as a function of terminal throughput**



**Figure 17 - cost per tonne abated for loading of less volatile products as a function of terminal throughput**



**Figure 18 - cost per tonne abated for loading of crude oil at mainland terminals**



The cost effectiveness for other petroleum products is much lower (ie the cost per tonne abated is much higher) for terminals loading non-gasoline petroleum products and chemicals than it is for terminals loading gasoline and crude oil. This is for two reasons - firstly, many of these products are much less volatile, so the VOC emission is much lower per tonne of liquid loaded but the volume of vent gas is the same, consequently, the same size of abatement plant would be required. Secondly, these products are shipped in much smaller

quantities than is gasoline, so abatement plant handling these emissions would have a lower utilisation.

## 8.2 SHIPS VAPOUR COLLECTION SYSTEMS

The cost of fitting a vapour collection system to a ship depends on the facilities already available on the ship. As was mentioned in section 2.2 above, ships that have closed loading systems and inert gas systems can be modified to transfer vapour to the shore at a lower cost than can a ship with no such systems already fitted.

For product and product/crude carriers, we assume that the distribution of ships fitted with these different systems is as shown in Figure 7 on Page 17 above.

To calculate a cost per tonne, we assume that existing ships will be retrofitted over a period of five years and that after that ships are scrapped and replaced with new ones at a rate of 3% of the population per year. We further assume that the cost of fitting a new ship is the same as that of retrofitting an existing one. This is reasonable, as the amount and type of labour and material is the same.

Industry contacts indicate that the approximately cost of fitting vapour collection systems to a ship is approximately 75 kEUR for a ship with closed loading and IGS, 150 kEUR for a ship that has closed loading but no IGS, 200 kEUR for a ship that has IGS but not closed loading and 275 kEUR for a ship with neither closed loading nor IGS.

**Table 18 - Estimated cost of ship board vapour collection systems.**

	Capital cost EUR	Ship population		Turnover rate	Retrofits		Newfits/year	
		%	numbers		No	Cost	No	Cost
Ship fitted with VCS	0	3%	36	3%	36	0	2	0
Closed loading with IGS	75,000	24.3%	292	3%	292	21,900,000	9	675,000
Closed loading without IGS	150,000	21.4%	257	3%	257	38,550,000	8	1,200,000
IGS without closed loading	200,000	2.2%	26	3%	26	5,200,000	1	200,000
no CL or IGS	275,000	49.1%	589	3%	589	162,030,000	18	4,950,000
			<b>1,200</b>			<b>227,625,000</b>		<b>7,025,000</b>

We then calculate a present value of the stream of future costs using a discount rate of 6%. The total cost needed to retrofit existing ships is  $x_A$  and the cost per year of fitting control systems to new ships is  $x_B$ . Assuming that  $1/5$  of the existing ships are retrofitted in each of the allowed 5 years, then the present value of the future cost stream is:

$$PV = \frac{x_A S_{1,5}}{5} + x_B S_{6,\infty}$$

where:  $S_{m,n} = \frac{(1+r)^{n-m+1} - 1}{(1+r)^{n+1} - (1+r)^n}$  and  $r$  is the discount rate (= 6%). Consequently:

$$\Rightarrow S_{1,5} = \frac{(1 + \frac{6}{100})^5 - 1}{(1 + \frac{6}{100})^{5+1} - (1 + \frac{6}{100})^5} = 4.2124 \text{ and } S_{6,\infty} = \frac{1}{(1 + \frac{6}{100})^6 - (1 + \frac{6}{100})^5} = 12.4543$$

For the costs in Figure 17 above PV = 279,259,339 EUR. To calculate the cost per tonne, we then need to re-annualise the present value of the cost. The annual cost, AC, is given by

$$AC = rPV, \text{ therefore, the annualised cost is } 279,259,339 \times \frac{6}{100} = 16,755,560 \text{ EUR.}$$

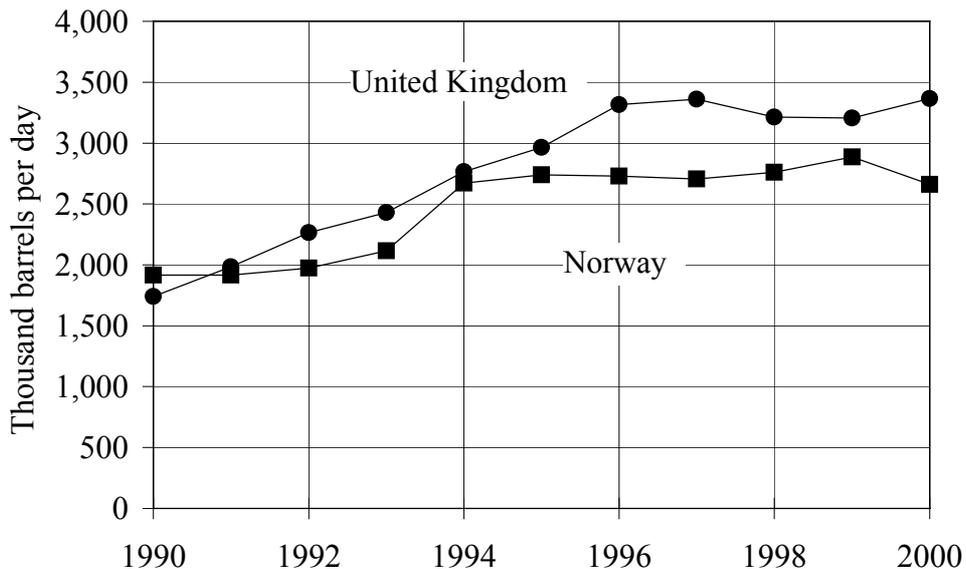
The annual emission from loading petroleum products is approximately 9,000 te/year and if the average efficiency of abatement is 90%, the tonnes abated is 8,100 te. The cost per tonne abated is therefore 2,068 EUR

Therefore, a figure of approximately 2,000 EUR/tonne must be added to the cost per tonne of shoreside equipment to give an overall cost per tonne.

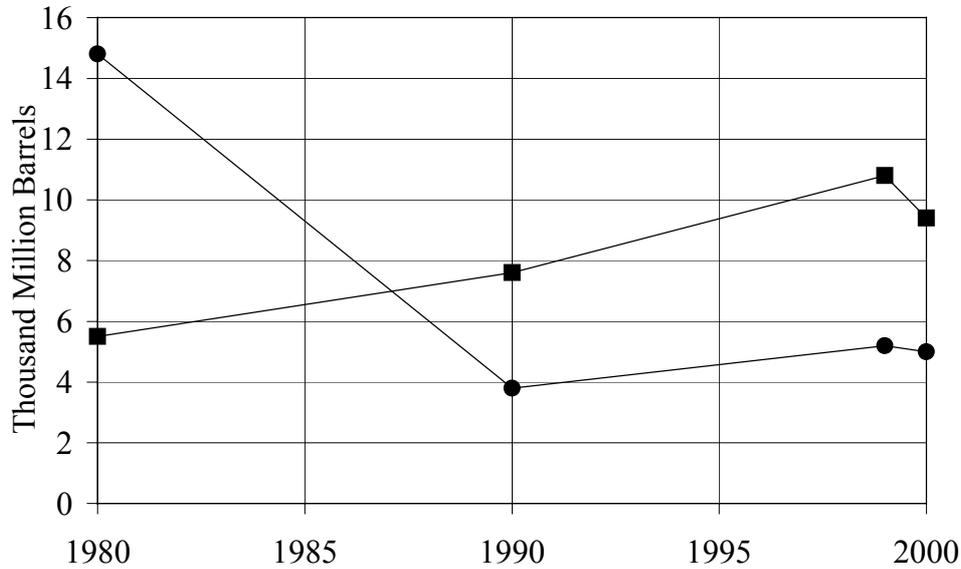
### 8.3 FPSOs AND SHUTTLE TANKERS

The cost effectiveness of measures applied to crude oil loading of crude oil from the North Sea depends on the expected lifetime of North Sea production. This is somewhat uncertain. Figure 19 and Figure 20 below show production and reserves in the UK and Norwegian sectors of the North Sea.

**Figure 19 - North Sea Oil Production, 1990 - 2000 [BP, 2000]**



**Figure 20 - Proven Reserves in the North Sea, 1980 - 2000 [BP, 2000]**



**Table 19 - Reserves and production in 2000 [BP, 2000]**

	<b>Production (2000) 10<sup>3</sup> barrels/day</b>	<b>Proven reserves (2000) 10<sup>9</sup> barrels</b>	<b>Years remaining at current production</b>
<b>UK</b>	2,660	5.0	5.15
<b>Norway</b>	3,365	9.4	7.65

If production carries on at current rates, then UK reserves would last another 5 years and Norwegian reserves would last 7 years. However, it is likely that as reserves are depleted production rates will fall. It is also possible that enhanced oil recovery techniques may be applied, resulting in a greater proportion of the reserves being extracted. These figures are therefore an absolute minimum lifetime of the remaining reserves.

For purposes of estimating the cost effectiveness of measures to reduce emissions from these sources, we assume the following costs, based on the information supplied by UKOOA and summarised in Table 14 above, and lifetimes of 5, 10 and 15 years respectively.

**Table 20 - cost effectiveness of VOC emission reduction from FPSOs derived from data in Table 14.**

	5 year lifetime		10 year lifetime		15 year lifetime	
	lower	upper	lower	upper	lower	upper
Capital Cost (GBP)	2,000,000	8,000,000	2,000,000	8,000,000	2,000,000	8,000,000
Exchange Rate	1.64	1.64	1.64	1.64	1.64	1.64
Capital Cost (EUR)	3,285,000	13,140,000	3,285,000	13,140,000	3,285,000	13,140,000
Discount Rate	6%	6%	6%	6%	6%	6%
Lifetime	5	5	10	10	15	15
Capital recovery Factor	0.2374	0.2374	0.1359	0.1359	0.1030	0.1030
Annualised Capital Cost (EUR)	779,847	3,119,389	446,326	1,785,305	338,233	1,352,931

	5 year lifetime		10 year lifetime		15 year lifetime	
	lower	upper	lower	upper	lower	upper
Annual Operating Cost (EUR)	229,950	919,800	229,950	919,800	229,950	919,800
Total Annualised Cost (EUR)	1,009,797	4,039,189	676,276	2,705,105	568,183	2,272,731
Oil Production (te)	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000
Emission (te)	2,000	2,000	2,000	2,000	2,000	2,000
Abatement Efficiency	70%	50%	70%	50%	70%	50%
Tonnes Abated	1,400	1,000	1,400	1,000	1,400	1,000
Cost Effectiveness (EUR)	721	4,039	483	2,705	406	2,273

**Table 21 - cost effectiveness of VOC emission reduction from Shuttle Tankers derived from data in Table 14.**

	5 year lifetime		10 year lifetime		15 year lifetime	
	lower	upper	lower	upper	lower	upper
Capital Cost (GBP)	5,000,000	10,000,000	5,000,000	10,000,000	5,000,000	10,000,000
Exchange Rate	1.64	1.64	1.64	1.64	1.64	1.64
Capital Cost (EUR)	8,212,500	16,425,000	8,212,500	16,425,000	8,212,500	16,425,000
Discount Rate	6%	6%	6%	6%	6%	6%
Lifetime	5	5	10	10	15	15
Capital recovery Factor	0.2374	0.2374	0.1359	0.1359	0.1030	0.1030
Annualised Capital Cost (EUR)	1,949,618	3,899,236	1,115,816	2,231,631	845,582	1,691,163
Annual Operating Cost (EUR)	574,875	1,149,750	574,875	1,149,750	574,875	1,149,750
Total Annualised Cost (EUR)	2,524,493	5,048,986	1,690,691	3,381,381	1,420,457	2,840,913
Oil Production (te)	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000
Emission (te)	2,000	2,000	2,000	2,000	2,000	2,000
Abatement Efficiency	70%	50%	70%	50%	70%	50%
Tonnes Abated	1,400	1,000	1,400	1,000	1,400	1,000
Cost Effectiveness (EUR)	1,803	5,049	1,208	3,381	1,015	2,841

The cost effectiveness of reducing emissions from FPSOs and shuttle tankers is therefore roughly in the range 400 to 4,000 EUR/tonne for FPSOs and 1,000 to 5,000 EUR/tonne for shuttle tankers, depending on the expected lifetime of the equipment.

## 9 Cost Effectiveness Comparisons

Figure 21, Figure 22 and Figure 23 show national cost curves calculated by the International Institute of Applied Systems Analysis (IIASA), Laxenberg, Austria. These data were downloaded from the IIASA web site ([http://www.iiasa.ac.at/~rains/voc\\_review/single.html](http://www.iiasa.ac.at/~rains/voc_review/single.html)).

The curves were calculated by IIASA using their “RAINS” integrated assessment model in support of the development of the technical basis for the recent UN ECE protocol signed at Gothenberg and the European Commission’s proposed Directive setting national emission

ceilings for emissions of nitrogen oxides, sulphur dioxide, ammonia and VOCs<sup>6</sup>. Integrated assessment modelling has been used as a basis to develop cost-effective strategies to address the environmental problems of acidification, eutrophication and ground-level ozone.

The curves are for 2010 based on a Business As Usual (BAU) scenario from 1999 (ie post UNECE VOC protocol). They represent the cost of achieving reductions in VOC emissions in 2010 assuming that no further measures have been taken subsequent to those necessary to achieve the emission reductions specified in the UNECE protocol.

Following adoption of the Commission's proposal the Council has reached political agreement on a set of less stringent emissions ceilings as set out in its Common Position of 7 November 2000<sup>7</sup>. Table 20 above shows the marginal cost, taken from the IIASA cost curves, of the last measure in the sequence required to meet National Emission Ceilings for NMVOC in the Commission's original proposal and in the Council's Common Position. These costs can then be compared with the marginal costs of controlling emissions from the various categories of ship loading considered in this study. At this stage it is difficult to predict the exact emission ceilings which will be finally adopted by the Council and the European Parliament. The Ceilings in the Common Position and the Commission's original proposal span the possible range though the final outcome is more likely to be nearer the Council's Common Position.

---

<sup>6</sup> COM(1999) 125 final; OJ C 56E, 29.2.2000, p. 34

<sup>7</sup> Common Position (EC) No 51/2000 adopted by Council on 7 November 2000, OJ C 375, 28.12.2000, p. 1

**Table 22 - Marginal cost of last measure required to meet the various National Emission Ceilings for NMVOC**

	<b>Commission Proposal<sup>8</sup></b>		<b>Common Position</b>	
	<b>Emission Ceiling (kte/y)</b>	<b>Marginal Cost of Last Measure in sequence (EUR/te)</b>	<b>Emission Ceiling (kte/y)</b>	<b>Marginal Cost of Last Measure in sequence (EUR/te)</b>
<b>Austria</b>	129	2,835	159	437
<b>Belgium</b>	102	4,265	139	900
<b>Denmark</b>	85	269	85	269
<b>Finland</b>	110	269	130	10
<b>France</b>	932	900	1,050	459
<b>Germany</b>	924	1,416 <sup>(9)</sup>	995	971 <sup>(10)</sup>
<b>Greece</b>	173	414	261	-18
<b>Ireland</b>	55	60	55	60
<b>Italy</b>	962	655	1,159	269
<b>Luxembourg</b>	6	479	9	0
<b>Netherlands</b>	156	1,255	185	650
<b>Portugal</b>	102	553	180	0
<b>Spain</b>	662	269	662	269
<b>Sweden</b>	219	900	241	479
<b>UK</b>	964	4,265	1,200	658

The marginal costs in Table 20 above vary widely from country to country. This reflects the different mix of industrial activities in the different countries as well as the different emission ceilings that have been set.

The marginal costs of the last measure required for the attainment of the national VOC emissions ceilings in the Commission's original proposal vary between €60 to €4,300 per tonne of VOC abated (where the highest values in those geographic areas where VOC control is most effective in abating the formation of ground level ozone). The costs for all but two countries (UK & Belgium) are less than €3,000 per tonne of VOC abated.

The marginal costs of the last measure required for the attainment of the national VOC emissions ceilings in the Council's Common Position are in the range €-18 to €1,746 per tonne where the costs for all but three countries in the EU being less than €500 per tonne of VOC abated.

<sup>8</sup> Optimised ceilings in EU15 with ceilings for non-EU countries at reference level (not including Gothenburg).

<sup>9</sup> Combined result from IIASA cost curves for Old Länder (Sector Code DEGR\_NEW, Control Technology LTPP, marginal cost 1,531 EUR/te, total cost 51.21 MEURO, emission abated 33.4 kte) & New Länder (Sector Code D\_REFDEP, Control Technology IFC+ST\_IAS, marginal cost 957 EUR/te, total cost 8.01 MEURO, emission abated 8.37 kte).

<sup>10</sup> Combined result from IIASA cost curves for Old Länder (Sector Code ARCH\_P, Control Technology EMU+WB+HS, marginal cost 1,051 EUR/te total cost 1.57 MEURO, emission abated 1.5 kte) & New Länder (Sector Code D\_REFDEP, Control Technology IFC+ST\_IAS, marginal cost 957 EUR/te, total cost 8.01 MEURO, emission abated 8.37 kte).

To recap, the total costs of installing both ship-based and shore based equipment to abate VOC emissions from the loading of gasoline lie in the range €3,300 to €19,000 per tonne of VOC abated (again for terminals with a throughput of between 2.5 million to 100,000 tonnes of gasoline per annum). Other petroleum products and organic chemicals generally have lower vapour pressures than gasoline and are generally shipped in smaller quantities. For these reasons it is unlikely that the marginal costs of vapour treatment for these operations will be cost-effective in comparison to controls on the loading of gasoline.

The estimated costs of loading crude oil at mainland terminals lie in the range of €300 to €2,000 per tonne of VOC abated for terminals with a throughput of crude oil in the range 30 million to 2.5 million tonnes per annum. There are also additional costs associated with the appropriate ship-based modifications (ca. € 2,000 per tonne of VOC abated). The costs associated with the modification of Floating Production, Storage & Offtake vessels (FPSOs) and shuttle tankers have been estimated as being in the range €400-4,000 and €1,000-5,000 per tonne of VOC abated respectively, depending on the assumptions made concerning the expected lifetime of North Sea oil reserves.

The cost-effectiveness of measures to abate emissions of VOC associated with the loading of gasoline and crude oil onto ships is generally less favourable than the most expensive measures needed to meet the national emission ceilings contained in the Council's Common Position on the NEC proposal.

Figure 21 - IIASA cost curves for VOC abatement - total costs

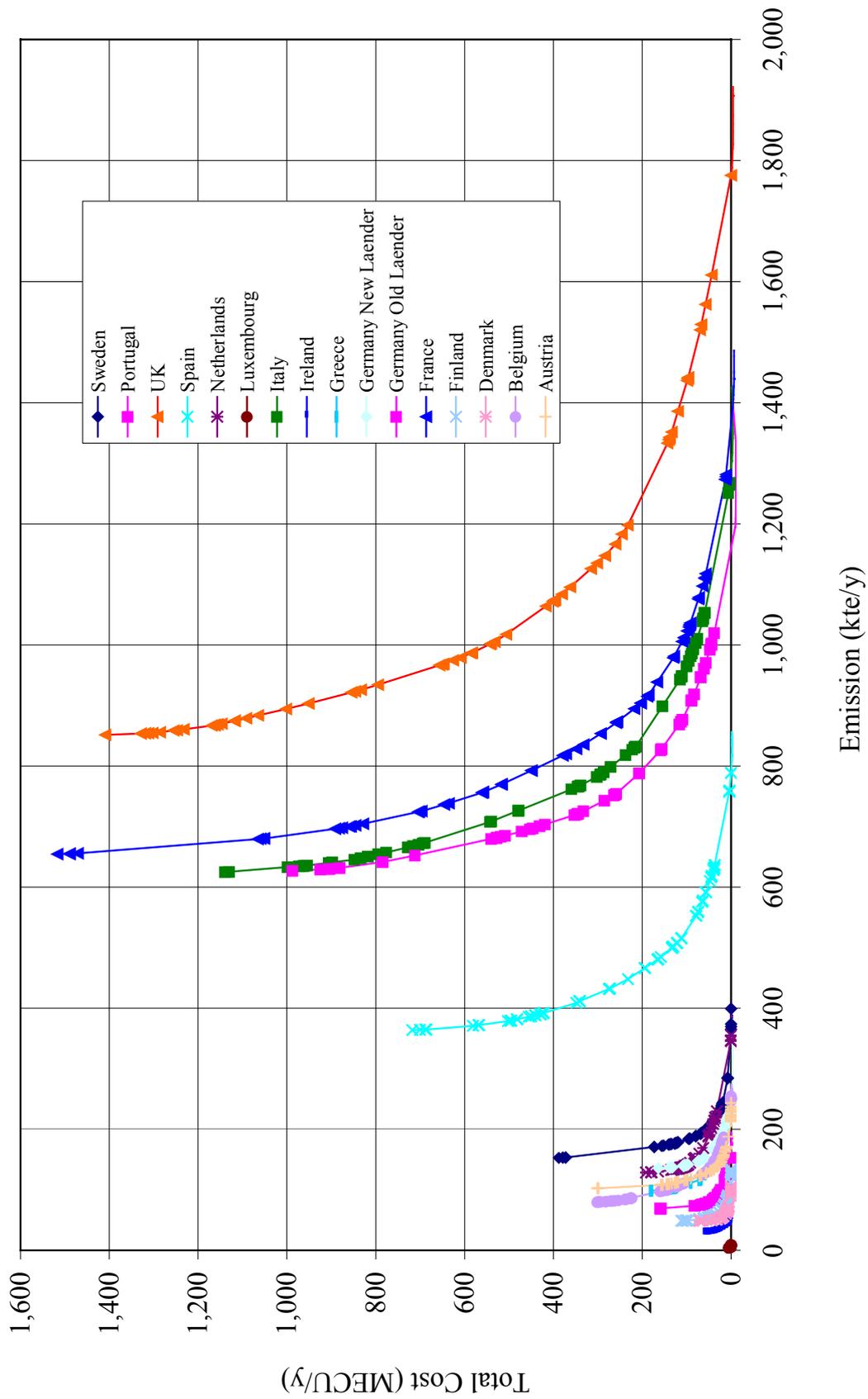


Figure 22 - IIASA cost curves for VOC abatement - marginal cost

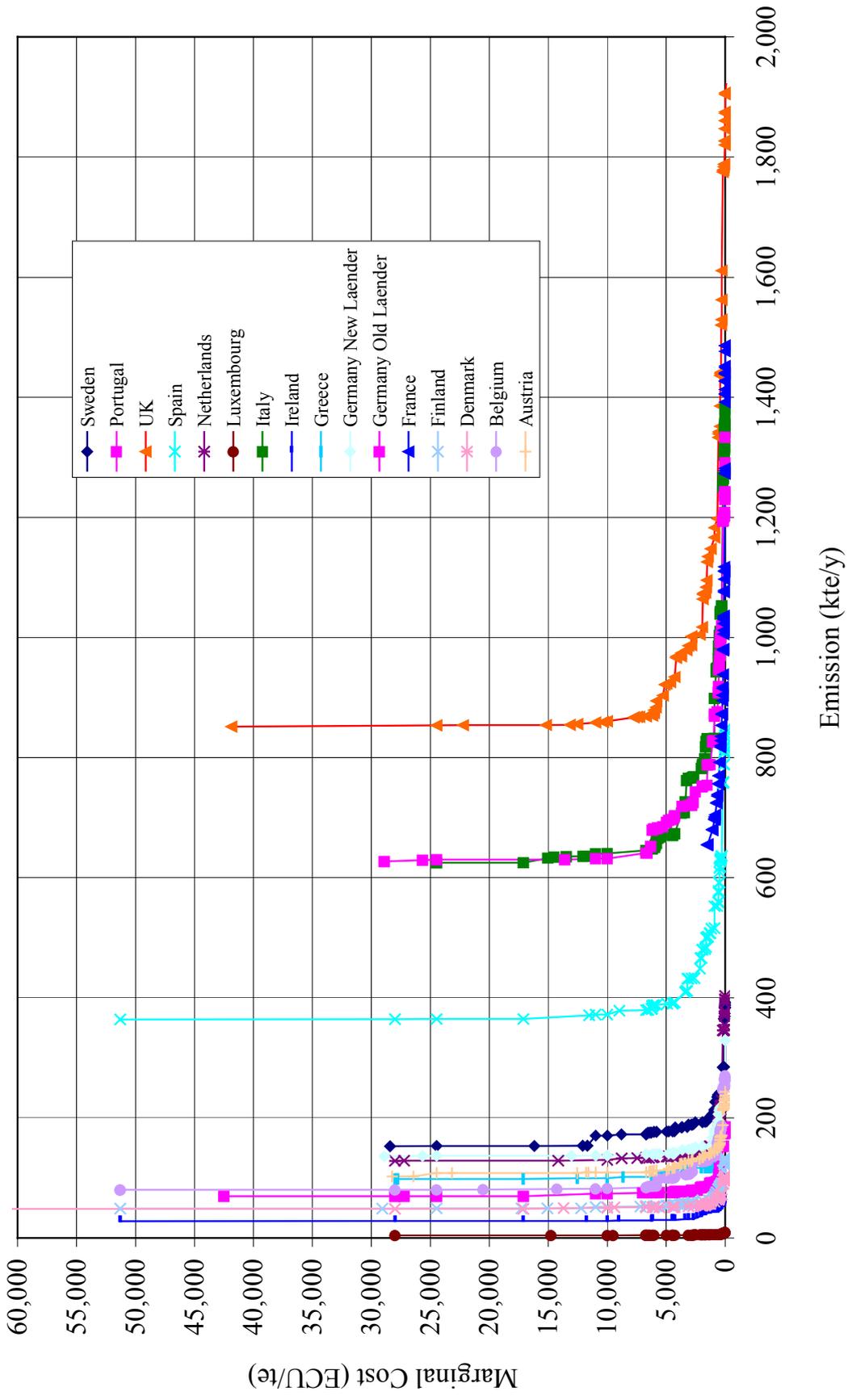
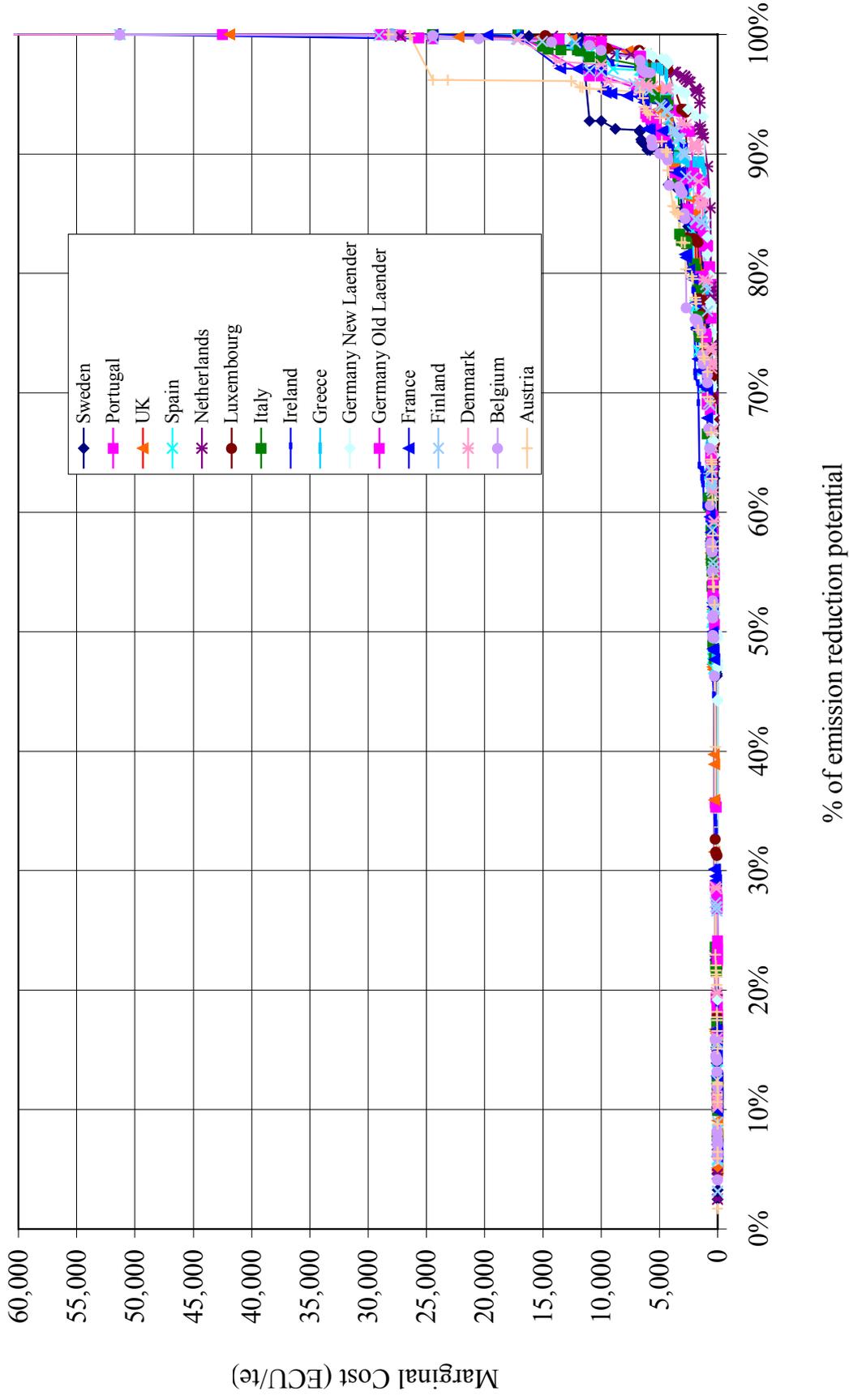


Figure 23 - Marginal cost as a function of the percentage of the total emission reduction potential achieved.



## 10 Safety Standards

The IMO Marine Safety Committee (MSC) issued Circular No 585, “Standards for Vapour Emission Control Systems” in April 1992. These are based on a set of standards published by the US Coast Guard in 19??.

To minimise risk in any activity it is necessary to identify the things that can go wrong (hazards) in advance. A hazard cannot be reduced or eliminated if it is not foreseen. Risk assessment therefore involves the following steps:

1. Identify the potential hazards
2. Prioritise them according to severity and likelihood
3. Identify measures that can be taken to reduce the likelihood of the most serious risks

To assess the effectiveness of the MSC Circular 585 in reducing the risk of safety incidents we therefore need to answer two questions:

1. Has it identified all the significant hazards?
2. Are the measures it recommends to reduce the probability of these hazards sufficient?

MSC 585 identifies the following hazards:

1. Fire or explosion due to ignition of flammable vapour/air mixtures
2. Tank rupture caused by overpressure or vacuum
3. Overfilling (which could lead to spillage and consequent marine pollution or to liquid being sent to the vapour treatment equipment)
4. Condensate build up in vapour return line
5. Misconnection of vapour return line to a shore side liquid loading line
6. Inadvertent addition of inert gas to the vapour return system
7. Mixing of cargoes that react with each other leading to evolution of heat or gases leading to tank rupture or explosion
8. Fouling of equipment due to particles from IG systems
9. Fires, explosions or other hazards caused by the effect of hazard conditions in neighbouring plant or equipment (eg a fire in a tank located near the VRU)

The measures proposed to alleviate these are listed in Table 23 below.

**Table 23 - Hazards addressed by MSC Circular 585 and specific measures included to mitigate them.**

<b>Hazard</b>	<b>Measure required in MSC Circ 585</b>	<b>Comments</b>
<p>1 Ignition of flammable vapour/air mixtures</p>	<p>2.2.4 A ship's vapour return lines should be electrically continuous with the hull.                  2.7.4 A cargo tank should not be opened to the atmosphere while the tank is connected to a vapour emission control system.                  3.1.1 A vapour emission control system's design and installation should eliminate potential tanker overspill hazards, tanker overpressure and vacuum hazards and sources of ignition to the maximum possible extent.                  3.1.4 Electrical installations in hazardous locations should be to the satisfaction of the national authority to the intended service.                  3.2.4.1 Vapour collection hose or arm should be electrically continuous.                  3.2.5 The terminal vapour connection should be electrically insulated from the tanker vapour connection using a insulating flange or a short section of insulating hose.                  3.4.1 Vent gases should be kept outside the flammable range by inerting, enriching or dilution where this has been identified as necessary in the hazard study. A safety system should be provided whereby the vapour shutoff valve is closed if the signal from an oxygen or hydrocarbon analyser indicates that the gas is near the flammable limits.                  3.2.4 If other explosion prevention systems are in place that make use of monitoring of other physical parameters such as temperature, pressure or flow rate, then if this system indicates an unsafe condition, the vapour cut-off valve should be closed.                  3.4.3 A detonation arrester should be fitted in close proximity to the terminal vapour connection.                  3.4.4 Detonation arrestors should be tested in accordance with a test standard acceptable to the competent shoreside authorities.</p>	<p>This is the most serious hazard that can occur. Some of these requirements are somewhat vague. They may not be sufficient to prevent fires or explosions in all circumstances. 3.1.1 is comprehensive but vague.</p>
<p>2 Overpressure or vacuum</p>	<p>2.6.1 Each cargo tank should have a pressure venting system capable of accommodating a flow rate equal to 1.25 times the loading rate.                  2.6.2 Each cargo tank should have a vacuum relief system capable of preventing a vacuum greater than the design value for the tank when the tank is being emptied at maximum unloading rate.                  2.6.3 a prototype of each PV venting device should be tested for venting capacity.                  2.6.4 Each tanker that is fitted with a vapour collection system that is common to two or more tanks should have a pressure-sensing device. This should have a high pressure alarm set at the pressure of the pressure relief valve and a low pressure alarm set at not less than atmospheric.                  2.2.6 the vapour collection system should not interfere with the proper operation of the cargo venting system.                  2.7.2 - The rate of cargo transfer should not exceed the maximum allowable as determined by the lesser of the following:</p>	<p>This is the second most serious hazard that could occur. This is a very long list of measures and it is difficult to see how tank rupture due to overpressure or vacuum could occur if all these recommendations are in operation.</p>

Hazard	Measure required in MSC Circ 585	Comments
	<p>1.25 the venting capacity of the pressure relief valves in the cargo tank divided by the vacuum relieving capacity of the vacuum relief valve in the cargo tank venting system</p> <p>the rate based on pressure drop calculations such that the pressure in any cargo tank does not exceed 80% of the opening set pressure of the pressure relief valves in the cargo tank.</p> <p>3.1.3 Vapour collection system piping, fittings and equipment should be suitable for the intended service. Material should generally be of steel or equivalent.</p> <p>3.3.1 A terminals vapour emission control system should have the capacity to handle at a rate not less than the facility's maximum loading rate multiplied by a factor of at least 1.25.</p> <p>3.3.2 A terminals vapour emission control system should be capable of maintaining the pressure in the settings of the tanks pressure and vacuum relief valves at any transfer rate <math>\leq</math> to the maximum transfer rate.</p> <p>3.3.3 each terminal main branch line at a berth should be provided with a pressure sensing device located as close as practical to the terminal vapour connection. This device should come into operation prior to the pressure in the cargo tanks going outside their allowed range,, give a visible and audible alarm to the facility operator and provide an agreed signal for sequential shutdown of onshore pumps.</p> <p>3.3.4 Safety features such as back flow preventer and pressure relief device should be provided to ensure that a malfunction in an inerting, enriching or diluting system does not overpressure the tanker.</p> <p>3.3.5 If a compressor, blower or eductor unit is used to draw vapours from the tanker, a vacuum relief device should be installed in the vapour collection line between the between the unit and the terminal vapour connection. It should have a capacity greater than that of the compressor, blower or eductor.</p>	
3	<p>Overfilling</p> <p>2.5.1 Each cargo tank should be equipped with an overflow control system.</p> <p>2.5.2 Technical specifications for overflow control system - not listed in detail here</p> <p>2.7.3 A cargo tank should not be filled higher than the level at which the overflow alarm is set.</p> <p>2.7.6 unless equipped with an automatic self-test feature, each tank overflow control system alarm should be tested fro proper operation before the start of cargo transfer.</p>	<p>This seems like a sufficient set of measures to prevent tank overfilling. The system test before each loading operation is critical.</p>
4	<p>Condensate build up in vapour return line</p>	<p>Maybe some form of monitoring for liquid in the vapour line would be useful and also some form of liquid trap to prevent entrained liquid passing beyond a certain point.</p>

<b>Hazard</b>	<b>Measure required in MSC Circ 585</b>	<b>Comments</b>
5 Misconnection of vapour return line to a shore side liquid loading line	<p>2.2.2 If a tanker simultaneously collects vapours that are incompatible, they should be kept separate throughout the entire vapour collection system.</p> <p>2.3.2 The end of each vapour collection pipe or vapour collection hose should be readily identifiable to prevent misconnection.</p> <p>2.3.3 Each tanker vapour collection flange should conform to the appropriate industry standard.</p> <p>3.2.2 The end of each vapour collection pipe, vapour collection hose or vapour collection arm should be readily identifiable to prevent misconnection.</p> <p>3.2.3 each terminal vapour collection flange should conform to the provisions in paragraph 2.3.3.</p> <p>2.9.1.1 Tanker transfer procedures should include a line diagram of the tanker's vapour collection piping indicating the location and purpose of all control and safety devices.</p>	
6 Inadvertent addition of inert gas to the vapour return system	<p>2.2.5 When inert gas distribution is used for vapour collection piping is used for vapour collection piping, means to isolate the inert gas supply from the vapour collection system should be provided.</p> <p>2.7.5 If the tanker is equipped with an inert gas system the isolation valve required by paragraph 2.2.5 should remain closed during vapour transfer.</p>	
7 Mixing of reactive cargoes	<p>2.2.2 if a tanker simultaneously collects vapours from cargoes that can react in a hazardous manner with other cargoes, it should keep these incompatible vapours separate throughout the entire vapour collection system.</p> <p>3.1.7 If a terminal simultaneously processes vapour from cargoes that react in a hazardous manner with other cargoes it should be designed to keep these incompatible vapours throughout the entire system.</p>	
8 Fouling of equipment due to particles from IG systems		
9 Fires, explosions or other hazards caused by the effect of hazard conditions in neighbouring plant or equipment (eg a fire in a tank located near the VRU)	<p>Due consideration should be given to the effect of external sources of heat generated as a result of fire or proximity of other equipment on the components of the vapour emission control system.</p>	

### 10.1.1 Hazard Study

In addition to these measures, the Circular also requires that before the construction of a vapour collection and control system a “hazard study” should be performed and that this should conform to the following requirements:

The system should be capable of continuous safe operation when receiving cargo vapour from tankers over the full range of transfer rates expected at the terminal

The system should be provided with the proper alarms and automatic control systems to prevent unsafe operation

The system should be equipped with sufficient safety systems to minimise damage to personnel, property and the environment if an accident were to occur

The operating procedures minimise the potential for improper or unsafe operation by personnel.

This is rather vague and we recommend that such studies should be carried out according to best current standards, such as the HAZOP procedure or better. The study should aim to identify all possible hazards and the chain of events that could lead up to them. It should prioritise hazards according to risk (the product of a measure of likelihood and a measure of severity). It should then try to identify measures to interrupt the chain of events leading up to the possible hazards, preferably at more than one place. Most attention should be focussed on the highest risks.

### 10.1.2 Procedures

MSC Circular 585 lists the following requirements for transfer procedures:

2.9.1 Tanker transfer procedures should contain information on the tankers vapour collection system including:

1. A line diagram of the tanker’s vapour collection piping indicating the locations and purpose of all control and safety devices
2. The maximum allowable transfer rate as limited by the venting capacity of the pressure or vacuum relief valves or any other factor that might limit the loading rate.
3. The maximum pressure drop in the vessel’s vapour collection system for various collection rates
4. The relief settings of each pressure or vacuum relief valve
5. Pre-transfer procedures
6. Procedures to be followed in the event of a fault during vapour collection operations

These requirements leave a lot to the discretion of the ship operator and could usefully be made more precise in terms of specific requirements for loading at terminals with vapour emission control.

No recommendations are given for procedures that should be followed by shore-side personnel. This is a serious omission.

### 10.1.3 Training

MSC Circular 585 specifies training requirements for ship’s personnel but not for shore side personnel.

## 10.2 HAZARDS NOT IDENTIFIED IN MSC CIRCULAR 585

A thorough exploration of possible hazards not already identified in MSC Circ. 585 would be an involved task, however, a number that come immediately to mind are:

- Exposure of personnel to hazardous substances
- Runaway exothermic reactions in vapour recovery equipment
- Injuries to personnel through falls, tripping, burns, asphyxiation etc
- Freezing of liquids in cold weather leading to blockages of lines
- Formation of ice in lines due to adiabatic expansion when pressure is reduced

These are all hazards whose effect is mainly on the shore side. MSC Circ. 585 does not, therefore, address all the potential hazards and the possible chains of events that could lead up to them.

## 10.3 CONCLUSIONS AND RECOMMENDATIONS

MSC Circular 585 includes a large number of safety precautions that should, if followed correctly, greatly reduce the likelihood of serious incidents occurring. However, no set of safety procedures is ever perfect and we recommend that the European Commission should promulgate a set of safety standards similar in scope to that of MSC Circular 585 but more precise in its requirements.

MSC Circular 585 is much more comprehensive in its treatment of hazards that may result in damage to the ship than it is in its treatment of hazards that may result in damage to shoreside facilities and personnel. This may be due to its origins in the shipping industry. Any EU safety standards should give equal attention to ensuring safety on the shore side.

Shell Oil (reported in [Jeffery, 1998] p 134) say that a number of incidents have occurred at some of their US facilities. These include:

- Tank ruptures resulting from line blowing operations, excessive loading rates and malfunctioning PV relief valves.
- Explosions have resulted from inadequate maintenance of inerting and detonation arrestment equipment.

However, the provisions in MSC 585 should have been sufficient to prevent these incidents. Avoidance of excessive loading rates and ensuring correct operation of PV valves is given a lot of attention in the circular. Their reported occurrence suggests that the standards were not being followed in these circumstances. However, it does suggest that provisions are necessary to have multiple lines of defence so that if a particular procedure is not carried out properly due to human error then there are back up systems in place that could prevent an incident that would otherwise have occurred. Any EU safety standards should ensure the provision of multiple lines of defence so that the chain of events leading up to a hazard situation is broken in as many places as possible.

We recommend that an EU safety standard should be drawn up by a competent organisation and should start by obtaining, collating and examining records of incidents, and reports of investigations into those incidents, that have occurred anywhere in the world where marine vapour emission control equipment has been installed. These records should form the basis of

a hazard assessment, which in turn should form the basis of a set of recommendation for safety standards.

Some particular requirements that come immediately to mind that could usefully be incorporated into such a standard are:

That the hazard study required before the implementation of a new vapour emission abatement system should conform to a recognised standard such as HAZOP.

That scope for the effects of human error should be minimised by:

- Designing systems to make it physically impossible or at least less likely to carry out some dangerous actions by mistake (eg making the flange on a vapour return line incompatible with that on a liquid loading line, having an interlock system to prevent loading starting when inspection and other hatches are open and so on)
- Having clear understandable and effectively enforced procedures.
- Ensuring that personnel are effectively trained.

That fail-safe characteristics should be designed into the system wherever possible.

That more than one line of defence against hazard conditions should be incorporated into safety systems (eg an automatic control system to maintain safe working conditions, an independent shut down system in the event of failure of the automatic control system and physical mitigation measures such as detonation arresters, relief valves etc)

That all safety systems should be subject to regular inspection, testing and maintenance.

All safety critical measurement instruments (for eg temperature, pressure, oxygen or VOC concentration) should be installed in sets three instruments in parallel and the control system should use the average of the two instruments that are most nearly equal as the control input (ie the two out of three protocol).

All safety critical measurement instruments should be regularly calibrated.

Records should be kept of all incidents involving vapour recovery systems. These should be collated by the Commission and used in a regular review cycle of the safety standards.

# 11 Legislation

## 11.1 USA

The USA's legislation regulating air emissions is derived from the Clean Air Act [USEPA, 1993]. This was originally passed in 1963 but currently in force is a 1970 version of the Act that was substantially amended in 1990 (the 1990 Clean Air Act Amendments). The 1970 Clean Air Act as amended in 1990 (often called the 1990 Clean Air Act) set up a framework for reducing air pollution. The Act defines two categories of air pollutant, "criteria" and "hazardous".

There are six criteria air pollutants:

- Ozone
- Nitrogen Dioxide
- Carbon Monoxide
- Particulate Matter (PM<sub>10</sub>)
- Sulphur Dioxide
- Lead

183 substances have been designated as hazardous air pollutants (HAPs) and of 11 these, taken together, could make up a significant proportion (possibly in the range 5% to 10%) of gasoline or crude oil vapour. These are:

- Benzene
- Biphenyl
- Cumene
- Ethylbenzene
- Hexane
- Methanol
- Methyl tert-butyl ether
- Naphthalene
- Styrene
- Toluene
- Xylenes (individual isomers or mixtures)

The Act sets up a framework for controlling air pollution, this involves the following steps:

### For "criteria" air pollutants:

1. EPA promulgates National Ambient Air Quality Standards (NAAQS's) and emission standards.
2. States identify non-attainment areas and agree these with the EPA.
3. States then have to take measures to reduce ambient concentrations in the non-attainment areas. A State Implementation Plan (SIP) must be agreed with the EPA. Members of the public are given opportunities to participate in review and approval of

state implementation plans. These plans may involve controlling sources outside the non-attainment areas.

4. If the operator of a source in a non-attainment area wishes to increase emissions, a reduction of a somewhat greater amount of the same pollutant (an *offset*) must be made either at the same site or elsewhere. Offsets may be purchased from other companies in the non-attainment area.
5. New sources have to comply with national emission standards irrespective of whether or not they are in a non-attainment area.

RACT, or Reasonably Available Control Technology, is required on existing sources in areas that are not meeting national ambient air quality standards (i.e., non-attainment areas). BACT, or Best Available Control Technology, is required on major new or modified sources in clean areas (i.e., attainment areas). LAER, or Lowest Achievable Emission Rate, is required on major new or modified sources in non-attainment areas. The specific criteria governing RACT, BACT or LAER vary but the general underlying approach is to require "best control" on all major existing, new, or modified sources.

**For “hazardous” air pollutants:**

The EPA lays down technology-based emission control standards at a federal level. These are called National Emission Standards for Hazardous Air Pollutants (NESHAPs) and are defined for each source sector. The NESHAPs are based on the concept of maximum achievable control technology (MACT). Emission standards are defined in terms of percentage reduction in mass emission (compared with the unabated emission) rather than by stack concentration limits as in Europe.

In addition to the general framework for controlling air pollution described above, the CAA also specifies the imposition of measures to reduce ground level ozone at a federal level. These are contained in Section 183 - “Federal Ozone Measures”. Section (f) of this contains specific requirements for the loading and unloading of ships at marine terminals.

On 19 September 1995 (60 FR 48388) EPA promulgated both RACT and MACT standards for marine tank vessels. Table 24 below reproduces Table 1 of 60 FR 48388, which summarises these standards.

**Table 24 - final standards, national costs, and emission reductions (from Table 1 of 60-FR-48388)**

Section of act	Subcategory	Standard	Emission reduction	Mg/yr Annual cost, \$MM
183(f)	New and existing terminals having throughput of ≥1.6 billion liters per year (10 million barrels per year) of gasoline or ≥32 billion liters per year (200 million barrels per year) of crude oil.	98 percent reduction in emissions if using combustion techniques; 95 percent reduction in emissions if using recovery techniques.	13,000 (VOC), 900(HAP).	20–40.
112	Existing major source terminals having emissions of hazardous air pollutants (HAP) of 10/25 tons per year or more from loading of marine tank vessels	97 percent reduction in HAP emissions	7,000 (VOC), 750 (HAP).	20–40.
112	Existing major source terminals	97 percent reduction in	Impacts	Impacts

	collocated at petroleum refineries having HAP emissions of 10/25 tons per year or more from loading of marine tank vessels; new major source terminals regardless of HAP emissions from marine tank vessel loading (both existing and new sources are regulated under the Gasoline Refineries NESHAP).	HAP emissions for existing sources, 98 percent reduction in HAP emissions for new sources; emissions averaging with petroleum refinery emissions points is allowed.	included in previous sub category data.	included in previous sub category data.
112	Existing major source terminals having HAP emissions of less than 10/25 tons per year from loading of marine tank vessels.	No control	None	None
112	New major source terminals regardless of HAP emissions from marine tank vessel loading.	98 percent reduction in HAP emissions	None	None
112 and 183(f)	Existing major source terminals located more than 0.8 kilometers (0.5 miles) offshore.	No control	None	None
112	New major source terminals located more than 0.8 kilometers (0.5 miles) offshore.	95 percent reduction in HAP emissions	None	None
112 and 183(f)	Alyeska Pipeline Service Company's Valdez Marine Terminal.	98 percent reduction in emissions with maximum throughput limits.	19,000 (VOC), 2,500 (HAP).	20.

These controls apply to gasoline loading or to the loading of any other HAP where the emissions (upstream of any control equipment) are large enough to make it a "major source".

States are not allowed to enforce less stringent standards than these. They may, however, impose more stringent standards if they so which or as part of a state improvement plan for an ozone non-attainment area. The information in Table 25 is from [Jeffery, 1998] not from the original sources.

**Table 25 - Controls on Marine loading in some US States (from [Jeffery, 1998])**

State	Threshold	Required Abatement
California		95% and 5.7 g/m <sup>3</sup>
Delaware	15,000 gallons per day loaded of gasoline (doesn't cover crude)	98% (combustion) or 95% (recovery)
Illinois	May 1 to Sept 15	95%
Louisiana	100 te/y emissions (pv > 1.5 psia)	90%
Massachusetts		
New Jersey	22.7×10 <sup>3</sup> m <sup>3</sup> per year loaded	95%

The US legislation does not appear to directly place requirements on ships. The pressure on ship operators to fit the required vapour collection and transfer facilities is commercial. Without them they would not be able to do business with US terminals.

## 11.2 NORWAY

Norway is a signed the UNECE VOC protocol on 19.11.1991 and ratified it on 07.01.1993.

Per capita emissions in Norway are among the highest in Europe. Even if we disregard emissions originating from transshipping of crude oil, per capita emissions in Norway are somewhat higher than in a number of Central European countries. Norway recognised that it would not be able to meet its target under the 1991 protocol without regulating VOC emissions from crude oil loading.

In 1994, Norwegian emissions of NMVOCs totalled 300 000 tons, and originated mainly from transshipping of crude oil (43 %) and road traffic (24 %). Other important sources include the use of solvents (14 %), the distribution of petrol (3 %) and wood-fired heating (3 %). Total VOC emissions increased throughout the 1980s as a result of the growth in road traffic and the increase in oil production in the North Sea. Emissions rose by 13 % from 1989, the base year for the VOC Protocol, until 1995. The introduction of new emission standards has not offset the growth in emissions from offshore activities.

A major effort was made to find ways of recovering NMVOCs released during transshipping of crude oil at the Sture oil terminal and during offshore loading. Following this, the Norwegian company Statoil has been trialling emission abatement technology at its Sture Oil Terminal (chilled liquid adsorption) and on board shuttle tankers.

Sources in the industry indicate that Norway has legislation requiring controls on crude oil loading, both on shore and off shore, but we were unable to find English language text describing the regulations.

General information on Norwegian Environmental Regulations can be found on the Norwegian Pollution Control Authority web site: <http://www.sft.no/english/>

## 12 Conclusions & Recommendations

Cost per tonne abated depends on the throughput of the terminal. Comparison with National Emission Ceilings depends on the country in which the terminal is located and on whether the ceilings are those in the original Commission proposal or the ones from the Common Position (see Table 22 above). If the latter are used then emission abatement from these sources is cost effective nowhere in the EU compared with the marginal cost of the last measure required for attainment of VOC Emission Ceilings.

However, if the former ceilings are used, and the terminals are in the UK or Belgium (the countries where the marginal cost of the last measure required for attainment of VOC Emission Ceilings is greatest) then gasoline terminals with a throughput of over 1 million tonnes per year and some crude loading terminals could come within the range where they could be considered cost effective.

For purposes of assessing cost effectiveness of emission control options, it is convenient to divide operations into four categories:

1. Gasoline loading
2. Loading of other petroleum products and organic chemicals
3. Onshore crude loading
4. Offshore crude loading

## **12.1 GASOLINE LOADING**

The minimum terminal size above which the cost per tonne abated is less than the marginal cost of the last measure required for attainment of VOC Emission Ceilings in the Commission proposal is approximately 1 million tonnes per year. There are approximately 10 terminals of this size in the EU. However, if the emission ceilings in the Common Position are used, then the marginal cost of the last measure required to meet the Emission Ceilings is everywhere less than the cost per tonne of fitting vapour collection equipment to the ships (see Section 12.5 below). Consequently, not even the largest terminals would attain cost effectiveness when the cost of upgrading the ships is taken into account.

The major factor influencing the cost of recovery is the geography of the site - that is, the distance from the berth to the nearest location at which it is feasible to build a vapour treatment plant. However, if a new terminal were being constructed, this constraint would not apply, as the vapour treatment plant could be located in an optimum position - provided that the berths are not at the end of a long jetty. In such cases it may be cost effective, compared with VOC reduction in other parts of the European economy, to treat vapour at terminals that load 300 to 400 kte/year of gasoline. It is, however, unlikely that new gasoline loading terminals will be built in Europe in the foreseeable future.

## **12.2 OTHER PETROLEUM PRODUCTS AND ORGANIC CHEMICALS**

These products are shipped in much smaller quantities than is gasoline, and they generally have lower vapour pressures. For these reasons, it is unlikely that vapour treatment, in terms of the cost per tonne of VOC abated, will be cost effective compared with the costs of VOC control in other sectors of the European economy.

## **12.3 ONSHORE CRUDE LOADING**

The cost per tonne abated for onshore crude loading is, despite the large size of the abatement plant required, relatively low. This is, as discussed above, mainly due to the relatively high emission factor for crude oil. However, the majority of crude oil loading takes place in areas of good air quality remote from other sources of VOC emission.

## **12.4 OFFSHORE CRUDE LOADING**

The cost per tonne for offshore crude loading is the sum of the cost per tonne for modifying FPSOs and the cost per tonne for modifying shuttle tankers. This is approximately in the range 700 to 5,000 EUR/tonne. This is higher the marginal cost of the last measure required to meet the Common Position Emission Ceilings everywhere in the EU and at the upper end of the range of such costs for the Commission proposal Emission Ceilings.

## 12.5 SHIPS

To make controls effective, all ships loading at controlled terminals must be capable of returning displaced vapour to the shore-side facilities. If a threshold ship size were allowed below which the ship did not have to have vapour return connections then a) the cost effectiveness of the shore side facilities would be reduced because not all the loading could be done with emission abatement and b) there would be an incentive on some operators to shift transport to ships below the threshold.

The legal issues associated with enforcing modifications to ships do not arise because the requirement is on the terminal operator to collect displaced vapour from the ship. If the ship is not equipped to return displaced vapour then the terminal operator cannot load into it. There will thus be a commercial pressure on ship operators to comply or lose business.

## 13 References

- [Jeffery, 1998]: Karl Jeffery, "Bulk Liquids vapour control", report published by Hazardous Cargo Bulletin, July 1998
- [EEA, 1999]: European Environment Agency, 'Guidelines for defining and documenting data on costs of possible environmental protection measures'. EEA Technical report No 27, 1999
- [Concawe, 2000a]: Concawe, Topic Paper - Vapour Emission Controls: Gasoline Loading of Sea-Going Vessels, Supplied by Concawe, 2000.
- [Concawe, 2000b]: CONCAWE Review Volume 9 Number 2 October 2000 (downloadable from <http://www.concawe.be>)
- [Benkert et al, 1987]: Committee on Control and Recovery of Hydrocarbon Vapors from Ships and Barges, Chairman, William M Benkert. Controlling Hydrocarbon Emissions from tank Vessel Loading. National Academy Press, Washington DC, 1987.
- [USEPA, 1993]: The Plain English Guide To The Clean Air Act EPA-400-K-93-001 April 1993. [http://www.epa.gov/oar/oaqps/peg\\_caa/pegcaain.html#index](http://www.epa.gov/oar/oaqps/peg_caa/pegcaain.html#index)
- [BP, 2000]: BP Amoco Statistical review of World Energy, downloaded from <http://www.bp.com/centres/energy/index.asp>
- [Petroleum Economist, 1999]: "Energy in Western Europe" CD ROM, available from The Petroleum Economist Ltd, Baird House, 15/17 St Cross Street, London, EC1N 8UN, UK
- [DUKES, 2000]: Digest of UK Energy Statistics, 2000. The Stationery Office Ltd, London, 1999, ISBN 0-11-515497-3

# Appendix 1 - analysis of emissions by port

Table 26 lists the URLs of the web sites from which the data were obtained.

**Table 26 - Web addresses of EU ports**

Name	WebAddress
Algeciras	<a href="http://www.apba.es">www.apba.es</a>
Amsterdam	<a href="http://www.portofamsterdam.com">www.portofamsterdam.com</a>
Antwerp	<a href="http://www.portofantwerp.be">www.portofantwerp.be</a>
Aveiro	<a href="http://www.cidadevirtual.com">www.cidadevirtual.com</a>
Bremen	<a href="http://www.bremen-ports.de">www.bremen-ports.de</a>
Cadiz	<a href="http://www.apc.es">www.apc.es</a>
Cartagena	<a href="http://www.apc.es">www.apc.es</a>
Dunkirk	<a href="http://www.portdedunkerque.fr">www.portdedunkerque.fr</a>
Faro	<a href="http://www.cidadevirtual.pt">www.cidadevirtual.pt</a>
Flushing	<a href="http://www.portofamsterdam.com">www.portofamsterdam.com</a>
Flushing East	<a href="http://www.portofamsterdam.com">www.portofamsterdam.com</a>
Fos	<a href="http://www.marseille-port.fr">www.marseille-port.fr</a>
Ghent	<a href="http://www.havengent.be">www.havengent.be</a>
Gothenburg	<a href="http://www.portgot.se">www.portgot.se</a>
Hamburg	<a href="http://www.port-of-hamburg.com">www.port-of-hamburg.com</a>
Hamina	<a href="http://www.hamina.fi">www.hamina.fi</a>
Huelva	<a href="http://www.puertohuelva.com">www.puertohuelva.com</a>
La Coruna	<a href="http://www.puertocoruna.com">www.puertocoruna.com</a>
La Palma	<a href="http://www.puertostenerife.com">www.puertostenerife.com</a>
Las Palmas	<a href="http://www.palmasport.es">www.palmasport.es</a>
Le Havre	<a href="http://www.havre-port.fr">www.havre-port.fr</a>
Livorno (Leghorn)	<a href="http://www.portauthority.li.it">www.portauthority.li.it</a>
Leixoes	<a href="http://www.cidadevirtual.pt">www.cidadevirtual.pt</a>
Lysekil	<a href="http://www.lysekil.se/Eng/engindex.html">www.lysekil.se/Eng/engindex.html</a>
Lulea	<a href="http://www.lulea.se/lulea/alltomlulea/engelska/default.htm">www.lulea.se/lulea/alltomlulea/engelska/default.htm</a>
Port de Bouc	<a href="http://www.rouen.port.fr">www.rouen.port.fr</a>
Rotterdam	<a href="http://www.port.rotterdam.nl">www.port.rotterdam.nl</a>
Rouen	<a href="http://www.rouen.port.fr">www.rouen.port.fr</a>
Savona	<a href="http://www.portnet.it/savona/ukindex.html">http://www.portnet.it/savona/ukindex.html</a>
Setubal	<a href="http://www.cidadevirtual.pt/porto-setubal">www.cidadevirtual.pt/porto-setubal</a>
Sines	<a href="http://www.cidadevirtual.pt">www.cidadevirtual.pt</a> <a href="http://www.portodesines.pt">www.portodesines.pt</a>
St. Michael's	<a href="http://www.cidadevirtual.pt">www.cidadevirtual.pt</a> <a href="http://www.portodesines.pt">www.portodesines.pt</a>
Tarragona	<a href="http://www.fut.es/~porttgna">www.fut.es/~porttgna</a>
Tenerife	<a href="http://www.puertostenerife.com">www.puertostenerife.com</a>
Terneuzen	<a href="http://www.zeeland-seaports.com">www.zeeland-seaports.com</a>
Trieste	<a href="http://www.porto.trieste.it">www.porto.trieste.it</a>

Name	WebAddress
Valencia	<a href="http://www.valenciaport.com">www.valenciaport.com</a>
Venice	<a href="http://www.port.venice.it">www.port.venice.it</a>
Vlissingen	<a href="http://www.zeeland-seaports.com">www.zeeland-seaports.com</a>
Wilhelmshaven	
Zebrugge	<a href="http://www.zeebruggeport.be">www.zeebruggeport.be</a>

Table 27 below lists data supplied by Lloyds Maritime Information Services Ltd on movements of Crude oil and petroleum products by ship from EU-15 ports and terminals. These data are derived from the capacities of individual ships over 10,000 DWT as they enter and leave the ports concerned.

**Table 27 - Product output data supplied by Lloyds Maritime Information Services, with information from the world wide web for comparison.**

Name	Country	LMIS Product Export	Web Product Export
Antwerp	Belgium	3,326,512	6,636,000
Ghent	Belgium	384,294	282,000
Copenhagen	Denmark	47,345	
Fredericia	Denmark	328,042	
Kalundborg	Denmark	436,883	
Naantali	Finland	14,669	
Skoldvik	Finland	593,171	
Donges	France	374,401	
Dunkirk	France	297,406	2,368,000
Fos	France	319,854	5,630,000
France	France	28,323	
La Pallice	France	54,805	
Le Havre	France	532,120	
Port de Bouc	France	1,902,085	
Port Jerome	France	419,456	
Rouen	France	27,208	
Bremen	Germany	12,087	
Brunsbüttel	Germany	12,000	
Hamburg	Germany	458,941	
Rostock	Germany	21,800	
Wilhelmshaven	Germany	1,158,225	
Agioi Theodoroi	Greece	71,267	
Eleusis	Greece	27,500	
Greece	Greece	256,800	
Piraeus	Greece	90,593	
Thessaloniki	Greece	110,713	
Augusta	Italy	2,763,856	
Civitavecchia	Italy	27,208	
Falconara	Italy	56,832	
Fiumicino	Italy	76,737	

<b>Name</b>	<b>Country</b>	<b>LMIS Product Export</b>	<b>Web Product Export</b>
Gela	Italy	398,197	
Genoa	Italy	113,073	
Italy	Italy	174,412	
Milazzo	Italy	154,868	
Santa Panagia	Italy	593,581	
Sardinia	Italy	40,000	
Sarroch	Italy	3,307,866	
Sicily	Italy	323,349	
Siracusa	Italy	59,932	
Taranto	Italy	123,561	
Torre Annunziata	Italy	10,000	
Venice	Italy	45,000	
Amsterdam	Netherlands	1,859,239	
Europoort	Netherlands	2,364,088	
Flushing	Netherlands	123,902	
Rotterdam	Netherlands	1,983,267	5,335,000
Terneuzen	Netherlands	9,562	61,000
Kaarsto	Norway	992,022	
Mongstad	Norway	929,048	
Slagen	Norway	625,756	
Stavanger	Norway	332,218	
Leixoes	Portugal	175,963	
Setubal	Portugal	50,000	
Sines	Portugal	528,683	
Algeciras	Spain	310,461	
Barcelona	Spain	66,335	
Bilbao	Spain	345,858	
Castellon	Spain	124,725	
Corunna	Spain	191,469	
Escombreras	Spain	58,000	
Huelva	Spain	133,628	
Las Palmas	Spain	284,821	
Tarragona	Spain	236,084	
Tenerife	Spain	66,017	
Brofjorden	Sweden	323,377	
Gefle	Sweden	145,000	
Gothenburg	Sweden	476,079	
Karlshamn	Sweden	28,000	
Sweden	Sweden	27,180	
Coryton	U.K.	268,190	
Fawley	U.K.	480,332	
Grangemouth	U.K.	134,000	
Immingham	U.K.	1,392,381	
Liverpool	U.K.	102,608	
London	U.K.	123,444	

Name	Country	LMIS Product Export	Web Product Export
Milford Haven	U.K.	1,108,895	
Shell Haven*	U.K.	87,997	
Stanlow	U.K.	75,913	
Tees	U.K.	753,693	
Tyne	U.K.	15,000	

**Table 28 - Crude output data supplied by Lloyds Maritime Information Services, with information from the world wide web for comparison.**

Name	Country	Lloyds Crude Export	Web Crude Export
Antwerp	Belgium	2,454,804	83,000
Fredericia	Denmark	2,680,021	
Kalundborg	Denmark	226,641	
Siri Field	Denmark	1,258,441	
Donges	France	60,000	
Dunkirk	France	64,560	
Fos	France	60,000	
Le Havre	France	80,000	
Wilhelmshaven	Germany	957,566	
Sarroch	Italy	50,000	
Amsterdam	Netherlands	281,773	
Europoort	Netherlands	3,139,860	
Flushing	Netherlands	91,226	
Rotterdam	Netherlands	810,138	533,000
Draugen Field	Norway	7,918,040	
Gullfaks Term.	Norway	12,535,614	
Heidrun Field	Norway	4,731,336	
Kaarsto	Norway	1,058,550	
Mongstad	Norway	35,114,721	
Narvik	Norway	72,508	
Njord Field	Norway	1,097,207	
Norne Field	Norway	2,245,816	
Slagen	Norway	2,086,461	
Statfjord Term.	Norway	19,511,388	
Stavanger	Norway	234,734	
Sture	Norway	17,159,398	
Tees(No)	Norway	25,512,452	
Brofjorden	Sweden	59,231	
Karlshamn	Sweden	64,732	
Alba Term.	U.K.	2,512,626	
Beryl Term.	U.K.	4,455,140	

\* Shell Haven is now closed.

Name	Country	Lloyds Crude Export	Web Crude Export
Blenheim Field	U.K.	97,614	
Braefoot Bay	U.K.	88,485	
Captain Field	U.K.	817,424	
Cromarty Firth	U.K.	1,165,746	
Curlew Field	U.K.	860,892	
Fife Field	U.K.	418,738	
Flotta	U.K.	16,801,869	
Foinaven Field	U.K.	1,247,512	
Gryphon Term.	U.K.	378,041	
Hamble	U.K.	3,874,739	
Harding Field	U.K.	3,295,341	
Hound Point	U.K.	31,831,546	
Kittiwake Field	U.K.	199,499	
Liverpool	U.K.	341,224	
Liverpool Bay	U.K.	202,448	
Maureen Field	U.K.	416,203	
Milford Haven	U.K.	199,708	
Nab Anch.	U.K.	115,000	
Nigg	U.K.	80,000	
Nigg Term.	U.K.	837,305	
Pierce Field	U.K.	484,117	
Ross-Parry Field	U.K.	678,703	
Shell Haven	U.K.	117,482	
Sullom Voe	U.K.	28,723,435	
Teal-Guillemot Field	U.K.	115,000	
Tees	U.K.	160,000	
Tetney Term.	U.K.	814,609	

The EU-15 countries have been covered in detail, but the accession countries have not. There are currently thirteen accession countries: Bulgaria, Cyprus, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia and Turkey. Of these, Bulgaria, Cyprus, Estonia, Latvia, Lithuania, Malta, Poland, Romania and Turkey border the sea. The following brief overview is of ports in the accession countries identified with the aid of [Petroleum Economist, 1999] and the World Wide Web.

### **Bulgaria**

Bulgaria has three oil refineries, two of which, Pleven & Burgas, are at coastal locations bordering the Black Sea. There are two tanker terminals, at Varna and Burgas on the Black Sea.

### **Cyprus**

Cyprus has an oil refinery, two multipurpose ports at Limassol and Larnaca, an industrial port at Vassiliko and the three specialised oil terminals at Larnaca, Dhekelia and Moni. The three oil terminals are import only and consequently are not involved in ship loading. Limassol, Larnaca and Vassiliko are visited by tankships, but it is not clear whether any loading takes place.

### **Estonia**

Estonia has a terminal at Muuga Harbour near Tallinn. This is operated by Pakterminal Ltd a 50-50 joint venture between Estonian firm Trans Kullo and the Dutch firm Vopak. This has three berths and had a throughput in 2000 of over 8.5 Mte of which 1.8 Mte was gasoline.

### **Latvia**

Latvia has a tankship terminal at Ventspils.

### **Lithuania**

Lithuania has a major refinery at Mazeikiai, which is at an inland location. Lithuania also has a large multipurpose port at Klaipeda where petroleum products are loaded.

### **Malta**

Malta has a major port (Malta Freeport) that carries out transshipment of petroleum products.

### **Poland**

Poland has two tanker terminals, Gdansk & Gdynia. Gdansk also has an oil refinery and the port is connected to the refinery at Plock via an oil pipeline.

### **Romania**

Romania has two tankship terminals at Constanta and Midia-Navodari on the Black Sea.

### **Turkey**

Turkey has four oil refineries. These are at Mersin, Izmit, Aliaga and Batman. Batman is at an inland location. Mersin is on the Mediterranean, Izmit (the largest) is on the Gulf of Izmit on the sea of Marmara and Aliaga is on the Aegean. There are four tanker terminals at Izmit, Aliaga, Izmir (also on the Aegean) and Gemlik (on the sea of Marmara). The refinery at Izmit was substantially damaged in the 1999 earthquake.

The costs of installing marine vapour emission controls are unlikely to differ between accession and member countries

## **EUROSTAT IMPORT AND EXPORT DATA**

Table 29 and Table 30 list data obtained from Eurostat for 1998 listing imports and exports of crude oil and petroleum products from EU countries. The figures are broken down into intra - EU trade and extra - EU trade.

**Table 29 - Imports of Mineral Fuels, Mineral Oils and Products of their Distillation; Bituminous Substances; Mineral Waxes from EU countries for 1998**

	<b>INTRA-EUR15 Tonnes</b>	<b>EXTRA-EUR15 Tonnes</b>	<b>Total Tonnes</b>
<b>EU15 Total</b>	247,773,743	806,565,831	1,054,339,574
<b>AUSTRIA</b>	3,777,181	14,164,570	17,941,751
<b>BELG.-LUXBG.</b>	54,715,712	27,328,384	82,044,096
<b>BELGIUM</b>	-	-	0
<b>DENMARK</b>	2,320,528	16,837,368	19,157,896
<b>FINLAND</b>	4,540,828	18,648,014	23,188,842
<b>FRANCE</b>	32,852,122	126,578,466	159,430,588
<b>GERMANY</b>	80,698,781	165,774,988	246,473,769
<b>GREECE</b>	718,505	20,587,176	21,305,681
<b>IRELAND</b>	5,018,057	5,996,327	11,014,384
<b>ITALY</b>	11,239,704	122,980,918	134,220,622
<b>LUXEMBOURG</b>	-	-	0
<b>NETHERLANDS</b>	24,117,696	89,585,346	113,703,042
<b>PORTUGAL</b>	5,138,791	18,208,600	23,347,391
<b>SPAIN</b>	6,240,770	89,396,979	95,637,749
<b>SWEDEN</b>	7,945,949	22,940,204	30,886,153
<b>UTD. KINGDOM</b>	8,449,119	67,538,491	75,987,610

**Table 30 - Exports of Mineral Fuels, Mineral Oils and Products of their Distillation; Bituminous Substances; Mineral Waxes from EU countries for 1998**

	<b>INTRA-EUR15 Tonnes</b>	<b>EXTRA-EUR15 Tonnes</b>	<b>Total Tonnes</b>
<b>EU15 Total</b>	255,613,843	113,566,309	369,180,152
<b>AUSTRIA</b>	234,055	1,366,311	1,600,366
<b>BELG.-LUXBG.</b>	19,306,292	11,208,615	30,514,907
<b>BELGIUM</b>	-	-	0
<b>DENMARK</b>	11,619,770	1,542,004	13,161,774
<b>FINLAND</b>	3,168,564	1,687,557	4,856,121
<b>FRANCE</b>	11,777,903	9,406,780	21,184,683
<b>GERMANY</b>	25,774,895	9,986,832	35,761,727
<b>GREECE</b>	475,627	5,290,714	5,766,341
<b>IRELAND</b>	1,522,052	331,877	1,853,929
<b>ITALY</b>	6,927,920	18,040,508	24,968,428
<b>LUXEMBOURG</b>	-	-	0
<b>NETHERLANDS</b>	80,057,315	14,064,264	94,121,579
<b>PORTUGAL</b>	1,056,456	1,676,532	2,732,988
<b>SPAIN</b>	9,352,244	10,495,666	19,847,910
<b>SWEDEN</b>	6,526,268	3,082,271	9,608,539
<b>UTD. KINGDOM</b>	77,814,482	25,386,378	103,200,860

Table 31 below compares exports derived from the Lloyds and WWW data with the export data from Eurostat. The column headed "max exports" contains numbers derived by taking the sum of Lloyds crude and product exports, or the sum of web crude, product and chemical exports, whichever is the largest.

Table 31 shows that for most EU countries exports by ship are typically 30% to 50% of total exports. For the UK it is approximately 100% as would be expected. The data for Portugal appear anomalous, and at present we have no explanation for this.

**Table 31 - Comparison with port export data with Eurostat export data**

<b>Country</b>	<b>Max Exports</b>	<b>Eurostat 1998</b>	<b>Port export as % of country export</b>
<b>Belgium</b>	9,563,000	30,514,907	31.3%
<b>Denmark</b>	4,977,373	13,161,774	37.8%
<b>Finland</b>	1,429,840	4,856,121	29.4%
<b>France</b>	11,476,398	21,184,683	54.2%
<b>Germany</b>	2,620,619	35,761,727	7.3%
<b>Greece</b>	556,873	5,766,341	9.7%
<b>Italy</b>	8,321,472	24,968,428	33.3%
<b>Netherlands</b>	13,789,088	94,121,579	14.7%
<b>Norway</b>	132,157,269		
<b>Portugal</b>	6,628,000	2,732,988	242.5%
<b>Spain</b>	5,997,314	19,847,910	30.2%
<b>Sweden</b>	4,002,520	9,608,539	41.7%
<b>U.K.</b>	105,872,899	103,200,860	102.6%
<b>Grand Total</b>	175,235,396	365,725,857	47.9%