Global Trade and Fuels Assessment - Future Trends and Effects of Requiring Clean Fuels in the Marine Sector

United States
Environmental Protection
Agency

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U.S. Environmental Protection Agency

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NOTICE

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SECTION 1
INTRODUCTION

The U.S. Environmental Protection Agency (EPA), along with other regulatory bodies in the United States and Canada, is considering whether to designate one or more SO_x Emission Control Areas (SECAs) along the North American coastline, as provided for by MARPOL Annex VI. This addition to the international MARPOL treaty went into effect on May 19, 2005, and places limits on both NO_x and SO_x emissions. According to the terms of the treaty, ships calling on ports in signatory countries must use bunker fuel—the industry vernacular for marine fuels—with sulfur content by weight at or below 4.5%. Countries participating in the treaty are also permitted to request designation of SECAs, in which ships must treat their exhaust to a level not exceeding 6.0 grams of SO_x per kilowatt-hour or further reduce the sulfur content of their fuel to 1.5%. The Baltic and North Sea areas have already been designated as SECAs, and the effective dates of compliance in these bodies of water were 2006 and 2007, respectively.

To evaluate possible recommendations regarding North American SECAs, EPA requires a thorough examination of potential responses by the petroleum-refining and ocean-transport industries to such a designation, along with any resulting economic impacts. EPA contracted with RTI International to provide a foundation for these recommendations through developing the knowledge, data, and modeling capabilities needed for such an analysis; assess technology alternatives for reducing sulfur emissions from ships; and estimate the impact a SECA designation would have on the petroleum-refining and ocean transport industries. The analytical team comprising RTI, EnSys Energy & Systems, and Navigistics Consulting has assessed current and future conditions in global fuels market to provide this foundation.

Accomplishing the goals of this report involved several component tasks:

- Examining the current petroleum-refining industry and bunker fuel markets.
- Developing a model of shipping activities to estimate future demand for marine bunker fuels.
- Enhancing the EnSys model of petroleum refining (World Oil Refining Logistics and Demand, or the WORLD model) to include the new information on bunker fuel markets and then using the model to establish baseline projections of future refining activities.
- Estimating the volume of bunker fuel consumed within selected distances from the U.S. coastline.
- Modeling how SECA compliance alternatives impacted fuel products, fuel refining, and fuel consumption, including prices and product specifications.

1.1 Regulations and Options for Compliance

Existing regulations regarding marine bunker fuels provide an important backdrop for the modeling conducted in this analysis and, thus, are summarized in this section—along with an initial discussion of how bunker fuel markets may comply with regulations. The International Maritime Organization's (IMO) "MARPOL Annex VI" sets out a series of regulations impacting international marine bunker fuels. These new regulations center on limits for emissions of nitrous oxides (NO_x), sulfur oxides (SO_x), and volatile organic compounds (VOCs). Fuel quality regulations in Annex VI have been implemented in the form of the ISO-8217 2005 specification (see Figure 1-2 for details and discussion). This specification updates selected bunker qualities, provides protections to prevent the blending of used lubricating oil (ULO) into marine fuels, and limits the presence of refinery streams that contain high levels of "catalyst fines."

The MARPOL Annex VI sets limits on NO_x emissions as a function of ships' engine speed, which range from a high of 17 grams per kilowatt-hour (g/kWh) for engines running at less than 130 rpm to a low of 9.8 g/kWh for engines running at or above 2,000 rpm. Since residual bunker fuels contain nitrogen that is typically at a level equal to around 20% of the fuel's sulfur content, NO_x emissions will be affected in part by fuel quality (as well as by specific combustion conditions). For example, a bunker fuel containing 3% sulfur will contain around 0.6% nitrogen, which translates into around 3g of NO_x per kWh (Hanashima, 2006). This level is well below the standard set for NO_x emissions; however, residuum desulfurization in a refinery also reduces nitrogen levels and can therefore play into the comparative economics of bunker fuel sulfur reduction versus other options (e.g., on-board abatement of SO_x).[1]

Through the ISO-8217 specifications, MARPOL Annex VI sets a limit on SO_x emissions, expressed as a maximum 4.5% fuel sulfur content. This compares to a prior maximum limit of 5%. The new level was set based on a survey of residual bunkers' qualities (the intermediate fuel oil, or "IFO," grades), which showed that essentially all bunkers currently supplied have sulfur contents below 4.5% (see Figure 1-1). Since the same survey showed global average residual bunker fuel content is currently around 2.7%, this change has limited practical impact on bunker fuel's quality. More significant for any potential future SO_x regulations is the fact that MARPOL Annex VI explicitly allows for on-board abatement as an alternative means for meeting SO_x requirements (thus recognizing that the ultimate goal is a reduction in SO_x

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[1] To cover the eventuality that NO_x may need to be considered in any future investigations of SECAs, EnSys added the nitrogen contents of residual streams to the WORLD model, along with impacts on nitrogen content of desulfurization.

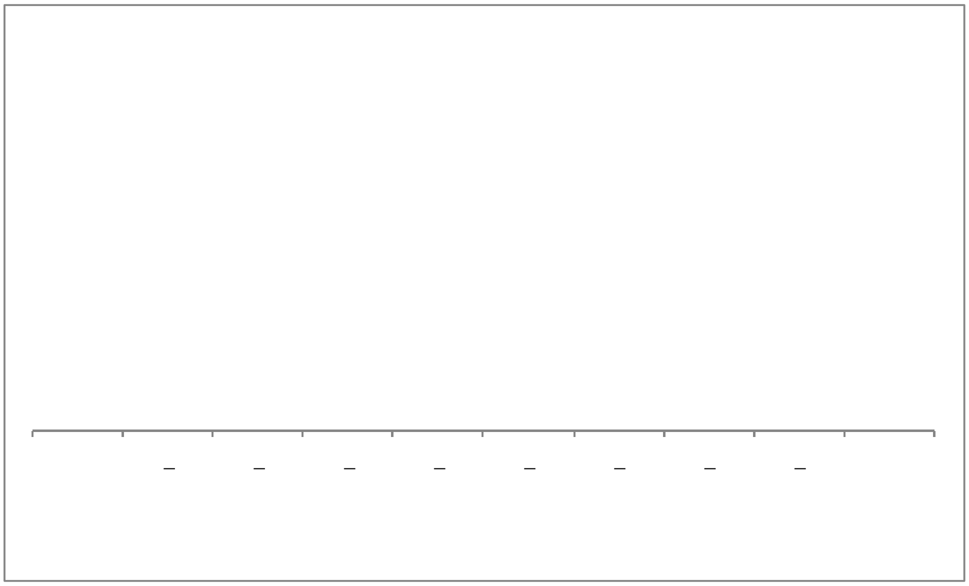
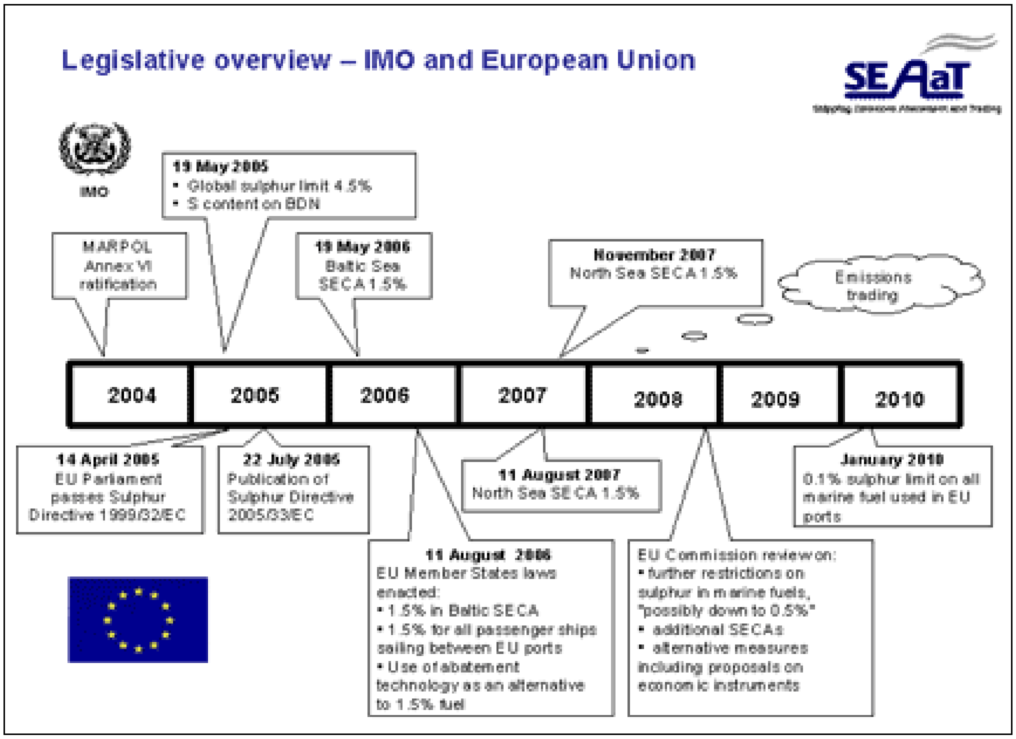


Figure 1-1. Sulfur Content in Bunker Fuels

emissions, rather than a reduction of fuel sulfur content *per se*). The IMO, however, has yet to set up necessary guidelines for this provision.

Figure 1-2 illustrates the current timeline of the MARPOL Annex VI and other SECA-related regulations. In addition to establishing emissions limits and considering reductions achieved through on-board abatement, MARPOL Annex VI and ISO-8217 2005 explicitly allow for the existence of regional SECAs. In the European Union (EU), these agreements have been established with a marine fuel sulfur maximum of 1.5%, potentially advancing to 0.2% and 0.1% on marine distillates. Again, these regulations recognize on-board abatement as an alternative, with a stated standard of 6g SO_x/kWh (to correspond to the initial 1.5% sulfur limit).

Beyond currently announced initiatives, it appears likely that the MARPOL Annex VI regulations and newly effective EU SECAs are only the first steps in progressively tightening regulation of marine fuels quality. This is being driven by the fact that, as major steps are being taken to reduce sulfur in other products, especially in gasoline and nonmarine distillates, bunkers are becoming an increasingly significant—and unacceptable—source of SO_x and other emissions. Already, there is a review of MARPOL Annex VI underway with international consultative meetings. Current intentions are for a second round of IMO/ISO marine fuels regulations to be established by 2008 and be enforceable by 2011/2012, with potential further steps beyond. In addition, the EU is expected to tighten the initial SECA regulations beyond 2008. Required residual bunker fuel sulfur levels could move to as low as 0.5% regionally, or even globally. One current element of uncertainty is the size of the geographic areas of future



Legislative overview – IMO and European Union

SEAaT

IMO

MARPOL Annex VI ratification

19 May 2005
- Global sulphur limit 4.5%
- S content on BDN

19 May 2006
Baltic Sea SECA 1.5%

November 2007
North Sea SECA 1.5%

Emissions trading

14 April 2005
EU Parliament passes Sulphur Directive 1999/32/EC

22 July 2005
Publication of Sulphur Directive 2005/33/EC

11 August 2007
North Sea SECA 1.5%

January 2010
0.1% sulphur limit on all marine fuel used in EU ports

11 August 2006
EU Member States laws enacted:
- 1.5% in Baltic SECA
- 1.5% for all passenger ships sailing between EU ports
- Use of abatement technology as an alternative to 1.5% fuel

EU Commission review on:
- further restrictions on sulphur in marine fuels, "possibly down to 0.5%"
- additional SECAs
- alternative measures including proposals on economic instruments

Figure 1-2. Timeline of MARPOL Annex VI and SECA Implementation

SECAs (i.e., how many miles offshore they will apply). This, in turn, affects the proportion of total bunkers' consumption that will need to comply with SECA regulations. Anticipated policy decisions on this issue will have significant implications for any analysis conducted in the future regarding the potential effects of North American SECAs.

The above proposals focus on improving the quality of the current mix of distillate and residual bunker fuels in the future. More radical alternatives have been put forward as part of the ongoing review by the IMO of MARPOL Annex VI. One—the group International Association of Independent Tanker Owners (INTERTANKO)—is proposing that all marine bunker fuels be converted to marine diesel oil (MDO) (i.e., no more residual bunker fuels) with a maximum sulfur content of 1% initially, dropping to 0.5% after 2015. Benefits claimed include greater reductions in SO_x, NO_x, and particulate matter (PM); elimination of need for onboard scrubbing and simplification of onboard fuel handling and storage; creation of a single global standard for marine bunker fuels; and an associated level competitive playing field among shippers. Improved vessel safety is also cited since the regulation would avoid the need for vessels to change fuel types when entering or leaving SECA areas, thereby eliminating the associated risk of engine outage, vessel loss of control, and potential environmental disaster.

Other groups, including BIMCO (an owners' organization covering a claimed 65% of the world merchant fleet), have proposed that all vessels use MDO (not intermediate fuel oil [IFO]) within SECA areas. This would lead to a partial shift in bunker demand from IFO to MDO.

The vigorous debate that has developed among the parties concerned with global shipping and fuels is ongoing at the time of the writing of this report. As a result, the realm of potential policy decisions on marine bunkers and hence analytical requirements goes beyond the immediate Annex VI and SECA regulations and has potentially far-reaching implications for U.S. and global refining and oil markets.

Marine Environment Protection Committee (MEPC) - 53rd session 18-22 July 2005

Review of Annex VI

The Committee agreed on the need to undertake a review of Annex VI and the NOx Technical Code with a view to revising the regulations to take account of current technology and the need to further reduce emissions from ships. MEPC instructed the Sub-Committee on Bulk Liquids and Gases (BLG) to carry out the review by 2007, and specifically to:

- examine available and developing techniques for the reduction of emissions of air pollutants; review the relevant technologies and the potential for a reduction of NOx emissions and recommend future limits for NOx emissions;
- review technology and the need for a reduction of SOx emissions and justify and recommend future limits for SOx emissions;
- consider the need, justification and possibility of controlling volatile organic compounds emissions from cargoes;
- with a view to controlling emissions of particulate matter (PM), study current emission levels of PM from marine engines, including their size distribution and quantity, and recommend actions to be taken for the reduction of PM from ships. Since reduction of NOx and SOx emission is expected to also reduce PM emission, estimate the level of PM emission reduction through this route;
- consider reducing NOx and PM emission limits for existing engines;
- consider whether Annex VI emission reductions or limitations should be extended to include diesel engines that use alternative fuels and engine systems/power plants other than diesel engines; and
- review the texts of Annex VI, NOx Technical Code and related guidelines and recommend necessary amendments.

The language in the Annex VI regulations and the economics of the refining and shipping industries lead to a situation where several, nonexclusive, options can potentially be used to achieve compliance with SECAs. While some of these options are not fully explored in this report (they will be evaluated in the next steps of the analysis), it is still important to note the range of responses. Among these options are the following:

1. Desulfurize refinery fuels and use lower sulfur content fuel.
2. Switch entirely or partially to middle distillates for bunker fuel.
3. Reduce SO_x emissions via onboard scrubbers (also helps reduce PM).
4. Reduce NO_x emissions by lowering nitrogen content of the fuel.
5. Reduce NO_x and PM via onboard emission controls and engine design.

6. Undertake custom blending of fuels on board and/or use segregated bunker tanks.
7. Establish emissions trading, which could allow trading of marine and shore-based credits.
8. Switch to alternative fuel sources (e.g., liquefied natural gas [LNG]).
9. To the extent feasible, some ship owners might also elect noncompliance through reregistration of ships to a country that has not ratified the IMO standards.

There is general industry agreement in principle on the need for SO_x emissions reduction. There are, however, major industry concerns over operational issues, such as custom blending of fuels onboard because of safety and other concerns (Gregory, 2006). Similarly, there is industry agreement about a reduction in NO_x limits for new engines, but also concerns about the application of NO_x limitations to existing engines because of practicality and cost factors (Metcalf, 2006) and concerns about a regional approach to NO_x controls due to technical considerations (Gregory, 2006).

With regard to emissions trading and sulfur reduction, the European Commission has been asked to give particular consideration to proposals for alternative or complementary measures and to consider submitting proposals on economic instruments in their 2008 review. For NO_x reductions, the Commission studies suggest that, given the range of technologies, there is a sound basis for a trading environment (Madden, 2006). In addition, SO_x emissions trading and compliance monitoring schemes are being actively promoted.

Initial studies indicate onboard scrubbing is cheaper in terms of cost per ton of SO_x removed than refinery residual desulfurization. However, the technology is only just reaching the commercial demonstration stage (with initial positive results). Issues have also been raised over how to ensure compliance and how to dispose onshore of the resulting sludge waste. Scrubbing requires an extended lead time to achieve widespread utilization and is least costly when built into new ships, rather than retrofitted onto existing ones (where retrofit costs are estimated on the order of $1 to $4 million). Current estimates also indicate ships will have to spend appreciable time in SECA areas for scrubbing to be economic. Conversely, building a refinery residual desulfurization unit with ancillaries could cost on the order of $500 million and, if done, would create a feedstock that could be more attractive for upgrading to light clean fuels than for sale as low-sulfur residual fuel for bunkers or inland use. Within any one SECA, it is not certain what proportion of compliance will be achieved by scrubbing versus fuel supply and what the impact on that balance is of complementary regulations on NO_x and PM in addition to SO_x.

1.2 Summary of the Analysis

The analytical team developed the information and modeling techniques that enabled the team and EPA to explore the potential effects of designating North American SECAs as part of the MARPOL Annex VI. This report details the development of techniques to estimate bunker demand in the shipping industry and also enhancements that have been made to the EnSys WORLD model of the petroleum-refining industry. The resulting information from these processes was used to establish baseline projections of international petroleum markets in the years 2012 and 2020, against which the effects of SECAs—and other potential regulatory scenarios—on shipping and bunker fuel demand were evaluated.

RTI and Navigistics Consulting developed a multistep approach for estimating future bunker demand involving (1) identifying major trade routes, (2) estimating volumes of cargo of various types on each route, (3) identifying types of ships serving those routes and carrying those cargoes, (4) characterizing types of engines used by those ships, and (5) identifying the types and estimated quantities of fuels used by those engines. In general, this approach can be described as an "activity-based" approach with a focus on the international cargo vessels that represent the majority of fuel consumption. Similar techniques for combining data on specific vessels with data on engine characteristics have been used in other analyses (e.g., Corbett and Koehler [2003, 2004]; Koehler [2003]; Corbett and Wang [2005]; and Gregory [2006]). The approach in this analysis extends these previous works by linking ship data to projections of worldwide trade flows from Global Insights (2005) to determine the total number of trips undertaken in each year and hence fuel use.

The methodology gives the following results for historical and forecasted bunker fuel consumption:

- Worldwide bunker use in 2001 was estimated at 278 million tons, of which around 212 million tons were residual fuels.
- Between 2001 and 2020, total consumption grows at an average annual rate of 3.1% (from 2006 to 2020, the growth rate is 2.6%).
- Around 47 million tons of bunker fuel were used in 2001 to transport international cargo flows into and out of the United States (not all of which is purchased in the United States).
- This fuel consumption related to U.S. trade is forecasted to grow at around 3.7% between 2001 and 2020 (or 3.4% from 2006 to 2020), which is somewhat higher than the world average because of high growth in container traffic arriving at U.S. ports.

The estimates of worldwide bunkers are quite similar to those in the published works cited above, in spite of differences in techniques. Koehler (2003) uses calculations of average engine loads, run times, and specific fuel consumption for the existing vessel fleet to come up with bunker fuel demand of around 281 million tons. Similarly, Corbett and Koehler (2003, 2004) estimate bunker demand at 289 million tons in 2001. These findings on fuel consumption tend to be significantly higher than data published by the International Energy Agency (IEA), which places international marine bunkers at around 140 million tons per year, of which around 120 million tons are residual fuels (see the discussion of these points in Section 4.2). Given the far-reaching implications of these demand estimates for petroleum markets and related potential effects of future SECAs, this analysis has chosen to evaluate baseline conditions in the refining industry for both IEA's bunker fuel estimates and the estimates developed in this report (called the "RTI" estimates for clarity).

For this report, these two bunker fuel estimates are incorporated in the EnSys WORLD model, which is a comprehensive, bottom-up model of the global oil downstream. It encompasses crude and noncrude supply; refining operations and investment; crude, products, and intermediates trading/transport; product blending/quality; and demand. It yields as outputs detailed simulations of how this global system can be expected to operate under a wide range of different circumstances, with outputs including price effects as well projections of sector operations and investments. WORLD is not a forecasting tool per se, but rather it uses as a starting point a global supply–demand world oil price outlook; in this study, the outlook is based on the Energy Information Administration's (EIA) *Annual Energy Outlook 2006* reference case.

To accomplish the goals of this study, WORLD has been expanded to incorporate seven grades of bunker fuels, covering the major distillate and residual grades used in the marine shipping industry. The latest international specifications applying to low-sulfur grades of these fuels were also included because of their applicability for future SECAs. In addition, flexibility was built in to allow the model user to vary the proportion of SECA compliance that is achieved through fuel sulfur reduction versus other means such as onboard abatement or emissions trading. This was necessary since it is feasible that widespread adoption of onboard abatement could enable shippers to continue using high-sulfur bunker fuels and might even enable refiners to raise the sulfur level toward the upper limit of 4.5% from today's average global level of 2.7% and still meet required SO_x emission standards. In addition, the model was given the capability of covering the "extreme" scenario of switching residual bunker fuels entirely to marine diesel. In addition, since any eventual estimates of bunker fuel production costs in SECA cases will derive directly from refinery processing costs, a technology review of the WORLD model assumptions was undertaken. This involved checking on capital costs for the processes with the most influence on costs of reducing sulfur in bunkers and on examining and adjusting processing and blending options to guard against production of unstable bunker fuels. Finally, to ensure that the model was correctly specified for any future policy scenarios that might be run on implementation of SECAs, the related regulations were thoroughly reviewed.

Once these processes were complete, business-as-usual (BAU) cases (consistent with the regional oil supply and demand projections from AEO) were set up in WORLD. The resulting BAU cases for the years 2012 and 2020 were then executed on both the IEA and RTI bunkers' estimates; key results from all four cases are included in the body of the report. The full results are rich in detail; however, the important drivers impacting the SECA analyses revolve around the outlook for product demand. Since the rigorous analysis of shipping activity and fuel consumption conducted in this report estimates high bunker demand, the impacts of SECAs or other marine fuels regulations will be similarly greater than for those estimated using lower demand forecasts. A second major driver evident in these and other WORLD analyses is that the ongoing shift toward distillates, especially in Europe and non-Organisation of Economic Co-operation and Development (OECD) regions, will materially alter gasoline and distillate trade patterns, their product pricing and refining investments, and economics. These developments will, in turn, impact the market and supply effects of SECAs and other global marine fuels regulations.

The overall objective of the refinery modeling was to develop and implement any modifications to the WORLD model that are needed to accommodate details of bunkers' grades and other issues such as updated technology costs, for example. These features have been successfully implemented and applied (the 2012 and 2020 BAU cases were developed and represent a sound starting basis to examine the impacts of broader SECA regulations and/or tighter global marine fuels limits). Section 5 provides details of the WORLD model estimates for the BAU cases.

The modeling foundation is particularly important because the nature of the MARPOL Annex VI regulations and goals, and the characteristics of the international marine fuels industry, meaning that there is a much greater potential for variability in future scenarios than is true for most types of fuels regulations.

Section 6 discusses technology alternatives for compliance available to the ship operators and to characterize them in terms of technology applicability (for different marine ships and/or market sectors), emissions reduction, and costs. This section provides technical background descriptions, cost information, and emissions reduction potential for onboard emissions abatement alternatives: fuel switching, in-engine fuel mixing, and exhaust gas scrubbing. A thorough understanding of the technically feasible alternatives is essential because it bounds the decision possibilities available to affected stakeholders and influences the burden of potential SECA requirements.

Section 7 extends the fuel consumption analysis to estimate ship fuel consumption in 2012 and 2020 with the boundaries of two SECA scenarios. The first scenario sets the boundary at 100 nautical miles (nm) off the Pacific coast and 50 miles off the Gulf and East coasts, or up to the boundary of the Exclusive Economic Zone (EEZ), whichever was nearest the coastline. The second scenario sets the SECA boundary at 200 miles off all coasts. Under the 100/50 nm SECA scenario, a total of 7.5 million tons is consumed in 2012, and a total of 8.9 million tons is consumed in 2020. Under the 200 nm SECA scenario, a total of 13.5 million tons is consumed within the boundaries in 2012 and 16.2 million tons in 2020.

Using the BAU cases as a starting point, the WORLD model was used to study the alternative SECA scenarios and address key uncertainties. Among these issues, as illustrated in the results in Section 8, for the SECA analyses, are the following:

- the regional make up of bunker fuel demand;
- associated with this, the extent to which consumption of low-sulfur bunker fuel for SECA compliance will be met by supplies within the SECA or elsewhere;
- the extent of switching, either regionally or globally, to marine distillate fuels;
- the degree to which compliance with the MARPOL regulations will be achieved through improved fuel quality versus via onboard scrubbing and/or emissions trading; using the WORLD model, plausible “high” and “low” scenarios were applied and analyzed; and
- whether bunkers’ blend compositions will need to be still further restricted to capture ship operational limits such as those relating to fuel instability.

1.3 Organization of this Report

The remainder of this report is organized as follows:

- Section 2 presents a profile of marine bunker fuels, their refining processes, and the overall supply chain used to deliver the fuels to marine vessels.
- Section 3 develops a model of shipping activity and estimates bunker fuel demand.
- Section 4 describes how the analysis of baseline conditions in petroleum markets is implemented in the WORLD model.

- Section 5 then presents estimated results from the WORLD model regarding BAU conditions in 2012 and 2020.
- Section 6 reviews fuel switching, in-engine fuel mixing, and exhaust gas scrubbing as well as other technology considerations for SECA compliance.
- Section 7 describes the SECA fuel consumption analysis.
- Section 8 describes the modeling results for selected SECA regulations.
- Appendix A reviews cost assumptions regarding refinery technologies used in the analysis of the WORLD model.

SECTION 2
OVERVIEW OF THE MARINE FUELS INDUSTRY

This section provides an overview of the marine fuels industry, which is characterized by a complex, international network of organizational and trade relationships. Marine distillates historically come from poorer-quality distillate recycle streams that are unsuitable for upgrading to diesel fuel or other low-sulfur products. Thus, the supply chain for the marine fuels industry begins with integrated petroleum refineries, where “bottoms” from atmospheric and vacuum distillation unit operations are combined to form the bulk of residual fuel stocks (see Section 2.1). The dominant producers of marine fuels are divisions of the major oil companies such as Shell Trading (STUSCO) and BP Marine. Around the world, these large producers are joined by hundreds of smaller firms that contract to transport, blend, and sell low-quality fuel stocks to the shipping industry.

Most of the worldwide bunker fuel volume is sold to firms that operate bunkering facilities around the world, although some of the major petroleum refiners also contract for and deliver marine fuels. These large refiners, including the Chemoil Group, O.W. Bunker, and the Chinese government-owned Chimbusco, purchase blended stocks from the producers and also blend, transport, and store some products themselves. As much as 25% of the world’s marine fuels are purchased and resold by brokers or other intermediaries that never actually take physical control of the bunker fuel. Arbitrage activities of these firms help keep the worldwide market efficient, as excess price differentials are quickly exploited and eliminated.

The final stage of the marine fuel supply chain is the bunkering itself, which can either be done while the ship is docked or directly from bunker barges while the ship is anchored. There are hundreds of bunkering ports around the world and thousands of firms that provide the actual bunkering service.

Logistics and transport cost factors influence the location of bunker ports. In addition to being located close to supply sources (petroleum refineries) and consumers of transported goods (major population centers), bunkering ports are often strategically located along high-density shipping lanes. The largest port of this type is in Singapore and handles more than twice as much bunker fuel volume as the next biggest provider. Panama and Gibraltar are other examples of strategically located facilities. In North America, the largest facilities follow the general pattern suggested by location theory; Los Angeles, San Francisco, New York, Philadelphia, Houston, and New Orleans are close to both refinery supply and transport destinations.

The following subsections briefly review the petroleum-refining process(focusing on distillation and additional downstream treatment processes that further refine crude oil into higher-value petroleum products), characteristics of marine fuels, and the supply chains that deliver the refined marine fuels.

2.1 Refining of Petroleum Products (Including Marine Fuels)

Marine fuels' characteristics are determined in part by the quality of the crude oil used to create them and in part by the refining process. We begin by reviewing petroleum refining to better illuminate the differences among marine fuels.

The refining processes used to produce petroleum products, including marine fuels, involve the physical, thermal, and chemical separation of crude oil into its major distillation fractions, followed by further processing (through a series of separation and conversion steps) into finished petroleum products. EPA's (1995) sector notebook on the petroleum industry details the primary products of refineries grouped into three major categories:

- **fuels** (motor gasoline, diesel and distillate fuel oil, liquefied petroleum gas, jet fuel, residual fuel oil, kerosene, and coke);
- **finished nonfuel products** (solvents, lubricating oils, greases, petroleum wax, petroleum jelly, asphalt, and coke); and
- **chemical industry feedstocks** (naphtha, ethane, propane, butane, ethylene, propylene, butylenes, butadiene, benzene, toluene, and xylene).

This discussion focuses on the "fuels" product category and specifically on the distillate and residual fuels that are blended to form marine fuels.

Refineries are complex operations and often have unique configurations based on the properties of the crude oil to be refined (which varies significantly depending on the source) and the variety of products to be produced. Figure 2-1 illustrates general unit operations and product flows for a typical refinery; the generalized unit operations outlined below are typical of most refineries.

Refinery operations can be broken down into four major stages: distillation, desulfurization, refining, and blending. Following an initial desalting process to remove corrosive salts and excess water, crude oil is fed into an atmospheric distillation column that separates the feed into the subsequent "distillation fractions." The lightest of the fractions are called "top gases" and include light gasoline, ethane, propane, and butane. Top gases are further processed through reforming and isomerization to produce gasoline, but they could also be

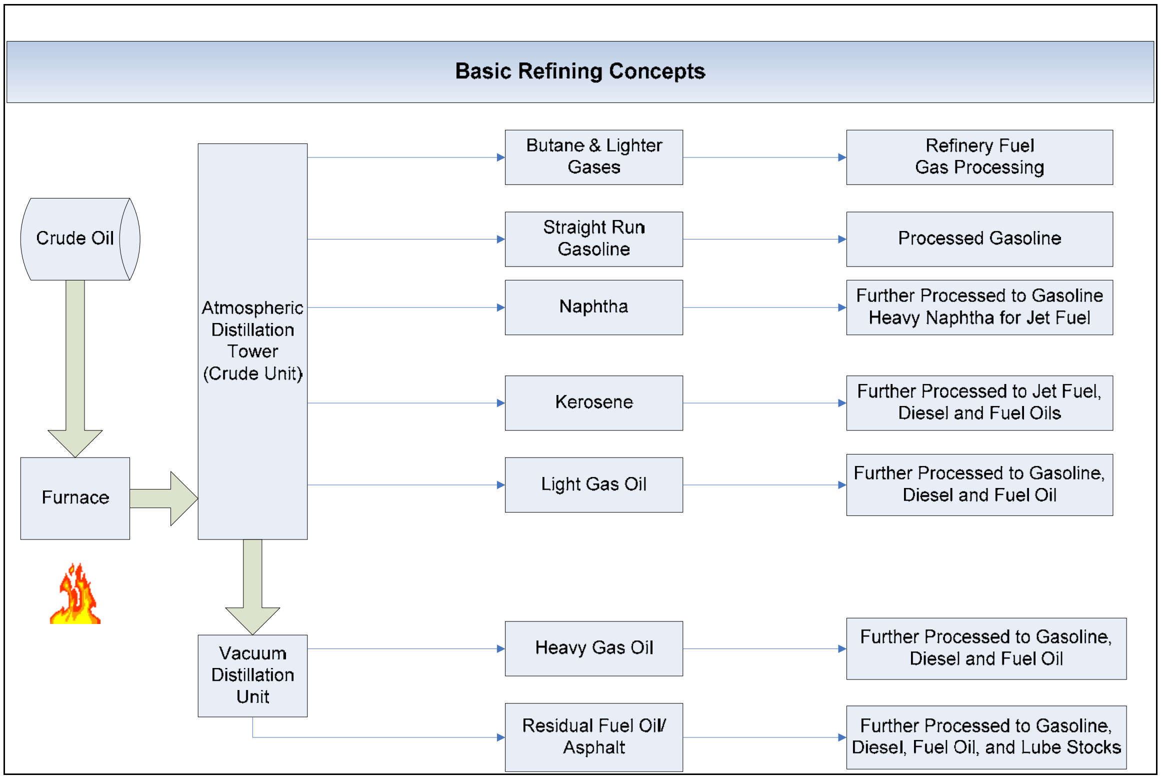


Figure 2-1. Basic Refining Process and Product Streams

Source: Adapted from Marcogliese, Rich. 2005. “Refining Fundamentals & Impact of Changing Fuel Specifications.” Presented on February 17, 2005 at the Lehman Brothers Analyst Teach-In. Valero Energy Corporation. Obtained on November 30, 2005. Available at: http://www.valero.com/Investor+Relations/Management+Presentations/.

diverted to lower-value uses such as liquefied petroleum gas (LPG) and petrochemical feedstocks. The middle-boiling fractions, which include kerosene, gas oil, and spindle oil, make up most of the aviation fuel, diesel, and heating oil produced. The remaining undistilled liquids are called “bottoms” and represent the heavier fractions that require vacuum distillation at very low pressures to facilitate volatilization and separation. Vacuum distillates and residues can be further processed through catalytic cracking and visbreaking into low-value products such as residual fuel oil, asphalt, and petroleum coke.

The lower-middle distillates from which marine fuels are made may also require additional downstream processing. These fractions are treated using one of several techniques:

- “cracking/visbreaking,” which breaks apart large hydrocarbon molecules into smaller ones;

- "combining" (e.g., alkylation, and isomerization), which joins smaller hydrocarbons to create larger more useful molecules, or reshaping them into higher-value molecules; and
- catalytic "hydrocracking" is a downstream processing method used to crack fractions that cannot be cracked in typical cracking units. These fractions include middle distillates, cycle oils, residual fuel oils, and reduced crudes. Typically, the feedstock to a hydrocracking unit is first hydrotreated to eliminate any impurities (e.g., sulfur, nitrogen, oxygen, halides, and trace metals) that could deactivate the catalyst.

Following the completion of downstream processing stages, several product streams are blended by the refinery to produce finished products. Generally, these blending operations include gasoline, middle distillate, and fuel oil blending.

2.1.1 Primary Refinery Inputs

Crude oil is the dominant input in the manufacture of refined petroleum products, accounting for approximately 79% of total material costs of U.S. refineries, or $132 billion in 2002, according to the latest Economic Census (U.S. Bureau of the Census, 2004). Table 2-1 provides a summary of these inputs. Similarly, crude accounts for over 92% of the volume of refinery inputs in the United States. Crude oil is likely to have greater representative share of both material costs and inputs in developing countries due to fewer environmental regulatory product specifications.

Table 2-1. Total U.S. Refinery Input of Crude Oil and Petroleum Products in 2004

Product	Year 2004 (1,000s barrels)	% of Total
Crude Oil	**5,663,861**	**92.3%**
Natural Gas Liquids	**154,356**	**2.5%**
Other Liquids	**316,838**	**5.2%**
Other Hydrocarbons/Oxygenates	150,674	2.5%
Other Hydrocarbons-Hydrogen	28,039	0.5%
Oxygenates	122,635	2.0%
Fuel Ethanol	74,095	1.2%
MTBE	47,600	0.8%
All Other Oxygenates	940	0.0%
Unfinished Oils (net)	186,826	3.0%
Motor Gasoline Blending Components (net)	−18,558	−0.3%
Aviation Gasoline Blending Components (net)	−2,104	0.0%
Total Input to U.S. Refineries	**6,135,055**	**100.0%**

Source: U.S. Department of Energy, Energy Information Administration (EIA). 2005a. *Petroleum Supply Annual 2004,* Volume 1. Washington, DC: U.S. Department of Energy, Energy Information Administration.

2.1.1.1 Crude Oil

Characteristics of crude oil—including relative density, sulfur, and acid content—have a significant influence on the products a refinery is able to produce. The cost of production also varies significantly depending on the type of crude oil used in the refining process.

Crude-oil density can be measured using the API gravity number, which provides a measure of relative density. Crude oils are typically classified as light, medium, and heavy oils. Light crude has the highest API number, equating to low density, which makes this crude type the easiest to refine into gasoline products. Heavy crudes, with the lowest API number and higher relative density, require additional processing to obtain the same distribution of refinery products.

Sulfur content determines whether a specific type of crude is “sweet” (low sulfur) or “sour” (high sulfur). Sweet crude is defined as crude oil with a sulfur content of less than 0.5%, and sour crude has sulfur content higher than 0.5%. Sweet crude is less corrosive because of low levels of sulfur compounds such as hydrogen sulfide (H_2S). Sour crude requires additional equipment and processing to extract the additional sulfur.

Crude oils’ relative density and sulfur content vary, depending on the region of the world that it was extracted from. Light, sweet crude types typically have the highest prices because of limited availability and high demand. Heavy, sour crude typically sells at a discount relative to the light sweet crude because of its relative abundance and its high sulfur content. Light sweet crude includes WTI (West Texas Intermediate) found in the western hemisphere and Brent (North Sea Crude) found in Europe. Heavy sour crude includes Arabian Heavy (Middle East) and Maya (Mexico). Figure 2-2 illustrates the spectrum of crude qualities. Density is plotted along the horizontal axis and sulfur content along the vertical axis.

In Figure 2-2, crude types near the lower right-hand corner of the figure represent the crude types that require the least amount of processing. As one moves toward the top left-hand corner of the figure, the crude is more difficult to process. The majority of the world’s supply of crude oil is light to medium sour, which is trending toward heavier and more sour crude as reserves of light sweet crude are depleted (Marcogliese, 2005).

WTI, Brent, and Dubai Fateh are the most commonly used benchmarks. These benchmark crude types are used in international trading, and varying qualities of crude are sold at a discount or premium relative to the benchmark price. OPEC has its own reference known as the OPEC Basket, which consists of 11 crude types and represents the weighted average of density and sulfur content for all the member countries’ crude types, according to production levels and export volumes (see Table 2-2).

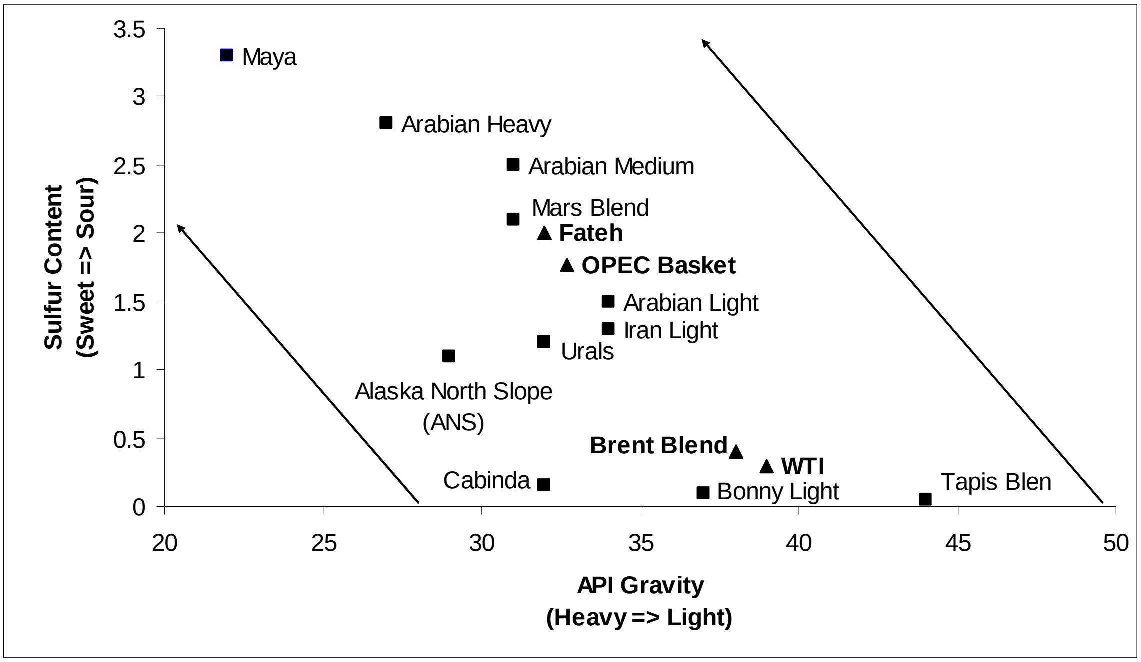


Figure 2-2. Quality by Crude Type

Source: Adapted from Marcogliese, Rich. 2005. “Refining Fundamentals & Impact of Changing Fuel Specifications.” Presented on February 17, 2005 at the Lehman Brothers Analyst Teach-In. Valero Energy Corporation. Obtained on November 30, 2005. Available at: http://www.valero.com/Investor+Relations/Management+Presentations/.

Note: ▲= Benchmark crude types

Table 2-2. Crude Oil Types Included in the OPEC Basket

Type of Crude	Country of Origin	Type of Crude	Country of Origin
Saharan Blend	Algeria	Bonny Light	Nigeria
Minas	Indonesia	Qatar Marine	Qatar
Iran Heavy	Islamic Republic of Iran	Arab Light	Saudi Arabia
Basra Light	Iraq	Murban	UAE
Kuwait Export	Kuwait	BCF 17	Venezuela
Es Sider	Libya		

Source: U.S. Department of Energy, Energy Information Administration (EIA). 2005b. “OPEC Brief” Washington DC: DOE/EIA. Obtained on November 29, 2005.Available at: http://www.eia.doe.gov/emeu/cabs/opec.html.

2.1.1.2 Blending Stocks and Additives

Following initial atmospheric distillation of crude oil, a variety of specialized inputs may be added to output product streams (see Figure 2-1) in downstream units to enhance the refinery's ability to recover a desired mix of products. Among these products might be unfinished oil, residual fuel oil used as input to a vacuum distillation unit (see Table 2-2 for a list of additives). Motor gasoline and aviation fuels require blending components that include oxygenates as well as other hydrocarbons. Although they are counted as "refinery inputs," they are brought to saleable specifications in terminals and blending facilities, not in conventional refineries.

2.1.2 Refinery Production Models

Across the globe, refineries are typically concentrated near major consumption areas, based on the principle that transporting crude oil is cheaper than transporting refined products. In addition, proximity to consumption areas allows refineries to more quickly respond to seasonal or weather-related demand shifts (Trench, 2005). Their goal is to meet the regional demand for petroleum products, hence maximizing the value of product mix produced. For example, in the United States, as well as other developed countries, refineries strive to maximize gasoline and low-sulfur diesel fuels, while simultaneously minimizing output of lower value heavy oils such as residual fuel and petroleum coke.

Building on the basic refinery concepts presented in Figure 2-1, refineries can be grouped into four basic configurations: topping, hydroskimming, cracking (*medium* conversion), and coking (*high* conversion). Each configuration builds on the previous production model by adding on additional downstream processing equipment that allows the refinery to further expand its yield of the desired mix of petroleum products.

2.1.2.1 Topping Refineries

Topping refineries are the simplest example of a refinery production model. Their primary function is to produce feedstocks for petrochemical manufacturing. Topping refineries typically consist of storage tanks, an atmospheric distillation unit, and recovery facilities for top gases and light hydrocarbons such as ethane/propane/butane. These facilities produce naphtha but do not produce gasoline (Reliance, 2005).

2.1.2.2 Hydroskimming Refineries

Building on the basic topping configuration, hydroskimming refineries incorporate hydrotreating (distillate desulfurizer) and catalytic-reforming units to improve the output of high-value fuels such as distillates and straight-run gasoline. Table 2-3 lists the typical mix of product yields from hydroskimming refineries. These facilities typically rely primarily on light sweet crude as their primary input to minimize resulting heavy fuel and residual fuel products because they have limited upgrading capabilities of distilled fractions.

Table 2-3. Typical Production Yield from a Hydroskimming Refinery

Product	% Yield
Propane/butane	4%
Gasoline	30%
Distillate	34%
Heavy fuel oil & other	32%
Total Yield	100%

Note: Gasoline includes reformulated gasoline (RFG), conventional, CARB, and Premium. Distillate includes jet fuel, diesel, and heating oil.

Source: Marcogliese, Rich. 2005. “Refining Fundamentals & Impact of Changing Fuel Specifications.” Presented on February 17, 2005 at the Lehman Brothers Analyst Teach-In. Valero Energy Corporation. Obtained on November 30, 2005. Available at: http://www.valero.com/Investor+Relations/Management+Presentations/.

Hydrotreating removes impurities such as sulfur, nitrogen, oxygen, halides and trace metals. It also upgrades the quality of these fractions by converting olefins and diolefins to paraffins to reduce gum formation in fuels (EPA, 1995). Catalytic reforming units process straight-run low-octane gasoline and naphthas into high-octane aromatics through four reactions that create aromatics by removing hydrogen from the feedstock (see EPA [1995] for details of these reactions).

2.1.2.3 Cracking Refineries

Cracking refineries build in complexity from the hydroskimming configuration by adding vacuum distillation, catalytic cracking, and alkylation units. The vacuum distillation unit further fractionates heavy bottoms from the atmospheric distillation process into gas oil and residual fuel. Table 2-4 lists the typical mix of product yields from cracking refineries. The total yield of 104% represents a volumetric gain due to the cat cracker’s ability to convert large hydrocarbon molecules into multiple smaller molecules. These facilities typically rely on light sour crude as the primary input. Moderate upgrading capabilities allow cracking refineries to increase the yield of higher-value products as well as gain volumetric output per volume of crude oil input (Marcogliese, 2005).

The catalytic cracking unit (i.e., fluidized and moving-bed) uses heat, pressure, and catalysts to breakdown heavy complex hydrocarbon molecules (i.e., gas oil) into smaller/lighter

Table 2-4. Typical Production Yield from a Cracking Refinery

Product	% Yield
Propane/butane	8%
Gasoline	45%
Distillate	27%
Heavy fuel oil & other	26%
Total Yield	104%

Note: Gasoline includes RFG, conventional, CARB, and Premium. Distillate includes jet fuel, diesel, and heating oil.

Source: Marcogliese, Rich. 2005. “Refining Fundamentals & Impact of Changing Fuel Specifications.” Presented on February 17, 2005 at the Lehman Brothers Analyst Teach-In. Valero Energy Corporation. Obtained on November 30, 2005. Available at: http://www.valero.com/Investor+Relations/Management+Presentations/.

molecules such as light cycle oil (LCO). LCO is then processed with other distillates in a hydrotreating process. Once the LCO and FCC gasoline are removed, an alkylation unit converts the remaining iosbutane feedstock into alkylates (i.e., propane/butane liquids), which are widely used blending additives in high-octane gasoline production.

2.1.2.4 Coking Refineries

Coking refineries extend the cracking refinery by adding hydrogen processing, hydrocracker, and delayed coking units to increase refineries’ capabilities to convert fuel oil into distillates (Reliance, 2005). Coking refineries are able to use medium to heavy sour crude as their primary input. These refineries also have the highest light product yields and volume gains, compared to other refinery configurations, as shown in Table 2-5 (Marcogliese, 2005).

Table 2-5. Typical Production Yield from Coking Refineries

Product	% Yield
Propane/butane	7%
Gasoline	58%
Distillate	28%
Heavy fuel oil and other	15%
Total Yield	108%

Note: Gasoline includes RFG, conventional, CARB, and Premium. Distillate includes jet fuel, diesel, and heating oil.

Source: Marcogliese, Rich. 2005. “Refining Fundamentals & Impact of Changing Fuel Specifications.” Presented on February 17, 2005 at the Lehman Brothers Analyst Teach-In. Valero Energy Corporation. Obtained on November 30, 2005. Available at: http://www.valero.com/Investor+Relations/Management+Presentations/.

The hydrogen facility produces hydrogen that is used as a feedstock in the hydrocracker as well as the hydrotreater units. The hydrocracker units apply hydrogen and significant pressure in a fixed-bed catalytic cracking reactor. Feedstocks for this unit include low-distillate fractions, as well as LCO, residual fuel oils. The hydrogen mitigates the formation of residual fuels and increases the yield of middle-distillate fuels, such as diesel and jet fuels (EPA, 1995). Delayed coking is a thermal cracking process that upgrades and converts petroleum residuum (heavy fuel oil) into liquid and gas product streams. The delayed coker unit eliminates residual fuel oil, leaving behind a solid concentrated carbon material known as petroleum coke (Ellis and Paul, 1998).

2.1.3 Refineries Around the World

There were 674 individual refining installations around the world with 82.4 million barrels per day of crude oil refining capacity at the end of 2004 (*Oil and Gas Journal* [*OGJ*], 2004). The number of operable refineries had fallen by 43 from 717 in 2003, a decline of 6.4%. Over the last 5 years, the number of refineries worldwide has declined, while the total crude capacity has continued to rise (Nakamura, 2004).

Table 2-6 summarizes the number, estimated crude capacity, and fuel “processing” capacity for refineries in seven world regions at the end of 2004. Historically, the mature markets of the United States and Europe have contained the largest number of refineries. However, recent dramatic growth in Asian markets has resulted in an increased number of refineries in South Korea, along with other South Pacific countries.

The concentrations of refineries in Asia, North America, and Western Europe represent approximately 68% of total refinery capacity. North American and Western European refineries have invested heavily in processing units that maximize their output of gasoline and other high-value outputs. This is illustrated by their processing capabilities as a percentage of crude capacity. In other regions of the world, refineries rely on atmospheric distillation to obtain straight-run product streams. As a result, residual fuel oil tends to be a greater share of total refinery output in these regions.

Refineries typically address regional fuel demand, while maintaining only a minimal stock of additional output for international trade and unexpected supply shocks due to weather. They are constrained by local demand, as well as the crude types that are proximal to the facility. Table 2-7 lists the 25 largest refinery companies in the world by total crude capacity. These firms represent 60% of the world’s crude refining capacity. The refinery companies on this list have

Table 2-6. Refinery Presence by World Region in 2004

Region	Refinery Count	Crude Capacity[a]	Fuels Processing Capacity[a,b]	Processing Capacity as % of Crude
Africa	46	3,230,362	506,470	2.4%
Asia & Oceania	161	20,695,031	2,052,728	10.0%
Central & South America	66	6,572,359	529,190	3.5%
Eastern Europe & Former U.S.S.R.	86	9,764,712	1,467,693	15.0%
Middle East	45	6,471,615	691,730	10.5%
North America	159	20,476,228	5,598,388	86.5%
Western Europe	111	15,198,594	2,480,458	76.8%
World Total	**674**	**82,408,901**	**13,326,657**	**16.2%**

[a] barrels per calendar day (b\cd)

[b] Processing capabilities are defined as conversion capacity (catalytic cracking, and hydrocracking) and fuel production processes (catalytic reforming and alkylation) divided by crude distillation capacity (% on crude). This measure represents the presence of downstream processing technology that improves the refinery's ability to produce high-value refined products such as high octane gasoline.

Source: *Oil and Gas Journal* (*OGJ*). 2004. "2004 Worldwide Refining Survey." *Oil and Gas Journal* 102(47):1-2.

focused on expanding capacity and reducing the total number of operable refineries over the last 10 years (Nakamura, 2004).

Many of the largest refinery companies have been investing heavily to supply Asian markets because of anticipated long-term growth in the region. Emerging Asian markets are growing at 4% annually, compared to the more mature markets of Europe and Japan that are expected to grow at less than 0.5% annually (Mergent, 2005). This high growth in Asia can largely be attributed to the transportation sector, including both freight shipping and personal vehicles.

As discussed, refinery products are diverse in character and functionality, and the specific mix of products will vary dramatically depending on the refinery's configuration and type of crude used. Table 2-8 summarizes how different refinery products vary across regions of world in 2003.

Motor gasoline is the highest-value product in the refinery output mix, and refineries typically engineer their unit operations to maximize its production. In North America, motor gasoline is typically the largest share of refined products, representing 45% of refinery output per

Table 2-7. World's Largest Refinery Companies by Capacity in 2004

Rank	Company	Crude Capacity (1,000s b/cd[a])	Rank	Company	Crude Capacity (1,000s b/cd)
1	ExxonMobil Corp.	5,693	14	National Iranian Oil Corp.	1,474
2	Royal Dutch/Shell	4,934	15	Nippon Oil Co. Ltd.	1,157
3	BP PLC	3,867	16	OAO Lukoil	1,150
4	Sinopec	2,793	17	Respsol YPF SA	1,106
5	Petroles de Venezuela SA	2,641	18	Kuwait National Petroleum Co.	1,085
6	Total SA	2,622	19	OAO Yukos	1,048
7	ConocoPhillips	2,615	20	Pertamina	993
8	ChevronTexaco Corp.	2,063	21	Marathon Ashland Petroleum LLC	935
9	Saudi Aramco	2,061	22	Agip Petroli SpA	906
10	Petroleo Brasileiro	1,965	23	Sunoco Inc.	880
11	Valero Energy Corp.	1,930	24	SK Corp.	817
12	Petroleos Mexicanos	1,851	25	Indian Oil Corp. Ltd.	777
13	China National Petroleum Corp.	1,782			

[a] b\cd

Source: Nakamura, David N. 2004. "Worldwide Refinery Capacity Creeps ahead in 2004." *Oil & Gas Journal* 102(47): 46-53.

Table 2-8. World Refinery Product Outputs of World Refineries per Day for 2003

Region	Motor Gasoline	Distillate Fuel Oil[a]	Residual Fuel Oil[a]	Other[a]	Total Refinery Products
Africa	0.5	0.7	0.7	0.8	2.7
Asia & Oceania	3.8	6.0	2.9	7.1	19.8
Central & South America	1.3	1.7	1.1	1.9	5.9
Eastern Europe & FSU	1.0	1.5	1.5	1.5	5.6
Middle East	0.9	1.8	1.7	2.1	6.4
North America	9.7	4.6	1.2	5.8	21.4
Western Europe	3.7	5.7	2.2	4.7	16.3
World Total	20.8	22.1	11.3	23.9	78.1

[a] million barrels/day

Source: U.S. Department of Energy, Energy Information Administration (EIA). 2005d. "International Energy Annual 2003: Table 3.2." Washington DC: DOE/EIA. Obtained on November 20, 2005. Available at http://www.eia.doe.gov/iea/.

day, while distillate and residual fuel accounted for 22% and 6%, respectively, in 2003. However, in all other major regions of the world, motor gasoline represented around 20% of total refinery output on average. Figure 2-3 illustrates these regional differences in the distribution of motor gasoline, diesel, and residual fuel production for seven world regions.

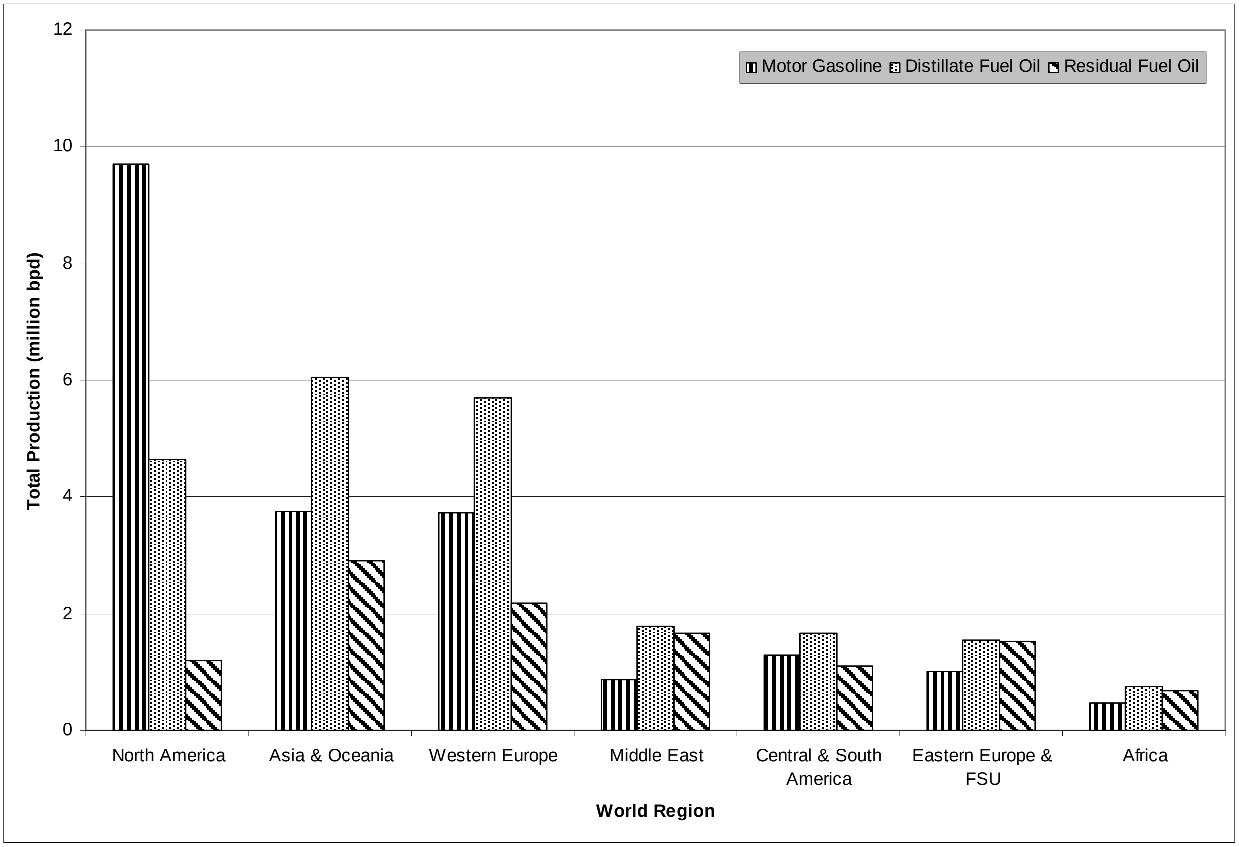


Figure 2-3. Product Outputs of World Refineries per Day in 2003

Source: U.S. Department of Energy, Energy Information Administration (EIA). 2005d. “International Energy Annual 2003: Table 3.2” Washington DC: DOE/EIA. Obtained on November 20, 2005. Available at http://www.eia.doe.gov/iea/.

Distillate fuel represents the largest share of refinery outputs for all regions outside of North America, accounting for about 31% of total refinery products in 2002. Residual fuel oil accounted for an additional 18%, on average. Other products such as petroleum feedstocks, jet fuels, and LPG gas accounted for 18%, 5%, and 5%, respectively.

The demand for gasoline in mature markets (e.g., United States, Europe, and Japan) and resulting refinery configurations have resulted in dramatic reductions in production of residual and distillates.. Despite the potential of hydroprocessing to treat high-sulfur residual fuels, the technology is not yet cost-effective for refiners.

For these reasons, bunker fuels may witness shortages as refineries continue to keep pace with demand for motor gasoline and other high-value refined products in North America and Western Europe, where motor gasoline prices are high relative to other refined products. (These trends are included in the WORLD model and discussed in Sections 4 and 5.) Industry experts have suggested that North America could witness a shortage of low-sulfur residual fuel of 20 million metric tons per year by 2015 and a surplus of high-sulfur residual oil of 40 million metric tons per year (Bunkerworld, 2005). To address these shortages, the industry expects an increase in low-sulfur residual fuel oil imported from South America or other areas of the world with low conversion capacity (and thus high residual fuel output).

In developing regions such as the African, Middle Eastern, and Asian markets, availability of sweet crude supplies, coupled with limited conversion capacity in existing regional refineries, will result in continued production of residual fuels. Over time, as sweet crude becomes increasingly scarce and the sulfur content of crude feedstocks increases, refineries in these regions will be forced to upgrade their conversion capacity by adding additional downstream processing to existing facilities, or the share of heavy distillates and residual fuel oils of their total refinery outputs will increase.

Finally, as China’s market for fuel demand increases, Chinese oil companies are competing with U.S. and European companies for depleting supplies of the world’s crude oil. The Energy Information Administration (EIA) predicts that China will begin to invest in petroleum projects in countries around the world, including Canada and South America, which have traditionally represented over 25% of the United States’ energy imports. China signed its first oil deal with Venezuela in 2004, marking the beginning of a battle for resources with more mature markets such as the United States. If China continues to increase its presence in the West through acquiring petroleum resources that traditionally supplied residual fuel oil demand in North America, any shortages in residual fuel oil could increase exponentially (Mergent, 2005).

2.2 Marine Fuel Types

There are three major types of marine fuel: distillate fuel, residual fuel, and a combination of the two to create a fuel type known as “intermediate” fuel oil (IFO). In this section, the various grades of marine fuel are introduced using the colloquial industry names to group the different fuel types. The purpose of this discussion is to introduce the reader to marine fuels in general to enable assimilation of more nuanced discussions that are presented in the balance of this report. Section 4 provides a technical discussion of marine fuel product specifications.

Distillate and residual fuels are blended into various combinations to derive the different grades of marine fuel oil. Table 2-9 lists examples of the major marine fuel grades and their colloquial industry names. In terms of cost, distillates are more expensive than intermediates, and residual fuels are the least expensive.

Table 2-9. Marine Fuel Types

Fuel Type	Fuel Grade	Colloquial Industry Name
Distillate	DMX, DMA, DMB, DMC	Marine gas oil (MGO) and marine distillate oil (MDO)
Intermediate	RME/F-25, RMG/H-35	Marine diesel fuel or intermediate fuel oil (IFO180 and IFO380)
Residual	RMA- RMH, RMK, and RML	Fuel oil or residual fuel oil

Source: Adapted from U.S. Environmental Protection Agency (EPA). 1999. *In-Use Marine Diesel Fuel*. EPA420-R-99-027. Washington, DC: U.S. Environmental Protection Agency.

Distillates and/or residual fuel oil stocks are blended with blending components or cutter stocks to achieve internationally accepted product specifications provided by the 1987 (revised in 1996) international standard, ISO 8217, that defines the requirements for fuel grades for use in marine diesel engines. Marine fuel grades carry three letters: the first “D” or “R” specifies “distillate fuel” vs. “residual fuel.” The second “M” signifies “marine fuel” use. The third letter designates the individual grade. Distillate marine (DM) fuels have three grades from A to C. Residual marine (RM) fuels have 15 grades depicted by letters A through H, K, and L. For example, RME-35 stands for “residual marine fuel E at a maximum viscosity (at 100° C) of 35 centistokes (EPA, 1999).

2.2.1 Marine Fuel Blending Stocks

As described in Section 2.1, “hydroskimming” type refineries produce straight-run stocks used in marine fuel blending, including light diesel, heavy diesel, and straight-run residue. More complex refineries derive similar blending stock components as the output from fluidized bed catalytic cracking (FCC) units. These stock components include light and heavy diesel, as well as light cycle gas oil (LCO) and heavy cycle gas oil (HCO). HCO also comes from the residual output from visbreaker units. These blending stocks are mixed with existing product streams from a refinery to manufacture a variety of marine fuel grades.

2.2.2 Marine Gas Oil (MGO)

Marine gas oil is the result of blending LCO with distillate oil to produce one of the highest marine fuel grades. MGO is more expensive because it is a lighter fraction and better quality fuel than diesel fuel. MGO is a fuel best suited for faster-moving engines (Spreutels and Vermeire, 2001).

2.2.3 Marine Distillate Oil (MDO)

MDO is manufactured by combining kerosene, light, and heavy gas oil fractions. DMA and DMB are typically used in small- to medium-sized marine vessels. DMC is heavier fuel oil and may sometimes be referred to as an intermediate fuel oil because it can be blended with residual fuel. MDO is manufactured by blending DMC with 10% to 15% residual fuel (Spreutels and Vermeire, 2001). MDO is more expensive than the more common intermediate fuel types.

2.2.4 Intermediate Fuel Oil (IFO)

Residual marine fuel grade G (RMG-35) is one of the most common residual fuels used in transoceanic ships. More commonly known as IFO380, this residual marine fuel is manufactured at the refinery and contains visbroken residue, HCO, and LCO (Spreutels and Vermeire, 2001). IFO380 typically has a high sulfur content that approaches 5%. IFO180 is another common IFO. IFO180 has a lower viscosity and metals content but maintains the same sulfur content as IFO380.

2.3 Bunker Fuel Suppliers

The bunker fuel supply chain includes traders, suppliers, brokers, bunkering-service providers or facility operators, and bunkering ports. The information available on different segments of the bunker fuel supply chain varies dramatically. Therefore, this section is not intended to be comprehensive but to provide an overview of the industry. We focus on four of the largest bunkering ports (Singapore, Rotterdam, Fujairah, and Houston).

Around the world, there are approximately 400 major bunkering ports. Logistics and transport cost factors influence the location of these bunker ports as well as local environmental regulations. In addition to being located close to supply sources (petroleum refineries) and consumers of transported goods (major population centers), bunkering ports are often strategically located along high-density shipping lanes. For example, Singapore handles more than twice the bunker fuel volume of Rotterdam, the next largest port. In North America, the largest facilities follow the general pattern suggested by location theory; Los Angeles, San

Francisco, New York, Philadelphia, Houston, and New Orleans are close to both refinery supply and transport destinations.

2.3.1 Singapore

Singapore’s strategic location on the Strait of Malacca makes it the largest port in the world in terms of cargo throughput and bunker fuel sales. The total cargo throughput in 2005 equaled 423 million tons. The port of Singapore handles large volumes of petroleum products and dry bulk cargo. In 2005, Singapore surpassed Hong Kong by almost 1 million twenty-foot equivalent units (TEUs) and claimed the lead in handling containerized cargo (Sina, 2006). Its tonnage of containerized, oil, and dry-bulk cargo has steadily increased over the past 5 years. Although the number of vessel calls has been slowly declining, Singapore still handles more vessel calls than any other port in the world—almost 173,000 vessel calls in 2005 (MPAS, 2005a).

Singapore is also the largest bunker fuel market in the world. Bunker turnover was reported at 25.48 mmt (million metric tons) in 2005 (MPAS, 2006b). Turnover at the port grew at the average rate of 5.6% over the past 6 years, equaling 20.8 mmt in 2003 and 23.6 mmt in 2004. Heavy fuel-oil sales accounted for 71% of total bunker sales by volume in 2004, with lighter fuel and distillate oils accounting for 19% and others (including lube oils) for the remaining 2% (MPAS, 2005c). The majority of bunker deliveries to vessels in the port of Singapore are made by bunker tankers; however, other types of deliveries are available as well.

2.3.1.1 Refineries

Singapore is one of the top three refining centers in the world; the others are Houston and Rotterdam. Petroleum refining accounted for approximately 16.5% of Singapore’s gross domestic product (GDP) in 2004. Singapore’s refineries have a major influence on Asian markets: their petroleum product exports were valued at $17.5 billion in 2004.[1] Singapore also exported $4.7 billion worth of bunker fuels, which equaled 2.6% of national GDP (SMTI, 2005).

Operating at 92% capacity, the top three refineries in Singapore have a combined production of around 1.3 million barrels per day (bpd) (EIA, 2005e). Out of that quantity, bunker fuels consumed in the Singapore shipping market comprise approximately 400,000 bpd. Another 400,000 bpd are consumed locally for various purposes, and the remainder (mostly gasoline and diesel fuels) are exported to Vietnam, China, and Indonesia (Reuters, 2006).

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[1] Numbers are reported in U.S. dollars.

Refineries producing bunker fuel that is sold in the local market are as follows:

- **Jurong Island Refinery**, owned by ExxonMobil
  - Capacity of 605,000 bpd
- **Pulau Bukom Island Refinery**, owned by Royal Dutch/Shell
  - Capacity of 458,000 bpd
- **SRC Jurong Island Refinery**, partially owned by Singapore Refining Corporation (SRC), partially owned by ChevronTexaco through its subsidiary Caltex
  - Primary plant—a joint venture between SPC and Caltex (ChevronTexaco) with 285,000 bpd capacity
  - Owns a bunker storage terminal on the Pulau Sebarok Island with storage capacity of 1.4 million barrels

These three refineries have a combined storage capacity of 88 million barrels. Singapore's three largest independent storage operators—Vopak, Oiltanking, and Tankstore—have been using 90% of their combined total capacity of 22.3 million barrels in the past 5 years. Production plans are underway that, when complete, will almost triple the storage capacity of local operators (EIA, 2005e).

Although refining has a strong presence in Singapore, imports of refined petroleum products equaled $12.6 billion (11.4% of national GDP) (SMTI, 2005). Consumption of imported oil products reached 750,000 bpd in 2004 (EIA, 2005e). The Singapore bunker fuel market is very diverse; fuel from all major refineries around the world gets delivered to the port. Even though no numerical data are readily available, based on qualitative assessments, the majority of these world imports come from Venezuela, Chile, and Russia (Bunkerworld, 2005d).

2.3.1.2 Bunker Traders

Bunker traders secure bunker volumes for their shipping clients in local supply markets or in their own refined-products distribution channels. Traders include both major oil companies as well as independents. Both types perform the functional service in the timely procurement of bunker fuel orders. Traders act as midway between local customers and refinery suppliers, where the majority of transactions occur under long-term contracts.

Twenty-three companies serve as traders in the Singapore shipping market.[2] Among them are smaller local companies such as Bunker House Petroleum, as well as larger international oil companies such as Lukoil and OW Bunker. Among the leaders are OW Bunker and Hin Leong, the latter of which recently scheduled construction of the largest petroleum terminal in the area with total storage capacity of 14.5 million barrels.

2.3.1.3 Bunker Suppliers

Thirty-four companies serve as bunker suppliers, with an additional 18 that perform functions of suppliers and traders. Three refinery operators are also among the top four suppliers (British Petroleum, Shell, and ExxonMobil). They are joined by Global Energy Trading, a smaller company that owns and operates 14 vessels at the port. Other large suppliers include Consort Bunkers, Singapore Petroleum Company, Chevron Singapore, OW Bunker, and Chemoil (SMP, 2006).

2.3.1.4 Barge Operators

Singapore has 32 independent barge operators. The bunker barge fleet contained approximately 120 vessels of various sizes in 2005 (Bunkerworld, 2005e). The largest among the barge operators is Ocean Tankers, a sister company of Hin Leong, which owns and operates 70 bunker barges.

2.3.2 Rotterdam

Rotterdam is the second largest port in the world with throughput of more than 369 million tons of cargo in 2005 (Port Authority of Rotterdam, 2005). Some 30,000 ocean-going ships call at the port every year and 110,000 to 120,000 inland vessels. Activities related to the port contribute around 12% of the Netherlands' GDP (Bunkerworld, 2000). Overall, the port of Rotterdam has experienced a 5% increase in cargo handling with the majority of growth coming from container cargo, which had a 12% increase to 9.3 million TEUs between 2004 and 2005. General cargo was up 7%, or 7 million tons, to a total of 110 million tons in 2005.

Rotterdam is the largest bunker port in Europe. Bunker turnover in 2004 for the port was 12.5 million cubic meters (m^3). In 2002 and 2003, bunker turnover was 10.6 and 11.4 million m^3,

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[2] Consort Bunkers Pte Ltd, Searights Maritime Services Pte Ltd, Bunker House Petroleum Pte Ltd, Northwest Resources Pte Ltd, Golden Island Diesel Oil Trading Pte Ltd, Lukoil Asia Pacific Pte Ltd, Alliance Oil Trading Pte Ltd, Costank (S) Pte Ltd, Sentek Marine & Trading Pte Ltd, Lian Hoe Leong & Brothers Pte Ltd, Standard Oil & Marine Services Pte Ltd, Panoil Petroleum Pte Ltd, Ocean Bunkering Services Pte Ltd (owned by Hin Leong Marine International Pte Ltd), O.W. Bunker Far East Pte Ltd, The Barrel Oil Pte Ltd, Fratelli Cosulich Bunkers (S) Pte Ltd, Prestige Marine Services Pte Ltd, Gas Trade (S) Pte Ltd, Wired Bunkering Pte Ltd, Cockett Marine Oil (Asia) Pte Ltd, Ignition Point Pte Ltd, Prosperbiz Petroleum (S) Pte Ltd.

respectively (Port Authority of Rotterdam, 2004a). These volumes include IFO, MGO, MDO, and lube oils (IFO represents the majority of overall bunker turnover). Russian oil imports represent a significant share of total refined oil product supply. Between 2002 and 2003, Russian imports of crude and refined oil products grew by 17% (Port Authority of Rotterdam, 2004b).

2.3.2.1 Refineries

In 2004, oil refineries represented 6.5% of the 58,000 workers directly employed at the Port. However, because of environmental regulations and European fuel market conditions, refineries in the region around Rotterdam produce less of the heavy fuel oil that typically dominates bunker markets (3% to 3.5% sulfur). Consequently, the local refinery output can no longer cover the Rotterdam bunker demand. This shortage has led to increased reliance on fuel oil from import sources. Fuel oil imports are estimated to be 300,000 to 400,000 metric tons per day.

The local refineries that still produce bunkers sold on the Rotterdam market include the following:

- **The Pernis Refinery**, owned by Royal Dutch/Shell
  - Capacity approximately 416,000 b/d.
- **NEREFCO** (Netherlands Refining Co.), owned by BP (69%) and Texaco (31%)
  - Capacity in excess of 380,000 b/d.
- **Q-8 refinery**, owned by Kuwait Petroleum Corporation
  - Capacity about 75,500 b/d.
- **The Esso Refinery** (ExxonMobil) does not produce fuel oil, but the company sources from a plant in Antwerp, Belgium, with capacity of 225,000 b/d.

2.3.2.2 Bunker Traders

Traders in the Rotterdam market include oil majors, such as Shell Marine Products and Lukoil. Shell Marine Products uses the majority of its Pernis refinery's marine fuel output for its own clients (Bunkerworld, 2000), while the majority of NEREFCO's output is purchased by independent traders in the local fuel-barge market.

Independents typically purchase their bunker fuel on the local barge market. In addition, it is common for traders to import cargos of bunker fuel and store the fuel in rented storage tanks in the petroleum zones of the port. Vitol, Allround Fuel Trading/Chemoil, and the oil majors, especially Texaco, BP, and Elf (TotalFinaElf), are the largest bunker traders of imported oil products (Bunkerworld, 2000).

2.3.2.3 Bunker Suppliers

Physical supplying of bunker fuel to ships is conducted by barge in the bunkering designated zones. Europort and Botlek areas are two primary bunkering areas within the port of Rotterdam. In 2000, over 90% of the bunkers in Rotterdam were delivered by barge (Bunkerworld, 2000).

Barges are loaded at various fuel-terminal facilities owned by Vopak and the oil majors. Most suppliers, including the oil majors, do not own or operate their own barges. Most majors and some independents have specially dedicated barges or barges on exclusive time charter. Among many independents, it is common practice to pool barge transportation services (Bunkerworld, 2000).

Because of the nature of physically supplying bunkers, large storage capacity is needed to enable flexibility in the suppliers' ability to respond to sudden fluctuations in bunker demand. The most recent example of traders enlarging storage capacity is the partnership of Lukoil and Fuel Transport Services (FTS)/Hofftrans (a local barge operator) partnering to build a bulk terminal named the Service Terminal Rotterdam (STR). STR is designed for better bunkering and ship–ship transhipment. This expansion is estimated to increase total storage capacity to 120,000 m^3. Another expansion is currently under way by the Vitol Group, which is constructing a 278,000 m^3 storage tank terminal in the Europort area. The Vitol facility is expected to begin operations in 2006 and will provide jetties capable of accommodating vessels ranging between bunker barges and very large crude oil carriers (VLCCs).

2.3.2.4 Barge Operators

The largest barge operator is VT/Unilloyd, which works exclusively in transportation and owns more than 20 barges. FTS/Hoftrans has around 10 barges of up to 2,000metric tons (mt) capacity. A group of companies, which includes the suppliers Atlantic/Postoils, operates their own fleet of 21 barges ranging from 300 to 3,900 mt capacity. These barges also deliver on behalf of other suppliers (Bunkerworld, 2000).

Additionally, some suppliers own their own fleet of barges. One example is Argos Bunkers BV, which has its own fleet of six barges ranging from 200 to 1,400 mt capacity, plus the company charters three more barges ranging from 700 to 2,000 mt. Ceetrans/Ceebunker Services BV is owned by Argos and has access to the same barges. Frisol Bunkering BV has three time-chartered barges totaling 4,270 mt in capacity. NIOC (Netherlands Independent Oil Co.) has access to the 23-strong barge fleet of its Belgian parent company, Wiljo Bunkering NV (Bunkerworld, 2000).

2.3.3 Fujairah

Fujairah is the third largest bunkering port in the world, supplying over 12 million mt of bunker fuel annually (Gulf News, 2006). The Fujairah bunker market comprises three port areas, which include the United Arab Emirates (UAE) ports of Khor Fakkan, Fujairah, and Kalba. Fujairah is situated in the middle of these three ports, with Khor Fakkan to the north. The three ports and their offshore counterpart in the Gulf of Oman constitute “the Fujairah bunker market.” Although there are some local differences, unless otherwise stated, “Fujairah” is seen as incorporating the entire area (Bunkerworld, 2002). Fujairah is located in the outer Gulf, just outside the Straits of Hormuz, which are the gateway to the Arabian Gulf. Because of Fujairah’s proximity to Middle Eastern oil production, Fujairah’s bunker customers are predominantly VLCCs, which are often anchored in the Gulf of Oman waiting for cargo in the inner Gulf.

Although official data regarding the turnover of bunker fuel in the Fujairah market are not available, industry experts have estimated the annual volume to be over 12 million mt in 2002, with an average monthly supply volume of 1 million mt. Because tankers are the major customers in the Fujairah market, large bunkers rather than numerous small deliveries are the norm. The average supply volume varies between 2,000 mt to 15,000 mt (Bunkerworld, 2002). Assuming an average volume per vessel, this implies that approximately 120,000 bunkering transactions take place in the Fujairah market each year.

Several estimates exist regarding the market share of each bunker fuel grade. IFO 380 is estimated to account for between 80% and 95% of total bunkers supplied. The remaining 5% to 20% are split between IFO180 and MGO, but exact shares are not available. Typically, Fujairah is host to the most competitive pricing of bunker fuel in the Arabian Gulf. However, the price differences between IFO380 and IFO180 grades in Fujairah are typically higher than those found in Singapore or Rotterdam (Bunkerworld, 2002). The significant price difference between IFO380 and IFO180 is due to a lack of cheap cutter stock typically used in blending to create lighter fuel grades in the Arabian Gulf. As a result, Fujairah’s bunker suppliers are forced to use MGO in blending activities, making purchasing lighter grades of residual fuel such as IFO180 less attractive in the Fujairah market (Bunkerworld, 2002).

2.3.3.1 Refineries

Fujairah itself has only one refinery facility—the Fujairah Refinery Company (FRC) (Nakamura, 2005). The FRC plays a vital role in supplying straight-run fuel oil to the Fujairah bunker market. Metro Oil Corporation ran the facility until the late 1990s when it was shutdown. The FAL Energy Company took over the facility in 2004 to use its 460,000 m^3 of storage capacity (Nakamura, 2005). The Fujairah government in 2005 announced a desire to revitalize the facility and update processing technologies. Currently, the FRC refinery does not contribute a huge amount of bunkers to the local market.

The Abu Dhabi National Oil Company (ADNOC) operates two refineries in the UAE, including the Umm Al Nar and Ruwais refineries. These two refineries produce over 23 million mt of products annually, which are sold to both international and local markets (Bunkerworld, 2002). The Umm Al Nar refinery processes 150,000 bpd of crude oil, and the Ruwais refinery has two units with a total design capacity of 350,000 bpd. The Emirates National Oil Company Limited (ENOC) operates the 120,000 bpd Jebel Ali plant (Nakamura, 2005).

Other refineries located near Fujairah cover 14 major refineries and include Bahrain National Oil Company's refinery, Aramco's five Saudi refineries, the National Iranian Oil Company's (NIOC) six refineries in Iran, and Kuwait Petroleum Corporation's (KPC) three Kuwaiti plants (Nakamura, 2005; Bunkerworld, 2002).

2.3.3.2 Bunker Traders

Bunker traders arrange supply deliveries in the Fujairah bunker market. These firms provide services that ensure that bunker supplies are available and delivered in a timely fashion. The Fujairah bunker market is presently serviced by approximately 11 trading companies, including FAL Energy Company, GAC Bunkers Co., and FAMM Middle East Ltd.

2.3.3.3 Bunker Suppliers

The offshore terminals in Fujairah make it an ideal bunkering stop-off for both inbound and outbound tankers leaving the Gulf (Bunkerworld, 2002). Typical bunkering entails bunker barges loading from storage tankers and supplying bunkers to passing vessel traffic that is moving through the Straits of Hormuz between the Arabian Gulf and the Gulf of Oman.

Most suppliers import their products and then store bunkers in large tankers that reside in the Gulf or in shore-based fuel terminals. The majority of companies purchase product from refineries in the UAE or other regional refineries. The port of Fujairah is serviced by 20 suppliers, representing a mix of local businesses as well as international bunker suppliers such as German-based Bominflot and BP Marine Middle East located in Dubai, UAE.

EPPCO International, a joint venture between ENOC and Caltex, owns and operates some of the largest refined-petroleum terminalling facilities in the UAE. The terminals are spread between Jebel Ali and Fujairah and represent 6.44 million barrels in storage capacity. In

2002, Vopak ENOC Fujairah Terminal Company had 30 tanks (10 tanks designed to handle fuel oil) with a total capacity of 1 million m^3 storing fuel oil, gas oil, gasoline, naphtha, and jet kerosene. The Vopak terminal offers products to the local market via three berths capable of accommodating vessels up to 175,000 dead weight tons (dwt) (Bluewater, 2002). Additional capacities are designed to serve the active fuel-oil market offshore, whether for cargo trading or for bunkering purposes.

Other examples of suppliers in the Fujairah market include FAL and EPPOC. The longest established bunker company in the UAE is FAL Energy Company, which leases storage capacity at the FRC and has 24 tanks with a combined capacity of 422,000 cubic meters storing fuel oil, gas oil, naphtha, and jet kerosene. Finally, the Emirates Petroleum Products Co. (Eppco), a subsidiary of ENOC, expanded its existing storage capacity from 100,000 m^3 to over 150,000 m^3 in 2003. These investments in supplier infrastructure indicate the growing importance of this bunker market.

2.3.3.4 Barge Operators

The Fujairah market is largely served through off-shore deliveries by barge. For this reason, many suppliers operate their own barge fleet in the Gulf of Oman. In addition, eight independent barge operators offer service. The FAL Energy Company has a number of bunkering vessels operating in both the Arabian Gulf and the Gulf of Oman. Larger international suppliers such as ExxonMobile's Marine Fuels (EMMF) Company often contract with independent barge operators in the Fujairah market, following detailed certification by EMMF (EMMF, 2006).

2.3.4 Houston

The Port of Houston ranks second in U.S. foreign waterborne commerce and total tonnage. In 2004, 6,539 ships called at Houston where traffic is dominated by container ships, tankers, and bulk carriers.

Houston is a mix of private and public terminals. The areas controlled by the Port of Houston Authority can be divided into four main areas:

- the City Dock, also called the Turning Basin
- Barbours Cut Terminal, the main terminal for containers (940,000 TEUs in 1996)
- Jacintoport Terminal, a general cargo handling port
- Woodhouse Terminal, for ro-ro cargo vessels

Development of a new container terminal is now in the design stage at the Port. It is intended to alleviate pressure at the Barbours Cut Terminal, which was forecast to pass one million TEUs by 1998.

2.3.4.1 Refineries

Several refineries are located near the port, including ExxonMobil's Baytown Refinery, BP's Texas City Refinery, Marathon Ashland's Texas City, and the Valero Refinery. While these refineries represent a significant share of the U.S. capacity in refined products, they do not produce marine fuels. Typically, marine fuel is imported from countries in the western hemisphere where refinery production of heavy fuel oil is greater than in the United States. As such, most marine fuels imports are sourced from Venezuela, Aruba, and Mexico.

2.3.4.2 Bunker Traders

Iso Industry Fuels and Chemoil Corporation are two bunker traders associated with the Port of Houston bunker market. In addition, several international trading groups conduct transactions in Houston.

2.3.4.3 Bunker Suppliers

Between 6 and 15 major suppliers operate in the Houston Port area, though major suppliers like Shell Marine Products, Valero Marketing and Supply Co., Chemoil Corp., BP Marine Fuels, and Bominflot Atlantic LLC dominate.

In addition several smaller suppliers have storage terminals in or near the port area and operate barge delivery services. Houston Marine Services and Midstream Fuel Services operate storage terminals, bunker supply vessels, and fleets of barges along the Gulf Coast. Matrix Marine Fuels, Enjet, and Difco Fuel Systems are examples of smaller suppliers in the Houston bunkering market. Suncoast Resources delivers primarily by truck at local berths, supplied by a network of fuel terminals in the Houston area (Bunkerworld, 2000).

2.3.4.4 Barge Operators

Currently, only very limited information is available on the barge market in Houston. Most existing barge operations appear to be conducted by local suppliers.

SECTION 3

DEMAND FOR BUNKER FUELS IN THE MARINE INDUSTRY

This section discusses the demand side of the marine fuels market. The analysis of current and expected future shipping activity in this section is used to estimate regional and worldwide projections of future marine bunkers demand through the year 2020. These consumption forecasts then provide a baseline for the WORLD model, against which the shipping industry's possible response to the adoption of a U.S. or North American SECA regulation could be evaluated.

3.1 Summary of the Modeling Approach

In general, the approach used to estimate marine bunker fuel use can be described as an "activity-based" approach with a focus on the international cargo vessels that represent the majority of fuel consumption. Components of the estimation include

- identifying major trade routes,
- estimating volumes of cargo of various types on each route,
- identifying types of ships serving those routes and carrying those cargoes,
- characterizing types of engines used by those ships, and
- identifying the types and estimated quantities of fuels used by those engines.

Implementing this approach involves combining information from a variety of sources: data on the existing fleet of shipping vessels from Clarksons (2005), information from Corbett and Wang (2005) and various industry sources on engine characteristics, and projections of future global trade flows from Global Insights (2005). The data on vessels and engines provide a characterization of fuel use associated with delivering a particular load of cargo, and the data on trade flows control how many times, and over what distances, these loads have to be delivered.

Estimating fuel consumption through an activity-based methodology that combines data on specific vessels with data on engine characteristics is similar to the approaches used in Corbett and Koehler (2003, 2004), Koehler (2003), Corbett and Wang (2005), and Gregory (2006). The approach in this report extends previous analyses by linking these ship data to projections of worldwide trade flows to determine the total number of trips undertaken in each year, and hence fuel use, rather than using estimates of the number of hours a ship/engine typically runs in a year.

Accordingly, the model developed in this section estimates fuel consumption based on an underlying economic model's projections of international trade by commodity category (Global Insights, 2005). Demand for marine fuels is derived from the demand for transportation of various types of cargoes by ship, which, in turn, is derived from the demand for commodities that are produced in one region of the world and consumed in another. The flow of commodities is matched with typical vessels for that trade (characterized according to size, engine horsepower, age, specific fuel oil consumption, and engine load factors). Next, typical voyage parameters are assigned, including average ship speed, round-trip mileage, tons of cargo shipped, and days in port. Fuel consumption for each trade route and commodity type thus depends on commodity projections, ship characteristics, and voyage characteristics.

Figure 3-1 illustrates the broad steps involved in developing baseline projections of marine fuel consumption. It is a multistep process that relies on data and forecasts from numerous sources, some of which are listed above, to inform the projections. The flow chart in the figure illustrates the relationships to be profiled in characterizing baseline marine fuel consumption by cargo vessels.

Also, although the focus of this analysis of bunker fuel forecasts is on projecting use by vessels carrying cargo among international ports, it includes other vessel types when estimating total demand for bunker fuels, as discussed below. These vessel types include passenger vessels such as ferries and cruise ships, service vessels such as tugs and offshore supply vessels (OSV), and military vessels.

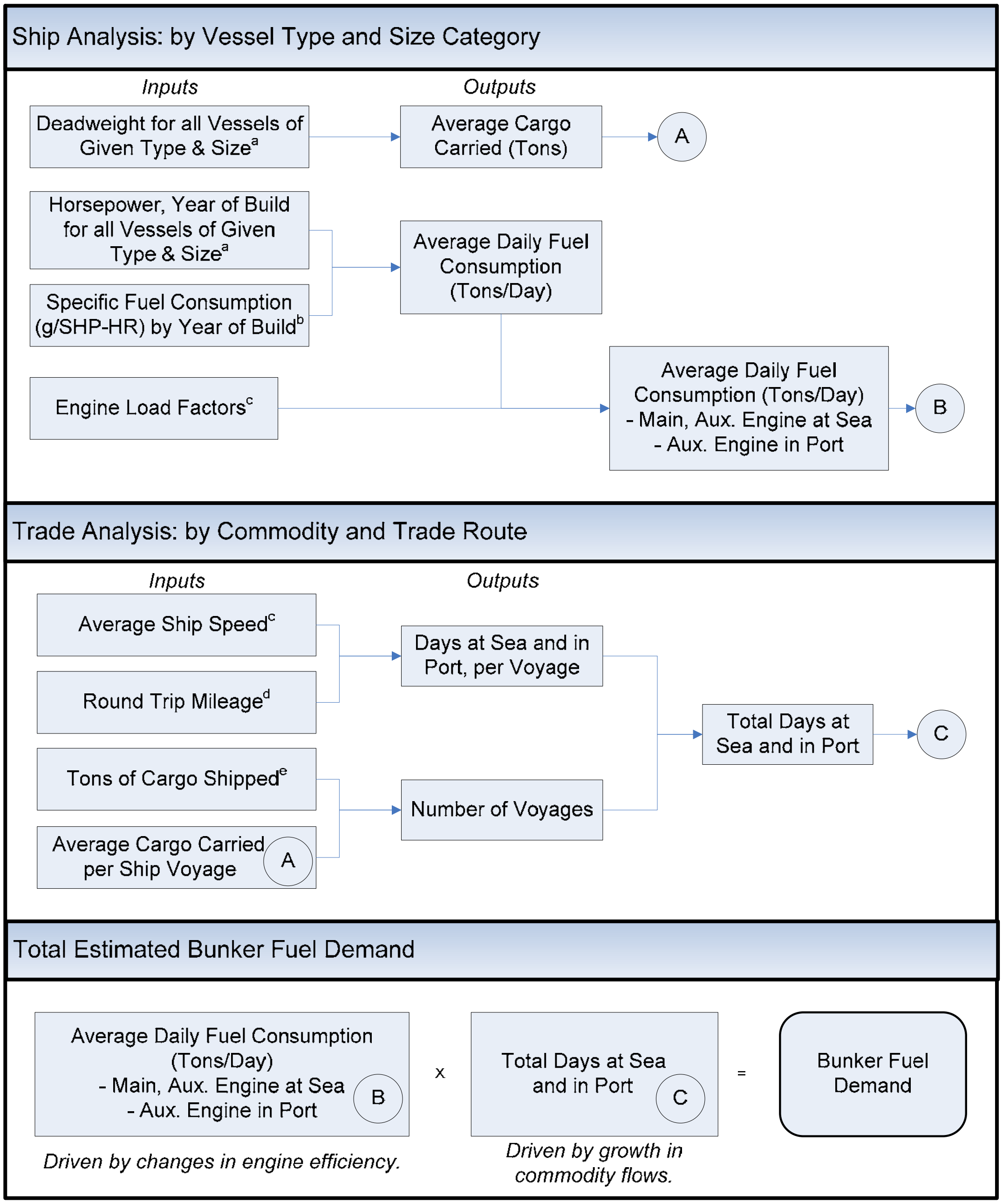
3.2 Methods of Forecasting Bunker Fuel Consumption

Underlying the projections of bunker fuel consumption by cargo vessels worldwide are projected flows of commodities between regions of the world. These are commodities produced in one region of the world and demanded in another.

3.2.1 Composite Commodities and Regions

The first step in analyzing trade flows was examining the relevant composite commodities and obtaining forecasts for them, which are based on the following categories:

- liquid bulk—crude oil
- liquid bulk—refined petroleum products
- liquid bulk—residual petroleum products
- liquid bulk—chemicals (organic and inorganic)
- liquid bulk—gas (including LNG and LPG)



a – Clarksons Ship Register Database
b – Engine Manufacturers' Data, Technical Papers
c – Corbett and Wang (2005) "Emission Inventory Review: SECA Inventory Progress Discussion"
d - Combined trade routes and heavy leg analysis
e – Global Insight Inc. (GII) Trade Flow Projections

Figure 3-1. Method for Estimating Bunker Fuel Demand

- dry bulk (e.g., grain, coal, steel, ores, and scrap)
- general cargo (including neobulk, lumber/forest products)
- containerizable cargo

Next, countries of the world were grouped into approximately 20 larger regions. Table 3-1 shows the mapping of countries to regions. From Global Insight, Inc. (GII) World Trade Service, a specialized forecast was obtained that reports flows of each commodity among regions for the period 1995–2024. GII's forecast of shipments of these commodities among these regions drives the overall forecast of demand for shipping services and thus for marine fuels.

GII is a widely recognized macroeconomic forecasting firm. The GII World Trade Service provides annual macroeconometric analysis and forecasts of economic activity and trade for over 200 individual countries and for the global economy. GII provides integrated analyses and forecasts for individual countries and regions of the world and for the world economy as a whole, including an analysis of the relationship of each region's economy to the world economy. To facilitate integration of the fuel demand analysis with the fuel supply analysis, GII grouped its countries and regions into aggregate regions comparable to those used in EnSys Energy's WORLD model. The aggregate regions and associated source countries/regions are shown in Table 3-1.

The GII World Trade Forecasting Model is a nonlinear multistage econometric switch model (GII, 2005). It uses several data sources, economic theory, and multistage modeling linked by top-down control adjustment to capture and project commodity flows in the world. No single data source provides a complete baseline picture of international trade. GII bases their model on UN historical international trade data (published by Statistics Canada). These data are supplemented with OECD International Trade by Commodity Statistics to reflect more realistic data for developing countries, and the U.S. Customs and IMF Direction of Trade data to calibrate and enhance historical commodity trade flows. Additional macroeconomic data (such as population, GDP, GDP deflators, industrial output, foreign exchange rates, and export prices by country) and geographical distances are used as exogenous variables.

The general structure of the model for calculating trade flows assumes a country's imports from another country are driven by the importing country's demand forces (given that the exporting country possesses enough supply capacity), and affected by the exporting country's export price and importing country's import cost for the commodity. GII then estimates demand forces, country-specific exporting capacities, export prices, and import costs. To arrive at each country's trade with each of its trading partners, nonlinear multistage switch modeling is required.

Table 3-1. Aggregate Regions and Associated Countries

Aggregate Regions	Containing GII Base Countries/Regions
U.S. Atlantic Coast	U.S. Atlantic Coast
U.S. Great Lakes	U.S. Great Lakes
U.S. Gulf Coast	U.S. Gulf Coast
E. Canada[a]	Canada[a]
W. Canada[a]	Canada[a]
U.S. Pacific North	U.S. Pacific North
U.S. Pacific South	U.S. Pacific South
Greater Caribbean	Colombia, Mexico, Venezuela, Caribbean Basin, Central America
South America	Argentina, Brazil, Chile, Peru, Other East and West Coast of S. America
Africa – West	Western Africa
Africa-North/East-Mediterranean	Mediterranean Northern Africa, Egypt, Israel
Africa-East/South	Kenya, Other Eastern Africa, South Africa, Other Southern Africa
Europe-North	Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Netherlands, Norway, Sweden, Switzerland, United Kingdom
Europe-South	Greece, Italy, Portugal, Spain, Turkey, Other Europe
Europe-East	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovak Republic
Caspian Region	Southeast CIS
Russia/FSU	The Baltic States, Russia Federation, Other Western CIS
Middle East Gulf	Jordan, Saudi Arabia, UAE, Other Persian Gulf
Australia/NZ	Australia, New Zealand
Japan	Japan
Pacific-High Growth	Hong Kong S.A.R., Indonesia, Malaysia, Philippines, Singapore, South Korea, Taiwan, Thailand
China	China
Rest of Asia	Viet Nam, India, Pakistan, Other Indian subcontinent

[a] Canada is treated as a single destination in the GII base model. Shares of Canadian imports from and exports to regions of the world in 2004 are used to divide Canada trade into shipments to/from Eastern Canada ports and shipments to/from Western Canada ports (Transport Canada, 2004).

Switch models are not continuous functions. Thus, they cannot be estimated using conventional derivative methods; a direct search method is used instead. Although uncommon for economics, this method is widely used in other scientific fields. A direct search method estimates switch functions, while allowing one to define error minimization functions and set boundaries for model parameters. GII's approach to forecasting is unorthodox as well. GII contends that the three commonly used approaches—bottom-up, top-down, and manual (hybrid) approach—fail because of their limitations.[1] GII uses a system that could be referred to as a controlled top-down approach.

GII defines four levels, with the bottom level being the most detailed: commodity flows between each pair of countries/regions. The third level is how much of each commodity each country exports/imports from the world. The second level is the total commodity flows that each country exports/imports from the world, and the first level is world trade of total commodities. The second, third, and fourth levels have their own behavioral equations, but individual forecasts at the lower levels are forecast under the constraint of their aggregate forecast at the higher level. Thus, if there is a discrepancy between the sum of individual forecasts and aggregate forecasts, the program identifies the items that could be adjusted and adjusts them step by step to eliminate the discrepancy.

GII's output for this project included detailed annual region-to-region trade flows for eight composite commodities, for the period 1995 to 2024. The projections for 2012 and 2020 are shown, along with baseline data for 2005, in Table 3-2. In 2005, dry bulk accounted for 41% of the total trade volume. Crude oil accounted for 28%, and containers accounted for 12%. Dry bulk and crude oil shipments grow more slowly over the forecast period than do container shipments; by 2020, dry bulk is 39% of the total, crude oil is 26%, and containers have risen to 17%.

3.2.2 Ship Analysis by Vessel Type and Size

Different types of vessels are required to transport these different commodities to the various regions of the world. Profiles of these vessels were developed to provide a characterization of ships assigned to transport commodities of each type along each route. These profiles analyze data provided by the Clarksons Ship Register (Clarksons, 2005) on size, horsepower, age, and engine fuel efficiency to identify typical vessels of each overall vessel type and each size category. The main purpose of the analysis is to determine the average amount of cargo carried by an average daily fuel consumption of each vessel type.

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[1] The bottom-up approach forbids forecasted items to be subject to total resource constraints or equilibrium. For example, this approach would disallow the possibility of a country's import limitations due to an income constraint. The top-down approach requires forecasted items to have identical dynamic patterns. However, the historical data reveal it is rare to find that a country's imports of a commodity from two different countries exhibit identical dynamic patterns. The hybrid method solves the problems of the latter two but is very time consuming.

Table 3-2. World Trade Estimates for Composite Commodities, 2005, 2012, and 2020

Commodity Type	2005 (in million tons)	2012 (in million tons)	2020 (in million tons)
Dry bulk	2,473	3,051	3,453
Crude oil	1,703	2,011	2,243
Container	714	1,048	1,517
Refined petroleum	416	471	510
General cargo	281	363	452
Residual petroleum and other liquids	190	213	223
Chemicals	122	175	228
Natural gas	79	91	105
Total international cargo demand	**5,979**	**7,426**	**8,737**

First, the eight GII commodity categories were mapped to the type of vessel that would be used to transport them. These assignments appear in Table 3-3.

Table 3-3. Assignment of Commodities to Vessel Types

GII Commodity	Ship Category	"Type" Defined in Clarksons Register[a]
Liquid bulk—crude oil	Crude oil tankers	Tanker
Liquid bulk—refined petroleum products	Product tankers	Product carrier
Liquid bulk—residual petroleum products	Product tankers	Product carrier
Liquid bulk—chemicals (organic and inorganic)	Chemical tankers	Chemical and oil carrier
Liquid bulk—natural gas (including LNG and LPG)	Gas carriers	LNG carrier, LPG carrier, chemical & LPG carrier, ethylene/LPG, ethylene/LPG/chemical, LNG/ethylene/LPG, LNG/regasification, LPG/chemical, LPG/oil, oil & liquid gas carrier
Dry bulk (e.g. grain, coal, steel, ores and scrap)	Dry bulk carriers	Bulk carrier
General cargo (including neobulk, lumber/forest products)	General cargo	General cargo liner, reefer, general cargo tramp, reefer fish carrier, ro-ro, reefer/container, ro-ro freight/passenger, reefer/fleet replen., ro-ro/container, reefer/general cargo, ro-ro/lo-lo, reefer/pallets carrier, reefer/pass./ro-ro, reefer/ro-ro cargo
Containerizable cargo	Container ships	Fully cellular container

[a] Vessel operators self-report these types to Clarksons Research Services for inclusion in their shipping databases.

Each of these vessel types was further classified by size in deadweight tons (DWT). Appropriate size categories were identified based on both industry definitions and natural size breaks within the data. Table 3-4 summarizes these subcategories and provides other information on the general characteristics of vessels represented in the Clarksons' data. The size descriptions imply the size limitations as defined by canals or straits through which ships of that size can pass. Crude oil tankers (VLCC) are the largest by DWT; the largest container ships (Suezmax) are also very large. For each ship type and size category, data on typical ships' capacity in DWT, speed, and horsepower are used to estimate average daily fuel consumption.

Table 3-4. Fleet Characteristics in Clarksons' Data

Ship Type	Size by DWT	Minimum Size (DWT)	Maximum Size (DWT)	Number of Ships	Total DWT (millions)	Total Horse-power (millions)
Container	Suezmax	83,000	140,000	101	9.83	8.56
	PostPanamax	56,500	83,000	465	30.96	29.30
	Panamax	42,100	56,500	375	18.04	15.04
	Intermediate	14,000	42,100	1,507	39.80	32.38
	Feeder	0	14,000	1,100	8.84	7.91
General cargo	All	All		3,214	26.65	27.07
Dry bulk	Capesize	79,000	0	715	114.22	13.81
	Panamax	54,000	79,000	1,287	90.17	16.71
	Handymax	40,000	54,000	991	46.50	10.69
	Handy	0	40,000	2,155	58.09	19.58
Crude oil tanker	VLCC	180,000	0	470	136.75	15.29
	Suezmax	120,000	180,000	268	40.63	5.82
	AFRAmax	75,000	120,000	511	51.83	8.58
	Panamax	43,000	75,000	164	10.32	2.17
	Handymax	27,000	43,000	100	3.45	1.13
	Coastal	0	27,000	377	3.85	1.98
Chemical tanker	All	All		2,391	38.80	15.54

(continued)

Table 3-4. Fleet Characteristics in Clarksons' Data (continued)

Ship Type	Size by DWT	Minimum Size (DWT)	Maximum Size (DWT)	Number of Ships	Total DWT (millions)	Total Horse-power (millions)
Petroleum product tanker	AFRAmax	68,000	0	226	19.94	3.60
	Panamax	40,000	68,000	352	16.92	4.19
	Handy	27,000	40,000	236	7.90	2.56
	Coastal	0	27,000	349	3.15	1.54
Natural gas carrier	VLGC	60,000	0	157	11.57	5.63
	LGC	35,000	60,000	140	6.88	2.55
	Midsize	0	35,000	863	4.79	3.74
Other	All	All		7,675	88.51	53.60
Total				**26,189**	**888.40**	**308.96**

Source: Authors' calculations based on data from Clarksons Ship Register (2005).

3.2.2.1 Fleet Average Daily Fuel Consumption

Average fuel consumption for each vessel type and size category was estimated in a multistep process using individual vessel data on engine characteristics. Clarksons' Ship Register provides each ship's horsepower (HP), type of propulsion (diesel or steam), and year of build. These characteristics are then matched to information on typical Specific Fuel Oil Consumption (SFOC) from engine manufacturers and the technical literature. SFOC is measured in grams of fuel burned per horsepower-hour, so to determine the average daily fuel consumption of the fleet, the following equation is used:

$$\text{Fleet AFC}_{v,s} = \frac{1}{N} \sum_{i \in v,s} \left[SFOC_i \times HP_i \times \left(\frac{24}{1{,}000{,}000} \right) \right] \tag{3.1}$$

where *i* denotes an individual ship of vessel type *v* and size category *s*. This calculation results in a fleet average value for daily fuel consumption, measured in metric tons per day.

3.2.2.2 Key Assumptions Affecting the Forecast

The specific SFOC numbers used for this analysis are based on historical data provided by Wartsila Sulzer, a popular manufacturer of diesel engines for marine vessels. An additional 10% has been added to their "test bed" or "catalogue" numbers to account for the guaranteed tolerance level and an in-service SFOC differential.[2] Figure 3-2 shows data used in the model regarding the evolution of SFOC rates for diesel engines over time. (For steam engines, a fixed SFOC of 220 g/HP-hr is used.)

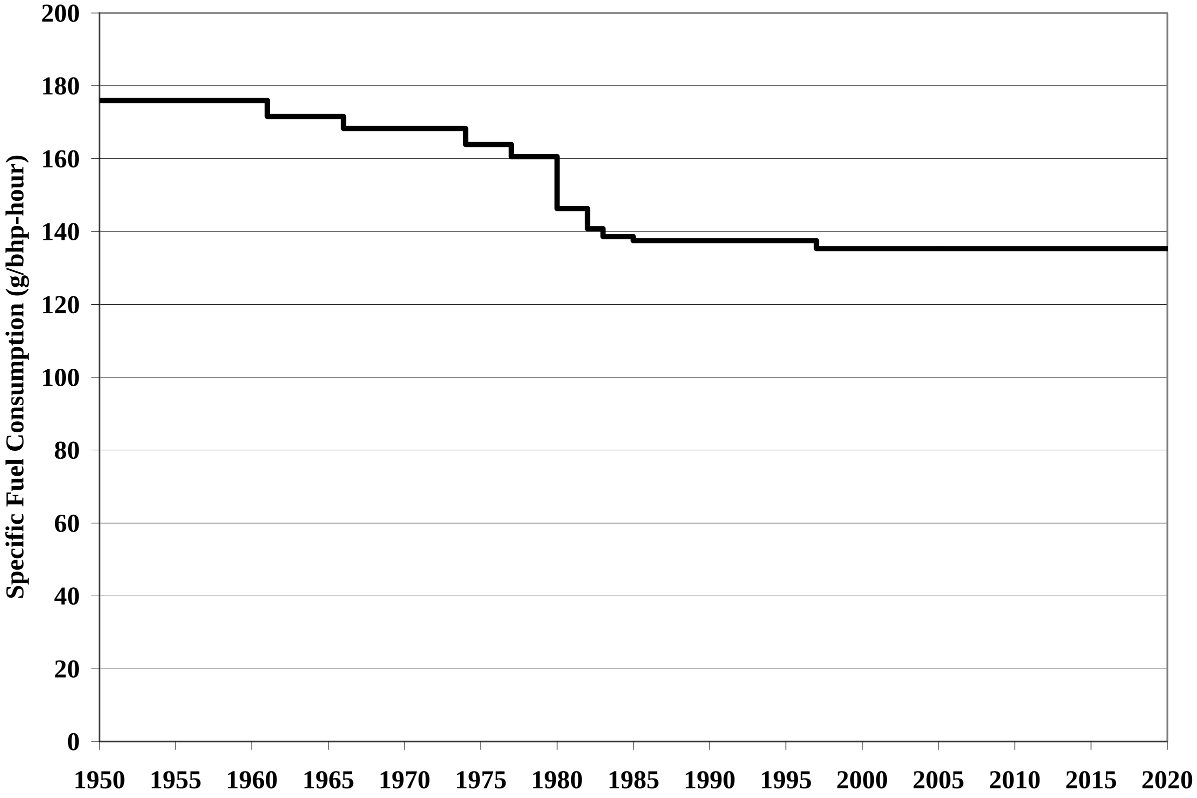

Figure 3-2. Specific Fuel Oil Consumption Over Time

Source: Authors' calculations based on communications with Wartsila Sulzer and other diesel engine manufacturers.

Engine efficiency in terms of SFOC has improved over time, most noticeably in the early 1980s in response to rising fuel prices. However, there is a trade-off between improving fuel efficiency and reducing emissions. Conversations with engine manufacturers indicate that it is reasonable to assume SFOC will remain constant for the 15-year time horizon of this study, particularly as they focus on meeting more stringent NO_x emissions requirements, such as those imposed by MARPOL Annex VI.

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[2] Overall this 10% estimate is consistent with other analyses that show variation between the "test bed" SFOC values reported in manufacturers' product catalogues and the actual SFOCs observed in service. The difference is explained by the fact that old, used engines consume more than brand new engines and that fuels used in-service may be different than the test bed ISO fuels. See Koehler (2003).

The values for fleet average daily fuel consumption calculated in Equation (3.1) are based on installed horsepower; therefore, they must be scaled down to reflect true engine loads. Engine load factors reported by Corbett and Wang (2005) are used to estimate average daily fuel consumption (tons/day) for the propulsion engine and auxiliary engines, both at sea and in port. These assumptions are summarized in Table 3-5.

Table 3-5. Assumptions Regarding Engine Loads

Vessel Type	Main Engine Load Factor	Auxiliary Engine as Percentage of Main Engine	Auxiliary Engine as Percentage of Main Engine at Sea
Container vessels	80 %	22.0 %	11.0 %
General cargo carriers	80 %	19.1 %	9.5 %
Dry bulk carriers	75 %	22.2 %	11.1 %
Crude oil tankers	75 %	21.1 %	10.6 %
Chemical tankers	75 %	21.1 %	10.6 %
Petroleum product tankers	75 %	21.1 %	10.6 %
Natural gas carrier	75 %	21.1 %	10.6 %
Other	70 %	20.0 %	10.0 %

Source: Corbett, James and Chengfeng Wang. October 26, 2005. “Emission Inventory Review SECA Inventory Progress Discussion.” page 11.

3.2.2.3 Changing Fleet Characteristics

The population of vessels operating is assumed to change over time as older vessels are scrapped and new ones are built. In our analysis, vessels built over 25 years ago are retired and are assumed to be replaced by new ships of the most up-to-date configuration. Specifically, these ships are assumed to have a new engine (rated at the current SFOC) and are assumed to weigh as much as the average ship built in 2005. So even though improvements in SFOC over the next 15 years are not assumed, the fuel efficiency of the fleet as a whole is expected to improve over time through retirement and replacement. In the same way, even though specific increases in the size of ships being built are not projected, the total deadweight of the fleet will increase over time as smaller ships retire and are replaced. The analysis also reflects trends on the trade routes between Asia and North America or Europe for container ships to increase in size over time.

3.2.3 Trade Analysis by Commodity Type and Trade Route

Based on information from Navigistics Consulting, the distribution of ship size categories deployed on each of the trade routes was identified. For example, to serve the large crude oil trade from the Middle East Gulf region to the U.S. Gulf region, 98% of the deadweight tonnage is carried on very large crude carriers (VLCCs), while the remaining 2% is carried on the smaller Suezmax vessels. In addition to the volume of trade being moved, the limitations of the canals through which the vessels must pass determine the size categories deployed on each trade route. These size category distributions are assumed to remain constant throughout the forecast horizon, with the exception of two of the largest container trade routes. We introduce Malacamax containerships (>11,000 TEU) to Trans-Pacific trade per a recent container vessel forecast for the ports of San Pedro Bay and at a similar rate to Europe-Asia trade (Mercator Transport Group, 2005).

Once a vessel type and size distribution have been assigned to each region pair and commodity trade type, a set of voyage parameters is estimated. Days at sea and in port are based primarily on ports called, sea distance, and ship speed. The number of voyages is based on the cargo volume projected by GII to move along a given route and the cargo capacity of the vessels on that route.

3.2.3.1 Days at Sea and Days in Port

Most trades are characterized by voyages that are essentially round trips, moving from a single region of origin to a single destination region and back.[3] For these trades, Navigistics Consulting identified ports that were either in the middle of the trade region or ports through which the particular commodity was most likely to travel. For example, the Port of Singapore was selected as the port of origin for the Pacific High-Growth region for most commodities, but for dry bulk, Inchon was selected. Then, for each route, information was gathered on the distances between ports (NGA, 2001; MaritimeChain, 2005).[4] Since carriers of crude oil, chemicals, petroleum products, natural gas, and dry bulk tend to travel full for a delivery and then return empty, round-trip distances were used to determine the length of the voyage. The days at sea are calculated by dividing the sea distance by the average vessel speed:

$$\text{Days at Sea Per Voyage}_{v,s,\text{route}} = \frac{\text{round trip distance route}}{\text{speed}_{v,s} \text{ x } 24 \text{ x } 1.1508} \tag{3.2}$$

---

[3] Vessels may stop at multiple ports within each region, but we assume that, for the most part, they do not string together trips to multiple regions. Two important exceptions to this are the general cargo and container trades, which are described in further detail below.

[4] http://maritimechain.com/. This calculator provides nautical distances, which account for the particular routes vessels must take when traveling from port to port (e.g., movement through straights or canals).

Table 3-6 presents the values used for speed by vessel type (based on Corbett and Wang [2005]). These values are the same for all size categories and are assumed to remain constant over the forecast period.

Table 3-6. Vessel Speed by Type

Vessel Type	Speed (knots)
Crude oil tankers	13.2
Petroleum product tankers	13.2
Chemical tankers	13.2
Natural gas carriers	13.2
Dry bulk carriers	14.1
General cargo vessels	12.3
Container vessels	19.9[a]
Other	12.7

[a] Length of voyages by container ships estimated from additional sources. See below.

Source: Corbett, James and Chengfeng Wang. October 26, 2005. "Emission Inventory Review SECA Inventory Progress Discussion." page 11.

In addition to calculating the average days at sea per voyage, the average days in port per voyage are also estimated. It is assumed that most types of cargo vessels spend 4 days in port per voyage; however, this can vary somewhat by commodity and by port.[5] Tables 3-7 and 3-8 show the results of these estimates of voyages lengths, focusing on U.S. trade routes. Table 3-7 presents average lengths across types of noncontainer vessels (these times are cargo specific and vary slightly based on the speed of the vessels—speeds are taken from Dr. Corbett's work). Two sources are used for noncontainer trades and voyage times in Table 3-7: Worldscale (2002) and Maritime Chain (2005).

The Worldscale tables, based on underlying BP Shipping Marine Distance Tables, are the industry standard for measuring port-to-port distances, particularly for tanker traffic. The reported distances account for common routes through channels, canals, or straits. This distance information was supplemented by data from Maritime Chain, a Web service that provides port-to-port distances along with some information about which channels, canals, or straits must be

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[5] Some ports do not run as efficiently because of a lack of good shoreside facilities, labor problems, or other inadequacies. The maximum number of days in port for a noncontainer trade is 8 days.

Table 3-7. Length of Voyages for Noncontainer Cargo Ships (approx. average)

	Days per Voyage				
Global Insights Trade Regions	**U.S. South Pacific**	**U.S. North Pacific**	**U.S. East Coast**	**U.S. Great Lakes**	**U.S. Gulf**
Africa East-South	68	75	57	62	54
Africa North-Mediterranean	49	56	37	43	47
Africa West	56	63	36	46	43
Australia-New Zealand	48	47	65	81	63
Canada East	37	46	7	18	19
Canada West	11	5	40	58	39
Caspian Region	95	89	41	46	48
China	41	36	73	87	69
Europe Eastern	61	68	38	45	46
Europe Western-North	53	60	24	32	34
Europe Western-South	54	61	30	37	37
Greater Caribbean	26	33	16	29	17
Japan	35	31	65	81	62
Middle East Gulf	77	72	56	65	83
Pacific High Growth	52	48	67	76	88
Rest of Asia	68	64	66	64	73
Russia-FSU	64	71	38	46	48
Rest of South America	51	30	41	46	44

passed on the voyage. This distance information was then combined with Dr. Corbett’s speed parameters to determine the length of a voyage in days.

As discussed above, voyage times for container trade in Table 3-8 are based on information from *Containerization International* (Degerlund, 2005) and calculations by Navigistics Consulting. This resource provides voyage information for all major container services. Based on the frequency of the service, number of vessels assigned to that service, and the number of days in operation per year, the average length of voyages for the particular bilateral trade routes in the Global Insights trade forecasts are estimated.

Table 3-8. Length of Voyages for Container-Ship Trade Routes

Origin—Destination Regions	Days per Voyage
Asia—North America (Pacific)	37
Europe—North America (Atlantic)	37
Mediterranean—North America	41
Australia/New Zealand—North America	61
South America—North America	48
Africa South—North America (Atlantic)	54
Africa West—North America (Atlantic)	43
Asia—North America (Atlantic)	68
Europe—North America (Pacific)	64
Africa South—North America (Pacific)	68
Africa West—North America (Pacific)	38
Caspian Region—North America (Atlantic)	42
Caspian Region—North America (Pacific)	38
Middle East/Gulf Region—North America (Atlantic)	63
Middle East/Gulf Region—North America (Pacific)	80

3.2.3.2 Number of Voyages

The number of voyages along each route for each trade was computed by dividing, for each vessel type *v* and size category *s* serving a given route, the tons of cargo moved by the estimated amount of cargo per voyage:

$$\text{Number of Voyages}_{\text{v,s,trade}} = \frac{\text{tons cargo to move}}{\text{Fleet Avg. DWT}_{\text{v,s}} \text{ x (utilization rate)}} \tag{3.3}$$

The cargo per voyage is based on the fleet average ship size (in deadweight tons) calculated in the vessel profile analysis. For most cargo trades, a utilization factor of 0.9 is assumed to account for the fact that ships do not always run at full capacity. This factor is assumed to be constant throughout the forecast period. Lowering this utilization factor would increase the estimated number of voyages required to move the forecasted cargo volumes, which would, in turn, increase our estimated fuel demand.

3.2.3.3 Exceptions: General Cargo and Container Trades

The exceptions to the above approach for calculating voyage parameters are the general cargo and container trades. These routes tend to have multiple stops, with cargo loaded and discharged at each stop. Unlike the other types of vessels, these carriers rarely travel empty. Thus, for each trade route, we focus only on the "heavy" leg of the journey, the direction with the highest trade volume.

For general cargo, port-to-port round-trip distances and the average vessel speeds are used to calculate days at sea. Days in port are estimated at 4 days per voyage. The difference is that the number of voyages is based only on the tons of cargo projected to be moved on the heavy leg of the journey. The assumption is that the projected trade volume associated with the "light" leg will be carried on the return trip of these round-trip voyages.

For the container trades, the voyage parameters are determined based on actual ship routings. Navigistics Consulting first identified major container trade lanes to which the individual region pairs were assigned. For example, trade volumes from the Pacific High Growth region to the U.S. South Pacific and from China to the U.S. North Pacific are both included on a Transpacific trade route. Major shipping lines active on these trade routes are identified and their individual container services are analyzed, as recorded in the *Containerization International (CI) Yearbook 2005* and other sources. The *CI Yearbook* provides detailed information about each container service, including the ports visited, the frequency and length of the voyage, and the vessels deployed. It is assumed there is 1 day in port for each port visited, and then the days at sea are calculated by subtracting total days in port from the total length of the voyage.

The number of voyages for the container trade is again calculated by dividing the projected volume on the heavy leg by the estimated average cargo per voyage (i.e., average ship size times a utilization factor). We use the information from the *CI Yearbook* about the vessels deployed to determine the average ship size on each major trade route. These sizes are reported in terms of TEU, a volume measure that we convert using a baseline capacity factor of 14 DWT per TEU. The utilization factor is calibrated so that the number of voyages implied by 2005 historical GII trade volume data matches the actual number of voyages recorded in the *CI Yearbook.* Table 3-9 reports these estimated factors for some of the major trade routes. These rates, which average 0.51 across all trade routes, are generally lower than the utilization factor of 0.9 used on all other commodity trades. However, these estimates are consistent with what

Table 3-9. Estimated Utilization Rates for Top 10 Container-Ship Trade Routes

Top 10 Container-Ship Trade Routes by Volume[a]	Utilization Rate
Asia—North America (Transpacific)	47%
Northern Europe—Asia	52%
Mediterranean—Asia	40%
North America—Northern Europe (Transatlantic)	66%
South America—North America	85%
South America—Europe	50%
Mediterranean—North America	27%
Australia—Asia	33%
South America—Asia	46%
West Africa—Europe	28%
Average for All Trades	51%

[a] Based on GII trade data for 2005.

industry experts predict for capacity utilization.[6] The main reason for the lower utilization rate is that container ships usually reach a maximum volume capacity well before they reach a maximum weight capacity. A vessel may be only 50% “full” in terms of deadweight, but still be unable to fit more containers on board.

3.2.4 Calculating Total Estimated Fuel Demand for Cargo Vessels

As described in Figure 3-1, estimates from the vessel analysis and trade analysis are used to obtain an estimate of total fuel demand related to international cargo trade flows.

3.2.4.1 Total Fuel Demand in Year y, for y = 2005, 2012, 2020

For each year, total marine fuel consumed is computed as the sum of fuel consumed on each route of each trade (commodity). Fuel consumed in each route of each trade is, in turn, computed by summing the fuel consumed for each route and trade for that year by propulsion engines and auxiliary engines, both at sea and in port.

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[6] The utilization factors estimated correspond to approximately 7 to 9 DWTs per TEU, which is the volume measure most often used to describe a container ship’s size. This is consistent with industry reports. Discussions with experts in the container trade stated that containers coming out of Asia to the United States and Europe weigh around 6.75 to 7 tons per TEU. Cargoes out of the United States weigh on the order of 9 to 9.5 tons per TEU. The combination of weight utilization (based on 14 tons per TEU) and a maximum workable slot utilization of 90% to 95% gives credence to our 51% overall utilization value.

$$
\begin{aligned}
\mathrm{FC}_{\mathrm{y}} &= \sum_{\mathrm{trade}} \sum_{\mathrm{route}} \mathrm{FC}_{\mathrm{trade,\,route,\,year}} \\
&= \sum_{\mathrm{trade}} \sum_{\mathrm{route}} \left[\mathrm{AFC}_{\mathrm{trade,\,route,\,y\,at\,sea}} \text{ x } \text{Days at Sea}_{\mathrm{trade,\,route,\,y}} + \mathrm{AFC}_{\mathrm{trade,\,route,\,y\,at\,port}} \text{ x } \text{Days at Port}_{\mathrm{trade,\,route,\,y}} \right]
\end{aligned}
$$

where

$$
\begin{aligned}
\mathrm{AFC}_{\mathrm{trade,\,route,\,y\,at\,sea}} &= \sum_{\mathrm{v,s,t,r}} (\text{Percentage of trade along route})_{\mathrm{v,s}} \left[\text{Fleet AFC}_{\mathrm{v,s}} \text{ x } \left(\text{MELF} + \text{AE at sea LF} \right) \right] \\
\mathrm{AFC}_{\mathrm{trade,\,route,\,y\,at\,port}} &= \sum_{\mathrm{v,s,t,r}} (\text{Percentage of trade along route})_{\mathrm{v,s}} \left[\text{Fleet AFC}_{\mathrm{v,s}} \text{ x AE import LF} \right] \\
\text{Days at Sea}_{\mathrm{trade,\,route,\,y}} &= \sum_{\mathrm{v,s,t,r}} (\text{Percentage of trade along route})_{\mathrm{v,s}} \left[\text{Days at sea per voyage}_{\mathrm{v,s}} \text{ x Number of voyages}_{\mathrm{v,s}} \right] \\
\text{Days at Port}_{\mathrm{trade,\,route,\,y}} &= \sum_{\mathrm{v,s,t,r}} (\text{Percentage of trade along route})_{\mathrm{v,s}} \left[\text{Days at port per voyage x Number of voyages} \right]
\end{aligned}
$$

MELF: Main Engine Load Factor
AE at sea LF: Auxiliary Engine at-sea Load Factor
AE in port LF: Auxiliary Engine in-port Load Factor

The parameters used in these last four equations are all derived from the vessel and trade analyses discussed above. The *(Percentage of trade along route)*$_{v,s}$ indicates the fraction of trade volume carried by each vessel size category, as discussed in Section 3.2. *Fleet AFC*$_{v,s}$ is the fleet average daily fuel consumption calculated using Equation (3.1). The main propulsion and auxiliary engine load factors are discussed in Section 3.2.2, and the specific values used are reported in Table 3-5. Days at sea per voyage and number of voyages are calculated using Equations (3.2) and (3.3), respectively.

3.2.5 U.S. Domestic Navigation

The GII forecasts are primarily designed to analyze international trade flows, so they do not include projected trade volumes for shipments within the United States. In addition, these domestic shipments are primarily transported by carriers that are governed by the restrictions of the Jones Act. For these reasons, the methodology for estimating fuel demand by vessels transporting cargo domestically differs slightly from the methodology for international cargo vessels presented in Sections 3.2.2 through 3.2.4.

3.2.5.1 Ship Analysis by Vessel Type and Size

This analysis begins with a vessel profile. Navigistics Consulting helped compile a database listing vessels in the “Jones Act fleet.” Four types of trade constitute a vast majority of the domestic cargo trade flows that are transported by ships through waterways: dry bulk trade on Great Lakes, crude oil trade (primarily from Alaska), petroleum product trade, and container trade. Accordingly, the four types of vessels that are used in these trades are considered: crude oil tankers, dry bulk carriers, container ships, and product tankers (which also carry chemicals).

As with international vessel fleets, vessel types of the domestic fleet were further classified by size in deadweight tons. Table 3-10 illustrates these breaks, along with summaries of deadweight and horsepower for each vessel type and size. As seen below, the Jones Act fleet composes only a small fraction of the international fleet. The Great Lakes bulk category makes up the largest share by the number of vessels, while the container category is the largest in terms of horsepower, and the crude oil tanker category is the largest in terms of deadweight. These four categories have a total of 151 vessels, with a combined deadweight of 7.9 million tons and a combined horsepower of 2.6 million.

Table 3-10. Jones Act Fleet

Vessel Type	Size by DWT	Minimum Size (DWT)	Maximum Size (DWT)	Number of Ships	Total DWT (thousands)	Total Horse-power (thousands)
Container*	Panamax	42,100	56,500	2	92.0	47.0
	Intermediate	14,000	42,100	35	924.0	890.4
	Feeder	0	14,000	1	13.9	22.9
Great Lakes Bulk**	Panamax	54,000	79,000	12	729.2	187.8
	Handymax	40,000	54,000	3	367.9	40.2
	Handy	0	40,000	33	800.1	218.8
Crude Oil Tanker***	VLCC	180,000	0	8	1,508.0	219.3
	Suezmax	120,000	180,000	10	1,289.4	299.1
	AFRAmax	75,000	120,000	4	367.9	98.0
	Panamax	43,000	75,000	1	57.7	17.0
Petroleum Product Tanker***	Panamax	40,000	68,000	24	1,112.4	300.4
	Handy	27,000	40,000	17	609.8	204.9
	Coastal	0	27,000	1	19.2	7.2
Total				**151**	**7,891.5**	**2,553.0**

Source: Authors' calculations based on data from Colton and Company (*), Greenwood's Directory (**), and U.S. Maritime Administration (***)

3.2.5.2 Fleet Average Daily Fuel Consumption

Average fuel consumption for each vessel type and size category was estimated using the same basic approach that was used to estimate fuel consumption for the international vessel fleet. The main difference lies in how fleet characteristics change over time through retirement and replacements.

U.S. Jones Act vessels are more costly to build and, therefore, are kept in service longer than international fleet vessels, making their replacement age above the international fleet average. Replacement ages for Jones Act vessel categories are listed below:

- Containers—35 years
- Great Lakes Bulk—60 years (these ships are not a subject to salt water and thus last longer)
- Crude Oil Tanker—35 years or OPA-90[7] requirement
- Petroleum Product Tanker—35 years or OPA-90 requirement

The replacement ships are assumed to have a new engine (rated at the current SFOC) and are assumed to weigh as much as the average ship of a similar category and deadweight class (for example, a Panamax Size Container Vessel) built in 2005, based on the statistics from the international fleet database.

3.2.5.3 Voyage Parameters

Calculation of the voyage parameters was also slightly different. The average number of days required for a trip and the average number of days spent in port were estimated based on actual ship routings and calculated distances between Alaska, Hawaii, Puerto Rico, and the continental United States.

The number of days the ships will be engaged in trade (activity level) are then estimated for each ship category. For container, crude oil tanker, and petroleum product tanker categories, activity levels are estimated at 350 days. The estimate of Great Lakes bulk vessels’ activity level was set at 290 days to account for winter weather conditions when the lakes are frozen over. Given the activity level and the average number of days required for a trip at sea and in port, the total number of days at sea and in port per ship per year are calculated as follows:

$$\text{Voyages per Year Per Ship} = \frac{\text{Activity Level}}{\text{Average Number of Trip Days}}_{s}$$

---

[7] Oil Pollution Act of 1990 (OPA-90) was introduced after the Exxon Valdez incident. OPA-90 requires all single-hull ships to be replaced by double-hull ships by a certain date, based on deadweight and horsepower.

$$\text{Total Number of Days at Sea per Ship} = \frac{\text{Average Number of Days at Sea}}{\text{Average Number of Trip Days}_{s}} \text{ x Voyages Per Year Per Ship}$$

$$\text{Total Number of Days in Port per Ship} = \frac{\text{Average Number of Days in Port}}{\text{Average Number of Trip Days}_{s}} \text{ x Voyages Per Year Per Ship}$$

The total number of days in port and at sea per year per ship is then multiplied by the number of vessels in each category to get the total number of days ships spend at sea and the total number of days ships spend in port each year. Given the average fuel consumption, the days at sea per voyage, and days in port per voyage for an average ship within each vessel category, the total estimated fuel demand is then calculated in the same way as for international vessel fleet.

3.2.6 Ship Analysis for Noncargo Vessels

As with domestic U.S. navigation, because the GII forecasts focus on international trade flows, they do not cover activities of several remaining types of vessels: passenger ships, fishing vessels, military vessels, and other support ships such as tugboats or supply ships. Data on fuel consumption by the ship categories have been based on available literature and information in the Clarksons database.

Historical fuel consumption by passenger ships, fishing vessels, and military vessels has been based on data from Corbett and Koehler (2003). Trends in passenger ships are based on a study by Ocean Shipping Consultants that projects increases in cruise-ship demand through 2020. Trends in fishing are based on data from the United Nation's Food and Agriculture Organization (FAO) on worldwide fish capture trends between 1997 and 2002. Trends in military vessel energy use are based on forecasts from the U.S. Energy Information Administration's *Annual Energy Outlook 2006*, which provides estimates of trends in future U.S. military distillate and residual consumption. Historical fuel consumption by other types of ships are based on data in the Clarksons database (the "Other" category shown in Table 3-4). These data on vessel characteristics were combined with engine load assumptions from Corbett and Wang (2005) and activity levels from Corbett and Koehler (2004) to determine fuel use. Trends in this fuel use were then assumed to follow patterns of economic activity as reflected in GDP forecasts from EIA.

3.2.7 Bunker Fuel Grades

Fuel consumption by specific grades is evaluated as follows: information from Koehler (2003) on consumption of IFO, MDO, and MGO by vessel type is used to assign overall fuel grades; this information is then combined with the main and auxiliary engine factors discussed in

Section 3.2.4, where main engines are assumed to use mostly IFO380 and auxiliary engines use IFO180.

3.3 Results of Bunker Fuel Forecasts

This section presents estimates of bunker fuel consumption based on the methodology outlined above. The focus of the discussion and associated graphs is on 1) worldwide bunker fuel consumption estimates that can be compared to those by IEA and in other published works; 2) U.S. regional fuel consumption estimates related to the cargo fleet engaged in international trade; and 3) on growth rates in bunker fuel demand and the underlying factors.

Figure 3-3 shows estimated worldwide bunker fuel consumption by vessel type. Fuel consumption in year 2001 is equal to 278 million tons, which can be compared to the estimate in Corbett and Koehler (2004) of 289 million tons. By 2020, bunker fuel demand reaches 500 million tons per year. Note, the "historical" bunker fuel data shown going back to 1995 are also model estimates based on historical Global Insights trade flows. (Comparisons of these estimates to others in the literature are discussed in more detail in Section 4.2, given their importance to modeling of the petroleum-refining industry in the WORLD model.)

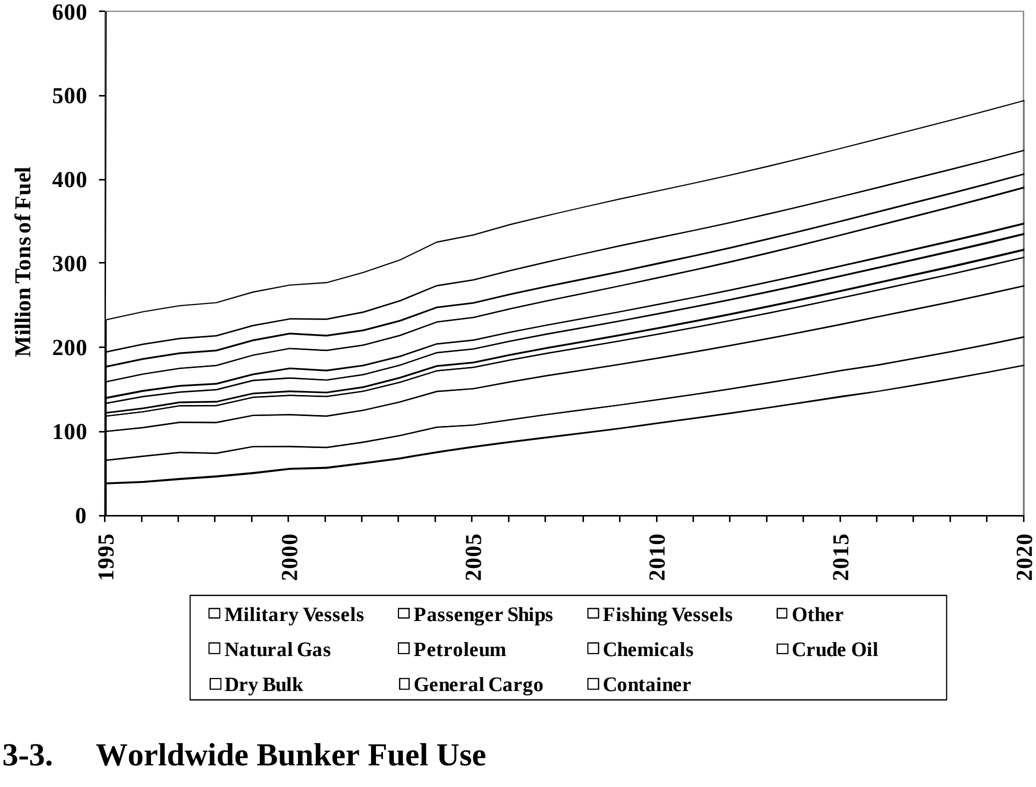

Figure 3-3. Worldwide Bunker Fuel Use

Figure 3-4 shows the annual growth rates by vessel-type/cargo that underlie the projections in Figure 3-3. Total annual growth is generally between 2.5% and 3.5% over the time period between 2006 and 2020 and generally declines over time, resulting in an average annual growth of around 2.6%. As shown in the "container" categories in Figures 3-3 and Figure 3-4, fuel consumption by container ships is the fastest growing component of worldwide bunker fuel demand; in 2004, consumption by container ships is around 75 million tons, growing to 87 million tons by 2006 and close to 180 million tons by 2020 (the historical estimates can be compared to Gregory [2006], which places container ship consumption in 2004 at 85 million tons, based on installed power). While overall growth is less than 3% a year, growth in container-ship demand remains above 5% a year on an average annual basis for the next 15 years. Across all vessel types, growth in bunker fuel consumption is somewhat lower than worldwide GDP growth forecasts from EIA (2005c) (*International Energy Outlook 2005*) of around 3.9% a year, but higher than IEA estimates of overall fuel consumption growth (around 1.6% in the *World Energy Outlook 2005*). The estimate of growth in marine bunkers over the next 15 years, however, is consistent with the historical growth of 2.7% per year shown in IEA data from 1983 to 2003.

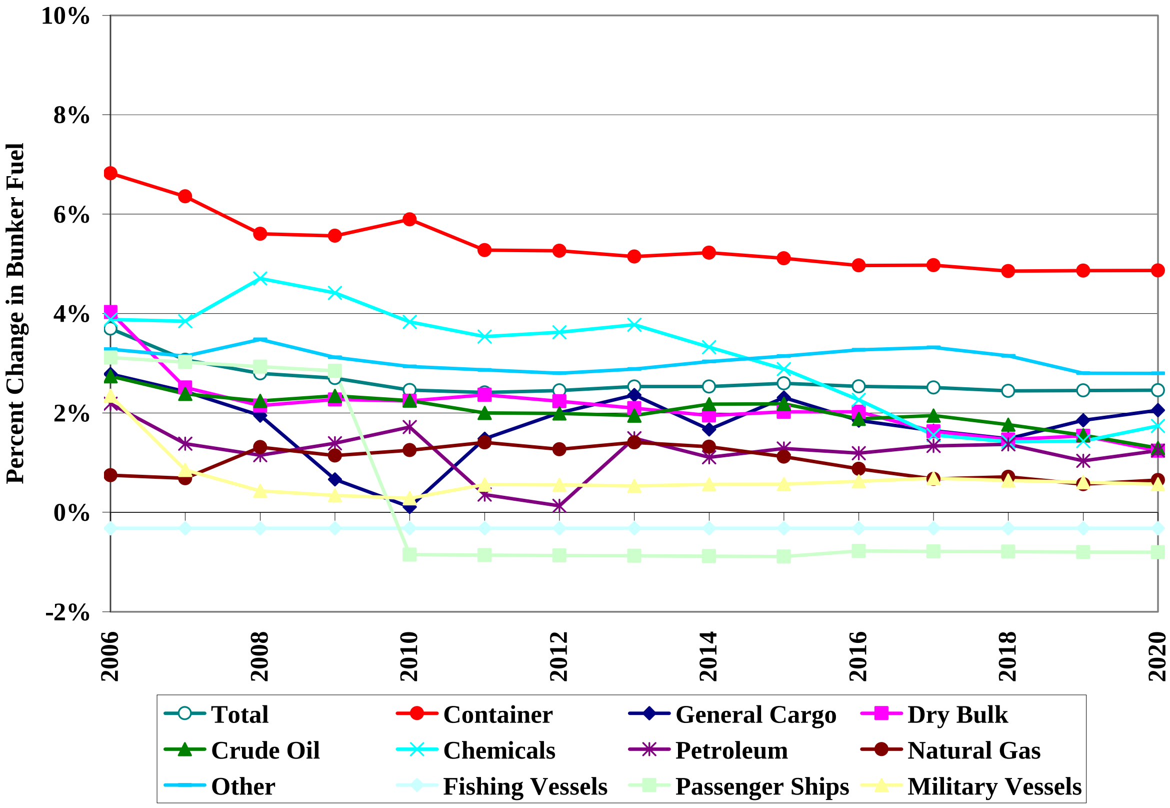

Figure 3-4. Annual Growth Rate in Worldwide Bunker Fuel Use

Growth in fuel use by container ships and the overall contribution by these vessels to worldwide demand is driven by several factors. The first is overall growth in worldwide GDP mentioned above. This growth leads to increases in international trade flows over time (shown in Figures 3-5 and 3-6 below). These figures illustrate that, although container trade is smaller in total volume than other categories, it is the fastest growing component of the trade flows. Measuring trade flows in tons of goods, as shown in Figure 3-5, also does not provide a good proxy for the fuel consumption needed to transport the goods. Liquids and dry bulk are much denser than container goods, for example. As mentioned in Section 3.2.3, it is estimated that utilization rates for container ships (comparing deadweight tons of capacity to actual cargo transported) are around 50%. Thus, it takes approximately twice as many ships to transport the same amount of container tons compared to liquid/dry bulk tons. This relationship tends to influence total bunker fuel use and weight it toward container trade. In addition, growth rates in particular trade flows such as Asia to the United States will also influence overall fuel consumption, especially as related to container ships as discussed in relation to United States regional trade flows below.

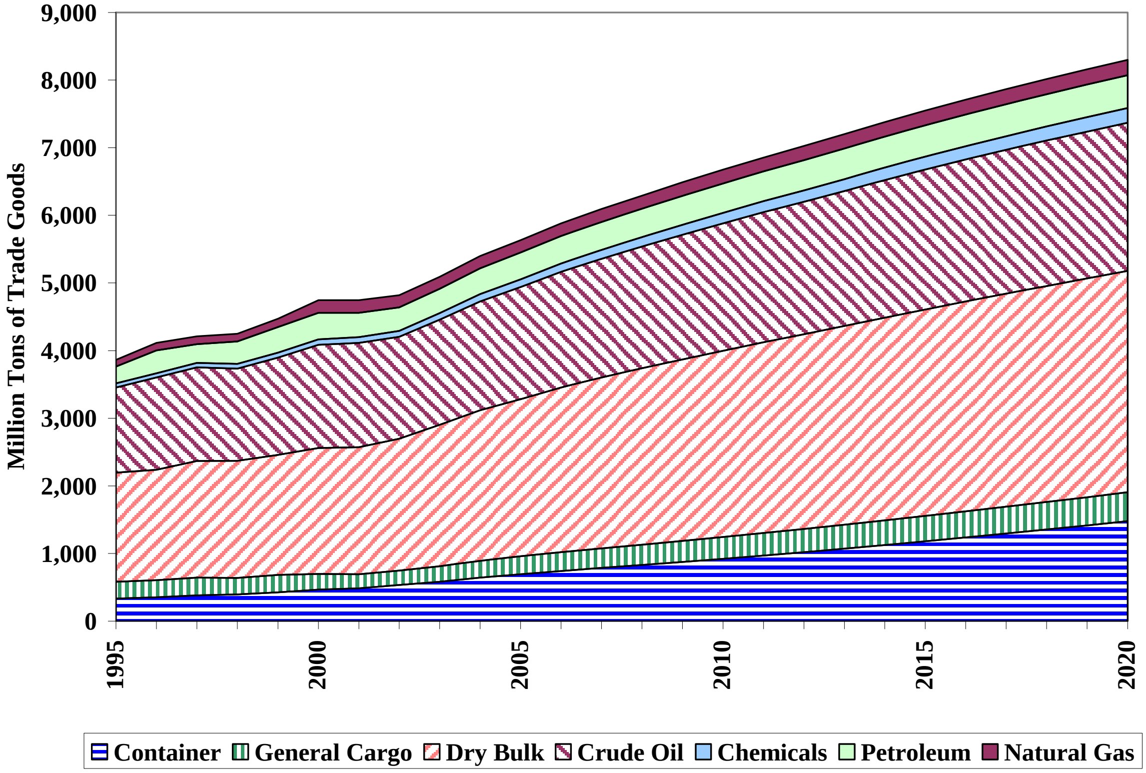

Figure 3-5. Worldwide Trade Flows (Global Insights)

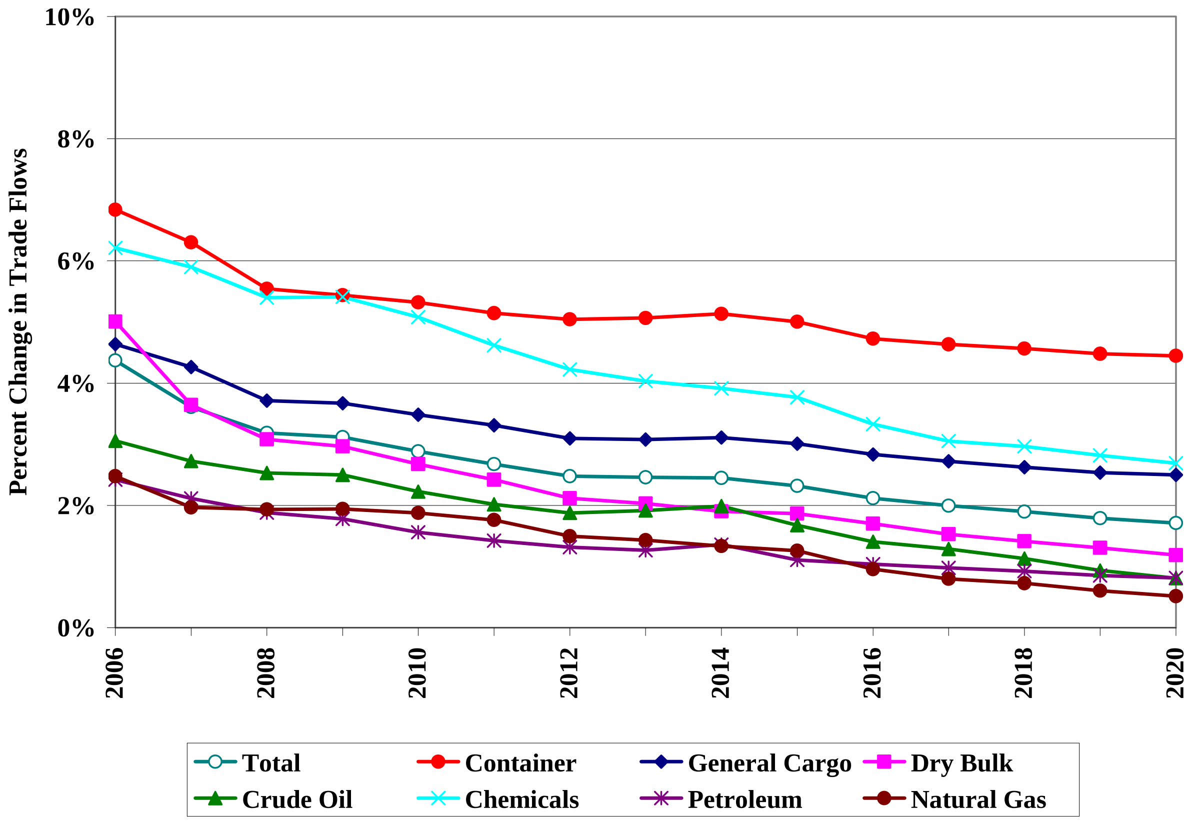

Figure 3-6. Annual Growth Rate in Worldwide Trade Flows

Figures 3-7 to 3-9 show estimated consumption of specific grades of bunker fuels from Figure 3-3.

Figures 3-10 to 3-13 present estimates of fuel use by the international cargo fleet engaged in delivering trade goods to and exporting trade goods from the United States. These estimates comprise part of the total worldwide bunker fuel use shown in Figure 3-3 and do not include fuel used for domestic navigation. The results in Figure 3-10 show estimated historical bunker fuel use in year 2001 of around 47 million tons (note, while this fuel is used to carry trade goods to and from the United States, it is not necessarily all purchased in the United States and is not all burned in U.S. waters). This amount grows to over 90 million tons by 2020 with the most growth occurring on trade routes from the East Coast and the “South Pacific” region of the West Coast.

Figure 3-11 shows the annual growth rate projections for the fuel consumption estimates in Figure 3-10. The South Pacific and East Coast regions of the United States are growing the fastest, largely as the result of container ship trade (see Figures 3-12 and 3-13). Overall, the average annual growth rate in marine bunkers associated with future U.S. trade flows is 3.4%

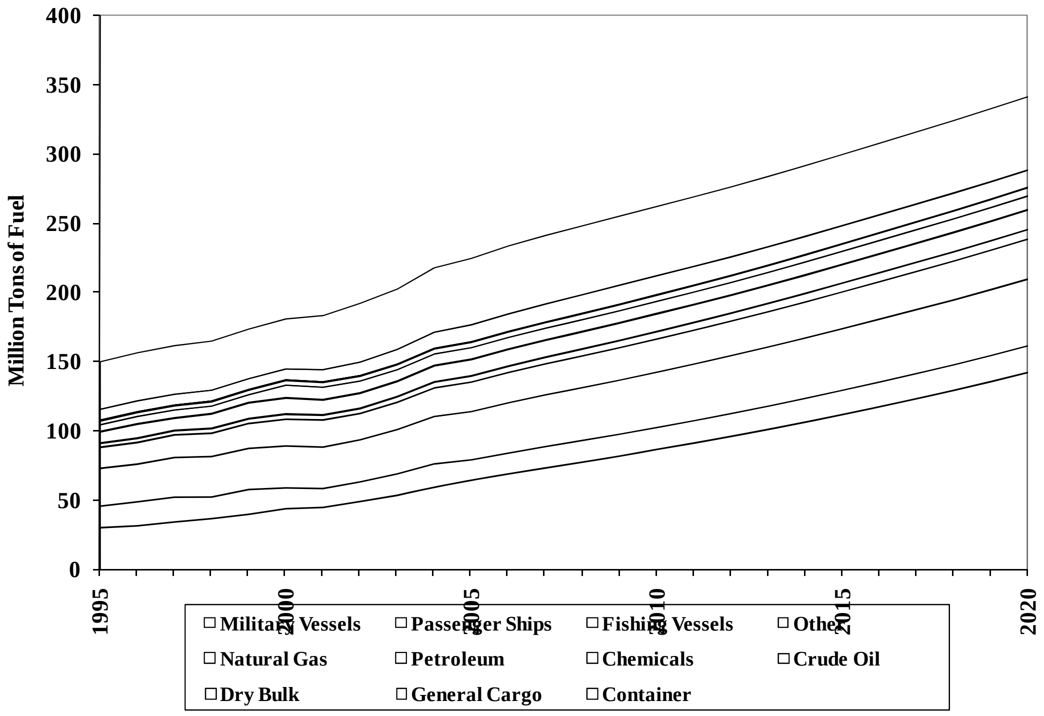

Figure 3-7. Worldwide IFO380 Use

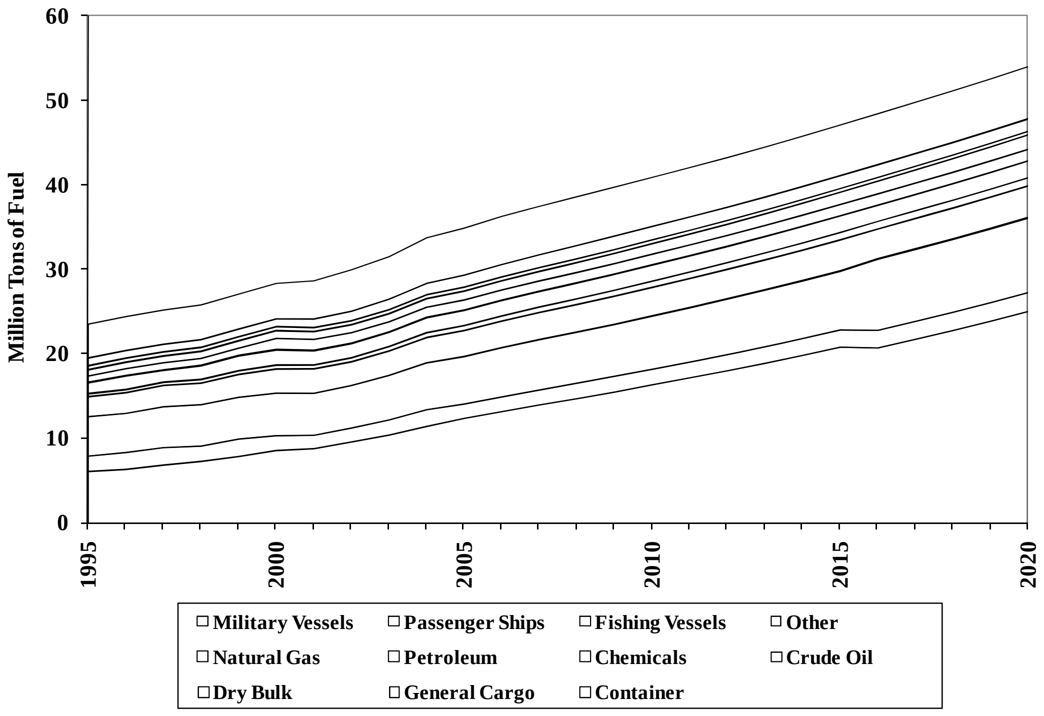

Figure 3-8. Worldwide IFO180 Use

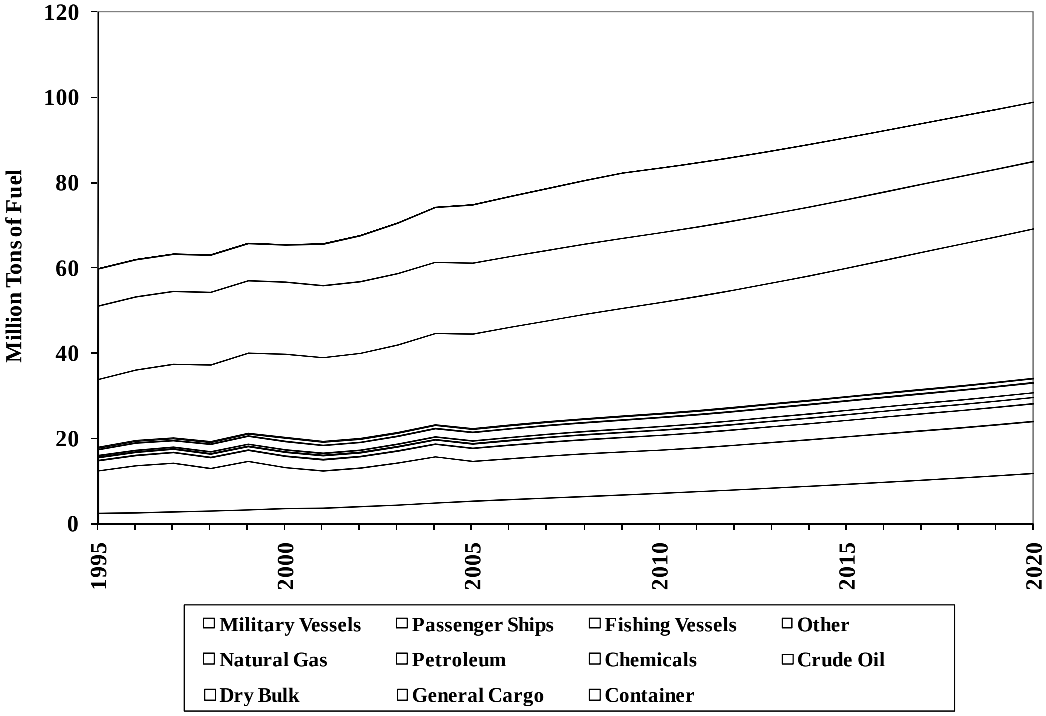

Figure 3-9. **Worldwide MDO-MGO Use**

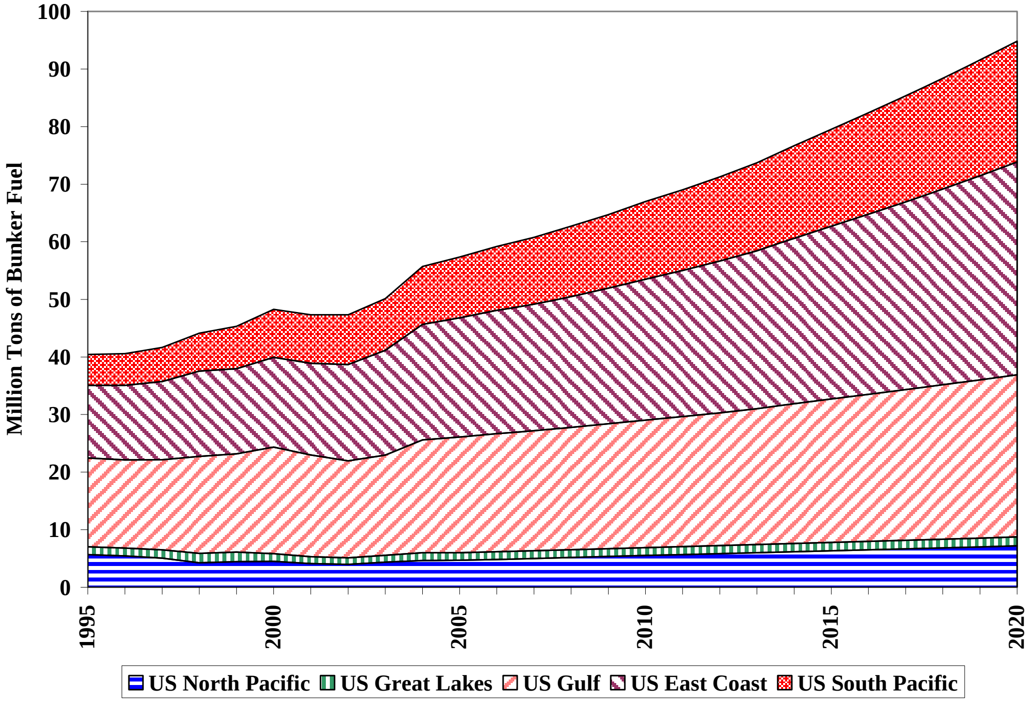

Figure 3-10. **Bunker Fuel Used by the International Cargo Fleet Importing to and Exporting from the United States (by Region)**

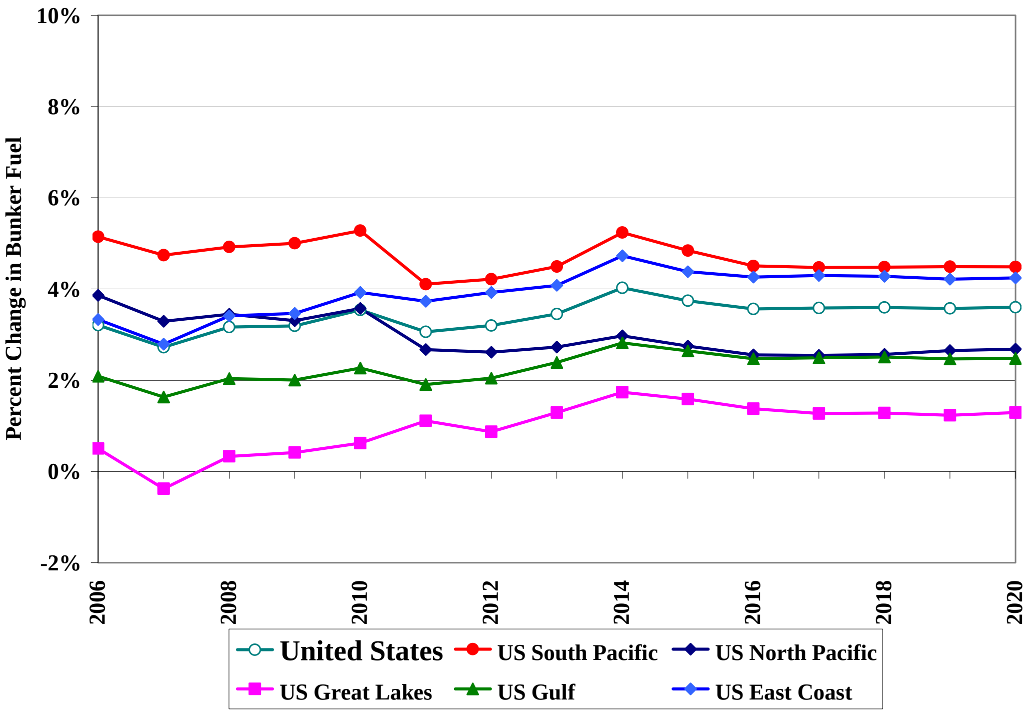

Figure 3-11. Annual Growth Rate in Bunker Fuel Used by the International Cargo Fleet Importing to and Exporting from the United States (by Region)

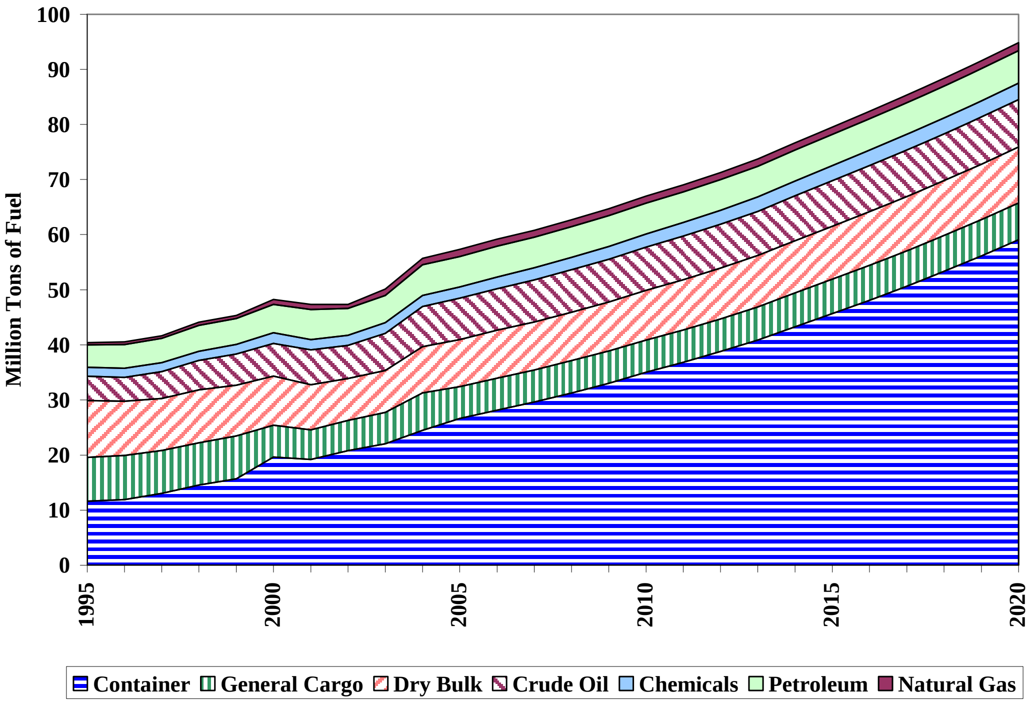

Figure 3-12. Bunker Fuel Used by the International Cargo Fleet Importing to and Exporting from the United States (by Vessel/Cargo Type)

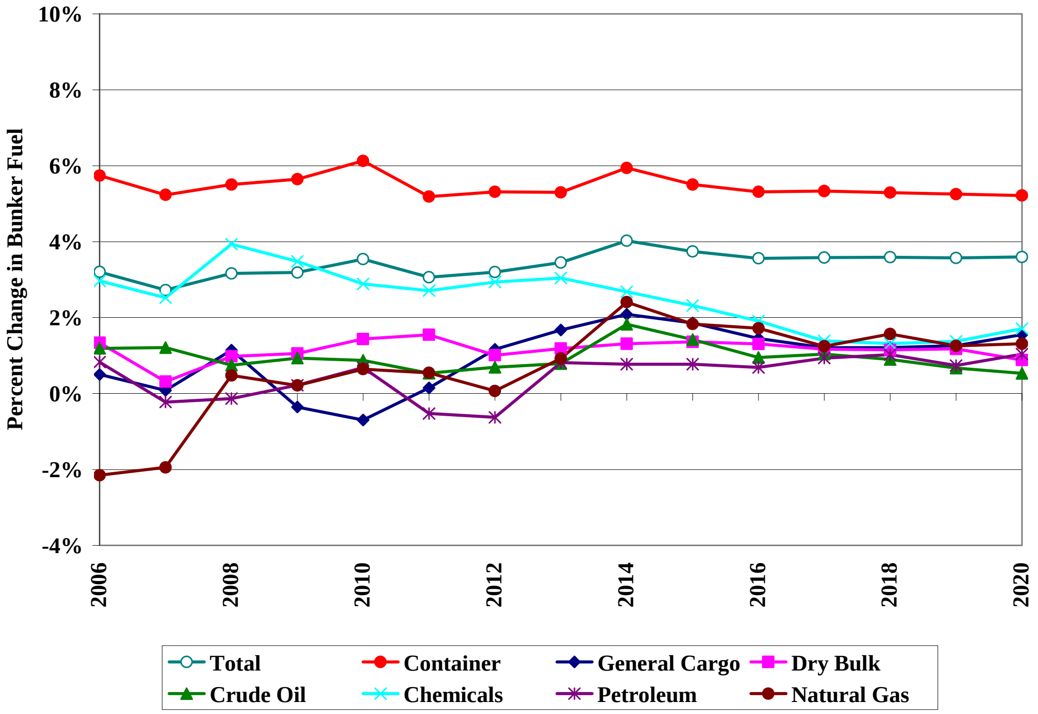

Figure 3-13. Annual Growth Rate in Bunker Fuel Used by the International Cargo Fleet Importing to and Exporting from the United States (by Vessel/Cargo Type)

between 2005 and 2020. This growth rate is somewhat higher than worldwide totals, but is similar to estimated GDP growth in the United States of 3.1% between 2005 and 2020 (EIA, 2006) and is influenced by particular components of U.S. trade flows.

The growth rate in bunker fuel consumption related to U.S. imports and exports is driven by container ship trade (see Figures 3-14 and 3-15), which grows by more than 4% a year. U.S. trade volumes are also influenced by high worldwide growth in GDP and resulting demand for U.S. goods. Along with the fact that container ships use a disproportionately large amount of fuel to move a given number of tons of cargo (as discussed in Section 3.2.3), fuel use by container ships is also influenced by shifts in trading routes over time. In the future, trade is expected to shift to the Pacific region (an increase in Asia–U.S. routes), which causes the average distance per voyage to increase. Thus, while ship efficiency is increasing over time as older ships retire, this effect to dominated by the increase in voyage distance, leading to higher bunker fuel growth.

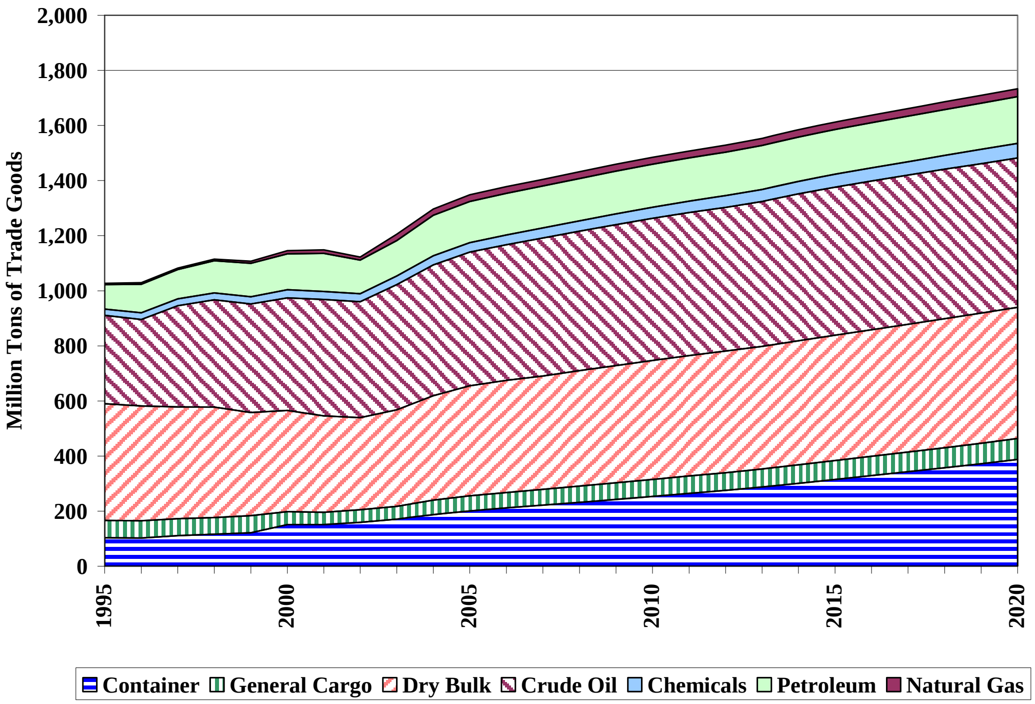

Figure 3-14. U.S. Trade Flows—Imports plus Exports (Global Insights)

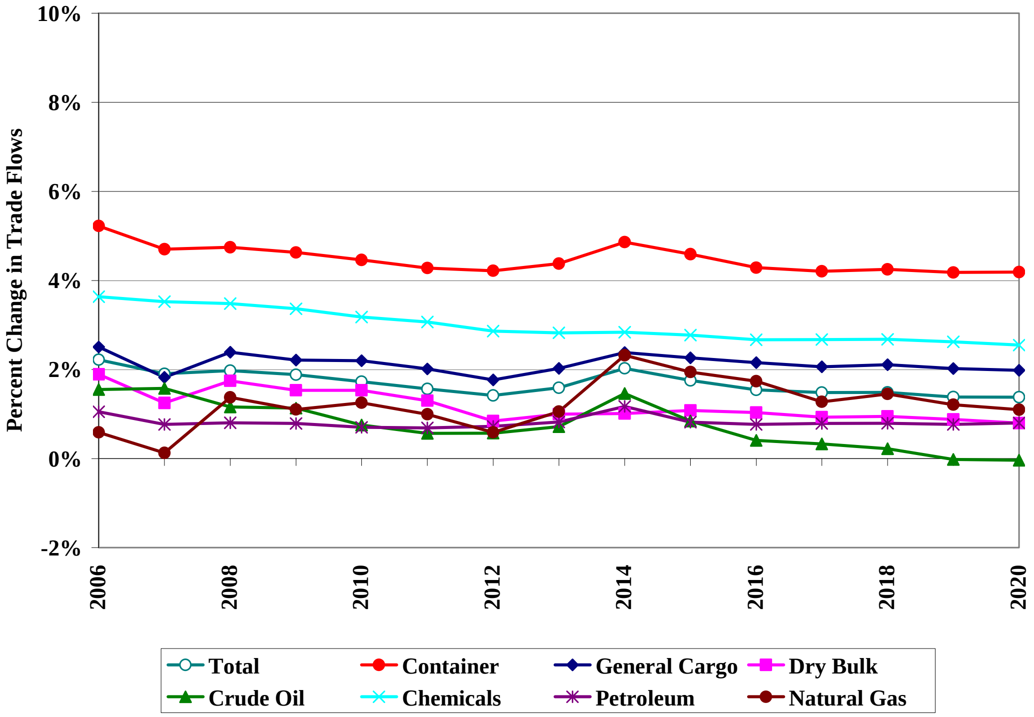

Figure 3-15. Annual Growth in U.S. Trade Flows—Imports plus Exports (Global Insights)

SECTION 4

ESTIMATING BUSINESS-AS-USUAL PROJECTIONS USING THE WORLD MODEL

A key component of Task 1 was to develop BAU projections for bunker fuels. This required enhancing an analytical tool focused on the petroleum-refining industry (i.e., the EnSys WORLD model) so it can provide a sound basis and starting point for future analyses of the effects of potential SECAs in North America and elsewhere, along with other possible global tightening of marine fuels quality. These enhanced capabilities were required for a time horizon covering the years 2012 and 2020.

Table 4-1 summarizes these and other changes made to the WORLD model structure and features for this analysis, followed by additional discussion of the specific premises used as the basis for the 2012 and 2020 BAU cases.

4.1 WORLD Model Enhancements to Accommodate Compliance Alternatives

WORLD is a comprehensive, bottom-up model of the global oil downstream that includes crude and noncrude supplies; refining operations and investments; crude, products, and intermediates trading and transport; and product blending/quality and demand. Its detailed simulations are capable of estimating how the global system can be expected to operate under a wide range of different circumstances, generating model outputs such as price effects and projections of refinery operations and investments. As part of the overall model enhancements, the refinery data, capacity additions, technology assumptions, and costs were reviewed (see Section 4.3).

Beyond these enhancements, the relevant regulations were thoroughly reviewed to ensure that the WORLD model was correctly positioned to undertake future analyses of marine fuels SECAs. Issues brought to light in this review, as discussed below, raise uncertainty about how compliance with SECAs and other potential regulations can be achieved within the petroleum-refining and shipping industries. The issues also tend to create an analytical situation that is less clear and more complex than, for example, a mandate to move all U.S. gasoline to 30 ppm sulfur. Among the issues and uncertainties considered are the following:

- the prospective timetable for reducing SECA marine fuel requirements from 1.5% to 1.0% to 0.5% sulfur;
- the possible scenario of part or all bunker fuel demand shifting to marine distillates;
- the costs and effects of shipboard emission reduction strategies;

Table 4-1. Summary of Structural Changes to the WORLD Model

Product Grades

The distillate and residual fuel specifications in the model were expanded to fully differentiate international marine bunker fuel from inland fuels and to enable clear distinctions between "traditional" and low-sulfur bunker grades. The resulting model bunker grades were

- MGO—marine gas oil
- MDO—marine diesel, high sulfur
- MDO—marine diesel, low sulfur
- IFO 180—high sulfur
- IFO 180—low sulfur
- IFO 380—high sulfur
- IFO 380—low sulfur

Notes:

1. Only one grade of MGO was represented per region on the basis that demand for MGO is small and mainly restricted to local ship movements; hence, any change in specification would apply to the whole MGO volume for the region.
2. Separate low- and high-sulfur grades were implemented for the main bunker grades precisely to correctly capture the processing, blending, and economic effects of regions moving partly or fully to low-sulfur specifications.
3. In reality, there is a trend in the market for IFO 380 grade to be displaced by IFO 500 and even 700. The approach was taken to simply tighten the IFO 380 viscosity specification, where appropriate, to represent this. This approach is adequate since the reduction in distillate cutter stock needed in the blend when going from 380 to 500 or 500 to 700 centistokes is small as is the associated cost impact.
4. The above grades were used to represent international or "blue water" consumption of bunker fuels. Domestic uses of marine fuels (primarily distillates) were accounted for under the corresponding inland diesel or residual fuel categories.

Product Specifications

The following specifications were already active in the model:

- MDO
- IFO

The following were added to these:

- Carbon residue—in order to prevent any inappropriate blends for MDO or IFO grades
- Nitrogen—to cover the possible need to study nitrogen as a component of NO_x regulation. Not activated in BAU cases.

The following were considered but not added:

- Vanadium was not added because (a) it appears to be a rarely limiting specification and (b) adding it in would have entailed significant model modifications.

Product Transportation

Product transportation matrices covering tanker, interregional pipeline, and minor modes were expanded to embody the additional distillate and residual bunker grades.

Bunker Fuel Demand

A new model subsystem was built to import the RTI bunker fuel demand projections. Given the differences between the RTI and IEA levels of demand, the model was set up so that it could be run on both bases. Under the RTI basis, global residual fuel demand is the same as that based on IEA for the 2000 base year, but for future years forecasts an increase in total global demand oil demand (i.e., upward adjustments versus the AEO 2006 reference case projections for 2012 and 2020).

Fuel Stability

As detailed above, yield patterns on the residuum desulfurization and visbreaker units were adjusted, and paraffinic streams were locked out of residual fuel blends.

Model Reports

Reports were added for blend composition of residual fuels and also for reporting of refinery CO_2 emissions.

- how fast and how effectively abatement technology may mature;
- the costs of refining, including the capital expenditures required to reduce bunker fuel sulfur content and the potential for process technology improvements;
- likely market reactions to increased bunker fuel costs, such as fuel grade availability, impacts on the overall transportation fuels balance, and competition with land-based diesel and residual fuels for feedstocks that can upgrade fuels;
- the effects of emissions trading; and
- the potential for low- and high-sulfur grade bunker sources and consumption to partially shift location depending on supply volume, potential, and economics.

The analytical system thus had to be set up to allow for alternative compliance scenarios, particularly with regard to (a) adequately differentiating bunker fuel grades; (b) allowing for differing degrees to which the SECA or other standards in a region were presumed to be met by bunker fuel sulfur reductions, rather than by other means such as scrubbing or emissions trading; and (c) allowing for all residual fuel bunker demand to be reallocated to marine diesel. Beyond any international specifications, the analytical system needed to be able to accommodate future consideration of regional, national, and local specifications (e.g., those being promulgated in California).

The primary approach taken to manage these issues was to

- expand the number of bunker grades in the model to three distillates and four residual grades,[1]
- allow for variation where necessary in (regional) sulfur standards on specific bunker grades, and
- enable residual bunker demand to be switched to marine diesel.

Nonetheless, the approach necessitates estimating—external to the main WORLD model—the details of compliance in any particular region. For example, as in the existing EU SECAs, we are required to estimate the percentage of the bunker consumption in the region that will be met by low-sulfur fuels versus high-sulfur fuels, exhaust gas scrubbing, or emissions trading (Section 6 provides more detailed background on the options for SECA compliance and how they are currently viewed in the model).

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[1] Specifically, the following seven grades were implemented: MGO, plus distinct high- and low-sulfur blends for MDO and the main residual bunker grades IFO 180 and IFO 380. The latest international specifications applying to these fuels were used, as were tighter sulfur standards for the low-sulfur grades applicable in SECAs.

A main focus to date of debates about SECA regulations has been on the degree to which the regulations will require refinery production of lower-sulfur residual fuels. However, the SO_x scrubbing option raises the possibility that *higher*-sulfur bunker fuels could be supplied.

The MARPOL SECA standard states an SO_x emission level of 6 g/kWh, which is equivalent to 1.5% sulfur content bunker fuel. A scrubber operating at 67% efficiency could enable a ship to burn 4.5% sulfur fuel and still meet the 6 g/kWh standard. Given that precommercial scrubber tests on European ferries have been reporting efficiencies in the range of 65% to 95%, the technology could enable a supply option whereby refiners continue to supply high-sulfur IFO bunker fuels at up to 4.5% sulfur. In other words, suppliers could maintain or increase sulfur levels versus the current worldwide average of 2.7%.

With a scrubber operating at 95% SO_x efficiency, a ship could easily surpass the possible EU 2008 standard of 2 g/kWh using 4.5% sulfur fuel versus otherwise using 0.5% sulfur fuel. Even the standard of 0.4 g/kWh, which corresponds to 0.1% sulfur fuel for in-port use, can be met using scrubbing and 2% sulfur fuel. This method of compliance enables refiners to avoid the costs of desulfurization and shippers to buy lower-priced fuels. The route also potentially plays into emissions-trading schemes since, provided emissions levels can be verified, a ship with a scrubber could reduce its emissions below the 6 or 2 g/kWh standards and realize credits (and any associated economic value). Shipboard scrubbing also helps reduce emissions of particulates but has limited impact on NO_x, partially explaining the interest that has been generated in using marine diesel in place of residual grades.

[The WORLD analytical process, therefore, needed to be able to capture potential economic trade-offs of scrubber use in terms of how its impacts might feedback on refinery bunker quality, supplies, and economics. A scrubber “unit” could be built into the WORLD model in the future, but additional information will need to be developed to allow accurate estimates of scrubbers’ costs and utilization potential. More operational experience is required to fully gauge scrubber costs, including such elements as onshore sludge disposal. Estimates to date, however, put the cost per ton of SO_x removal via scrubbing at around one-third or less of the cost via residual fuel desulfurization (Meech, 2006). Therefore, given this simple degree of cost difference, the WORLD model would always opt for the scrubber route to the extent it was allowed. The net effect is that a key scenario variable, developed external to the model (or in conjunction with cost functions developed for the model), is the proportion of SECA-compliant regional bunker fuel that needs to be supplied in the form of low-sulfur product versus high-sulfur product being scrubbed. The WORLD model is readily capable of studying parametric effects associated with varying this proportion.]

4.2 WORLD Model Enhancements to Accommodate Alternate Fuel Demand Forecasts

The WORLD model was also modified to accommodate the bunker demand forecasts estimated in Section 3. These projections required appreciable rethinking and reworking of the model since the estimates of recent historical bunker demand are twice the levels used by IEA and EIA. This has far-reaching implications, leading to reduced current and future demand for inland residual fuels and increased future total residual demand because bunker demand growth is projected to be significant, while that of inland residual is declining.

The net implication of the findings in Section 3 is that other forecasters, including IEA, EIA, and OPEC, are currently underestimating future global residual and total oil demand. In order to accommodate these differing demand projections, and to enable their implications to be understood, the WORLD model was modified so that it could be run for each time horizon on either an IEA fuel demand or an RTI fuel demand basis.

Although the bunker fuel estimates in Section 3 (equal to 278 million tons in 2001) are higher than IEA estimates of around 140 million tons, these findings are comparable to estimates from other works (e.g., Koehler [2003] at 281 million tons or Corbett and Koehler [2003, 2004] at 289 million tons). Industry sources contacted by Navigistics Consulting indicated that there is no agreement on worldwide bunker demand. Meech (2006) estimated world demand at 255 million tons in 2004, and Madden (2006) placed IFO use at roughly 185 million tons in 2004, based on data from Meech (2006).

Given the differences between fuel demand projections, it was necessary to incorporate the RTI bunker estimates carefully into the WORLD model. During this process, when establishing a historical base within WORLD, the view was taken that total reported global oil demand and with that total distillates and residual fuels demand are correct. Therefore, there is no issue of underreporting of total historical demand. Rather, the issues across bunker estimates represent a misallocation of residual fuels (i.e., fuel that is reported as [inland] residual fuel is, in fact, used as marine bunker fuel). The potential for such misreporting is evident. For instance, statistical sources tend to show total bunker demand for the Middle East that is less than that for the port of Fujairah alone and show essentially no bunker demand in the FSU. In the industry press, references can be found to the lack of transparent reporting of bunker sales (see the illustrative text below).

Excerpt from the Bunkerworld Library on Bunker Ports

So how big is the Fujairah bunker market? There are no official data available regarding the size of the Fujairah market, but according to Harbour Master, Captain Tamer Masoud, from the Port of Fujairah, the annual volume of bunker in the area is approximately 12 million metric tons. The average monthly supply volume of bunker is around 1 million metric tons.

It is unclear whether this volume includes export figures. Some players appear to survive mainly by exporting fuel cargoes, for example, to nearby countries such as Pakistan for power stations.

In Fujairah, approximately 60% to 80% of the supplied bunker is IFO380, and the rest is divided between IFO180 and MGO, though it is difficult to estimate exact figures.

In the Arab Gulf, if we include sales from ports in Saudi Arabia, Iran, Kuwait, as well as other UAE ports, the total volume of bunker is well over 1 million mt per month. The Fujairah market is definitely the largest single bunker market in this area.

Exactly how much the Fujairah bunker market accounts for is, it transpires, a subject of much dispute, with established players worried that newcomers and relative ‘outsiders’ have an unrealistic view of the market size and its potential profit margins.

In terms of simulating the global oil downstream today, a potential misallocation between bunker and inland fuel is not significant since the ultimate fuel volumes and qualities are not affected. However, this changes when future years are considered. This is because the growth rate for inland residual fuel is essentially 0% globally, whereas for marine bunkers it is around 3% per year in RTI’s and other projections. (It should be noted that the RTI bunker growth rate is consistent with a historical growth rate of 2.7% per year. in IEA data from 1983 to 2003).

Petroleum product demand projections are built up sector by sector. What appears to be happening in current forecasts, on the basis of the bunker estimates from Section 3 and the related works, is that total inland residual fuel demand is being overestimated, but its demand growth is flat, and total bunker demand, with its attendant appreciable growth rate, is being underestimated. The net effect/implication is that today’s oil demand projections by EIA, IEA, and others underestimate total future bunker demand, residual demand, and global oil demand.

Table 4-2 and Figure 4-1 show the impacts on 2003, 2012, and 2020 oil demand projections, based on the AEO 2006 reference case, of applying IEA and alternatively the RTI estimates of bunker fuel demand. Both bases have the same growth rates for each product type as listed in Table 4-3.

As Table 4-2 shows, total demand for other products such as gasoline and naphtha, are not affected. Total distillate demand is slightly impacted, but there is a significant shift under the RTI basis to distillate bunker grades with less land-based diesel. The main impacts are on product quality since on-road and off-road diesel specifications are advancing more rapidly toward low and ultra-low sulfur levels than are marine distillate fuels. Demand for residual fuel

Table 4-2. Global Oil Demand by Product Category—IEA and RTI Bases for Bunker Fuels

Bunkers Basis	2003 IEA	2003 RTI	2003 Impact of Switch to RTI Basis	2012 IEA	2012 RTI	2012 Impact of Switch to RTI Basis	2020 IEA	2020 RTI	2020 Impact of Switch to RTI Basis
Demand by product type									
Ethane	1.11	1.11	0.00	1.60	1.60	0.00	1.82	1.82	0.00
LPG	6.71	6.71	0.00	7.82	7.82	0.00	8.56	8.56	0.00
Naphtha	4.63	4.63	0.00	5.83	5.83	0.00	6.88	6.88	0.00
Gasoline	21.03	21.03	0.00	23.40	23.40	0.00	25.20	25.20	0.00
Kero/Jet	6.33	6.33	0.00	7.43	7.43	0.00	8.07	8.07	0.00
Gas oil/diesel/NO2	21.19	20.25	(0.94)	26.59	25.36	(1.23)	30.59	29.15	(1.44)
Gas oil/diesel—BKRS—MGO	0.02	0.18	0.16	0.02	0.19	0.17	0.02	0.19	0.17
Gas oil/diesel—BKRS—MDO	0.43	1.16	0.74	0.53	1.47	0.94	0.61	1.73	1.12
Residual—Inland incl RFO	8.20	6.67	(1.53)	8.28	6.83	(1.46)	8.17	6.84	(1.33)
Residual—BKRS—IFO180	0.31	0.55	0.24	0.40	0.76	0.36	0.47	0.95	0.48
Residual—BKRS—IFO380	2.01	3.48	1.47	2.67	4.77	2.10	3.23	5.92	2.69
Other	7.49	7.49	0.00	8.57	8.57	0.00	9.83	9.83	0.00
Transport losses	0.18	0.18	0.00	0.21	0.21	0.00	0.24	0.24	0.00
Total oil demand	79.64	79.78	0.15	93.35	94.23	0.88	103.70	105.38	1.68
Total distillates demand	21.63	21.60	(0.03)	27.14	27.01	(0.13)	31.22	31.07	(0.15)
Total residual demand	10.52	10.70	0.18	11.35	12.36	1.01	11.87	13.71	1.84

is also significantly modified. Under the RTI basis, it is 1.0 million barrels per day (mmbpd) higher in 2012 (bunker and inland grades combined) and for 2020, the figure is 1.84 mmbpd. The implication is that the IEA basis for bunker fuel understates future global oil demand: by 0.9 mmbpd in 2012 and 1.7 mmbpd by 2020 versus the AEO reference case figures.

The increase in residual demand will materially impact total refining investments and economics as well as increase oil supply requirements. Of further significance is that, with higher volumes of bunker fuels, the impacts of marine fuels regulations and SECAs will be

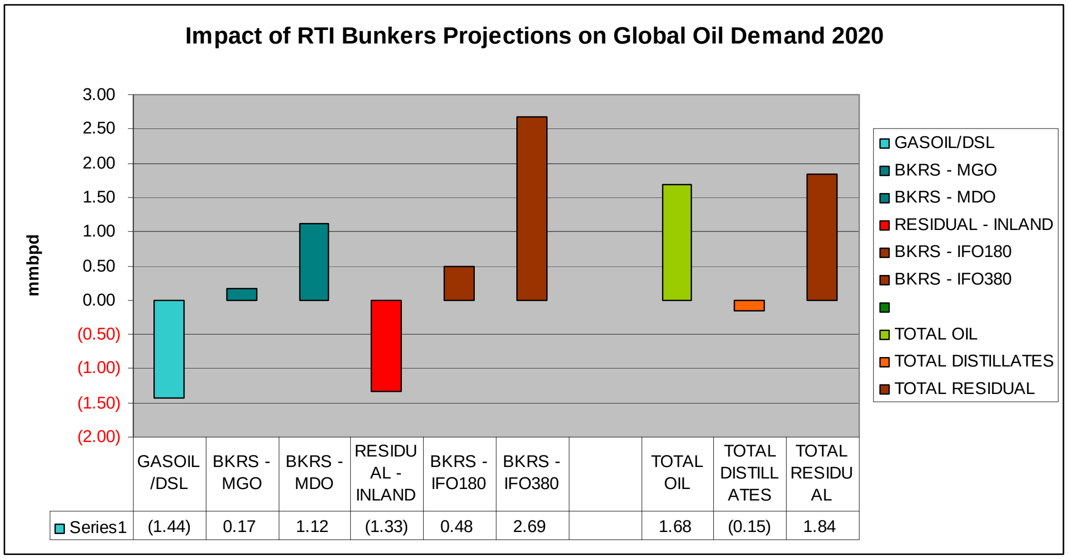

Figure 4-1. Impact of RTI Bunker Projections on Global Oil Demand in 2020

Table 4-3. Product Growth Rates

RTI Basis—Bunkers Projection	2000[a] to 2012	2020
Ethane	2.06%	1.89%
LPG	1.99%	1.65%
Naphtha	2.53%	2.36%
Gasoline	1.46%	1.25%
Kero/jet	1.25%	1.17%
Gas oil/diesel/NO2	2.51%	2.21%
Gas oil/diesel—BKRS—MGO	0.13%	0.20%
Gas oil/diesel—BKRS—MDO	2.73%	2.46%
Residual—Inland incl RFO	0.09%	0.06%
Residual—BKRS—IFO180	3.61%	3.30%
Residual—BKRS—IFO380	3.59%	3.25%
Other	1.12%	1.42%
Transport losses	1.50%	1.50%
Total oil demand	1.82%	1.66%

[a] World base demand year is 2000.

correspondingly greater, in terms of volumes of marine fuels that may have to be produced to low-sulfur standards and the associated impacts on refining investments and supply economics.

To deal with these bunker demand projections and to accommodate potential SECA scenarios including differing assumptions about the degree to which SO_x targets are met by fuel sulfur reduction versus abatement and trading, the WORLD model was modified so that it could (a) work with oil demand projections on both the IEA and RTI bases for bunker fuels and (b) could accommodate user-specified proportions of low-sulfur MDO and IFO for any horizon and region. In addition, the model user has the ability to set the sulfur level for each horizon and region for each high- and low-sulfur fuel (e.g., to capture potential progression under the EU SECAs from 1.5% to 0.5% sulfur).

Another facet of marine bunker demand is that shippers have flexibility in terms of where they bunker. Bunker fuel demand can shift to some degree from region to region. This phenomenon is part and parcel of the daily bunker business, and buyers shift their buying based on a few dollars per ton price differences. For Task 1, this situation was recognized, but bunker demand was kept static; no feature was introduced to partially shift demand toward regions where supply is least expensive.

4.3 Enhancements to Ensure Bunker Fuel Stability

During the early stages of the study, concerns were raised about the potential impact of quality and compositional changes on the stability of the residual bunker fuel grades. A literature search was undertaken and knowledgeable individuals contacted in industry to ensure a sound understanding of fuel stability issues as a basis for ensuring the WORLD model processing and blending options were consistent with stable IFO blends.

Fuel instability is a serious and not uncommon issue in bunkering. It centers on the asphaltenes contained in the blend precipitating out, which renders the fuel unusable and, if already on board, the only remedy is to debunker the ship. The presence in the blend of different classes of blendstocks acts to either prevent or cause precipitation of asphaltenes.

Conversations with industry experts on bunker fuels confirmed that there is a degree of “black art” in bunker blending in that refiners and blenders learn what blends work and stick to these. Further, the blending “art” is highly refinery specific. Although capturing differences between individual refineries was not possible within the WORLD model, steps were taken to prevent the model from producing IFO blends that could tend to be unstable. The main factors reviewed and steps taken were as follows:

- The **visbreaker** yields in the model were reviewed and adjusted. Data from Maples states that the propensity for visbreaker vacuum residuum product streams to be unstable is highly dependent on the feed asphaltene content; hence, to maintain stability, the heavier, more asphaltic feeds need to be processed at reduced severity relative to less asphaltic feeds. This view was reinforced by bunker experts. Again, according to Maples, who undertook a specific study of visbreaking and fuel stability, the typical range of conversion is 8% to 12%, where the objective is to maximize distillate production and 6% to 10%, where it is to reduce residual viscosity, with an overall observed conversion range of 4% to 16%. To reflect these ranges and to establish a conservative set of visbreaker yields across vacuum residuals from low- to high-sulfur/asphaltene contents, a graduated set of yields was applied. Conversion was inversely related to residuum quality such that it was limited to 6% for the poorest quality resid, rising to 10% for the highest quality feed. In addition, visbreaker utilities' consumption and capital cost were checked.

- The **vacuum and atmospheric residuum hydro-desulfurizer** yields, utilities, and costs were reviewed. With the prospect of lower IFO sulfur limits, the VRDS and ARDS units gain additional importance. Feedback from industry contacts and literature research was that, for purposes of maintaining stability in residual fuel blends, VRDS/ARDS operating severities should not be so severe as to cause significant hydro-cracking. Information from Meyers and other sources indicates a typical percentage desulfurization range from the high 80%s to 95% to 97%. Yields and desulfurization levels in the model were adjusted to close to 90% in order to stay in the conservative range.
- The **physical properties** of the potential main IFO blend components were reviewed with particular attention paid to gravity, sulfur, carbon residue, and viscosity. Adjustments were made to the viscosities of several vacuum and atmospheric residuum streams. These had been previously overstated, leading to excessive levels of distillates and cracked stocks in early case run blends.
- **Carbon residue specification** was added as a control against unstable blends.
- The **blendstocks allowed into the IFO blends** were also reviewed. All kerosene type blendstocks were checked as blocked from residual fuel blends (inland as well as bunker). Similarly all paraffinic middle distillate and vacuum gas oil stocks were blocked from residual blending. Cracked stocks, notably FCC cycle and clarified oils, were allowed into all residual blends but concentrations were limited to a maximum of 25% based on literature research and industry feedback. Visbroken vacuum residuum streams were limited to a maximum 10% regional average,[2] again based on feedback. The overall intent here was to prevent the model from producing blends that could be readily unstable.
- **Fuel stability additives** were considered but were not included in the modeling analysis. Reputable suppliers do make available additive packages designed to improve fuel stability. However, they are not universally used for marine bunker fuels. Major oil company suppliers are known to not use additives. Also, feedback from industry experts was skeptical in terms of the degree of reliance that could be placed on such additives to prevent fuel stability issues. Thus, they were excluded from the analysis. At worst, this may mean the analysis slightly understates the costs of future bunker fuels by omitting the cost of the additive package.

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[2] The limits on visbroken residuals and also on cracked stocks are regional averages. Therefore, they allow that, in the real world individual blends/suppliers would have levels either higher or lower.

4.4 Enhancements to WORLD Model Reporting

Given the importance attached to fuel stability and the focus of the study on bunker fuels, the WORLD model reports were extended to directly summarize the regional blend compositions of each residual grade (inland and bunker). Thus, any anomalous blends could be more easily identified.

In addition, since greenhouse gas emissions are becoming part of the debate on bunker fuels, a recently added feature to post-optimally report the CO_2 emissions from each world refining region was activated. This enabled quantitative comparison of the effects of moving to more intense processing of bunker (or other) fuels to achieve lower sulfur content and/or shift to distillate grades.

4.5 WORLD Model Assumptions and Structural Changes

4.5.1 AEO 2006 Outlook—Supply/Demand/Price Basis

Overall, oil supply, demand, and price parameters were set in the model based on the AEO 2006 reference case as summarized in Table 4-4. Detailed supply premises, including production by crude type by country/region, were based on internal WORLD model data and projections. Noncrude supply in the model was detailed by major fuel type and region. Projections were set based on in-house data with reference to detailed EIA data.

Product demand for 2012 and 2020 was set using a year 2000 basis of historical data by product type with growth rates by region and product. These growth projections are believed to be in line with those of other current forecasts:

- the strongest growth was for distillates among the major fuel categories, including continuing dieselization in Europe;
- emphasis on distillates in Asia/China;
- no major shifts in U.S. transport fuels patterns;
- essentially flat growth for inland residual fuel consumption; and
- significant growth for naphtha and LPG.

4.5.2 Product Quality

The 2012 and 2020 BAU cases were on the basis of a “best estimate” of fuel quality, given implementation of already active regulations and continuation of current product quality trends. Specific premises built into the cases are discussed below.

Table 4-4. AEO 2006 Petroleum Supply Forecast (million barrels per day, unless otherwise noted)

	2005	2012	2020	2004–2030
Crude Oil Prices (2004 dollars per barrel)				
Imported Low Sulfur Light Crude Oil Price	55.93	47.65	50.70	1.3%
Imported Crude Oil Price	49.70	43.59	44.99	1.3%
Production (Conventional)				
Mature Market Economics				
United States (50 States)	8.33	9.51	9.51	0.2%
Canada	2.45	1.56	1.45	−2.0%
Mexico	4.13	4.06	4.48	0.8%
Western Europe	6.68	5.64	5.22	−1.7%
Japan	0.14	0.08	0.07	−2.8%
Australia and New Zealand	0.64	0.86	0.84	0.7%
Total Mature Market Economies	22.37	21.71	21.58	−0.3%
Transitional Economies				
Former Soviet Union				
Russia	9.61	9.65	10.66	0.7%
Caspian Area	2.36	3.47	5.16	4.6%
Eastern Europe	0.26	0.32	0.39	2.5%
Total Transitional Economies	12.23	13.44	16.21	1.9%
Emerging Economies				
OPEC				
Asia	1.44	1.45	1.26	−0.9%
Middle East	22.25	25.09	26.99	1.5%
North Africa	3.07	3.50	3.70	0.6%
West Africa	2.01	2.44	2.61	1.7%
South America	2.88	3.48	3.70	1.5%
Non-OPEC				
China	3.17	3.30	3.33	0.0%
Other Asia	2.59	2.50	2.61	−0.5%
Middle East	1.71	2.15	2.45	1.9%
Africa	3.67	3.97	5.41	3.2%
South and Central America	4.36	4.62	5.83	2.0%
Total Emerging Economies	47.15	52.49	57.89	1.4%
Total Production (Conventional)	81.74	87.65	95.68	1.1%
Production (Nonconventional)				
United States (50 states)	0.25	0.63	0.94	7.6%
Other North America	0.96	1.98	2.67	5.4%

(continued)

Table 4-4. AEO 2006 Petroleum Supply Forecast (million barrels per day, unless otherwise noted) (continued)

	2005	2012	2020	2004–2030
Western Europe	0.04	0.10	0.12	6.4%
Asia	0.31	0.83	1.25	9.4%
Middle East	0.02	0.57	0.73	18.3%
Africa	0.13	0.28	0.53	9.4%
South and Central America	0.73	1.32	1.78	6.1%
Total Production (Nonconventional)	2.44	5.71	8.02	7.1%
Total Production	84.18	93.36	103.70	1.4%
Consumption				
Mature Market Economies				
United States (50 states)	20.82	22.82	24.81	1.1%
United States territories	0.34	0.34	0.38	1.2%
Canada	2.17	2.14	2.25	0.3%
Mexico	2.01	2.15	2.24	0.5%
Western Europe	13.55	13.38	13.52	0.2%
Japan	5.17	4.72	4.40	−0.9%
Australia and New Zealand	1.10	1.18	1.28	1.2%
Total Mature Market Economies	45.17	46.74	48.89	0.6%
Transitional Economies				
Former Soviet Union	4.16	4.58	4.93	1.0%
Eastern Europe	1.42	1.64	1.87	1.6%
Total Transitional Economies	5.59	6.22	6.81	1.2%
Emerging Economies				
China	7.35	9.09	11.38	3.2%
India	2.53	3.08	3.81	2.7%
South Korea	2.26	2.44	2.57	0.7%
Other Asia	6.37	8.06	9.85	2.6%
Middle East	6.32	7.39	8.34	1.7%
Africa	3.12	3.78	4.31	1.9%
South and Central America	5.49	6.56	7.75	2.1%
Total Emerging Economies	33.43	40.40	48.01	2.3%
Total Consumption	84.18	93.36	103.70	1.4%
OPEC Production	32.15	37.34	40.27	1.5%
Non-OPEC Production	52.03	56.02	63.43	1.3%
Net Eurasia Exports	6.64	7.22	9.40	2.4%
OPEC Market Share	0.38	0.40	0.39	0.2%

4.5.2.1 Industrialized World

USA/Canada/Europe/Japan/Australia

- Gasoline, on-road and off-road diesel ultra-low sulfur regulations are fully in place by the 2010/2011 time frame (i.e., before 2012 with an essentially total phase-out of nonultra low-sulfur gasolines and diesel fuels).
- Gasoline clear pool octanes remain flat.
- MTBE phase-out is completed in the United States in 2006, and the RFS is in place.
- MTBE is assumed to not be phased out in other world regions.
- Regulations that impact other fuels' quality, such as EPA toxics "anti-backsliding," Euro V, and CARBIII, are in place.
- Consumption of high-sulfur inland residual fuel entirely replaced by low-sulfur fuel (1% or less).

4.5.2.2 Non-OECD Regions

- Completion of lead phase-out in gasoline.
- An overall gradual upward trend in regional pool octanes such that, by 2020, all non-OECD regions are within 1 octane or less of U.S. average pool octane. Globally, the octane rise is moderated by the fact that the large gasoline volumes in OECD regions are projected to remain at constant, even slightly declining, octane levels.
- Progressive adoption of advanced (generally Euro II/III/IV) fuels standards for transport fuels such that a moderate proportion of transport fuel demand has reached advanced standards by 2012 and the majority by 2020.
- A gradual/partial trend toward mandates for low-sulfur residual fuel for inland use.

4.5.3 Residual Fuel for Industrial/Inland Use

As the result of trends across both OECD and non-OECD regions, the global percentage of low-sulfur industrial/inland residual fuel (less than 1% sulfur content) rises from an estimated 41% in 2000, to 52% in 2012, and to 63% in 2020. Thus, the basis is that these progressive shifts toward low sulfur residual fuel will be occurring in addition to parallel shifts toward lower-sulfur residual bunker fuels. The same is true for distillates, where the continuing global trend toward low and ultra-low sulfur standards for on- and off-road diesels will be occurring over the same time frame as the shift to tighter sulfur standards for marine fuels.

4.5.4 Biofuels

The AEO 2006 reference case contains large increases in U.S. and global biofuels production. Initial WORLD case projections were set at total global supply/demand of 1.5 mmbpd of biofuels by 2012 and 1.8 mmbpd by 2020. These were later refined based on more detailed analysis and projections contained in the IEA World Energy Outlook, 2006, released in November 2006 as summarized in Table 4-5. At 1.4 mmbpd for 2012 and 1.94 mmbpd for 2020, these projections are similar to the original AEO numbers.

Table 4-5. Projected Biofuels Consumption

	Ethanol Consumption (kbpd)			**Biodiesel Consumption (kbpd)**		
	2005	**2012**	**2020**	**2005**	**2012**	**2020**
OECD	274	785	1,060	61	231	253
North America	258	482	608	5	68	83
United States	254	465	585	5	66	78
Canada	4	17	23	0	2	5
Europe	16	298	444	56	160	164
Pacific		5	8		3	6
Transition Economies		2	2		1	1
Russia		2	2		1	1
Developing Countries		0	0		0	0
Developing Asia		0	0		0	0
China	17	9	26		14	40
India	5	2	5		3	8
Indonesia		3	6		5	9
Rest of Dev Asia		11	22		17	34
Middle East		1	2		2	3
Africa		8	16		12	25
North Africa		0	2		0	3
Rest of Africa		7	14		11	22
Latin America		0	0		0	0
Brazil	277	275	382	1	22	39
World	**579**	**1,094**	**1,523**	**62**	**306**	**413**

Source: IEA World Energy Outlook 2006, Chapter 14 & Tables 14.1, 14.2, 14.4

Recent oil price rises and energy security concerns have spurred numerous biofuels projects and legislative incentives in the United States, Europe, and elsewhere. The IEA projection used was taken from their reference scenario, not the alternative scenario that had more aggressive biofuels' growth projections.

According to the IEA reference scenario, the United States, Brazil, and Europe will continue to dominate biofuels' supply and consumption. In both the United States and Brazil, the IEA projects that the proportion of biodiesel will slowly rise. Conversely, the IEA estimates that, in Europe, where biodiesel currently comprises 84% of total biofuels supply, the proportion will drop steadily because the main growth is expected to lie in ethanol production. Based on IEA and other data, current biofuels supply and consumption is assessed at approximately 75% Northern Europe (dominated by Germany and secondarily France), 20% Southern Europe (mainly Italy and Spain), and 5% Eastern Europe. These proportions were assumed to remain constant throughout the period to 2020. According to the IEA, Europe's growth in biofuels supply will result in these fuels constituting around 4.9% of total transport fuel demand by 2010, versus a declared EU target of 5.75%. The 2020 biofuel volumes correspond to around 7.5% of European transport fuel demand as projected in the WORLD BAU case. Relatively small volumes of biofuels are projected by IEA to be forthcoming in Asia (led by China) and Africa. In the WORLD cases, the majority of these biofuels were projected to be biodiesel.

Total U.S. plus Canada biofuels production was projected to reach 0.69 mmbpd by 2020, dominated by ethanol. Ethanol was allowed to be used in RFG by adding to RBOBs at either 0%, 5.7%, or 10% ethanol by volume (maximum 5.7% for CARB RFG). Additional ethanol was allowed to be absorbed in CG at concentrations up to 3.7 percent by weight maximum oxygen content. In reality, a small but increasing volume of ethanol looks likely to be sold as "E85" type gasoline. Consideration was initially given to modeling E85 as a distinct grade, but the decision was made to not model it explicitly.

4.5.5 Regional Bunker Demands

As discussed above, the WORLD model was set up so that it could be run under both IEA and RTI premises for bunker fuel base demand and growth. A two-step procedure was adopted. Firstly, the bunker basis was set to "IEA," and overall and regional oil supply and demand projections were matched to the AEO 2006 reference case for either 2012 or 2020, respectively, 93.4 and 103.7 mmbpd. Then, the bunker basis was reset to RTI's basis. This led to an increase in total residual and total oil demand, which was met by rebalancing supply through raising OPEC production.

The bunker demand projections were taken directly from findings discussed in Section 3. A primary issue here entailed the regional allocation of bunker consumption, given that the base 2003 IEA bunker demand totaled 145 mmtpa and the RTI demand is estimated at 305 mmtpa. Table 4-6 summarizes 2003 bunker demand per IEA and the findings in Section 3 and then projections for 2012 and 2020.

As can be seen, judgment was applied to allocate the 157 million metric tons per year (mmta) change in demand. All regions were increased versus IEA forecasts, but with the major increases in non-OECD areas. The regional allocations were driven in large part by the trade flows built into the shipping model developed in Section 3. The allocation was also considered logical on the basis that bunker fuel demand is less likely to be accurately separated out and reported in the national statistics of non-OECD regions. As discussed above, there is open acknowledgement that bunker consumption data are incomplete. For instance, IEA data report bunker demand for Africa at a total of only 9.5 mmtpa or 6.4% of global bunker demand. However, Bunkerworld data on ports and companies active in bunkering list some 93 bunkering ports spread across 38 countries in Africa and with often several suppliers active in each port. This does not seem consistent with data indicating only minimal bunker consumption. Note that the situation regarding these statistics and estimation reinforces that the regional allocations of bunker demand used in the BAU cases are approximate and that further work could be pursued to arrive at more rigorous values.

4.5.6 Regulatory Outlook for Bunker Fuels

4.5.6.1 Primary Bunker Quality Regulations

For the BAU cases, the bunker demand and quality basis was that existing regulations would apply, but that there would be no additional regulations, thus setting the modeling framework for later subject cases to quantify the impacts of U.S. SECAs, etc (see tables 4-6 and 4-7). Specifically:

- MARPOL Annex VI (ISO 8217 2005) specifications were applied to all international distillate and residual bunker fuels as set out in Figures 4-2 and 4-3. MGO specifications were taken from those for DMA and the MDO specifications from DMC. Based on industry advice, buyers almost exclusively opt for the higher grade versions of IFO180 and 380. These are the ISO8217 2005 grades RME and RMG, respectively (rather than RMF and RMH). RME and RMG have tighter specifications for carbon residue and vanadium. The carbon residue specifications, at 15 and 18, respectively, were activated in the model to provide a limit on possible future degradation of IFO quality. Carbon residue was also activated on the DMC MDO blend, even though this is likely to play less of a role as sulfur limits on MDO are tightened.
- The EU Baltic and North Sea SECAs took effect in 2006 and therefore were applied. They were, however, “locked” at the 1.5% sulfur level, even though current EU initiatives make it clear that the intent is to achieve the equivalent of 0.5% sulfur fuel across a broad swath of EU waters by 2012. Note, the ISO8217 2005 specification explicitly allows for the 1.5% sulfur grades in SECAs.

Table 4-6. World Regional Bunker Sales

World Region Basis	Bunker Sales 2003 IEA	Bunker Sales 2003 RTI	Comparison Delta	RTI vs. IEA Percent	Bunker Sales 2012 RTI	Bunker Sales 2020 RTI	Growth Rates to from 2003 2012 RTI	Growth Rates to from 2003 2020 RTI
USEC[a]	6.0	7.5	1.5	124%	9.5	11.2	2.7%	2.4%
USGICE[b]	8.9	11.6	2.6	130%	14.7	17.2	2.7%	2.4%
USWCCW[c]	5.5	8.4	2.9	152%	10.7	12.5	2.7%	2.3%
GrtCAR[d]	4.5	11.7	7.2	260%	15.9	21.5	3.4%	3.7%
SthAm[e]	5.4	16.8	11.4	312%	21.0	24.0	2.5%	2.1%
AfWest[f]	1.2	2.3	1.1	186%	2.7	2.9	1.9%	1.5%
AfN-EM[g]	4.6	12.3	7.6	265%	14.5	16.1	1.8%	1.6%
Af-E-S[h]	3.7	7.1	3.5	194%	8.7	10.0	2.2%	2.0%
EUR-No[i]	32.4	42.3	9.9	131%	52.8	60.0	2.5%	2.1%
EUR-So[j]	14.9	27.1	12.2	182%	34.8	42.4	2.8%	2.7%
EUR-Ea[k]	0.5	1.4	0.9	293%	2.0	2.6	4.0%	3.7%
CaspRg[l]	0.0	0.0	0.0	0%	0.0	0.0	3.1%	2.5%
RusFSU[m]	0.4	7.8	7.3	1,865%	10.3	12.3	3.2%	2.8%
MEGulf[n]	10.3	25.0	14.7	242%	31.8	36.8	2.7%	2.3%
PacInd[o]	6.1	25.9	19.8	421%	29.0	31.6	1.3%	1.2%
PacHi[p]	37.6	57.0	19.5	152%	69.4	78.4	2.2%	1.9%
China	5.4	31.5	26.1	587%	66.5	101.5	8.7%	7.1%
RoAsia[q]	0.3	9.2	8.9	2,853%	12.0	14.1	2.9%	2.5%
World	147.8	304.9	157.2	206%	406.2	495.3	3.2%	2.9%

[a] U.S. East Coast
[b] U.S. Gulf Coast and Interior, plus Eastern Canada
[c] U.S. West Coast, plus Western Canada
[d] Greater Caribbean
[e] South America
[f] Africa West
[g] Africa North and the Mediterranean
[h] Africa East and South
[i] Europe North
[j] Europe South
[k] Europe East
[l] Caspian Region
[m] Russia/Former Soviet Union
[n] Middle East Gulf
[o] Pacific Industrialized
[p] Pacific High Growth
[q] Rest of Asia

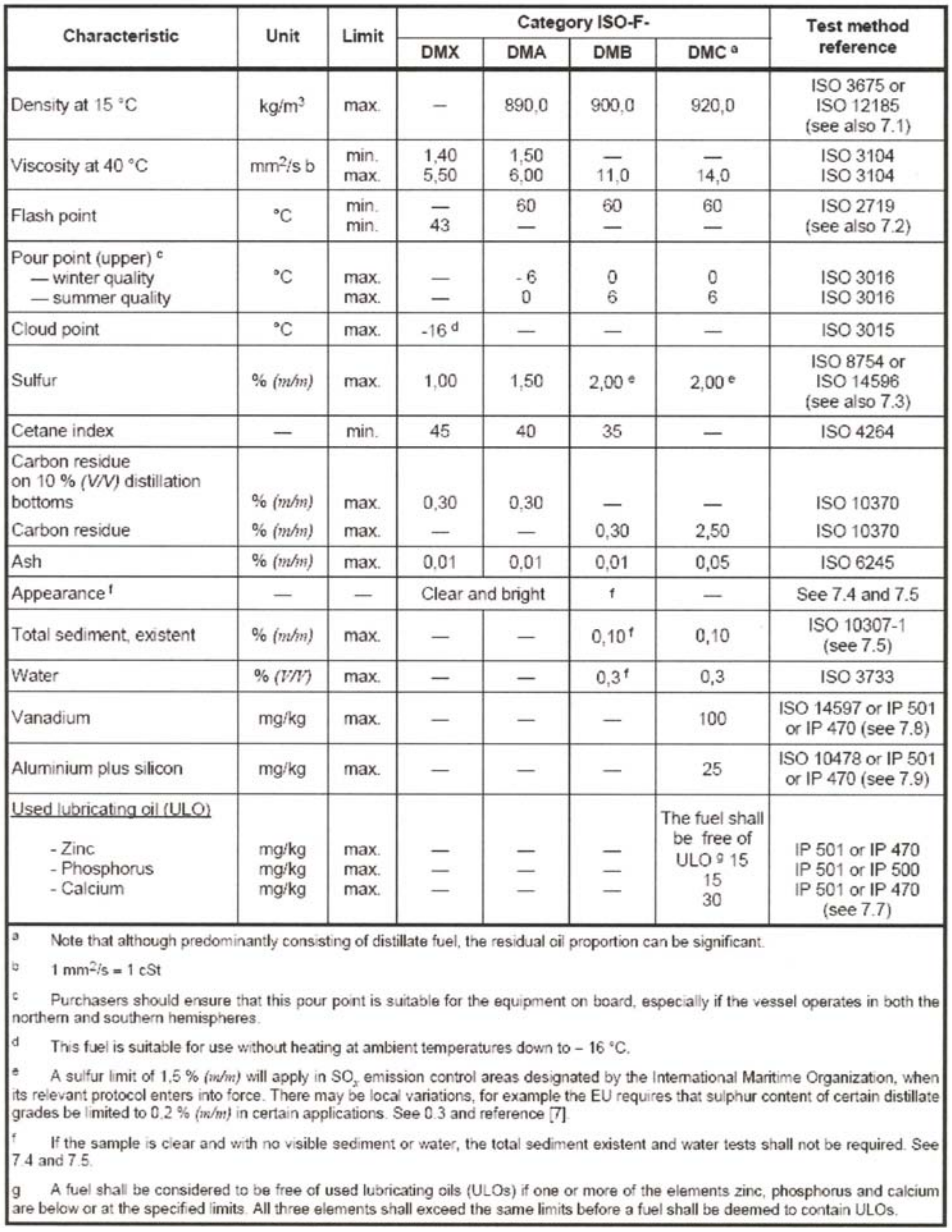
Table 4-7. Summary of Bunker Sulfur Specifications Used for 2012 and 2020 BAU Cases

	Annex VI / ISO8217 2005	**EU SECAs**	**Percentage of N WE Bunker Under SECA**		**Percentage of SECA Fuel Requirement Met by LSFO**	
			2012	**2020**	**2012**	**2020**
MGO	1.5%	0.2% [a]	50%	50%	95%	80%
MDO	2.0%	1.5%	50%	50%	95%	80%
IFO180/380	4.5%	1.5%	50%	50%	95%	80%
California		**CA Jan 2007 Reg.**	**Percentage of Model's USWCCW Region MGO/MDO Under CA Jan 2007 Reg.**		**Percentage of CA MGO/MDO Under Jan 2007 Reg. Met by LSFO**	
MGO/MDO		0.5% [b]	75%	75%	95%	80%

[a] The EU has proposed tightening MGO to 0.1% from 2008. BAU case is on basis of 0.2%.

[b] CARB has proposed tightening the MGO regulation to 0.1% by January 2010, but 0.5% was used in the BAU cases.

- Regulations currently being finalized were applied to California bunker consumption. There are two regulatory tracks under way in the state that will be examined as part of the future subject cases. Firstly, CARB is considering additional bunker fuel regulation. Specifically, the CARB rule under which both MGO and MDO in California regulated waters used in auxiliary engines must comply with a 0.5% sulfur maximum was included in the 2012 and 2020 BAU cases. CARB is evaluating further tightening of PM, NO_x, and SO_x limits on auxiliary engine emissions, including a possible 0.1% limit for MGO by January 2010, with analysis due by July 2008. In addition, the port authorities for Long Beach and Los Angeles have finalized their own plans, which go beyond the CARB regulations. The San Pedro Bay Ports Clean Air Action Plan contains measures to require ships to use MGO with a sulfur content of less than 0.2% in their main and auxiliary engines within a 40-nautical mile zone. The regulations will either be implemented fully in 2007–2008 or will be applied more gradually through 2011 as shipping companies' lease agreements are renegotiated. A report on the legality of the ports' plans by the California Office of Administrative Law is due by December 5, 2006. Note, these regulations replace use of IFO fuels with the highest quality marine fuel MGO, not MDO.



Characteristic	Unit	Limit	Category ISO-F-				Test method reference
			DMX	DMA	DMB	DMC [a]	
Density at 15 °C	kg/m^3	max.	—	890,0	900,0	920,0	ISO 3675 or ISO 12185 (see also 7.1)
Viscosity at 40 °C	mm^2/s [b]	min.	1,40	1,50	—	—	ISO 3104
		max.	5,50	6,00	11,0	14,0	ISO 3104
Flash point	°C	min.	—	60	60	60	ISO 2719
		min.	43	—	—	—	(see also 7.2)
Pour point (upper) [c]							
— winter quality	°C	max.	—	- 6	0	0	ISO 3016
— summer quality		max.	—	0	6	6	ISO 3016
Cloud point	°C	max.	-16 [d]	—	—	—	ISO 3015
Sulfur	% *(m/m)*	max.	1,00	1,50	2,00 [e]	2,00 [e]	ISO 8754 or ISO 14596 (see also 7.3)
Cetane index	—	min.	45	40	35	—	ISO 4264
Carbon residue on 10 % *(V/V)* distillation bottoms	% *(m/m)*	max.	0,30	0,30	—	—	ISO 10370
Carbon residue	% *(m/m)*	max.	—	—	0,30	2,50	ISO 10370
Ash	% *(m/m)*	max.	0,01	0,01	0,01	0,05	ISO 6245
Appearance [f]	—	—	Clear and bright		f	—	See 7.4 and 7.5
Total sediment, existent	% *(m/m)*	max.	—	—	0,10 [f]	0,10	ISO 10307-1 (see 7.5)
Water	% *(V/V)*	max.	—	—	0,3 [f]	0,3	ISO 3733
Vanadium	mg/kg	max.	—	—	—	100	ISO 14597 or IP 501 or IP 470 (see 7.8)
Aluminium plus silicon	mg/kg	max.	—	—	—	25	ISO 10478 or IP 501 or IP 470 (see 7.9)
Used lubricating oil (ULO)						The fuel shall be free of ULO [g]	
- Zinc	mg/kg	max.	—	—	—	15	IP 501 or IP 470
- Phosphorus	mg/kg	max.	—	—	—	15	IP 501 or IP 500
- Calcium	mg/kg	max.	—	—	—	30	IP 501 or IP 470 (see 7.7)

[a] Note that although predominantly consisting of distillate fuel, the residual oil proportion can be significant.

[b] 1 mm^2/s = 1 cSt

[c] Purchasers should ensure that this pour point is suitable for the equipment on board, especially if the vessel operates in both the northern and southern hemispheres.

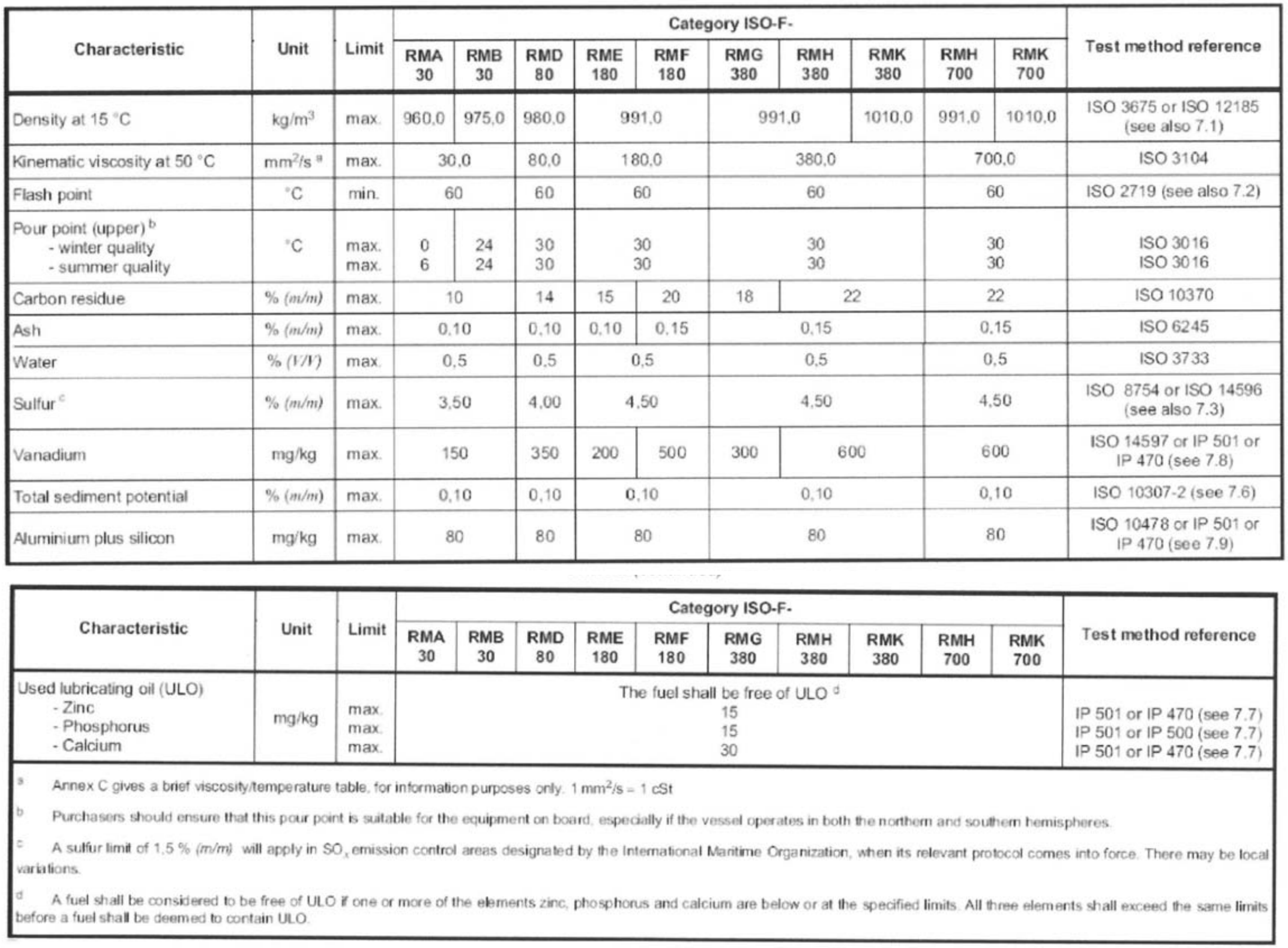
[d] This fuel is suitable for use without heating at ambient temperatures down to – 16 °C.

[e] A sulfur limit of 1,5 % *(m/m)* will apply in SO_x emission control areas designated by the International Maritime Organization, when its relevant protocol enters into force. There may be local variations, for example the EU requires that sulphur content of certain distillate grades be limited to 0,2 % *(m/m)* in certain applications. See 0.3 and reference [7].

[f] If the sample is clear and with no visible sediment or water, the total sediment existent and water tests shall not be required. See 7.4 and 7.5.

[g] A fuel shall be considered to be free of used lubricating oils (ULOs) if one or more of the elements zinc, phosphorus and calcium are below or at the specified limits. All three elements shall exceed the same limits before a fuel shall be deemed to contain ULOs.

Figure 4-2. Requirements for Marine Distillate Fuels



Characteristic	Unit	Limit	Category ISO-F-										Test method reference
			RMA 30	RMB 30	RMD 80	RME 180	RMF 180	RMG 380	RMH 380	RMK 380	RMH 700	RMK 700	
Density at 15 °C	kg/m³	max.	960,0	975,0	980,0	991,0		991,0		1010,0	991,0	1010,0	ISO 3675 or ISO 12185 (see also 7.1)
Kinematic viscosity at 50 °C	mm²/s [a]	max.	30,0		80,0	180,0		380,0			700,0		ISO 3104
Flash point	°C	min.	60		60	60		60			60		ISO 2719 (see also 7.2)
Pour point (upper) [b] - winter quality - summer quality	°C	 max. max.	 0 6	 24 24	 30 30	 30 30		 30 30			 30 30		 ISO 3016 ISO 3016
Carbon residue	% (*m/m*)	max.	10		14	15	20	18	22		22		ISO 10370
Ash	% (*m/m*)	max.	0,10		0,10	0,10	0,15	0,15			0,15		ISO 6245
Water	% (*V/V*)	max.	0,5		0,5	0,5		0,5			0,5		ISO 3733
Sulfur [c]	% (*m/m*)	max.	3,50		4,00	4,50		4,50			4,50		ISO 8754 or ISO 14596 (see also 7.3)
Vanadium	mg/kg	max.	150		350	200	500	300	600		600		ISO 14597 or IP 501 or IP 470 (see 7.8)
Total sediment potential	% (*m/m*)	max.	0,10		0,10	0,10		0,10			0,10		ISO 10307-2 (see 7.6)
Aluminium plus silicon	mg/kg	max.	80		80	80		80			80		ISO 10478 or IP 501 or IP 470 (see 7.9)

Characteristic	Unit	Limit	Category ISO-F-										Test method reference
			RMA 30	RMB 30	RMD 80	RME 180	RMF 180	RMG 380	RMH 380	RMK 380	RMH 700	RMK 700	
Used lubricating oil (ULO) - Zinc - Phosphorus - Calcium	mg/kg	 max. max. max.	The fuel shall be free of ULO [d] 15 15 30										 IP 501 or IP 470 (see 7.7) IP 501 or IP 500 (see 7.7) IP 501 or IP 470 (see 7.7)

[a] Annex C gives a brief viscosity/temperature table, for information purposes only. 1 mm²/s = 1 cSt

[b] Purchasers should ensure that this pour point is suitable for the equipment on board, especially if the vessel operates in both the northern and southern hemispheres.

[c] A sulfur limit of 1,5 % (*m/m*) will apply in SO_x emission control areas designated by the International Maritime Organization, when its relevant protocol comes into force. There may be local variations.

[d] A fuel shall be considered to be free of ULO if one or more of the elements zinc, phosphorus and calcium are below or at the specified limits. All three elements shall exceed the same limits before a fuel shall be deemed to contain ULO.

Figure 4-3. Requirements for Marine Residual Fuels

4.5.6.2 EU SECA Compliance

A decision process was followed to set up the 2012 and 2020 premises related to the EU SECAs (essentially the same process will need to be followed for all other SECAs studied in the future). The WORLD model contains projections of total bunker demand broken down into MGO, MDO, IFO180, and IFO380 for the North Europe region.

The first step in the process was to assess the proportion/volume of each type of bunker fuel that would fall under the SECA standard (Baltic plus North Sea in this instance) within the region. For the two North Europe SECAs, this was estimated at 50%, equivalent to 26 mmtpa total in 2012.[3] Secondly, an assessment was made regarding how much of the affected fuel would be low sulfur (i.e., what part of the SECA fuel requirement would be met by this means, rather than through abatement [or emissions trading]). For 2012, the base premise was that 90% of the bunker fuel would be low sulfur; for 2020, 60%. The underlying rationale was that abatement technology needs time to be proven commercially and to be taken up by the shipping fleets. This will constrain the proportion of SECA requirements that can be met by abatement (or emissions trading) in 2012, but by 2020 its potential expands. These premises can readily be altered and need to be in the future subject cases to examine the refining/supply impacts of growing SECA areas and tightening emissions standards with alternative compliance scenarios.

For California, the proportion of the MGO/MDO in the WORLD model region called USWCCW needing to comply with the California regulation was estimated at 75% (i.e., that California’s economy, trade, and shipping dominates this West Coast region). It was further estimated that, of this, 90% of compliance would be achieved by LSFO in 2012 and 60% in 2020 in the BAU cases. Again, these premises can be revised and also sensitivities studied.

4.5.7 IFO Viscosity/Grade Mix

Many marine engines today can handle IFO with a viscosity higher than 380 centistokes. Raising viscosity to 500 or 700 centistokes slightly reduces the cutter stock content of the bunker fuel. In today’s market, this has led to IFO 380 to IFO500 price differentials on the order of $2 to $4/ton. This, in turn, has created a growing interest in supplies of IFO500 and even IFO700. The trend has been especially marked in Singapore where IFO500 sales have grown rapidly in the last 2 years. To reflect this trend, the maximum viscosity of the “IFO380” bunker grade in the model was raised moderately.

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[3] Robin Meech at the DC MARPOL Consultative Meeting (February 2006) estimated 2012 North Europe SECA bunker fuel at approximately 21 mmtpa but against a base projection understood to be based primarily on IEA statistics. This figure was adjusted to arrive at the 2012 base volume to be used.

The global bunker market is trending toward higher viscosity fuels containing less distillate. Since raising the distillate content of an IFO fuel is one way to lower its sulfur content, the SECA regulations could have the effect of reversing this trend in the affected regions. The model was not set up to allow switching from IFO180/380 to MDO as a means to meet sulfur standards. Such a feature was not considered necessary because the model was set up to allow IFO180/380 viscosities to be lowered, thereby allowing more distillate streams into the IFO blend if found to be economic as the means to reduce sulfur.

4.5.8 Refinery Capacity and Projects

The WORLD model contains a detailed bottom-up database by process unit and refinery worldwide. This is brought up to date as new refinery capacity survey data are published. EnSys has found, however, that extensive cross-checking of and corrections to data presented in sources such as *Oil & Gas Journal* (*OGJ*) are necessary. The BAU cases were run with a capacity database that was based on January 2005 *OGJ* data plus extensive review and revision.

For forward cases, WORLD has four ways of modifying the base capacity:

1. adding known projects to the base.
2. revamping selected existing units is allowed to take place (principally conventional to ultra-low distillate desulfurization).
3. debottlenecking selected major units is allowed, subject to annual limits.
4. entering investments in major new unit capacity.

The projects database used for the BAU cases was based on detailed review of project announcements through the end of 2005. In WORLD, projects are classified at four levels: under construction, under engineering, planned, and announcement. These correspond to descending levels of follow through to completion and also an increasing tendency for project delays versus the initial start-up target date. The model user sets parameters by region that govern both the proportion of each class of project to be completed and the associated delay profile.

Since mid-2005 especially, there have been numerous announcements of new projects, many for major refinery expansions or new grassroots refineries. Nearly 11 mmbpd of refinery crude unit capacity expansion projects are currently listed, with somewhat higher figures according to more recent project reviews. However, based on experience, factors were applied to curtail and delay particularly the “planned” and “announcement” projects in order to arrive at a realistic level of projects likely to go ahead.

The net effect was that the 2012 and 2020 BAU cases contained a total of 6.1 mmbpd of new project capacity as summarized in Table 4-8. (This estimate compares to a figure of around 8 mmbpd by 2015 according to a Wood Mackenzie [2006] review.) The main regions expected to see expansions are the United States and then the Middle East, China, and the rest of Asia (India). The growing list of project announcements in India was particularly discounted. Capacity expansion in Europe is projected to be minimal. While Table 4-8 lists crude unit major capacity additions, the complete project database covers the full suite of refinery processes, including upgrading and desulfurization. In the BAU cases, the model added capacity, using first the low-cost revamp and debottlenecking potential allowed and then balanced on major new unit additions.

Table 4-8. Major Capacity Additions

Based Major Capacity Additions Included in 2012 and 2002 cases

	Mmpbcd
USEC	0.0
USGICE	0.8
USWCCW	0.1
GrtCAR	0.4
SthAm	0.2
AfWest	0.1
AfN-EM	0.1
Af-E-S	0.1
EUR-No	0.0
EUR-So	0.1
EUR-Ea	0.0
CaspRg	0.1
RusFSU	0.0
MEGulf	1.4
PacInd	0.0
PacHi	0.0
China	1.6
RoAsia	1.0
Total	6.1

4.5.9 Refinery Technology and Costs

Based on a review of refinery process technologies centered on desulfurization, adjustments were made to process unit capital costs in the model. Details of the base data researched as part of the technology review are set out in Appendix A. Technologies in the

WORLD model represent those that are proven or recently commercialized. In any long-term study, this approach is conservative because it does not allow for the possible effects of more far-reaching technology advances. An example in this study that could prove to be significant in the future is the development of ultrasound-based desulfurization processes, as in that of Sulphco. That particular technology is nearing commercial scale with the installation of seven 30,000 bpd units in Fujairah. Should the supplier's claims be verified by sustained operation, the outlook for future desulfurization and partial upgrading of residual fuels, crudes, and other streams could be markedly altered relative to the projections made in this study. Other similar developments may also occur. Excluding such processes does have the effect of ensuring that the quantitative modeling results are based on known, feasible, and economic process paths.

The WORLD technology database has been the subject of ongoing review. A further review was made to check the capital and operating costs and yields of units most likely to impact bunker fuel economics, notably residual hydro-desulfurization and visbreaking, as described in Section 4.3.

The process unit capital costs in WORLD originally were based on the year 2000 (U.S. Gulf Coast). The impacts of changes that have occurred since to raise costs of construction were examined. The Nelson Farrar Refinery Construction Inflation Index was found to have risen by a factor of 1.32 between 2000 and February 2006, driven by well-publicized increases in costs for steel, cement, specialty equipment items, and labor. However, applying this multiplier directly to the 2000 basis capital costs in WORLD would have had the effect of stating that the costs of new construction would remain at this elevated level for all new investments through 2020. The large increase in the costs of refining and other oil-sector facilities is reflected in the IEA World Energy Outlook, 2006. IEA estimates that capital costs will "fall back somewhat after 2010" based on conditions in the A&E sector gradually easing.

In WORLD, the decision was made to use a multiplier of 1.30 for capacity additions in the 2012 case and 1.20 for additions in the period from 2012 to 2020 (i.e., in the 2020 case). Similarly, Nelson indices indicate that refinery chemicals' "OVC" type costs have risen by some 60% since 2000. Multipliers of 1.50 and 1.30 were used for the 2012 and 2020 cases, respectively.

WORLD results are sensitive to the interplay between crude (and fuel) costs, refinery capital costs, and freight rates.

- Raising crude oil prices results in more refinery capacity investment, especially in upgrading processes, with the logical effect of reducing the volume of, now high-cost, raw material used to make a given product slate.
- Raising refinery process unit costs has an opposite effect; total dollar investments may rise, but the new capacity bought for the money is less, and the industry responds by using somewhat more crude oil.
- Raising tanker freight rates has the effect of, in turn, justifying additional refinery process investment in order to minimize high-cost interregional movements of crude and products.

Part of the "dilemma" of the EPA analysis was that we have entered into a high-cost world where the traditional levels of and relationships between capital cost, crude and fuel costs, and transport costs are being rewritten. In the BAU cases, higher crude oil price (versus history) was a given, hence also higher refinery fuel and natural gas prices. Both refinery capital costs and tanker freight rates were moved upward relative to history. This resulted in scenarios where all costs—crude, fuel, OVCs, and freight—were elevated versus historical levels.

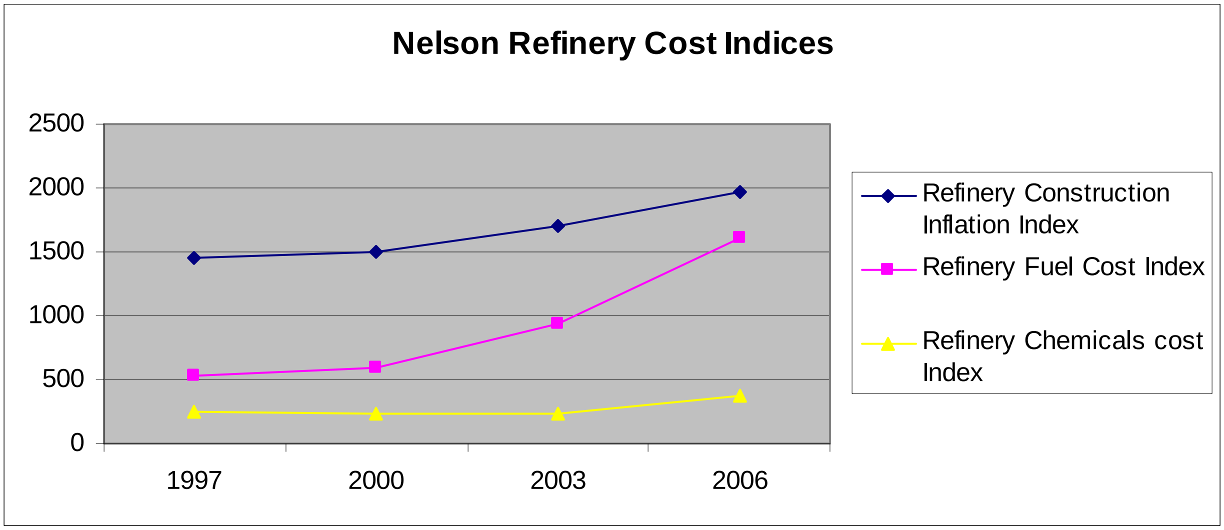


Figure 4-4. Nelson Refinery Cost Indices

4.5.10 Transportation

WORLD contains details of interregional crude, noncrude, finished, and intermediate product movements by tanker, pipeline, and minor modes. Each tanker movement is assigned to one of five tanker size classes, and freight costs are built up based on the WorldScale flat rate times the percentage of WorldScale plus ancillary costs such as canal dues and lightering, where applicable, as well as duties. Reflecting the factors reviewed above, WorldScale percentage rates were applied (see Table 4-9) that were higher than recent freight rate history. Again these reflect

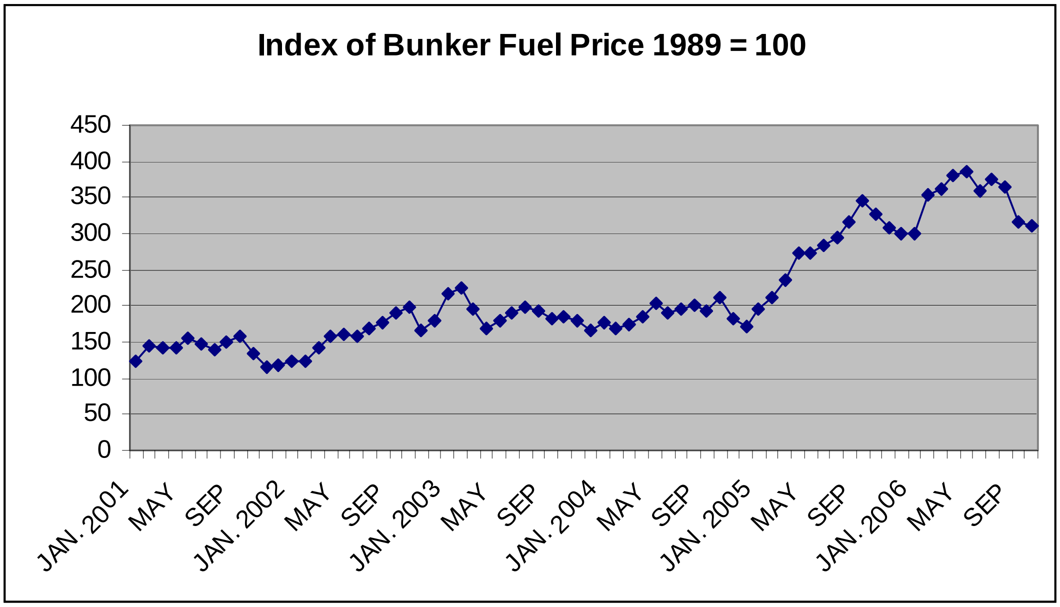
Table 4-9. Tanker Class

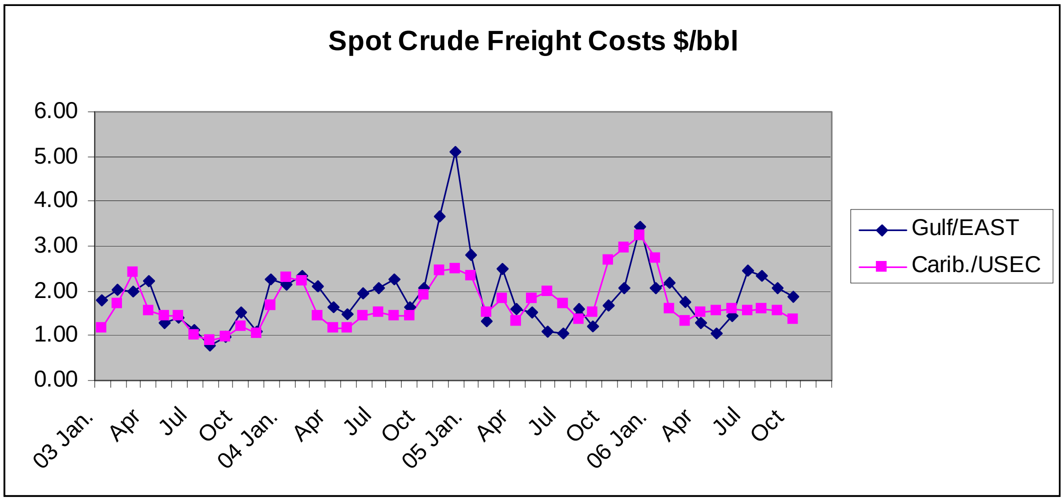
Tanker Class	Size DWT	Percent WS 2012/2020
MR@	40,000	260
Pana Max	55,000	220
AFRA max	70,000	180
Suez Max	135,000	130
VLCC	270,000	90

increases in steel/construction and fuel costs plus the fact that (a) there is current tightness in capacity in shipbuilding yards; (b) there is an ongoing requirement to turn over world fleets to new vessels, in part because of double hull regulations; and (c) there is a need to expand the world's tanker fleets to meet growing trade requirements.

In general, high steel prices directly impact the cost of a tanker and, thus, may place a damper on orders for new ships. High steel prices also indicate a potential "tight" supply of steel that can also place a constraint on shipyard contracting practices (i.e., higher prices or flexible pricing requirements). High steel prices also increase the price paid for scrap tankers, potentially inducing tanker owners to hasten scrapping. In general, the supply of tankers looks to be constrained in the next few years by shipyard construction capacity. Tankers are competing for new construction space (berths) with LNG, container, and dry bulk ships. Usually only one sector is doing well financially, which increases pressure for new building in the strong sector. At this time, all sectors (LNG, container, and dry bulk ships) are doing very well. This has led to difficulty for tanker owners to secure new building contracts. This all leads to higher prices for new buildings.

In WORLD, freight rates are arrived at by multiplying the percentage of WorldScale by the WorldScale 100 flat rate. (Other cost items such as canal tariffs or lightering are also added in where relevant.) One issue is that the WorldScale Association issues updated flat rates each January. These reflect cost changes, including for fuel (i.e., the underlying flat rates are not constant over time). To best assess how to represent future freight rate levels in the model, recent freight rate history was examined. Figure 4-5 shows that, although bunker fuel costs have risen





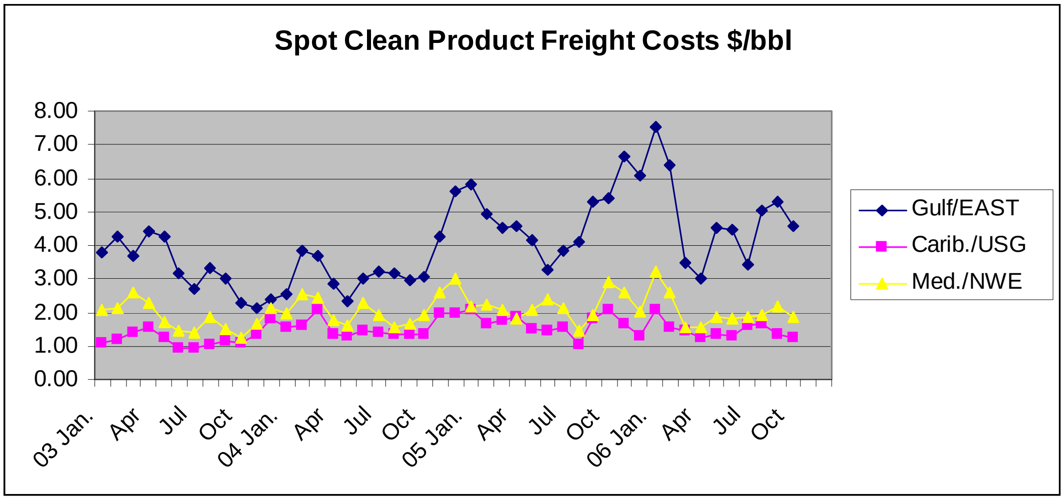


Figure 4-5. **Spot Market Costs**

substantially since 2002–2003 and the other factors described above have been at play, most freight rates (stated as $/bbl) have increased only slightly.

In addition, we noted that, in the planned Phase II SECA etc. cases, tightening of bunker fuel regulations and/or shifts from IFO to marine diesel will inevitably increase bunker fuel costs and consequently freight rates (i.e., in those cases, freight rates will need to be adjusted upward, potentially regionally). EnSys intends to employ an in-house tanker cost model to assess the appropriate increases for those cases.

As a component of recent assignments, care has been taken in WORLD to build in accurate representations of major new, expanded, and existing pipelines. Particular emphasis has been put on ensuring an accurate profile of pipelines and expansions for export routes for crudes (including syncrudes) from Canada and export routes both east and west from Russia and the Caspian. For Canada, the BAU premise was that one, but not both, of the export lines to the West Coast/PADD V/Pacific would go ahead. This impacts the amount of syncrude and conventional crudes routed into the U.S. PADDs II, IV, and potentially III versus west to PADD V and Asian regions. For Russia, based on recent developments, the BAU case assumed the pipeline to the Pacific would go ahead and would have a spur into China. In reality, this latter will most likely partially displace growing rail movements of crude into China from Russia that were already in the model.

4.6 Input Prices for the WORLD Model

4.6.1 Marker Crude Price

WORLD operates with a single marker crude price, and all other crudes and nearly all noncrude supplies and product demand is fixed. Crude and product prices are thus generally produced as model outputs. For the BAU cases, the model was run with Saudi Light as the marker crude. This crude price was taken from the AEO 2006, but since EIA uses a U.S. average acquisition price as its “world oil price,” the EIA price was adjusted to obtain a corresponding Saudi Light price using recent historical crude price data.

4.6.2 Natural Gas Price

Certain other prices are also inputs in the model. The most important among these is natural gas prices as natural gas is the balancing refinery fuel supply in most regions, as well as a primary feedstock for hydrogen production. Regional natural gas prices (major industrial user) were set in the range of $4 to $6 per MMBTU—in line with AEO 2006 and third-party long-term projections.

4.6.3 Miscellaneous Prices

Input prices for the by-products—coke low sulfur, coke high sulfur, and elemental sulfur—were set respectively at $25, $5, and $10 per ton. Purchased electricity prices were taken for the U.S. regions from AEO 2006 and were generally in the range of 6 cents per kWh.

4.7 Reporting

The WORLD model's standard reports were modified to accommodate the revised distillate and residual fuels products structure. Standard reports provide global and regional information on

- refinery throughputs, capacity additions, investments;
- interregional crude, intermediate and product movements;
- supply/demand balance;
- crude FOB and CIF prices; and
- regional product prices.

As discussed in Section 4.4, blend reports were added for the residual grades, in part as a check to ensure avoidance of potentially unstable blends.

SECTION 5
THE WORLD MODEL'S BAU PROJECTIONS FOR 2012 AND 2020

This section presents results for the 2012 and 2020 WORLD model cases, based on the projections and premises reviewed in Section 4. Business as usual (BAU) projections were estimated for these 2 years using both the IEA and the RTI bunker demand assumptions.

Adopting the RTI fuel demand forecasts leads to a 2020 global demand for residual bunker fuels of 6.87 mmbpd versus 1.92 mmbpd based on IEA forecasts. RTI's larger estimate is partially offset by a reduction in inland residual fuel from 6.5 to 5.2 mmbpd. RTI's 2020 forecasts for MGO and MDO are equivalent to 1.9 mmbpd versus 0.6 mmbpd based on IEA forecasts. Thus, RTI's forecasts imply that estimated impacts of SECAs or other marine fuels regulations will be greater than those projected by IEA forecasts.

The second major driver in the WORLD analyses discussed in this section is the ongoing shift toward distillates, especially in Europe and non-OECD regions. This shift is expected to materially alter gasoline and distillate trade patterns, pricing, and refining investments. These developments will also affect impacts of SECAs and global marine fuels regulations.

5.1 Supply–Demand Balance

Tables 5-1 and 5-2 summarize the supply and demand inputs and model run results from the 2012 and 2020 WORLD BAU cases for both the RTI and the IEA forecasts. As discussed in Section 4, the IEA base case was matched to the AEO 2006. A second case was run with RTI's forecast, which increases bunker and total residual demand globally. The needed incremental supply was taken to be OPEC crude. WORLD results generally do not match exactly the underlying forecast numbers for total oil supply and demand. This is because several demand factors, including internal refinery fuel, coke, and sulfur by-products, are dynamic within WORLD and not fixed.

The 2012 and 2020 cases reflect the overall global trend for (a) an increase in demand to be predominantly light, clean products and (b) growth globally to be concentrated in distillates, particularly as diesel consumption in Europe increases and the demand growth for gasoline there subsides.

The main effect of applying the RTI bunker projections is to raise total residual demand by 1 mmbpd by 2012 and over 1.8 mmbpd by 2020. Increasing demand also entails a switching

Table 5-1. WORLD Model Case Results—Supply

Bunker Basis	**2012 IEA**	**2012 RTI**	**2020 IEA**	**2020 RTI**
Supply—Crudes (includes syncrudes and condensates)	MMBPD	MMBPD	MMBPD	MMBPD
Crude gross production	**79.637**	**80.352**	**86.667**	**88.160**
of which				
Crude direct use	0.832	0.832	0.832	0.832
Crude direct loss total	0.638	0.638	0.638	0.638
Crude net to refineries before TRLOS	78.167	78.882	85.197	86.690
Crudes net to refineries	After TRLOS	After TRLOS	After TRLOS	After TRLOS
GSY—syn crude (fully upgraded)	1.164	1.164	1.555	1.555
GCO—condensate	1.922	1.922	2.062	2.062
GSW—sweet <0.5%S	26.257	26.473	29.432	29.771
GLR—LT ST>35 API>0.5%S	11.022	11.214	10.806	11.122
GMR—MD SR 36-29 API > .5S	25.813	26.055	28.140	28.871
GHR—HVY SR 20-29 API>.5S	9.067	9.131	9.529	9.633
GXR—XHVY SR <20 API>.5S	2.149	2.149	2.882	2.882
Crude supply to refineries	77.395	78.108	84.405	85.896
Crude direct loss in refineries	0.638	0.638	0.638	0.638
Crude TRLOS	0.135	0.136	0.154	0.156
Crude net, to refs before TRLOS	**78.167**	**78.882**	**85.197**	**86.690**
Supply—Noncrudes				
NGL ethane	1.597	1.597	1.797	1.797
NGLs C3+	5.587	5.587	6.387	6.387
Petchem returns	0.709	0.709	0.789	0.789
Biomass	1.527	1.527	1.866	1.866
Methanol (EX NGS)	0.130	0.128	0.146	0.146
GTL liquids (EX NGS)	0.796	0.796	1.248	1.248
CTL liquids (EX COAL)	0.488	0.488	0.891	0.891
Hydrogen (EX NGS)	0.981	0.940	1.307	1.205
Total	11.815	11.771	14.431	14.328
Process Gain	**2.223**	**2.151**	**2.602**	**2.509**

Table 5-2. WORLD Model Case Results—Demand

Bunker Basis	2012 IEA	2012 RTI	2020 IEA	2020 RTI
External Demands—Finished Products Nonsolid				
Ethane	1.597	1.597	1.797	1.797
LPG	7.856	7.856	8.632	8.632
Naphtha	5.850	5.850	6.930	6.930
Gasoline	23.535	23.535	25.426	25.426
Jet/kero	7.459	7.459	8.139	8.139
Distillate	27.255	27.128	31.459	31.298
Residual fuel	10.082	11.088	10.235	12.060
Other products (excl coke, sulphur)	3.532	3.532	3.808	3.808
Crude direct use	0.832	0.832	0.832	0.832
Petr coke low sulphur MMBPD	0.416	0.442	0.352	0.405
Petr coke high sulphur MMBPD	0.527	0.240	0.906	0.510
Petr coke LS as % of total	44%	65%	28%	44%
Petr coke total MMBPD	0.943	0.681	1.259	0.914
Elemental sulphur MMBPD	0.215	0.193	0.261	0.229
Total	**1.158**	**0.874**	**1.520**	**1.143**
Internal Demands/Consumption				
Refinery fuel—crude-based streams				
Process gas	2.458	2.415	2.574	2.477
FCC catalyst coke	0.377	0.388	0.379	0.383
Minor streams	0.000	0.000	0.000	0.000
Residual fuel	1.291	1.291	1.682	1.682
Natural gas to RFO	1.641	1.614	1.813	1.849
Total incl natural gas	5.766	5.708	6.448	6.391
RFO incl NGS as pct of crude to refs	7.5%	7.3%	7.6%	7.4%
RFO excl NGS as pct of crude to refs	5.3%	5.2%	5.5%	5.3%
Merch FO—internal streams	0.005	0.005	0.007	0.007
Total internal consumption and loss excl nat gas	**4.130**	**4.099**	**4.641**	**4.548**
Transport/distribution losses				
Transport loss total	**0.189**	**0.190**	**0.215**	**0.219**
Allocation to crude	0.135	0.136	0.154	0.156
Allocation to products and intermediates	0.054	0.054	0.061	0.063
Supply—Total	**WORLD**	**WORLD**	**WORLD**	**WORLD**
Crude—gross production incl condensates and syn crudes	79.637	80.352	86.667	88.160
Noncrudes incl H2 ex NGS	11.815	11.771	14.431	14.328
Process gain	2.223	2.151	2.602	2.509

(continued)

Table 5-2. WORLD Model Case Results—Demand (continued)

Bunker Basis	2012 IEA	2012 RTI	2020 IEA	2020 RTI
Total Supply	**93.675**	**94.275**	**103.699**	**104.998**
Crude as percentage of total supply	85%	85%	84%	84%
Demand—Total				
External—gases and liquid products (incl crude direct use but not loss)	87.998	88.877	97.258	98.922
External—solid products	1.158	0.874	1.520	1.143
Internal—fuel excl natural gas incl FCC cat coke	4.130	4.099	4.641	4.548
Internal—process and crude losses	0.000	0.000	0.000	0.000
Internal—transport/distribution losses	0.189	0.190	0.215	0.219
Total Demand	**93.475**	**94.040**	**103.634**	**104.832**
Total demand—total supply	(0.21%)	(0.25%)	(0.06%)	(0.16%)
Total demand—total supply	(0.200)	(0.234)	(0.065)	(0.166)

between inland and bunker residual fuel grades. In the IEA-basis BAU cases, global inland residual fuel quality was projected to progress partially toward a 1% standard by 2020. The RTI-basis BAU cases increase total residual fuel demand, but, because the only active SECAs are in Northern Europe in the cases, they shift global residual fuel toward higher average sulfur.

The change in overall global demand between the IEA and RTI cases is 0.6 mmbpd for 2012 and 1.3 mmbpd for 2020. The increase in residual demand is met by an increase in OPEC crude runs. The incremental crude supply contains both light and heavy cuts..

5.2 Refining Capacity Additions

Table 5-3 and Table 5-4 summarize the refinery capacity additions, investments, and utilizations for each case. Again, a major effect of the RTI basis is to ease the requirement for residual fuel upgrading and desulfurization. As a consequence, less refining investment is needed by 2020 under the RTI basis ($107.7 billion) than under the IEA basis ($117.6).[1] The effect is to

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[1] The capital investments detailed in current WORLD reports are generally lower than those projected by the IEA, for example, for the same time frame. There are three reasons for this. First, the WORLD costs are currently reported in 2001 dollars. This will be changed in the future. Second, the stated WORLD investments generally need to be increased to allow for extra capacity to cover seasonal variations (e.g., summer gasoline peak). Third, the WORLD reports do not include an allowance for ongoing capital replacement. This is typically estimated at 1.5% to 3% per annum of the total installed capital base (which, of course, grows over time). It is EnSys' intent to expand the WORLD reports in the future to make the basis consistent with IEA and others.

Table 5-3. Capacity Additions and Investment

Bunker Basis	2012 IEA	2012 RTI	2020 IEA	2020 RTI
Capacity Additions and Investments—Over and Above 2005 Base + Known Construction				
Refinery		**$ billion ($2001)**		
Revamp	$5.4	$5.3	$6.4	$6.1
Debottlenecking	$0.5	$0.5	$1.4	$1.2
Major new units	$58.2	$54.9	$109.8	$100.4
Total refining	$64.1	$60.7	$117.6	$107.7
Merchant				
Major new units	$0.3	$0.3	$0.9	$0.9
Total refining + merchant	$64.4	$61.1	$118.5	$108.6
Crude Distillation Base Capacity and Additions		**mmbpcd**		
Base capacity	83.74	83.74	83.74	83.74
Firm construction	5.82	5.82	6.08	6.08
Debottlenecking additions	0.92	1.01	1.80	1.90
Major new unit additions	2.07	2.66	7.87	9.04
Total additions over base	8.80	9.49	15.74	17.01
	83.6%	83.8%	84.9%	85.3%
Total crude unit capacity used	77.39	78.11	84.41	85.90
Secondary Processing Capacity Additions—Debottlenecking + Major Units				
Coking + visbreaking	0.10	0.13	0.25	0.15
Catalytic cracking	0.10	0.16	0.39	0.25
Hydro-cracking	0.70	0.48	3.48	2.85
Catalytic reforming—incl revamp	1.16	1.10	2.02	2.03
Catalytic reforming	0.54	0.53	0.92	1.01
Desulphurization (total)	7.16	6.91	11.18	10.12
Gasoline—ULS	1.81	1.72	2.70	2.62
Distillate ULS—incl revamp	4.93	4.79	7.02	6.68
Distillate ULS—revamp only	4.25	4.22	6.25	6.02
Distillate conv/LS	0.16	0.17	0.44	0.41
VGO/resid	0.26	0.23	1.01	0.41
Hydrogen (MMBFOED)	0.52	0.48	0.87	0.75
Sulphur plant (TPD)	6,350	5,400	14,400	9,230
MTBE to iso-octane (revamping USA)	0.08	0.08	0.08	0.08

Table 5-4. Refinery Capacity Additions

REFINERY CAPACITY ADDITIONS (VS 2005 + CONSTRUCTION), THROUGHPUTS & UTILISATIONS											2012:BASE (RTI Bunkers)								
		1	3	5	7	9	B	D	F	H	J	L	N	P	R	T	V	X	Z
Category		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
CRUDE DISTILLATION BASE CAPACITY & ADDITIONS																			
BASE CAPACITY	**83.74**	**1.75**	**13.51**	**3.62**	**5.28**	**3.07**	**0.73**	**2.30**	**0.78**	**8.97**	**5.69**	**1.83**	**1.40**	**7.22**	**5.88**	**5.56**	**7.40**	**6.04**	**2.70**
FIRM CONSTRUCTION	5.82	0.00	**0.79**	**0.10**	**0.36**	**0.17**	**0.11**	**0.10**	**0.12**	0.00	**0.05**	**0.03**	**0.14**	**0.02**	**1.33**	0.00	0.00	**1.57**	**0.93**
DEBOTTLENECKING ADDITIONS	1.01	**0.10**	**0.44**	**0.06**		**0.04**		**0.03**	**0.01**			**0.02**			**0.05**	**0.11**	**0.08**	**0.06**	**0.03**
MAJOR NEW UNIT ADDITIONS	2.66					**0.20**			**0.08**					**0.35**	**0.33**			**1.63**	**0.07**
TOTAL ADDITIONS OVER BASE	**9.49**	**0.10**	**1.23**	**0.16**	**0.36**	**0.41**	**0.11**	**0.13**	**0.21**	0.00	**0.05**	**0.05**	**0.14**	**0.37**	**1.71**	**0.11**	**0.08**	**3.26**	**1.03**
TOTAL BASE + ADDITIONS 2012	**93.23**	**1.85**	**14.74**	**3.78**	**5.64**	**3.48**	**0.84**	**2.42**	**0.99**	**8.97**	**5.74**	**1.88**	**1.54**	**7.58**	**7.59**	**5.67**	**7.48**	**9.30**	**3.73**
TOTAL CRUDE CAP USED 2012	**78.11**	**1.79**	**11.91**	**3.70**	**4.60**	**3.11**	**0.66**	**2.10**	**0.84**	**6.82**	**4.48**	**1.63**	**0.75**	**6.03**	**6.80**	**5.07**	**6.62**	**8.04**	**3.15**
Refinery Utilisation	**83.8%**	**96.5%**	**80.8%**	**97.9%**	**81.5%**	**89.5%**	**79.5%**	**86.5%**	**84.5%**	**76.1%**	**78.2%**	**86.5%**	**48.8%**	**79.5%**	**89.5%**	**89.5%**	**88.5%**	**86.5%**	**84.5%**

											2020:BASE (RTI Bunkers)								
		1	3	5	7	9	B	D	F	H	J	L	N	P	R	T	V	X	Z
Category		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
CRUDE DISTILLATION BASE CAPACITY & ADDITIONS																			
BASE CAPACITY	**83.74**	**1.75**	**13.51**	**3.62**	**5.28**	**3.07**	**0.73**	**2.30**	**0.78**	**8.97**	**5.69**	**1.83**	**1.40**	**7.22**	**5.88**	**5.56**	**7.40**	**6.04**	**2.70**
FIRM CONSTRUCTION	6.08	0.00	**0.85**	**0.10**	**0.36**	**0.18**	**0.15**	**0.11**	**0.12**	0.00	**0.05**	**0.03**	**0.14**	**0.02**	**1.44**	0.00	0.00	**1.57**	**0.97**
DEBOTTLENECKING ADDITIONS	1.90	**0.22**	**0.88**	**0.11**		**0.08**		**0.06**	**0.02**			**0.07**			**0.11**		**0.17**	**0.12**	**0.06**
MAJOR NEW UNIT ADDITIONS	9.04					**1.01**	**0.41**	**0.22**	**0.25**			**0.00**		**1.13**	**0.49**		**0.64**	**4.22**	**0.67**
TOTAL ADDITIONS OVER BASE	**17.01**	**0.22**	**1.73**	**0.21**	**0.36**	**1.26**	**0.56**	**0.38**	**0.39**	0.00	**0.05**	**0.11**	**0.14**	**1.14**	**2.05**	0.00	**0.82**	**5.91**	**1.69**
TOTAL BASE + ADDITIONS 2020	**100.75**	**1.97**	**15.23**	**3.84**	**5.64**	**4.33**	**1.28**	**2.68**	**1.17**	**8.97**	**5.74**	**1.94**	**1.54**	**8.36**	**7.93**	**5.56**	**8.22**	**11.95**	**4.40**
TOTAL CRUDE CAP USED 2020	**85.90**	**1.90**	**13.32**	**3.67**	**5.05**	**3.88**	**1.02**	**2.31**	**0.99**	**6.58**	**4.85**	**1.68**	**0.81**	**6.65**	**7.10**	**4.77**	**7.27**	**10.34**	**3.72**
Refinery Utilisation	**85.3%**	**96.5%**	**87.4%**	**95.8%**	**89.5%**	**89.5%**	**79.5%**	**86.5%**	**84.5%**	**73.3%**	**84.5%**	**86.5%**	**52.5%**	**79.5%**	**89.5%**	**85.8%**	**88.5%**	**86.5%**	**84.5%**

reduce the required capacity additions for coking/visbreaking, catalytic cracking, and especially hydrocracking facilities. Vacuum gas oil/residual desulfurization requirements drop under the RTI basis because demand for low-sulfur inland residual fuel is less. Similarly, the increase in proportion of the total distillate pool occupied by bunker products moderately lowers the proportions of ultra low-sulfur diesel in the distillate pool and thereby reduces the total requirement for distillate desulfurization slightly.

The WORLD model projects that refinery utilization rates will continue to rise globally through 2020. This stems in part from an assumption that levels in current low-utilization regions (notably Russia/FSU, Caspian, Africa) will gradually improve. Appreciable capacity growth is projected for North America, South America, Africa, and Russia as driven by AEO projections of regional demand growth. The most significant refinery capacity growth areas are projected to be the Middle East and Asia, led by China, which is projected to double its capacity by 2020. Conversely, essentially no crude capacity growth is projected for Western Europe and only a modest increase for Eastern Europe.

5.3 Refining Economics and Prices

Tables 5-5 and 5-6 summarize key price results from the 2012 and 2020 cases. In reviewing these results, it should be noted that the WORLD model was run for 2012 and 2020 in “long-run” mode. In other words, opportunities for investment were kept open, and price results equate to long-run equilibrium prices, not short-run ones under which investment opportunities are not permitted. Long-run equilibrium prices are more stable than short-run prices because they incorporate an assumed long-run return on capital. Short-run prices can be relatively higher or lower, depending on whether refining capacity is tight as it is currently or slack.

A central feature of these and other recent EnSys WORLD cases is that the global higher growth rates for distillates relative to gasoline, driven by Europe’s dieselization policy and distillate-oriented demand growth in many non-OECD regions, lead to a situation where future distillate prices are projected to exceed those for gasoline. Projected ultra low-sulfur diesel to ultra low-sulfur gasoline premiums lie in the range of $3/bbl USGC by 2012 and 2020, and up to $7 to $9/bbl in Asia and especially Europe.

Table 5-6 summarizes (long-run) price differentials as output from the WORLD cases. For ultra low-sulfur diesel versus high-sulfur IFO380, differentials average $14/bbl. Light-heavy product price differentials (gasoline and diesel to IFO380) narrow by around $1/bbl USGC and

Table 5-5. Product Prices

Bunker Basis	2012 IEA	2012 RTI	2020 IEA	2020 RTI
Crude Prices Selected Major Crudes (FOB)				
Saudi Arabian light (33.4, 1.8) input—marker crude price	$44.10	$44.10	$45.50	$45.50
WORLD Output Prices				
Texas West Intermediate (40.1, 0.4)	$47.68	$47.61	$49.30	$49.07
Texas West Sour (34, 1.9)	$46.67	$46.71	$47.92	$48.07
GOM Deep Sour (35, 1.3)	$46.90	$46.92	$48.34	$48.31
UK North Sea Brent (36.9, 0.3)	$45.54	$45.46	$47.07	$46.84
Nigerian Bonny/Light (38.3, 0.14)	$46.32	$46.17	$48.06	$47.66
Nigerian Medium (25, 0.28)	$46.16	$45.90	$47.40	$47.27
Russia Urals (32.5, 1.56)	$44.49	$44.63	$45.95	$45.97
UAE Dubai (32.6, 1.96)	$43.50	$43.58	$44.74	$44.85
Iraq Basrah (33.9, 2.08)	$42.04	$42.35	$43.25	$43.66
Saudi Arabian Heavy (28.2, 2.84)	$41.51	$41.94	$42.53	$43.12
Alaskan North Slope (30, 1.05)	$43.72	$43.73	$45.29	$45.60
California SJV Heavy (14.1, 1.06)	$42.54	$42.75	$44.05	$44.99
Mexican Isthmus (32.8, 1.51)	$45.94	$45.94	$47.22	$47.34
Mexican Maya (22, 3.3)	$40.71	$40.79	$41.52	$41.99
Venez Heavy (Bach Light) (17.4, 2.8)	$41.42	$41.45	$42.42	$42.78
Canadian Light (42.5, 0.3)	$46.13	$46.03	$46.88	$46.64
Canadian Heavy (25, 2.8)	$38.65	$38.74	$39.33	$39.85
Canadian Syncrude (33.5, 0.05)	$47.44	$47.36	$49.25	$48.94
Product Prices **WORLD Output Prices**				
USGC				
LPG	$45.20	$45.08	$46.46	$46.63
Petchem naphtha	$40.31	$40.45	$41.51	$41.31
CG—ULS Premium	$54.81	$54.96	$56.16	$55.90
CG—ULS Regular	$51.10	$51.18	$52.77	$52.45
RFG—Premium (0/5.7/10% ETOH)	$52.33	$52.40	$53.38	$53.10
RFG—Regular (0/5.7/10% ETOH)	$48.36	$48.33	$49.71	$49.35
Kero/jet JTA/A1	$52.78	$52.59	$54.75	$54.49
DSL NO2 ULSD (50–10 ppm)	$55.08	$54.73	$56.96	$56.67

(continued)

Table 5-5. Product Prices (continued)

Bunker Basis	2012 IEA	2012 RTI	2020 IEA	2020 RTI
MGO NO2 HSD (5,000–15,000 ppm)	N/A	$50.33	N/A	$51.91
MOD NO4 HSD (5,000–20,000 ppm)	$47.28	$48.08	$48.65	$49.78
Resid <.3%	$49.61	$49.34	$50.18	$50.63
Resid .3–1.0%	$44.60	$44.51	$44.48	$45.52
IFO180 HS	$42.49	$42.38	$43.37	$44.01
IFO380 HS	$41.56	$41.49	$42.31	$43.01
Petchem gas oil	$51.00	$51.12	$52.69	$52.74
Aromatics	$55.73	$55.84	$57.39	$56.77
Lubes and waxes	$66.97	$67.15	$71.22	$71.09
Asphalt	$34.99	$35.13	$35.00	$36.13
Northwest Europe				
LPG	$46.52	$46.40	$47.81	$47.98
Petchem Naphtha	$40.53	$40.51	$41.96	$41.62
RFG—Premium (EURO III/IV/V)	$51.74	$51.82	$53.11	$52.80
RFG—Regular (EURO III/IV/V)	$48.31	$48.33	$49.37	$49.03
Kero/Jet JTA/A1	$54.09	$53.94	$56.24	$56.02
DSL NO2 RFD	$57.32	$57.02	$58.96	$58.73
MGO NO2	$50.50	$50.43	$52.75	$52.55
MOD NO4 HSD (5,000–20,000 ppm)	$46.00	$46.81	$48.05	$48.95
MOD NO4 LSD (10–1,500ppm)	$46.50	$47.44	$48.87	$49.22
Resid <.3%	$48.34	$47.60	$49.29	$49.10
Resid .3–1.0%	$43.61	$43.33	$45.24	$44.98
IFO180 LS	$43.73	$44.52	$45.50	$46.19
IFO180 HS	$43.43	$44.36	$43.97	$44.80
IFO380 LS	$42.85	$43.50	$44.55	$45.15
IFO380 HS	$42.27	$43.30	$42.63	$44.65
Aromatics	$54.16	$54.32	$55.97	$55.07
Lubes and Waxes	$70.55	$70.53	$73.33	$73.21
Asphalt	$37.41	$37.88	$36.92	$38.52

(continued)

Table 5-5. Product Prices (continued)

Bunker Basis	2012 IEA	2012 RTI	2020 IEA	2020 RTI
Pacific (Singapore)				
LPG	$48.80	$48.69	$50.10	$50.27
Petchem naphtha	$41.19	$41.18	$43.13	$42.69
RFG—Premium (EURO III/IV/V)	$52.37	$52.44	$54.97	$54.59
RFG—Regular (EURO III/IV/V)	$49.53	$49.57	$51.89	$51.46
Kero/jet JTA/A1	$54.56	$53.94	$57.19	$56.49
DSL NO2 RFD	$56.00	$55.27	$58.56	$57.92
DSL NO2 LSD (500 ppm)	$55.10	$54.47	$57.77	$57.10
DSL NO2 MSD (1,000–5,000 ppm)	$54.15	$53.47	$56.78	$56.01
DSL NO2 HSD (5,000–10,000 ppm)	$53.67	$53.05	$56.16	$55.34
MGO NO2 HSD (5,000–15,000 ppm)	$53.13	$52.61	$55.46	$54.59
MOD NO4 HSD (5,000–20,000 ppm)	$45.66	$46.89	$47.19	$47.91
Resid <.3%	$48.08	$48.37	$50.13	$50.08
Resid .3–1.0%	$45.35	$45.80	$46.80	$47.13
Reside 1.0–3.0%	$43.88	$44.46	$44.50	$45.28
IFO180 HS	$42.66	$43.67	$43.96	$45.19
IFO380 HS	$41.34	$42.55	$42.50	$43.95
Aromatics	$51.68	$51.85	$53.48	$52.59
Lubes and waxes	$65.77	$66.28	$70.12	$69.99
Asphalt	$35.56	$37.73	$34.99	$38.12

$2/bbl Europe and Asia for 2020. The effect is less marked in 2012 because the impact on residual fuel demand volumes is smaller. In the BAU cases, only the Northern European SECAs were included. Thus, it is the Northwest Europe prices that provide the best insight into the pricing of high- versus low-sulfur marine fuels. For IFO180 and IFO380 (nominal sulfur limits of 4.5% for high sulfur and 1.5% for low sulfur, respectively), the indicated price differential is around $1/bbl. For low- versus high-sulfur MDO, it is lower. The price differentials appear to be reasonable as a starting point for examining the effects of wider SECA designations and/or a further tightening of marine fuels standards regionally and/or globally. Such developments, which would be the subject of follow-up WORLD cases, will raise price differentials versus those seen here with the degree of change dependent on specific scenarios for sulfur specifications and for the compliance methods used by shippers.

Table 5-6. Product Price Differentials

Bunker Basis	2012 IEA	2012 RTI	2020 IEA	2020 RTI
Product Price Differentials **WORLD Output Prices**				
USGC				
CG ULS REG—IFO380 HS	$9.54	$9.69	$10.46	$9.44
DSL ULSD—IFO380 HS	$13.53	$13.24	$14.65	$13.66
MDO HS—IFO380 HS	$5.72	$6.59	$6.34	$6.77
RESID 1% S—IFO380 HS	$3.04	$3.02	$2.17	$2.52
IFO180 HS—IFO380 HS	$0.93	$0.89	$1.06	$1.01
CG ULS REG—DSL ULSD	−$3.98	−$3.55	−$4.19	−$4.22
DSL ULSD—MDO HS	$7.80	$6.65	$8.30	$6.89
Northwest Europe				
RFG REG (EURO)—IFO380 HS	$6.04	$5.03	$6.74	$4.38
DSL ULSD (EURO)—IFO380 HS	$15.05	$13.72	$16.33	$14.08
MDO HS—IFO380 HS	$3.74	$3.51	$5.42	$4.30
RESID 1% S—IFO 380 HS	$1.34	$0.04	$2.61	$0.33
RESID 1% S—IFO180 HS	−$0.13	−$1.18	−$0.26	−$1.21
IFO180 LS—IFO380 LS	$0.89	$1.01	$0.95	$1.04
IFO180 HS—IFO380 HS	$1.16	$1.06	$1.34	$0.15
RFG REG (EURO)—DSL ULSD (EURO)	−$9.01	−$8.69	−$9.59	−$9.70
DSL ULSD (EURO)—MGO	$6.82	$6.59	$6.21	$6.18
DSL ULSD (EURO)—MDO HS	$11.32	$10.21	$10.91	$9.78
MDO LS—MDO HS	$0.50	$0.63	$0.82	$0.26
Pacific (Singapore)				
RFG REG (EURO)—IFO380 HS	$8.19	$7.02	$9.40	$7.51
DSL ULSD (EURO)—IFO380 HS	$14.66	$12.72	$16.06	$13.97
MDO HS—IFO380 HS	$4.32	$4.34	$4.69	$3.96
RESID 1% S—IFO 380 HS	$4.01	$3.25	$4.30	$3.18
IFO180 HS—IFO380 HS	$1.32	$1.12	$1.47	$1.23
CG ULS REG—DSL ULSD	−$6.47	−$5.70	−$6.66	−$6.46
DSL ULSD—MDO HS	$10.34	$8.38	$11.37	$10.01

5.4 Crude and Product Trade

Figures 5-1 through 5-6 summarize interregional trade movements from WORLD for the 2012 and 2020 RTI basis cases. Major trends and highlights on crude trade include the following:

- Growing production from West and North Africa (totaling nearly 12 mmbpd by 2020) offsets some of the decline in North Sea production. Significant volumes move into the US PADDs I, II, and III as well as into Eastern Canada.
- West African crudes are widely distributed, including to the Caribbean/South America, Europe, Asia/Pacific, and even the U.S. West Coast.
- Considerable uncertainty continues to exist over future Russian crude production volumes and export routes. The 2012 and 2020 cases were run with export options open with the result that Russian crudes continue to move in substantial volumes into Western and Eastern Europe but otherwise move predominantly into Asia/Pacific. No Russian crude is projected to be exported to the United States, although this could change if northerly routes via Murmansk and the Baltic are expanded. Russian crude production was projected at below 11 mmbpd for 2020 with domestic demand growing to 6.5 mmbpd. This, in turn, reduces the volume of crude available for export.
- Middle Eastern crudes are projected to be refined increasingly within the region as the region’s export refining capacity grows and demand in Asia/Pacific grows. Continuance of movements into Europe and the United States depends on the level of competition with other suppliers and on discounting policy by Saudi ARAMCO and other Middle East Gulf producers.
- The 2012 and 2020 cases are exhibiting a new phenomenon that bears further investigation, relating ultimately to the level of Canadian crude production. The AEO 2006 has a high level of Canadian production: 4.5 mmbpd in 2020. Even with western outlets to the Pacific and the U.S./Canada West Coast expanded to a projected 0.8 mmbpd, the high production volume moves predominantly into the U.S. interior (PADDs II, IV, and potentially some to PADD III). This has the effect of reallocating Caribbean crude to Europe and reallocating Middle Eastern crude to Asia/Pacific, the highest demand growth area.

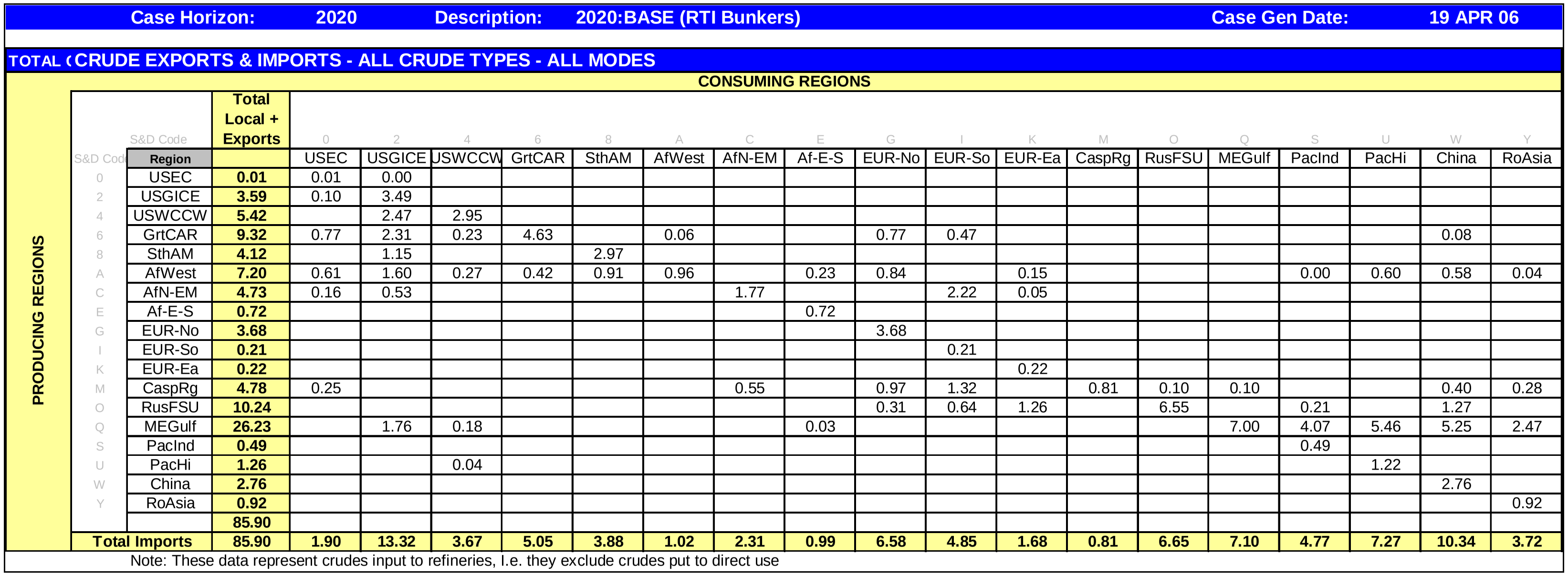
Case Horizon: 2012 **Description:** 2012:BASE (RTI Bunkers) **Case Gen Date:** 19 APR 06

TOTAL CRUDE DELIVERIES TO REFINERIES (AFTER TRANSPORT LOSSES)

			CONSUMING REGIONS																	
	S&D Code	Total Local + Exports	0	2	4	6	8	A	C	E	G	I	K	M	O	Q	S	U	W	Y
	Region		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
PRODUCING REGIONS	USEC	**0.01**	0.01	0.01																
	USGICE	**4.52**	0.05	4.47																
	USWCCW	**4.53**		1.40	3.13															
	GrtCAR	**8.02**	0.74	1.09	0.30	4.30		0.02			1.08	0.48							0.01	
	SthAM	**3.17**		0.78			2.38													
	AfWest	**5.74**	0.72	1.30	0.11	0.30	0.73	0.65		0.17	0.77		0.20					0.56	0.17	0.06
	AfN-EM	**4.58**	0.03	0.45					2.05			2.04								
	Af-E-S	**0.56**								0.56										
	EUR-No	**4.25**	0.16								4.09									
	EUR-So	**0.17**										0.17								
	EUR-Ea	**0.19**											0.19							
	CaspRg	**3.13**	0.07						0.04		0.51	1.10		0.75	0.10	0.10			0.40	0.04
	RusFSU	**9.25**			0.12						0.37	0.70	1.24		5.93		0.50		0.40	
	MEGulf	**24.00**		2.41						0.10						6.70	4.00	4.48	4.10	2.22
	PacInd	**0.57**															0.57			
	PacHi	**1.46**			0.04													1.42		
	China	**2.96**																	2.96	
	RoAsia	**1.00**																0.16		0.83
		78.11																		
	Total	**78.11**	**1.79**	**11.91**	**3.70**	**4.60**	**3.11**	**0.66**	**2.10**	**0.84**	**6.82**	**4.48**	**1.63**	**0.75**	**6.03**	**6.80**	**5.07**	**6.62**	**8.04**	**3.15**

Note: These data represent crudes input to refineries, I.e. they exclude crudes put to direct use and are net of transport losses

Figure 5-1. Total Crude Deliveries



Case Horizon: 2020 **Description:** 2020:BASE (RTI Bunkers) **Case Gen Date:** 19 APR 06

TOTAL (CRUDE EXPORTS & IMPORTS - ALL CRUDE TYPES - ALL MODES

PRODUCING REGIONS

CONSUMING REGIONS

S&D Code	S&D Code	Total Local + Exports	0	2	4	6	8	A	C	E	G	I	K	M	O	Q	S	U	W	Y
S&D Code	**Region**		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
0	USEC	**0.01**	0.01	0.00																
2	USGICE	**3.59**	0.10	3.49																
4	USWCCW	**5.42**		2.47	2.95															
6	GrtCAR	**9.32**	0.77	2.31	0.23	4.63		0.06			0.77	0.47							0.08	
8	SthAM	**4.12**		1.15			2.97													
A	AfWest	**7.20**	0.61	1.60	0.27	0.42	0.91	0.96		0.23	0.84		0.15				0.00	0.60	0.58	0.04
C	AfN-EM	**4.73**	0.16	0.53					1.77			2.22	0.05							
E	Af-E-S	**0.72**								0.72										
G	EUR-No	**3.68**									3.68									
I	EUR-So	**0.21**										0.21								
K	EUR-Ea	**0.22**											0.22							
M	CaspRg	**4.78**	0.25						0.55		0.97	1.32		0.81	0.10	0.10			0.40	0.28
O	RusFSU	**10.24**									0.31	0.64	1.26		6.55		0.21		1.27	
Q	MEGulf	**26.23**		1.76	0.18					0.03						7.00	4.07	5.46	5.25	2.47
S	PacInd	**0.49**															0.49			
U	PacHi	**1.26**			0.04													1.22		
W	China	**2.76**																	2.76	
Y	RoAsia	**0.92**																		0.92
		85.90																		
Total Imports		**85.90**	**1.90**	**13.32**	**3.67**	**5.05**	**3.88**	**1.02**	**2.31**	**0.99**	**6.58**	**4.85**	**1.68**	**0.81**	**6.65**	**7.10**	**4.77**	**7.27**	**10.34**	**3.72**

Note: These data represent crudes input to refineries, I.e. they exclude crudes put to direct use

Figure 5-2. Total Crude Exports

Case Horizon: 2012 Description: 2012:BASE (RTI Bunkers) Case Gen Date: 19 APR 06

PRD GAS+LIQ PRODUCTS PRLQ

CONSUMING REGIONS

PRODUCING REGIONS

S&D Code	Total Production ex Refinery	0	2	4	6	8	A	C	E	G	I	K	M	O	Q	S	U	W	Y
Region		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
USEC	**2.63**	2.58				0.05													
USGICE	**12.99**	2.48	10.10	0.20	0.20					0.01									
USWCCW	**4.00**		0.07	3.83												0.05		0.06	
GrtCAR	**4.53**	0.16	0.63	0.02	2.73	0.62				0.37									
SthAM	**3.71**	0.21	0.17	0.00		3.21	0.13												
AfWest	**0.69**	0.08	0.11				0.34			0.13	0.04								
AfN-EM	**1.91**	0.04						1.68		0.01	0.09								0.09
Af-E-S	**0.93**								0.86								0.07		
EUR-No	**7.98**	0.49			0.43					7.01		0.02							0.04
EUR-So	**4.85**	0.35			0.06			0.23		0.22	3.90	0.10							
EUR-Ea	**1.72**	0.00			0.05					0.07	0.01	1.57							
CaspRg	**0.75**									0.11	0.01		0.64						
RusFSU	**5.14**	0.36			0.02			0.16		0.72	0.18			3.43		0.05	0.23		
MEGulf	**6.97**					0.02			0.04						5.15		0.84		0.91
PacInd	**5.54**			0.00												5.06		0.48	
PacHi	**7.35**			0.02					0.02								7.13	0.04	0.15
China	**8.57**			0.23												0.18		8.15	
RoAsia	**3.29**			0.14											0.15		0.07		2.93
	83.55																		
Total Prdn	**83.55**	**6.74**	**11.08**	**4.43**	**3.49**	**3.90**	**0.47**	**2.07**	**0.92**	**8.64**	**4.23**	**1.70**	**0.64**	**3.43**	**5.30**	**5.34**	**8.35**	**8.73**	**4.11**

PRODUCT MOVEMENTS MMBPD GASOLINE - TOTAL GSLN

CONSUMING REGIONS

PRODUCING REGIONS

S&D Code	Total Production ex Refinery	0	2	4	6	8	A	C	E	G	I	K	M	O	Q	S	U	W	Y
Region		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
USEC	**1.36**	1.36																	
USGICE	**5.53**	0.99	4.33		0.20					0.01									
USWCCW	**1.72**			1.66														0.06	
GrtCAR	**1.25**		0.58		0.47	0.21													
SthAM	**1.32**	0.21	0.17	0.00		0.82	0.13												
AfWest	**0.17**		0.11				0.05			0.01	0.00								
AfN-EM	**0.19**	0.04						0.15											
Af-E-S	**0.28**								0.28										
EUR-No	**2.35**	0.49			0.43					1.43									
EUR-So	**1.23**	0.35			0.06			0.21			0.60								
EUR-Ea	**0.40**	0.00			0.05							0.35							
CaspRg	**0.22**												0.22						
RusFSU	**1.18**	0.12												1.06					
MEGulf	**1.36**					0.02									1.20		0.10		0.04
PacInd	**1.47**			0.00												1.26		0.21	
PacHi	**1.34**			0.02					0.02								1.18		0.13
China	**1.58**			0.23												0.11		1.25	
RoAsia	**0.59**			0.13											0.13		0.03		0.29
	23.53																		
Total	**23.53**	**3.55**	**5.18**	**2.04**	**1.21**	**1.04**	**0.18**	**0.36**	**0.30**	**1.45**	**0.60**	**0.35**	**0.22**	**1.06**	**1.34**	**1.37**	**1.32**	**1.52**	**0.45**

Figure 5-3. Production in 2012

Case Horizon: 2020 **Description:** 2020:BASE (RTI Bunkers) **Case Gen Date:** 19 APR 06

PRD — **GAS+LIQ PRODUCTS** — PRLQ

CONSUMING REGIONS

PRODUCING REGIONS

S&D Code	Total Production ex Refinery	0	2	4	6	8	A	C	E	G	I	K	M	O	Q	S	U	W	Y
Region		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
USEC	**2.89**	2.83				0.06													
USGICE	**14.12**	2.26	11.22	0.40	0.22					0.02									
USWCCW	**4.30**		0.07	4.07												0.10		0.06	
GrtCAR	**5.18**	0.37	0.52	0.01	2.90	0.78				0.59									
SthAM	**4.90**	0.31	0.09	0.10		3.99	0.16											0.24	
AfWest	**1.07**	0.10	0.15				0.37			0.42	0.04								
AfN-EM	**2.20**	0.02						1.99		0.00	0.02								0.16
Af-E-S	**1.12**								0.99								0.13		
EUR-No	**7.86**	0.53			0.50					6.76		0.01							0.06
EUR-So	**5.26**	0.40			0.10			0.29		0.13	4.09	0.26			0.00				
EUR-Ea	**1.77**	0.02			0.05					0.07		1.63							
CaspRg	**0.81**									0.06	0.03		0.72				0.01		
RusFSU	**5.48**	0.37			0.08			0.09		0.68	0.20			3.64			0.37	0.05	
MEGulf	**7.42**				0.00	0.01			0.02						5.85		0.35		1.18
PacInd	**5.09**			0.02												4.79		0.29	
PacHi	**8.48**								0.05		0.03						8.34		0.06
China	**11.04**			0.17												0.18	0.21	10.34	0.14
RoAsia	**4.10**			0.07											0.11		0.17		3.74
	93.09																		
Total Prdn	**93.09**	**7.22**	**12.04**	**4.86**	**3.84**	**4.84**	**0.52**	**2.36**	**1.06**	**8.74**	**4.41**	**1.90**	**0.72**	**3.64**	**5.97**	**5.06**	**9.57**	**10.98**	**5.33**

PRODUCT MOVEMENTS MMBPD — **GASOLINE - TOTAL** — GSLN

CONSUMING REGIONS

PRODUCING REGIONS

S&D Code	Total Production ex Refinery	0	2	4	6	8	A	C	E	G	I	K	M	O	Q	S	U	W	Y
Region		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
USEC	**1.46**	1.46																	
USGICE	**6.04**	0.99	4.83		0.20					0.02									
USWCCW	**1.93**			1.87														0.06	
GrtCAR	**1.35**		0.45		0.47	0.43													
SthAM	**1.78**	0.31	0.09	0.10		0.88	0.16											0.24	
AfWest	**0.22**	0.03	0.15				0.04												
AfN-EM	**0.22**	0.02						0.20											
Af-E-S	**0.29**								0.29										
EUR-No	**2.22**	0.53			0.50					1.19									0.00
EUR-So	**1.25**	0.40			0.10			0.24			0.52	0.01							
EUR-Ea	**0.40**	0.02			0.05							0.34							
CaspRg	**0.28**												0.28						
RusFSU	**1.21**	0.06									0.00			1.14				0.01	
MEGulf	**1.46**														1.46				
PacInd	**1.41**			0.02												1.23		0.17	
PacHi	**1.53**								0.05								1.46		0.02
China	**1.69**			0.16												0.13		1.25	0.14
RoAsia	**0.68**			0.07											0.10		0.09		0.43
	25.43																		
Total	**25.43**	**3.82**	**5.51**	**2.22**	**1.31**	**1.31**	**0.20**	**0.44**	**0.34**	**1.22**	**0.52**	**0.34**	**0.28**	**1.14**	**1.55**	**1.36**	**1.55**	**1.74**	**0.59**

Figure 5-4. Production in 2020

PRODUCT MOVEMENTS MMBPD MIDDLE DISTILLATES DIST 2012 BASE CASE (RTI Bunkers)

CONSUMING REGIONS

PRODUCING REGIONS

S&D Code	Total Production ex Refinery	0	2	4	6	8	A	C	E	G	I	K	M	O	Q	S	U	W	Y
Region		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
USEC	**0.54**	0.54																	
USGICE	**3.69**	1.00	2.69																
USWCCW	**1.02**		0.01	1.01												0.01			
GrtCAR	**1.54**	0.07	0.05		0.93	0.13				0.36									
SthAM	**1.45**					1.45													
AfWest	**0.21**						0.15			0.06									
AfN-EM	**0.74**							0.74											
Af-E-S	**0.30**								0.30										
EUR-No	**2.76**									2.76		0.01							
EUR-So	**1.70**							0.01			1.63	0.06							
EUR-Ea	**0.66**											0.66							
CaspRg	**0.23**									0.07			0.16						
RusFSU	**1.74**	0.00						0.04		0.59	0.12			0.98					
MEGulf	**2.48**								0.00						1.74		0.52		0.22
PacInd	**1.28**															1.26		0.03	
PacHi	**1.93**																1.93		
China	**3.38**															0.07		3.31	
RoAsia	**1.47**																		1.47
	27.13																		
Total	**27.13**	**1.61**	**2.75**	**1.01**	**0.93**	**1.59**	**0.15**	**0.79**	**0.30**	**3.84**	**1.75**	**0.73**	**0.16**	**0.98**	**1.74**	**1.34**	**2.45**	**3.33**	**1.69**

PRODUCT MOVEMENTS MMBPD MIDDLE DISTILLATES DIST 2020 BASE CASE (RTI Bunkers)

CONSUMING REGIONS

PRODUCING REGIONS

S&D Code	Total Production ex Refinery	0	2	4	6	8	A	C	E	G	I	K	M	O	Q	S	U	W	Y
Region		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
USEC	**0.58**	0.58																	
USGICE	**3.89**	0.74	3.14	0.01															
USWCCW	**1.19**			1.19												0.00			
GrtCAR	**2.06**	0.35	0.07		1.05					0.59									
SthAM	**1.87**					1.87													
AfWest	**0.45**						0.16			0.29									
AfN-EM	**0.82**							0.82											
Af-E-S	**0.33**								0.33										
EUR-No	**2.42**									2.41		0.01							
EUR-So	**2.04**							0.04			1.81	0.19							
EUR-Ea	**0.70**											0.70							
CaspRg	**0.23**									0.05	0.01		0.17						
RusFSU	**1.98**	0.11						0.06		0.58	0.13			1.10					
MEGulf	**2.77**					0.01			0.02						1.95		0.15		0.64
PacInd	**1.23**															1.21		0.02	
PacHi	**2.52**																2.52		
China	**4.64**															0.05	0.21	4.38	
RoAsia	**1.58**																		1.58
	31.30																		
Total	**31.30**	**1.78**	**3.21**	**1.20**	**1.05**	**1.88**	**0.16**	**0.92**	**0.35**	**3.93**	**1.95**	**0.90**	**0.17**	**1.10**	**1.95**	**1.26**	**2.88**	**4.40**	**2.22**

Figure 5-5. Product Movements

PRD RESID Bunkers RBKR 2012 BASE CASE (RTI Bunkers)

CONSUMING REGIONS

PRODUCING REGIONS

S&D Code	Total Production ex Refinery	0	2	4	6	8	A	C	E	G	I	K	M	O	Q	S	U	W	Y
Region		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
USEC	**0.04**	0.04																	
USGICE	**0.21**		0.21																
USWCCW	**0.14**			0.14															
GrtCAR	**0.60**	0.09			0.23	0.28													
SthAM	**0.06**					0.06													
AfWest	**0.03**						0.03												
AfN-EM	**0.21**							0.21											
Af-E-S	**0.13**								0.13										
EUR-No	**0.84**									0.84									
EUR-So	**0.33**										0.33								
EUR-Ea	**0.05**										0.01	0.03							
CaspRg	**0.00**																		
RusFSU	**0.06**										0.05			0.01					
MEGulf	**0.46**														0.46				
PacInd	**0.62**															0.50		0.12	
PacHi	**0.96**																0.96		
China	**0.79**																	0.79	
RoAsia	**0.02**																		0.02
	5.53																		
Total	**5.53**	**0.13**	**0.21**	**0.14**	**0.23**	**0.34**	**0.03**	**0.21**	**0.13**	**0.84**	**0.40**	**0.03**	**0.00**	**0.01**	**0.46**	**0.50**	**0.96**	**0.91**	**0.02**

PRD RESID Bunkers RBKR 2020 BASE CASE (RTI Bunkers)

CONSUMING REGIONS

PRODUCING REGIONS

S&D Code	Total Production ex Refinery	0	2	4	6	8	A	C	E	G	I	K	M	O	Q	S	U	W	Y
Region		USEC	USGICE	USWCCW	GrtCAR	SthAM	AfWest	AfN-EM	Af-E-S	EUR-No	EUR-So	EUR-Ea	CaspRg	RusFSU	MEGulf	PacInd	PacHi	China	RoAsia
USEC	**0.15**	0.15																	
USGICE	**0.24**		0.24																
USWCCW	**0.17**			0.17															
GrtCAR	**0.56**				0.31	0.25													
SthAM	**0.15**					0.15													
AfWest	**0.04**						0.04												
AfN-EM	**0.24**							0.24											
Af-E-S	**0.15**								0.15										
EUR-No	**0.89**									0.89									
EUR-So	**0.43**										0.43								
EUR-Ea	**0.04**											0.04							
CaspRg	**0.00**																		
RusFSU	**0.18**									0.09	0.08			0.01					
MEGulf	**0.54**														0.54				
PacInd	**0.56**															0.56			
PacHi	**1.04**																1.04		
China	**1.42**																	1.42	
RoAsia	**0.07**																0.05		0.02
	6.87																		
Total	**6.87**	**0.15**	**0.24**	**0.17**	**0.31**	**0.40**	**0.04**	**0.24**	**0.15**	**0.99**	**0.51**	**0.04**	**0.00**	**0.01**	**0.54**	**0.56**	**1.09**	**1.42**	**0.02**

Figure 5-6. Residual Bunker

The period through 2020 will witness continued growth in trade of finished and intermediate products, as illustrated by the WORLD case results. The case projections point to the following main trends:

- Increases in product volumes being shipped into and between Asia/Pacific regions.
- Continued products and intermediates exports from Russia, mainly into Europe but also into the United States and Far East.
- Potentially major exports from Europe of gasoline, on the basis of continuing dieselization. WORLD cases indicate these exports growing to over 1.75 mmbpd by 2020. However, the cases also show the premium for diesel in Europe at $9/bbl above gasoline, which raises questions about whether European authorities and consumers will continue to opt predominantly for diesel vehicles.
- Should dieselization continue, its impacts on product trade patterns will be far reaching; 2020 exports of European gasoline to the United States are projected at close to 1 mmbpd with other destinations likely to include Africa, Asia, and the Caribbean. Offsetting the gasoline exports are a projected 1.65 mmbpd (2020) of distillates imports from Russia, Caspian, Caribbean, and Africa.
- With U.S. refining capacity projected to not keep up with demand, gasoline imports continue to rise into the U.S. East Coast (nearly 1.4 mmbpd into PADD I in 2020 from Europe, Caribbean, South America, Africa, and Russia) but also are indicated into the U.S. Gulf Coast and Interior (over 0.4 mmbpd net) and the U.S. West Coast (0.3 mmbpd net).
- Interregional movements of residual fuels are projected as limited, except for small volumes of low-sulfur residual moving into the U.S. East Coast and of high-sulfur residual and vacuum gas oil streams from Russia, mainly into Europe.
- This situation is projected as applying to residual bunker fuels (Figure 5-6), although shifts in assumed locations of bunker demand could well lead to changes in trade patterns.

5.5 Bunker Fuels’ Quality and Blending

The current WORLD version does not possess standard reports for the details of fuel blends. For the BAU cases, spot blends were inspected. MGO blends included light and middle distillate streams characteristic of a lower quality, higher sulfur No. 2 type fuel. MDO No. 4 fuel blends included heavier streams, consistent with a minimum API gravity allowed of 22.3, and tended to limit on sulfur, and carbon residue (maximum 2.5%). Blend components included vacuum gas oils and small proportions of atmospheric and vacuum residua, subject to the limits placed by carbon residue, sulfur, viscosity (14 cks max at 40°C), and gravity.

The residual IFO blends for 2012 and 2020 comprised predominantly vacuum and visbroken residual cut back with kerosene cutter stock plus small constrained (max 5%) volumes of FCC clarified oils. In a departure from historical patterns, the blends contained small proportions at most of atmospheric residual and no vacuum gas oils. (A traditional IFO blend would contain either atmospheric residual and cutter stock or a mix of vacuum residual and vacuum gas oil and cutter stock.) This development in the blend compositions would appear to be logical given that global demand growth is predominantly for light clean products that can be readily produced *inter alia* from vacuum gas oils via catalytic and hydro-cracking. In other words, in the future, vacuum gas oil will be too valuable as potential gasoline and distillate to blend into bunker fuels. It will be more economical to blend in vacuum and visbroken residua plus a higher than traditional quantity of kerosene, which is the most effective cutter stock by virtue of its low viscosity. The IFO blends are universally limited on maximum viscosity. Sulfur was a limiting constraint on the low-sulfur (1.5% nominal) blends but otherwise rarely constrained (at 4.5%).

The indicated shift in residual bunker blend compositions does raise questions. First, in the model cases, expansion of visbreakers was partially constrained because the general trend has been to invest in cokers. Shifting to the RTI bunker basis from IEA led to a significant cut back in coker throughputs because of the rise in residual fuel demand. For 2020, the global coker throughput was 4.7 mmbpd in the IEA basis case and 3.7 under the RTI basis. However, the case allowed little additional visbreaker throughput/capacity addition. Yet an increase in demand for residual bunker fuels argues for an increase in attractiveness of visbroken vacuum residua. In short, the BAU cases should arguably be tested with additional visbreaking allowed. Unlike residual desulfurization, visbreaking is a low-cost process and one refiners could readily engage in.

The second question these blends bring forward is an operational one. Namely, are there any operational issues with residual bunker blends that comprise “dumbbell” blends of kerosene with visbroken and vacuum residua?

SECTION 6
TECHNOLOGY CONSIDERATIONS

RTI examined the various technology considerations associated with clean fuel requirements in the marine sector. There is a linear relationship between the sulfur content of fuel and SO_x emissions, and this chapter reviews the technology alternatives that may be available to ocean-going ships to comply with SECA emissions requirements. MARPOL Annex VI explicitly allows for onboard abatement as an alternative means for meeting SO_x requirements, thus recognizing that the ultimate goal is a reduction in SO_x emissions rather than a reduction of fuel sulfur content per se.

The objectives of this section are to identify the compliance options available to the marine vessel operators and to characterize the compliance options in terms of technology applicability (for different marine vessels or market sectors), emissions reduction, and costs. A thorough understanding of the technically feasible alternatives is essential because it will bound the decision possibilities available to affected stakeholders and will greatly influence the burden of potential SECA requirements.

This section provides technical background descriptions, cost information, and emissions reduction potential for three onboard emissions abatement alternatives:

- fuel switching
- in-engine fuel mixing
- exhaust-gas scrubbing

The data were combined with Navigistics' and RTI's in-depth knowledge of marine vessels, the shipping industry, and these technology options. RTI incorporated data, as available, from various studies on these technology issues conducted in U.S. (primarily California) and European markets. We also received input from leading technology providers such as MAN B&W, Wartsila (Sulzer), marine engineers, oil companies, industry associations (e.g., INTERTANKO), and vessel operators through technical literature (reports and presentations) and personal interviews to gather additional information. These sources and the experience of the RTI team, together with EPA's input, provided the expertise to identify technically feasible compliance options and to analyze their control costs.

In considering the impact of low sulfur fuel requirements on fuel volumes and costs, RTI considered scenarios with and without the use of scrubbers on limited vessels. EPA provided scrubber penetration scenarios for 2012 and 2020.

6.1 Fuel Switching

Since the first oil shock in the early 1970s, the primary goal in ship power plant design has been to reduce fuel costs. Reducing fuel costs has come about through two primary mechanisms:

- improvement of the fuel efficiency by reducing the specific fuel consumption (SFC) of the engines
- facilitation of marine power plants to burn lower quality and lower cost per ton fuel

This approach to marine power plant design has been very successful, with large, slow-speed, 2-stroke marine diesel engines replacing steam power plants on virtually all large ships.[1]

Prior to the 1973–1974 oil shock, the primary goal of ship diesel engine designers had been to increase engine output to meet the demand of larger ship sizes and greater power requirements. Steam power plants were installed on vessels that required more power than was available from diesel engines. Steam power plants cost less to install (on a dollar per horsepower basis) but were significantly less fuel efficient than diesel engines of similar sizes. SFC on the largest and most efficient marine steam turbine power plants was about 212 grams per shaft horsepower-hour (at full power and maximum efficiency), while marine diesel engines were achieving test-bed SFCs of 165 grams per brake horsepower-hour. Despite diesel engines' greater fuel efficiency, steam power plants of that era were able to burn lower quality, and therefore lower cost, residual fuel (e.g., bunker "C").

Following the oil shocks, diesel manufacturers shifted their emphasis from engine output to improved fuel efficiency and the ability to operate on lower quality fuels (Institute of Marine Engineers [IME], 1979). Marine diesel engine manufactures developed engines that were capable of running on these low-quality fuel oils. Prior to the introduction of large slow-speed diesel engines, marine diesel engines were medium-speed, 4-stroke engines that required higher quality distillate fuel oil for both full-time operation and operation during maneuvering (i.e., when speed changes rapidly, such as during in-port operations).

Today's marine diesel engines for ships are slow-speed, 2-stroke marine diesel engines that typically operate on residual fuel oils at virtually all times. These power plants are sometimes referred to as "unifuel" plants (Herbert Engineering Corp., 2007). SFC is approximately 135 grams per brake horsepower-hour, though some manufacturers claim that

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[1] LNG tankers continued to use steam power plants because of the availability of LNG boil-off for propulsion fuel. Diesel engine manufacturers have now introduced engines that are capable of running on traditional marine fuels and LNG boil-off. These new engines are typically referred to as "dual fuel" engines.

they are achieving test-bed measurements below 115 grams per horsepower-hour. Such SFCs approach Carnot cycle efficiencies (i.e., theoretical maximum efficiency) for a diesel engine (Aabo, 2007). Noted exceptions to full-time residual fuel consumption include preparation for long-term shutdown for overhaul and emergencies, when fuel heating capability is lost. As experience was gained with main diesel engines operating on residual fuel, engine manufacturers began producing smaller engines that also could run on residual fuels. These smaller "auxiliary" engines are used on ships for generators or as prime movers on smaller vessels.

However, improving fuel efficiency through engine design does little to reduce SO_x emissions beyond that associated with a reduction in fuel consumption. There is a linear relationship between the sulfur content of fuels and SO_x emissions. Thus, one immediate focus for reducing shipboard SO_x emissions is on reducing the sulfur content of the fuel burned. With the current establishment of SECAs and the expected future establishment of more SECAs in various areas around the world, it is anticipated that the easiest, although not necessarily most cost-effective, approach to SECA compliance will be through the use of fuel with lower sulfur content by weight. Because of the cost differential of low-sulfur fuel, it is also anticipated that ship owners and operators will try to burn low-sulfur fuel when in the SECA but not elsewhere.

This section addresses the practicality of switching from IFO to low-sulfur IFO or MDO when in a SECA.[2] Section 2.1 reviewed various marine fuel types. This section addresses

- shipboard fuel pretreatment and heating plants;
- burning of low-sulfur fuel in marine diesel engines;
- practicality of switching to low-sulfur fuels in SECAs;
- other fuel switching-related approaches to using low-sulfur fuels in SECAs; and
- fuel switching's emission reduction potential.

6.1.1 Primer on Bunker Fuel Treatment and Heating Plants

Because of their high viscosity and residual fuel components (including contaminants), heavy marine fuels must be treated onboard before injection into a diesel engine. Onboard treatment includes purification and heating to obtain the proper viscosity before injection. The following discussion provides a primer on bunker fuel treatment and heating systems to better

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[2] Two different compliance actions might be adopted by marine vessel operators in this category: (1) carrying both high- and low-sulfur fuels and switching fuel sources as they approach or exit SECAs (commonly referred to as "fuel switching") and (2) converting to low-sulfur fuel oils for all of their fuel needs (referred to as "fuel converting").

illustrate how fuel switching can be implemented and the engineering considerations that must be made when switching fuels at sea.

A bunker fuel pretreatment and cleaning plant is designed to circulate fuel, remove solids, and maintain the proper injection viscosity through temperature control. Fuel circulation and temperature control are used to maintain viscosity and prevent heavy fuel oils from solidifying in the fuel system. Removing solids improves operational efficiency and maintains the integrity of the fuel circulation, injection, and combustion systems. The heavier the fuel, the more complex the fuel treatment system must be (Rowan et al., 2005).

A ship’s pretreatment system consists of storage, settling tanks, filters, and purifiers (Fisher and Lux, 2004). This system removes solids and sediments and improves the overall quality of the fuel such that it can be burned in diesel engines without causing damage or excessive wear.

The engineering schematic in Figure 6-1 shows a typical shipboard pretreatment and cleaning plant. Transfer pumps bring fuel from heated bunker tanks to the settling tank, which serves a dual purpose. At any given time, enough fuel for 2 days of travel is held in this tank. The settling tank also has heating coils to heat the fuel. As the fuel resides in the tank, heavy solids settle to the bottom. The fuel to be burned is drawn off the top of the tank. If the fuel is allowed to cool at any stage in the pretreatment, cleaning, or supply systems, it will become too viscous to pump.

Next, feed pumps move the fuel from the settling tank through a preheater to one or more separators. The separators act as centrifuges, removing as many of the remaining solids as possible. The pretreated and cleaned fuel is stored in the day tank, which includes heating elements to maintain fuel temperature and viscosity. At any given time, fuel sufficient for 1 full day of travel is stored in this tank.

Figure 6-2 shows the pressurized fuel oil system. The day tank, or heavy fuel oil service tank, is the main repository for fuel before it is combusted. The fuel supply system draws fuel from the day tank and continuously circulates the fuel from the day tank to the injection system

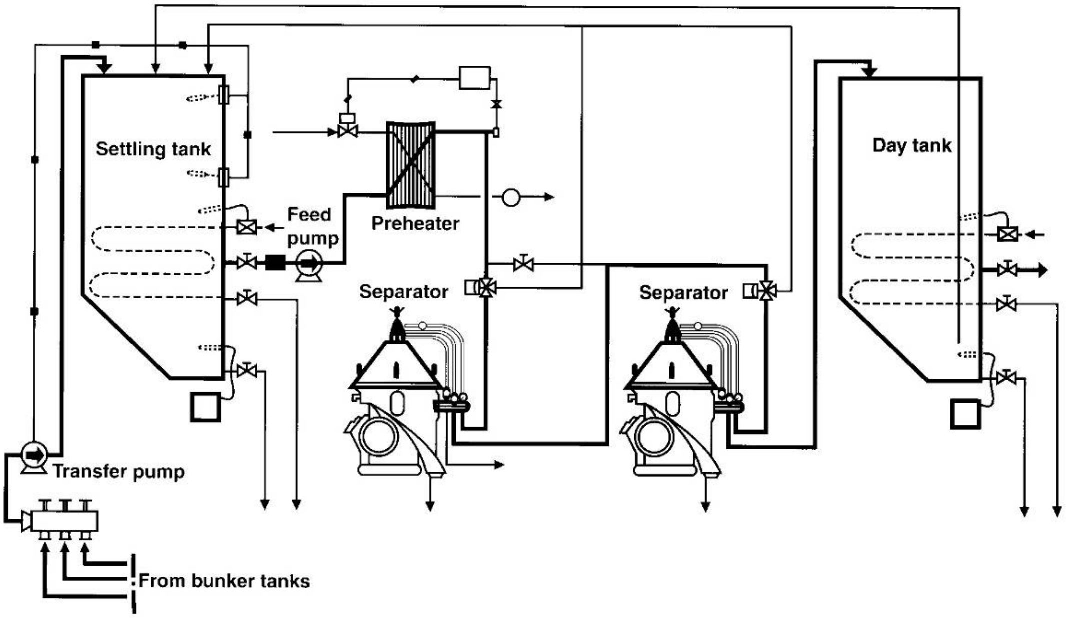

Figure 6-1. **Typical Shipboard Pretreatment and Cleaning Plant**

Source: MAN B&W Diesel A/S (MAN B&W). 2005. *Operation on Low Sulphur Fuels: Two-Stroke Engines*. Published November 26, 2005.

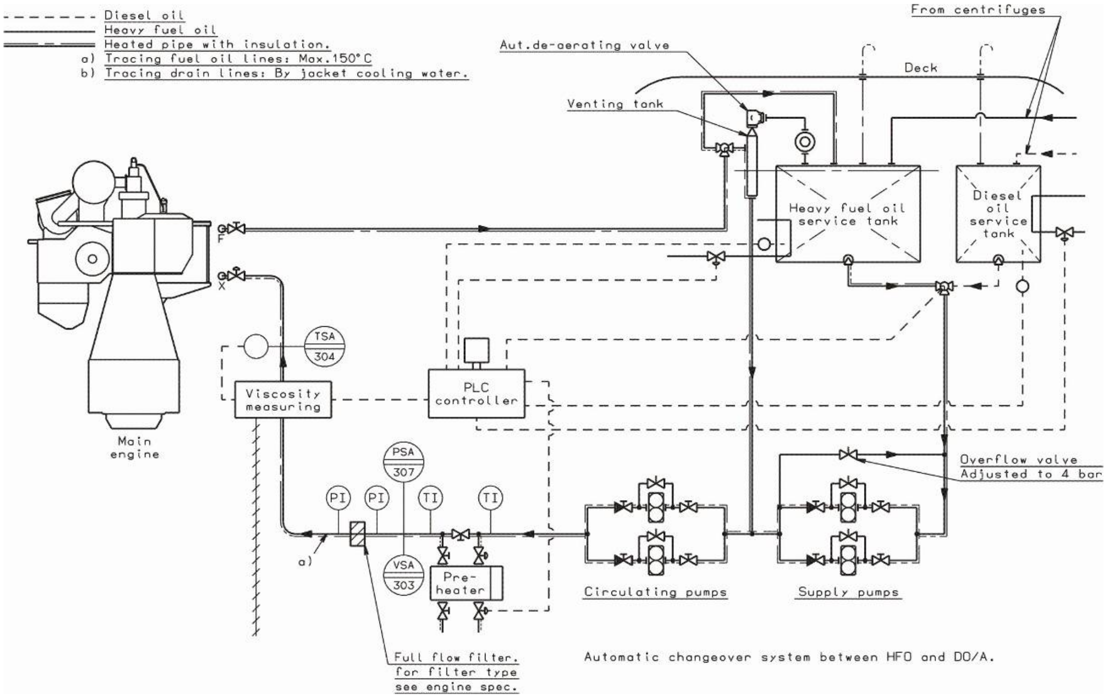

Figure 6-2. **Pressurized Fuel Oil System**

Source: MAN B&W Diesel A/S (MAN B&W). 2005. *Operation on Low Sulphur Fuels: Two-Stroke Engines*. Published November 26, 2005.

and back to the day tank—more fuel is pumped in circulation than is drawn off to the injectors—to prevent solidification anywhere in the supply system. Two sets of pumps, supply pumps and circulating pumps, pressurize the system and maintain the free flow of fuel. Included is a preheater, controlled by a viscosimeter, to maintain fuel temperature throughout the onboard fuel-handling system. Before fuel is brought to the main engine's injection system, it is filtered one last time to remove solids larger than 300 microns.

6.1.2 Burning Low-Sulfur Fuels in Main Engines

The concerns regarding burning low-sulfur fuels in marine engines are related to either the steady state operation on low-sulfur marine distillates or issues relating to the changeover from IFO to MDO/MGO and back. The primary issues related to the steady-state operation of low-sulfur fuel in diesel powered ships are

- cylinder lubricants and feed rates and
- viscosity and temperature control.

6.1.2.1 Lubricating Oil Systems

Marine lubricating oils contain alkaline additives to counteract the acidity caused by sulfur oxides. The base number (BN) of the lubricating oil (the measure of its alkalinity) must match the sulfur content of the fuel used. Acid corrosion is the most significant cause of cylinder wear and occurs during condensation of IFO's sulfur content in the combustion chamber (MAN B&W, 2005). The sulfur from the fuel and water vapor combine to form sulfur trioxide. Cylinder oil contains alkalines that control the deposition of acids in the cylinders and, thus, the wear. According to MAN B&W (2005), some controlled deposition is helpful for the proper tribology for maintaining a film of lubricating oil.

When running on fuels that are 1.5% or more sulfur, ships are recommended to use 70BN cylinder oil. When running on fuels that are less than 1.5% sulfur, they are recommended to use 40BN cylinder oil (Wartsila, 2006a). In this way, they are able to maintain a proper BN-to-sulfur (BN/S) ratio. Most ships' diesel engines are slow-speed, 2-stroke engines that inject lubricating oil into the fuel just prior to combustion and therefore require separate fuel-feed systems to implement fuel switching.

If low-sulfur fuels are used in conjunction with 70BN cylinder oil, ships risk excessive ash deposit in the combustion chamber, exhaust valves, and turbocharger. 70BN has high ash content, and this ash may be deposited on the piston crown head, causing bore polishing that may lead to engine seizure. Although ships may run with low-sulfur fuels for a short time with 70BN, if the sulfur content is 1% or less, they are strongly recommended to use 40BN (Wartsila, 2006a).

These issues are compounded when operating on different fuels inside and outside of a SECA. Fuel switching increases the difficulty of maintaining a proper BN/S ratio in the lubricating oil system. Although short periods of out-of-balance BN/S ratios do not generally lead to excessive engine wear, compliance with low-sulfur fuel limits may require extended operation with the low-sulfur fuel. Ships may require a two-cylinder lubricating system (storage, service, and supply) to avoid excess engine wear when running on different fuels.

If ships run on IFO and continuously use low BN cylinder oil, they risk corrosion in the engine. The low BN cylinder oil cannot neutralize the sulfuric acid generated during combustion. Fuel switching requires monitoring BN levels and selecting lubricants that maintain the proper BN/S ratio (Wartsila, 2006a).

If the fuel’s sulfur level is below 1%, 40BN or 50BN lubricating oil is recommended by MAN B&W (2005). However, a ship should only change over to 40BN or 50BN from 70BN if it is to operate on fuel that is 1% sulfur or less for more than 1 week. If the fuel sulfur level is between 1% and 1.5%, 40BN, 50BN, or 70BN lubricating oil can be used. Ships are recommended to use 70BN lubricating oil exclusively when using fuels that are 1.5% sulfur or greater.

6.1.2.2 Fuel Viscosity and Feed Temperature

Another issue that must be considered when using MDO/MGO in marine diesel engines is viscosity. Marine diesel manufacturers design injection systems to operate with a minimum fuel viscosity of between 1.8 and 3.0 centistokes (cSt) depending on specific engine type (Wartsila, 2006). MDO/MGO is significantly less viscous than IFO. IFO380 has a viscosity of 35 cSt at 100°C. IFO380’s viscosity is reduced by heating onboard to provide fuel at the injectors of a suitable viscosity. The DMA specification requires fuel to be between 1.5 and 6.0 cSt at 40°C, and the DMB specification requires fuel to be between 2.5 and 11.0 cSt at 40°C. The world average viscosity of DMA in 2006 was 3.5 cSt, and the U.S. average was 3.0 cSt at 40°C. The world average viscosity of DMB in 2006 was 4.2 cSt, and the U.S. average was 3.9 cSt at 40°C (DNV, 2007). These viscosity figures are based on a 40°C standard. However, on marine vessels, the temperature of the fuel will normally rise above 40°C, further reducing the viscosity (Herbert Engineering Corp., 2007). Viscosity only becomes an issue when MDO or MGO is delivered at near-minimum specification.

Low viscosity in 4-stroke diesel engines is generally not a major problem, but in severe cases, damage to the fuel injection equipment may occur, and the running parameters of the engine will be affected. In exceptional cases, there may be a risk of loss of capability to produce full power, unexpected shutdown, and starting problems. The effect of low viscosity on 2-stroke marine diesel engines is typically minor (Wartsila, 2006a). The low viscosity problem, however, may arise, with the pumps in the fuel treatment system causing pump failure and unexpected engine shutdown.

The immediate solution to low viscosity concerns is to cool the fuel to a suitable temperature and viscosity. This would require the installation of a fuel cooler and associated piping and viscosimeter in the fuel treatment system. The retrofit of a fuel cooler (using the main engine cooling system) and associated system can be done at a ship's normal dry docking (Herbert Engineering Corp., 2007). The cost for this retrofit is likely to be less than $50,000 (Herbert Engineering Corp., 2007). A concern, however, is that a seawater-based heat exchanger may not be able to cool MGO (DMA) sufficiently in all parts of the world during summer months. Preventing this problem may require the installation of a fuel chiller (i.e., refrigeration system) that would be more costly. Other solutions may come about through the use of improved or different materials (e.g., ceramics) in the fuel system (e.g., injectors, pumps).

If low sulfur IFO is used in the SECAs, viscosity and temperature are not a concern because IFO and low-sulfur heavy fuel oil (LSIFO) have similar viscosity characteristics.

6.1.3 Practicality of Switching to Low-Sulfur Fuels in SECA

Switching from IFO to a low-sulfur distillate (MDO/MGO) when entering a SECA raises the following two primary concerns:

- fuel compatibility
- temperature change and thermal shock

These are both concerns because, in existing fuel treatment plants, the fuel is drawn from either the MDO/MGO day tank or the IFO day tank outside of the fuel recirculating loop (see Figure 6-2). This means that, during the changeover from IFO to MDO/MGO, the two types of fuel are cohabitating the pipes, pumps, filters, and heat exchangers in the recirculating loop.

6.1.3.1 Fuel Compatibility

The first consideration for the practicality of switching to low-sulfur fuels is fuel compatibility. Prior to the 1980s, most refineries were hydro-skimming or straight-run refineries that produced predominately paraffinic fuel oils. There were few compatibility issues with mixing different paraffinic fuel oils. Over the past 25 years, complex refineries have become the norm, and aromatic heavy fuel oils have become the dominant fuel type. These fuels have high levels of asphaltenes (high molecular weight hydrocarbons that are insoluble in n-heptane but soluble in toluene). Mixing aromatic fuel oils with paraffinic fuel oils can cause significant sludge formation. Even when mixing aromatic fuel oils, instability in the fuel oil can result, leading to high sludge formation. Sludge formation results in fuel value loss through high sludge removal rates in the centrifuge and can lead to clogged filters, blocked centrifuges, and other mechanical difficulties. Consequently, switching or mixing different fuels is generally avoided in current practice.

Although fuel switching historically has been avoided because of these uncertainties, this does not imply that, given economic incentives, fuel switching will not become a viable alternative in many instances. Catalytically cracked low-sulfur distillates (i.e., distillates with high aromaticity) will generally be compatible with heavy fuel oils from complex refineries. Developing costs of this implementation strategy must include the costs of fuel compatibility testing and the likelihood of increased maintenance due to occasional excess sludge formation.

Fuel compatibility testing can be accomplished manually onboard using testing kits or by contracting with third-party testing laboratories. Although fuel compatibility problems seldom occur because of the low incidence of fuel switching, they are likely to occur more often once fuel switching becomes more prevalent (MAN B&W, 2005).

6.1.3.2 Fuel Feed Temperature

Using lower-temperature fuels in a system designed for high-temperature fuels risks thermal shock during the changeover from IFO to MDO. Appropriate fuel-switching procedures must ensure a gradual changeover that avoids rapid fuel temperature changes. The fuel switching cannot be too abrupt or the rapid change in fuel oil temperature may cause uneven thermal expansion of the fuel injection equipment, which could cause seizure (i.e., thermal shock) of the injection system.

Wartsila (2006) recommends continuous operation with IFO for engines and plants designed for running on IFO. Changing MDO is only recommended when absolutely necessary, such as, when flushing the engine before maintenance, when the heating plant is not available, or when it is required for environmental reasons (e.g., when low-sulfur fuel is required). Risks may be mitigated by arranging the fuel system to permit a controlled, slow change in fuel temperature.

If a ship does not have double IFO systems and does not have low sulfur IFO available when entering a SECA, the only alternative will be to switch all IFO engines to MDO at sea. In this case, the MDO temperature and the temperature change gradient need to be considered. For 2-stroke engines, a controlled temperature gradient is recommended, with a reduced engine load. If MDO is mixed in while the fuel temperature is still very high, there is a possibility of gassing in the fuel oil service system, with subsequent loss of power. For 4-stroke engines, the fuel changeover generally can be performed via the mixing tank at any load (Wartsila, 2006a).

Procedures or arrangements for switching from IFO to MDO may include fuel preheaters, fuel pipe trace heating, a three-way valve in the suction line from the service tanks, redirection of the return fuel to the MDO service tank, an MDO cooler, the possible need to control engine load, and monitoring of the pressure difference of the fuel filter (Wartsila, 2006).

According to Wartsila (2006), if a ship is to operate on different IFO qualities inside and outside of SECAs, it would be beneficial to install double IFO settling and service tanks for reasons of operational convenience, economy, and safety. A double settling and service tank system will reduce the time required for the fuel delivery system to be fully flushed of all fuels exceeding the 1.5% sulfur limit before entering the SECA. Ships also would avoid consumption of the more expensive LSIFO or distillates before entering or after exiting the SECA.

Studies of fuel switching conducted by MAN B&W (2005) indicate that, when dual fuel systems are used, it takes approximately 55 minutes for a 2-stroke engine to change over from diesel fuel to heavy fuel oil. Fuel temperature cannot be changed by more than 2º per minute. Thus, if the system contains 40º C diesel fuel and it needs to be 80º C before heavy fuel oil can be added, 20 minutes is required to heat the diesel fuel. The heavy fuel oil needs to be 25º C higher than diesel fuel, or 105º C, requiring 12.5 additional minutes before it can be added to the diesel fuel. As the system changes to heavy fuel oil, the temperature must rise to 150º C, which requires an additional 22.5 minutes. In this case, it takes 32.5 minutes before heavy fuel oil is in the system and an additional 22.5 minutes before the system is operating with 150º C heavy fuel oil (MAN B&W, 2005).

6.1.3.3 Fuel System Configuration

On board fuel treatment systems are not identical, and the actual changeover from IFO to MDO/MGO will vary based on the design of the fuel oil system. MAN B&W (2005) identified three principal fuel system configurations for fuel switching:

1. **One Distillate System and One Heavy Fuel System.** In a dual fuel system, each fuel type has a dedicated bunkering, settling, centrifuging, and service tank system. The distillate and heavy fuel systems are independent until fuel supply pressurization. Most ships have distillate systems onboard; however, fuel switching may require modification to accommodate greater distillate usage (Figure 6-3).
2. **One Distillate System and Two Heavy Fuel Settling Tanks.** Regular heavy fuel oil and LSIFO have separate bunkering and settling systems. The two heavy fuel systems merge at the centrifuges. As in the first option, the distillate system may connect with the heavy oil supply lines before fuel supply pressurization (Figure 6-4). Additional fuel-delivery equipment needs may include additional bunker tanks, bunkering systems, bunker-heating systems, a settling tank, and a transfer pump.
3. **One Distillate System and Two Separate Heavy Fuel Oil Systems.** In contrast to Option 2, heavy fuel systems have separate centrifuges and service tanks and are isolated up until fuel supply pressurization. As in the first option, the distillate system may connect with the heavy oil supply lines before fuel supply pressurization (Figure 6-5). Additional fuel delivery equipment needs may include those from Option 2, as well as additional centrifuges, service tanks, piping, and instrumentation.

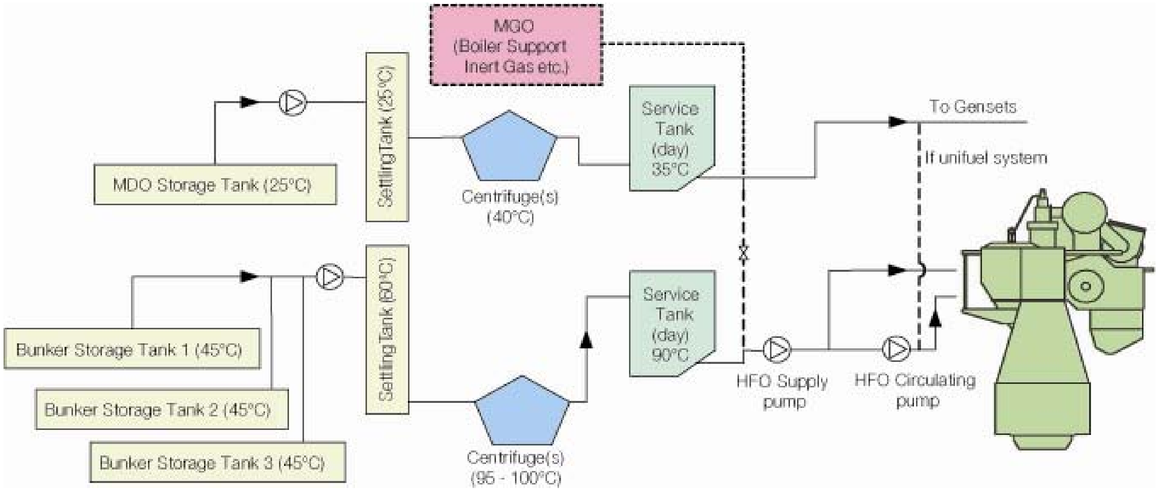

Figure 6-3. Fuel System with One MDO Settling Tank and One IFO Settling Tank

Source: MAN B&W Diesel A/S (MAN B&W). 2005. *Operation on Low Sulphur Fuels: Two-Stroke Engines*. Published November 26, 2005.

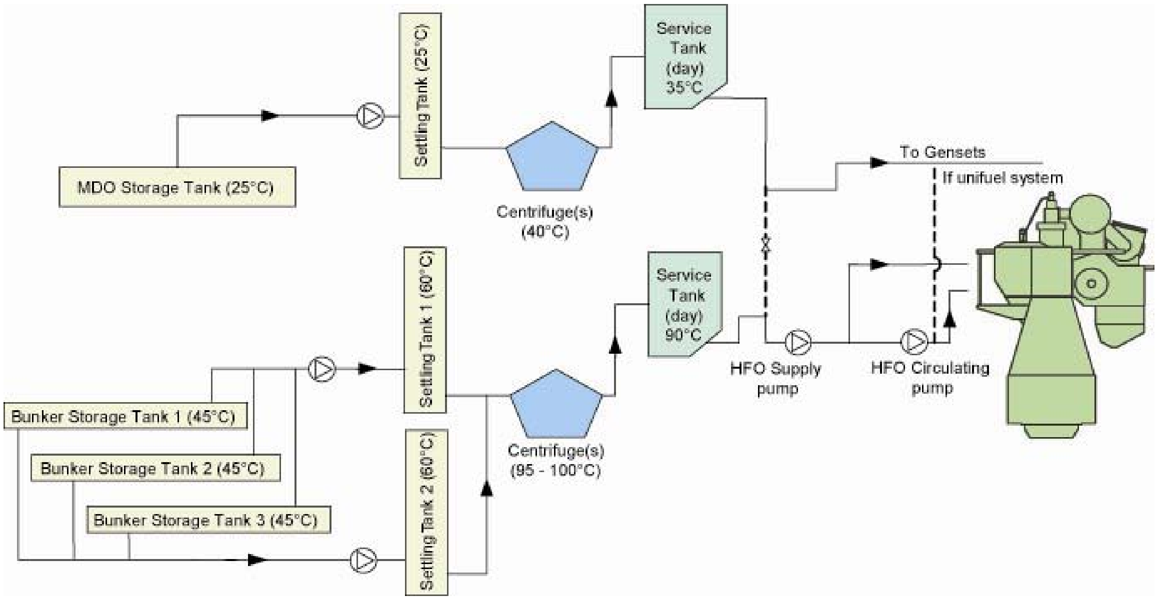

Figure 6-4. Fuel System with One MDO Settling Tank and Two IFO Settling Tanks

Source: MAN B&W Diesel A/S (MAN B&W). 2005. *Operation on Low Sulphur Fuels: Two-Stroke Engines*. Published November 26, 2005.

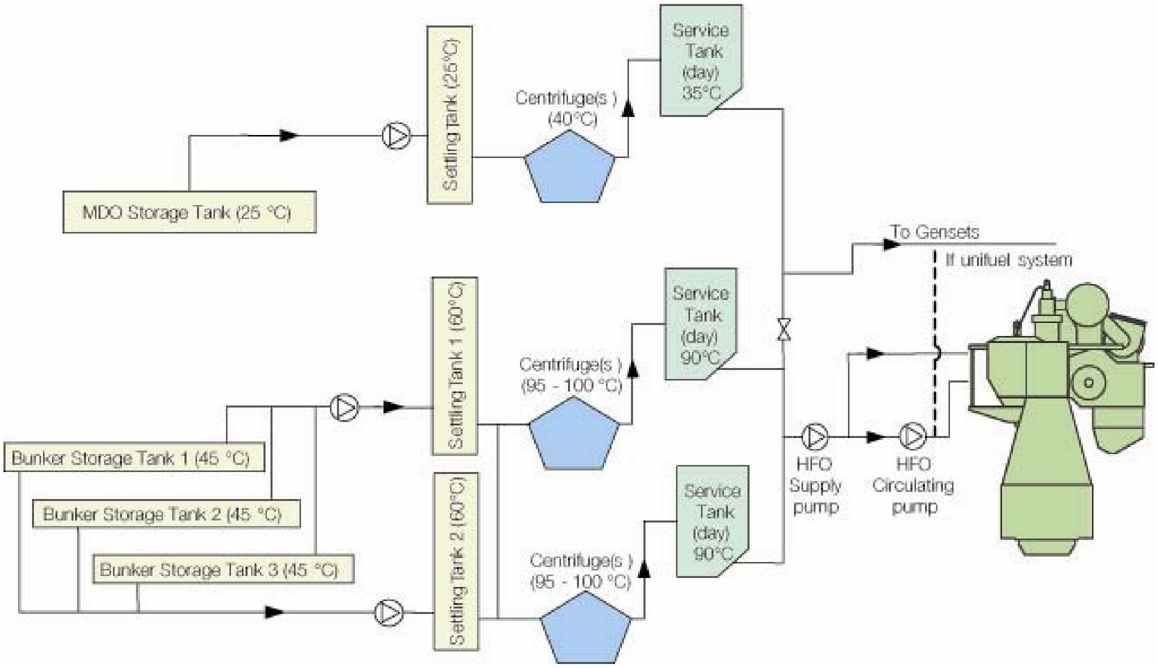

Figure 6-5. Fuel System with One MDO Settling Tank and Two Sets of IFO Settling and Service Tanks

Source: MAN B&W Diesel A/S (MAN B&W). 2005. *Operation on Low Sulphur Fuels: Two-Stroke Engines*. Published November 26, 2005.

6.1.3.4 Shipboard Fuel Oil Tankage

There has been concern expressed that ships do not have sufficient onboard storage capacity (i.e., tankage) to accommodate fuel switching in SECAs. Herbert Engineering Corp. (2007) addressed the issue of onboard fuel oil tankage in a presentation to CARB on July 24, 2007. Herbert described the common features for all ships' fuel oil tankage as follows:

- Ships devote the minimum space practical to fuel and machinery to maximize cargo.
- Minimal space is provided for distillate oil tanks on unifuel ships.
- Some ships have two IFO tank systems—one for IFO and one for LSIFO.

The most common arrangement is for one IFO tank system with multiple IFO tanks. The IFO tank system will include IFO storage tanks, an IFO settling tank, and an IFO service (or day) tank. The distillate oil system will usually have one or more MDO/MGO storage tank(s) and a corresponding service (or day) tank. Typical fuel tank capacities for oil tankers are shown in Table 6-1. Typical fuel tank capacities for containerships are shown in Table 6-2.

Table 6-1. Fuel Tank Capacities for Oil Tankers

Tank Type/Size	IFO Tankage Description	IFO Capacity (m^3)	MDO/MGO Tankage Description	MDO Capacity (m^3)
50,000 DWT Panamax	2 IFO storage, 1 settling, and 1 service tank	1,500	1 storage and 1 service tank	150
110,000 DWT Aframax	4 IFO storage, 1 settling, and 1 service tank	3,000	1 storage and 1 service tank	250
160,000 DWT Suezmax	4 IFO storage, 1 settling, and 1 service tank	4,000	1 storage and 1 service tank	350
300,000 DWT VLCC	4 IFO storage, 2 settling, and 1 service tank	5,500	1 storage and 1 service tank	450

Source: Herbert Engineering Corp. 2007, July. "Fuel Oil Systems." Paper presented at the California Air Resources Board Working Group on Fuel Switching.

Table 6-3 includes the at-sea cruising range (with a 15% reserve) for each ship type when burning MDO/MGO in both the main engine and auxiliary engines, based on the fuel oil tank capacities from Tables 6-1 and 6-2.

Table 6-2. Fuel Tank Capacities for Containerships

Tank Type/Size	IFO Tankage Description	IFO Capacity (m^3)	MDO/MGO Tankage Description	MDO Capacity (m^3)
2,500 TEU Feedership	6 IFO storage, 1 settling, and 1 service tank	3,200	1 storage and 1 service tank	300
4,000 TEU Panamax Containership	8 IFO storage, 1 settling, and 1 service tank	7,000	1 storage and 1 service tank	350
6,000 TEU Post-Panamax Containership	10 IFO storage, 2 settling, and 1 service tank	8,000	1 storage and 1 service tank	400
9,000 TEU Post-Panamax Containership	12 IFO storage, 2 settling, and 2 service tanks	10,000	2 storage and 1 service tank	800

Source: Herbert Engineering Corp. 2007, July. “Fuel Oil Systems.” Paper presented at the California Air Resources Board Working Group on Fuel Switching.

Table 6-3. Ship Fuel Ranges When Fuel Switched to MDO/MGO

Ship Type/Size	Range (days)	Range (nautical miles)
50,000 Panamax Tanker	3.3	1,200
110,000 Aframax Tanker	3.5	1,300
160,000 Suezmax Tanker	3.6	1,300
300,000 VLCC	3.3	1,200
2,500 TEU Feedership	2.6	1,300
4,000 TEU Panamax Containership	1.9	1,100
6,000 TEU Post-Panamax Containership	1.7	1,000
9,000 TEU Post-Panamax Containership	1.8	1,100

Source: Herbert Engineering Corp. 2007, July. “Fuel Oil Systems.” Paper presented at the California Air Resources Board Working Group on Fuel Switching.

Herbert Engineering Corp.’s (2007) analysis concludes that existing distillate oil tank capacities should be sufficient to accommodate main and auxiliary engine operation in SECAs. The analysis also concludes that existing engines and fuel oil systems are suitable for continuous operation on distillate.

6.1.3.5 Maersk Pilot Fuel Switch Initiative

Maersk, the world’s largest containership operator, has entered into a voluntary program in which all vessels calling at California ports switch main and auxiliary engines from IFO fuel to MDO/MGO with a sulfur content of less than 0.2% when within 24 nautical miles of Los Angeles and Oakland. This program started with the *M/V Sine Maersk’s* voyage on March 31,

2006. As of April 2007, 78 different vessels involving 298 fuel switches were involved in this study. The containerships involved are all large, slow-speed, 2-stroke diesel engines made by either MAN B&W or Wartsila (Sulzer). The ships operate at sea on residual fuels (either RMH 380/700 or RMK 380/700). In California waters, they use either DMA or DMB (with DMX carried for emergency generators and lifeboat engines). All ships are equipped with separate service tanks for residual and distillate fuels.

Fuel switches are carried out per engine manufacturers' instructions with no special training for the crew provided. The change is considered normal engineering practice. No problems have been encountered to date with regard to the fuel changeover. The changeover only has engines running on LSFO for short periods of time and does not require change in cylinder lubrication oil.

6.1.4 Other Approaches to Using Low-Sulfur Fuels in SECAs

Besides the obvious switching from IFO to low-sulfur fuel oil using existing shipboard systems, other approaches to using low-sulfur fuels in SECA include full-time switching to low-sulfur fuel oil, onboard blending of IFO and MDO/MGO to achieve low-sulfur fuel, and installation of a separate low-sulfur fuel oil fuel system.

6.1.4.1 Full-Time Fuel Switching

Full-time fuel switching, also referred to as "fuel converting," is permanently converting from high-sulfur to low-sulfur fuels. Converting to distillate fuel from traditional residual fuel has occurred in several shipping fleets in California and the EU. Converting to low-sulfur distillates does not require new equipment, but, as discussed above, it does require use of a different lubricating oil.

Fuel cleanliness has a direct effect on the wear and tear of engine components that come into contact with heavy fuel or the byproducts of heavy fuel combustion. Slow- and most medium-speed engines can run on low-sulfur distillates; however, owners accept fuel-cleaning costs and increased engine maintenance in exchange for heavy fuel oil's lower price (Rowan et al., 2005). Implicit in this economic trade-off are the advantages to combusting only distillates that offset the price premium (Fisher and Lux, 2004). Specific advantages of converting to distillates include the following:

- Conversion avoids fuel heating prior to injection to the combustion chamber. Distillates are bunkered at the ambient temperature, and their low viscosity permits ships to avoid heating systems dedicated to making the fuel more manageable. Consequently, maintenance costs and inconvenience are expected to be lower.

- Conversion requires less extensive settling, centrifuge, or filtration (fuel pretreatment) systems, lowering maintenance costs and inconvenience.
- Conversion entails using lower BN lubricants (40BN or 50BN), which are less expensive than higher BN lubricants (70BN).
- Conversion enables greater fuel efficiency, because the energy content per unit of distillate fuel is greater than that of heavy fuel oil.

Several studies of ships converting to low-sulfur marine distillate fuel have found reduced maintenance and higher fuel efficiency with the low-sulfur distillates. There are few current examples of converting to low-sulfur fuels from conventional heavy fuel oils. Although this conversion may require additional operational changes in lubricating oils and the fuel heating system (to ensure proper viscosity at the fuel injectors), the primary hindrance to fuel conversion is the higher price of the low-sulfur fuels.

For smaller vessels that travel primarily within SECAs, conversion to 100% low-sulfur fuels is likely to be the most economic option. For larger vessels that operate a significant portion of the time outside of SECAs, fuel switching is likely to be the most economic compliance option.

INTERTANKO submitted a proposal to the MARPOL convention’s Annex VI working group to designate the whole world as a SECA. This proposal would entail large-scale fuel conversion.

6.1.4.2 Onboard Blending

Ships may acquire blended fuels from suppliers or may blend fuels onboard. It is preferable for ships to acquire blended fuels from suppliers that run blend optimization programs. Ships’ fuel systems are not designed with fuel blending per se, and suppliers’ optimization programs can determine the optimum price, viscosity, density, flash point, ash content, and sulfur content (Fisher and Lux, 2004). To avoid fuel incompatibility, ships segregate fuels of different origins and types and submit fuel samples to independent testing laboratories to confirm each fuel’s properties. If ship engineers blend fuels onboard, it is incumbent upon them to optimize the blended fuel.

Ships have two options for blending: steady-state blending and transient blending. In a steady-state configuration, MDO is continuously blended with conventional IFO (Wartsila, 2006b). The advantage of blending IFO and LFO is that the ship avoids carrying low sulfur IFO, which, in turn, circumvents complex changes to the fuel supply and bunkering systems. The tradeoff is increased consumption of more expensive MDO. The fuel supply system would require a blending unit to blend the IFO and MDO to reach the required fuel sulfur content.

In a transient fuel-blending system, the settling tank is topped with low sulfur IFO, while still containing IFO. When in the SECA, the blending unit injects MDO into the fuel supply system until the sulfur content of the combined IFO and low sulfur IFO coming from the day tanks meets compliance standards (Wartsila, 2006b).

6.1.4.3 Installation of a Separate Low Sulfur Fuel Oil System

Installing a separate low sulfur fuel oil fuel system (including injectors), such as is done on LNG tankers (dual fuel diesel engines burning both residual fuel and LNG boil-off), is the likely next-generation response to SECA fuel switching; because the fuels would be entirely isolated, a separate low sulfur fuel oil fuel system would avoid fuel compatibility, viscosity, and thermal shock issues.

6.1.5 Emissions Reduction Potential

The emissions reduction potential of fuel switching, in terms of grams per horsepower-hours, depends on the baseline fuel grade and the fuel grade selected for use in SECAs. Because of the linear relationship between sulfur content and SO_x, emissions reduction potential can be reasonably estimated.

The components of exhaust gas emissions from ships are NO_x, SO_x, CO, CO_2, HC, and particulates. On average, the sulfur content of heavy fuel oil consumed by marine engines is around 2.7% (MAN B&W, 2004, 2005). The three principal inputs required for an engine to produce work are air, fuel, and lubricating oil (Figure 6-6). The exhaust gas will consist of nitrogen, CO_2, oxygen, and various pollutants.

Pollutants are measured as concentrations in the exhaust gas. If the engine is running on 3% sulfur fuel, then its exhaust gas is estimated to contain approximately 600 parts per million by volume (vppm) SO_x. For 2.5% sulfur, 74% of emissions is N_2, 11.3% is O_2, 8.1% is H_2O, 6% is CO_2, and 0.3% is pollutants. Of those pollutants, 0.25 g/kWh is PM, and 10 g/kWh is sulfur (Koehler and Windelev, 2001).

Total emissions reduction potential from ships fuel switching in SECAs is dependent on a number of factors and will vary by number of vessels, vessel type, estimated time spent in and outside of SECAs, engine type, load factors, and fuel selection. The actual emissions reduction

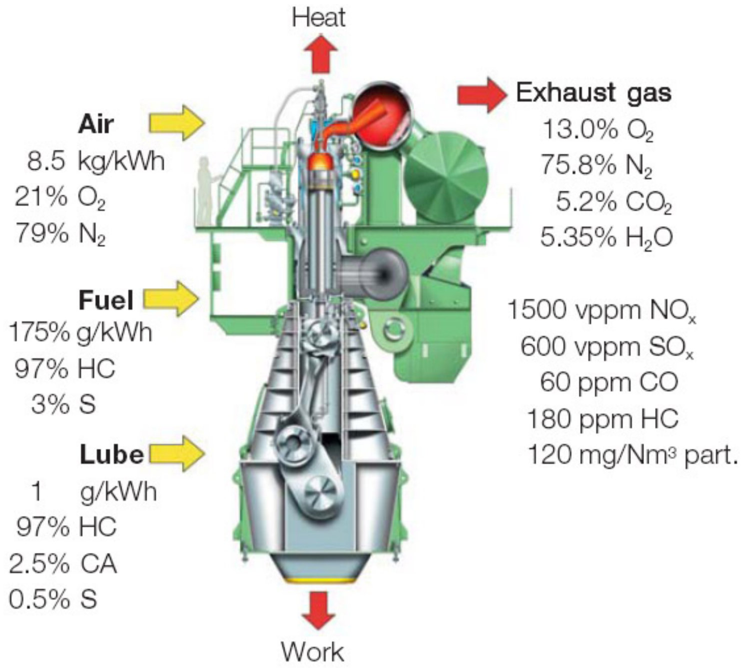

Figure 6-6. Components of Marine Diesel Engine Exhaust Gas

Source: MAN B&W Diesel A/S (MAN B&W). 2004. *Emission Control: MAN B&W Two-Stroke Diesel Engines*. Published January 9, 2004.

any one ship experiences will further vary because of differing equipment designs, maintenance, and operating conditions (Entec, 2005b).

Recent original studies that calculated the emissions reduction potential for fuel switching have measured the emissions reduction potential of fuel switching from the global average of 2.7%S IFO to 1.5%S IFO or 0.5% MDO, including the 2002 and 2005 Entec studies commissioned by the Directorate General–Environment for the European Commission to estimate SO_x emissions in European waters. The study found that switching from 2.7% sulfur to 1.5% or 0.5% sulfur reduces SO_x emissions by 44% or 81%, respectively.

6.2 Exhaust Gas Scrubbing

An alternative to fuel switching or fuel converting is exhaust gas cleaning using seawater scrubbing systems. Exhaust gas scrubbing systems are a mature technology for land-based applications that have recently been adapted for use by ships (Entec, 2005a), although only a few ship trials have taken place. Scrubbers transfer SO_2 from ships' exhaust gas to seawater, which is then cooled and filtered before discharge into the seas. Exhaust gas scrubbing using seawater is believed to be an effective alternative because of seawater's natural alkalinity and because seawater contains a large amount of sulfur naturally, making it a relatively safe reservoir (Entec, 2005b).

6.3 Description of Scrubber Technology

Scrubbing systems have four key components: (1) the scrubbing unit installed on the exhaust stack, (2) water supply and discharge systems, (3) a water filtration plant, and (4) a settling tank for solids (Figure 6-7). The scrubber is large and fitted on top of the exhaust pipe. It removes SO_x from exhaust gases by mixing gases and seawater in a turbulent cascade (Marine Exhaust Solutions [MES], 2007). Scrubbed exhaust gases are then ventilated from the system, and contaminated water is discharged into a filtration system that removes soot and solids. The filtration system diverts the soot and solids into a settling tank for removal in port or combustion in the ships' incinerator(s). Filtered discharge water is split into two streams, one of which passes through a heat exchanger before being discharged overboard below the ship's lowest waterline. The second stream returns to the water circulation system to provide cooling. The manufacturer MES states that the discharge water meets or exceeds EPA Clean Water Act requirements and that its systems are capable of removing 80% to 95% of SO_x, depending upon water temperature and salinity.

The maritime industry is very skeptical regarding the claim by MES that the scrubber effluent stream will meet or exceed EPA Clean Water Act requirements for discharge within a port area or even in offshore portions of the U.S. Exclusive Economic Zone (EEZ). There is concern that the pH of the effluent stream will be so low as to necessitate a stainless steel handling system and, probably, a stainless steel holding system for shore-side discharge. There are also serious concerns regarding the cost and availability of shore-side reception facilities. If discharge of the effluent stream is banned within the SECA (some of which will likely be no-discharge zones), the effluent stream must be contained and possibly treated before discharge. The IMO discharge rules for sulfuric acid are rigorous and may affect the discharge of the effluent stream and require significant dilution before discharge is permitted.

Ship owners will incur increased capital, retrofit, or maintenance expenses to bunker the same pre-SECA fuel grade when operating in SECA. Scrubbing systems required additional maintenance and add complexity to ships' mechanical systems, as well as higher electrical demand. Exhaust gas scrubbing emerged as a compliance alternative because of the limited availability of low-sulfur fuel.

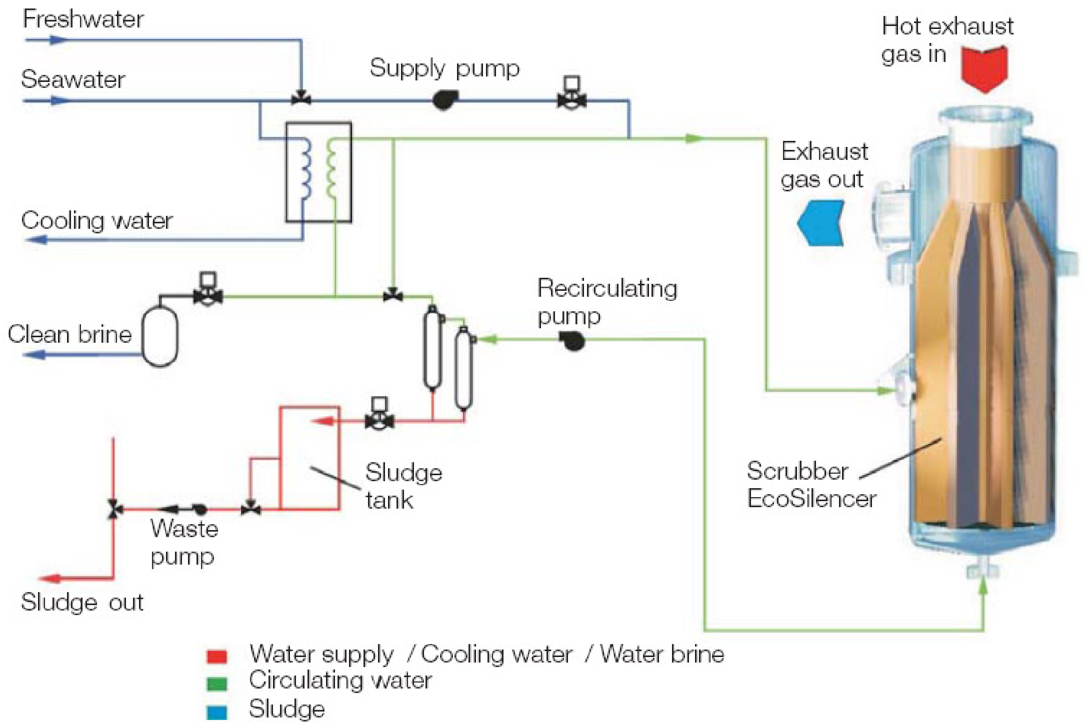

Figure 6-7. EcoSilencer Exhaust Gas Scrubber

Source: MAN B&W Diesel A/S (MAN B&W). 2004. *Emission Control: MAN B&W Two-Stroke Diesel Engines*. Published January 9, 2004.

6.4 Scrubber Penetration Scenarios

As an alternative to the use of low-sulfur fuel, EPA is considering a program in which ships would have the option of using exhaust gas cleaning units, such as SO_x scrubbers. The purpose of this discussion is to estimate the potential penetration of scrubber technology on ocean-going ships and the effects this would have on the demand for low-sulfur marine fuel.[3] The penetration of scrubbers into the market would likely be dependent on the relative cost of operating on low sulfur fuel versus using scrubbers and the availability of resources to install scrubbers.

In the near term, it does not seem reasonable that every ship owner who would benefit economically from the use of a scrubber would necessarily have the opportunity to install a scrubber. There are two limiting factors. First, there is a limitation on demand. In the near term, only a small portion of the fleet would be replaced with new vessels. Scrubber installations

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[3] The standards under consideration would apply to engines on all vessels propelled by Category 3 marine engines (i.e., engines with a per cylinder displacement of 30 liters or greater). For simplicity, the term "ship" is intended to represent these vessels.

would be expected to be easier for new ships. For a retrofit, the ship would need to be taken out of service. It may be that the schedule for periodic major maintenance on the ship would not allow for a scrubber installation. Also, it may not be economical to retrofit an older ship that may be near the end of its service life. Second, there may be a limitation on supply. Scrubber manufacturers are largely still developing their systems and may not be able to meet high scrubber demand. In the long term, it may be more reasonable to estimate scrubber penetration based simply on consideration of cost.

EPA provided RTI with scrubber penetration scenarios for 2012 and 2020. For each scenario, Table 6-4 presents both the percentage of ships projected to use scrubbers and the corresponding percentage of fuel used on these ships.

Table 6-4. Near- and Long-Term Scrubber Penetration Scenarios in the U.S. EEZ

Estimate	Percentage	2012	2020
Low Estimate	% ships	0%	0%
	% fuel	0%	0%
Medium Estimate	% ships	NA	5%
	% fuel	NA	31%
High Estimate	% ships	1%	10%
	% fuel	5%	47%

Source: EPA Estimates.

In both years, the low scrubber penetration scenario is the null case. In other words, all of the vessels operating in the EEZ would use low sulfur distillate fuel. For the high scrubber penetration scenarios, it should be noted that the percent of fuel affected is higher than the percent of ships affected. This is due to the expectation that scrubbers would be applied first to ships operating more often in the SECAs. This is reasonable given that these vessels, without a scrubber, would be subject the highest fuel switching costs.

6.5 Summary Remarks

Enhancing efficiency through engine design does little to reduce SO_x emissions beyond the reductions resulting from burning less fuel of the same sulfur content. The accepted practice among ship owners is to use lower sulfur fuels to reduce SO_x emissions because of the linear relationship between the sulfur content of fuels and SO_x emissions. Fuel switching is expected to be one of the primary compliance options selected by many vessel types. Until recently, such changeovers between fuels with major differences in viscosity were only carried out before a major engine overhaul or prolonged engine shutdown. However, with ships operating both within and outside of SECAs, fuel switching may occur more often, requiring routine changeover procedures and systems. Engine manufacturers and marine engineering experts believe that fuel switching can be implemented safely—but with varying degrees of complexity based on ships' individual fuel system configurations—so long as proper procedures and operating protocols are followed. Recent original studies have measured the emissions reduction potential of fuel switching from the global average of 2.7% sulfur IFO to 1.5% sulfur IFO or 0.5% sulfur MDO. The studies found that switching from 2.7% sulfur to 1.5% or 0.5% sulfur reduces SO_x emissions by 44% or 81%, respectively. An alternative approach to fuel switching may be the use of exhaust gas scrubbers.

SECTION 7

SECA FUEL CONSUMPTION ESTIMATES

This section estimates the volume of bunker fuels consumed in 2012 and 2020 under two mileage zone scenarios. The first scenario designates a SECA boundary in U.S. territorial waters at 100 nm off the Pacific Coast and 50 nm off the East and Gulf Coasts. The second scenario designates a SECA boundary at 200 nm off the East, Gulf, and Pacific Coasts.

Using the baseline estimates calculated in Section 3 as the primary input, we generated SECA fuel consumption estimates. The methodologies discussed in this section continue the bunker fuel demand forecast discussion; thus, the focus here is on estimating the amount of fuel forecasted in Section 3 that is consumed within the SECA boundaries. The forecasts from this section were inserted into the WORLD modeling cases as the affected fuel volumes in Section 8.

7.1 Summary of the SECA Fuel Consumption Modeling Approach

In general, estimating the amount of bunker fuel consumed within SECA boundaries involved reviewing U.S.-related trade routes, estimating whether and to what extent ships would alter their routing to minimize travel within the SECA, and calculating the volume of fuel consumed within the SECA boundaries. As such, the primary input for the SECA fuel consumption analysis was the time series of bunker fuel consumption from Section 3 disaggregated by route and by commodity type. The discussion in this section does not reiterate the activity-based methodology for developing the time-series data; rather, this discussion focuses on how fuel consumption in U.S. trading routes was apportioned to the SECA.

Key steps in the SECA fuel consumption analysis included

- isolating the trading routes, voyage characteristics, and fuel consumption estimates for U.S.-related shipping activity;
- calculating the distance traveled within the SECA boundaries for each route;
- estimating whether ships would adjust routing to optimize time spent within the SECA;
- calculating the number of days each voyage spent in U.S. ports; and
- apportioning estimated intra-SECA fuel consumption estimates by major U.S. SECA zones by reviewing the distance each voyage traveled within the zones.

This analysis also estimated port of purchase for SECA fuel consumption for input into the WORLD model.

7.2 SECA Scenario Boundaries

There are five distinct regions for which fuel consumption estimates were generated, as established by the U.S. coastline:

1. North Pacific, including the Alaskan Coast from Kodiak Island east and south to the Oregon-California land border
2. South Pacific, including all U.S. waters off the coast of California
3. Gulf Coast, covering U.S. waters from Brownsville, Texas, to the Florida Keys
4. East Coast, encompassing U.S. waters from the Florida Keys and the Straits of Florida to Maine
5. Great Lakes, including all of Lake Michigan and U.S. waters of the other four lakes up through the end of the U.S. portion of the St. Lawrence River at Cornwall Island

EPA requested that RTI provide fuel consumption estimates for two SECA mileage zone scenarios: (1) one in which the SECA boundary is set at 100 nm off the Pacific Coast and 50 nm off the East and Gulf Coasts and (2) the other in which the SECA boundary is set at 200 nm off the Pacific, East, and Gulf Coasts. Apart from the varying distances at which the SECA boundary was placed, the two SECA scenarios share the following characteristics:

- The SECA boundary in the North Pacific is just east of Kodiak Island, Alaska; the Bering Sea and U.S. territorial waters established by the Aleutian Islands are excluded from the SECA.
- Western Canadian waters are assumed to be part of the SECA; innocent passage of U.S.-related voyages (i.e., commodities, containers, Jones Act, and other vessels) in Western Canadian waters is included in the U.S. North Pacific SECA fuel consumption estimates.
- U.S. territorial waters in the Great Lakes are included in the SECA.
- U.S. territorial waters established by Hawaii are excluded from the SECA scenarios.
- U.S. territorial waters established by overseas territories and protectorates are excluded from the SECA, with the exception of Puerto Rico, which is included in the East Coast estimates.

7.3 Estimating Distances Traveled within SECA Boundaries

In brief, RTI and Navigistics reviewed the industry-standard distance, voyage time, and routing information employed in the global fuel consumption analysis to identify distance traveled within the SECA. We used the ratio of distance traveled in SECA to total distance traveled to apportion global at-sea fuel consumption estimates. We derived in–U.S. port fuel consumption estimates by reviewing the ports of call and assigning relevant in-port fuel consumption to the SECA.

Each international commodity, international container, and Jones Act voyage was reviewed under both the 200 nm and the 100/50 nm boundary scenarios. As discussed in Section 3, data from Worldscale (2002), Maritime Chain (2005)—which is based on underlying BP Shipping Marine Distance Tables—and *Containerization International* (Degerlund, 2005) provided key routing data needed to develop the activity-based fuel consumption estimates. We reviewed the same data for this component of the analysis. RTI and Navigistics reviewed trading routes and frequency of service at major ports to calculate the mileage each voyage spent in the SECA under both of EPA's scenarios. For domestic noncargo ships, deployment, cruise, and fish catch data were used to approximate the proportion of activity occurring within the SECA boundaries because, with the exception of cruise ships, these vessels do not follow established routes.

Navigistics also optimized ship routing to accommodate the SECA's SO_x emissions requirements where it was likely that a ship would exit the SECA and reenter at another point. Few adjustments were made under the 200 nm scenario; however, some voyages on the East Coast that included more than one U.S. port were optimized to minimize in-SECA travel.

All trading routes were reviewed, after which it was known for all voyage, cargo type, and ship-type combinations under the 100/50 nm and 200 nm SECA scenarios:

- the optimized, in-SECA route distance, including mileage within multiple SECA regions;
- the number of ports called on within each SECA region; and
- the proportion of total distance traveled.

Incorporating this information with the fuel consumption results from the base case enabled RTI to determine the quantity of IFO380, IFO180, and MDO/MGO consumed at sea and in port within each SECA region.

7.4 100/50 nm SECA Fuel Consumption Estimates

Under the 100/50 nm scenario, a total of 3.7 million tons of fuel is consumed by international trading vessels (Table 7-1) in 2012. Including the domestic fleet brings total fuel consumption to 7.5 million tons in 2012 (Table 7-2).

In 2020, international trading ships consume 4.9 million tons of fuel within the 100/50 nm SECA boundary (Table 7-3). Including domestic ships, total SECA fuel consumption amounts to 8.9 million tons (Table 7-4).

Table 7-1. 2012 SECA Fuel Consumption Estimates at 100/50 nm, International Trading Ships

Commodity Group	Region	IFO380 (thousand tons)	IFO180 (thousand tons)	MDO/MGO (thousand tons)	Total (thousand tons)
International Commodities Trade	US_Great_Lakes	96	33	17	145
	US_Gulf	394	223	63	681
	US_North_Pacific	78	41	21	141
	US_South_Pacific	49	35	19	103
	US_East	170	135	44	349
	SECA Subtotal	787	467	164	1,417
International Container Trade	US_Great_Lakes				
	US_Gulf	139	119	19	276
	US_North_Pacific	56	97	11	164
	US_South_Pacific	354	292	46	692
	US_East	579	521	79	1,179
	SECA Subtotal	1,129	1,028	155	2,311
International Trade Subtotal	US_Great_Lakes	96	33	17	145
	US_Gulf	533	342	82	957
	US_North_Pacific	135	137	32	304
	US_South_Pacific	404	326	65	795
	US_East	749	655	123	1,527
	SECA Subtotal	56,112	8,546	6,923	3,728

Source: Authors' calculations.

Table 7-2. 2012 SECA Fuel Consumption Estimates at 100/50 nm, All Ships

Commodity Group	Region	IFO380 (thousand tons)	IFO180 (thousand tons)	MDO/MGO (thousand tons)	Total (thousand tons)
International Trade Subtotal	US_Great_Lakes	96	33	17	145
	US_Gulf	533	342	82	957
	US_North_Pacific	135	137	32	304
	US_South_Pacific	404	326	65	795
	US_East	749	655	123	1,527
	SECA Subtotal	56,112	8,546	6,923	3,728
Domestic Fleet (Jones Act and Other Vessels)	US_Great_Lakes	100	57	231	389
	US_Gulf	409	84	289	782
	US_North_Pacific	352	73	341	766
	US_South_Pacific	248	52	534	834
	US_East	373	64	583	1,020
	SECA Subtotal	1,482	331	1,978	3,791
Total SECA	US_Great_Lakes	195	90	248	533
	US_Gulf	942	426	370	1,739
	US_North_Pacific	487	210	373	1,070
	US_South_Pacific	651	379	599	1,629
	US_East	1,122	720	706	2,547
	SECA Total	3,398	1,825	2,296	7,519

Source: Authors' calculations.

Table 7-3. 2020 SECA Fuel Consumption Estimates at 100/50 nm, International Trading Ships

Commodity Group	Region	IFO380 (thousand tons)	IFO180 (thousand tons)	MDO/MGO (thousand tons)	Total (thousand tons)
International Commodities Trade	US_Great_Lakes	98	33	17	149
	US_Gulf	424	242	68	734
	US_North_Pacific	83	44	21	148
	US_South_Pacific	54	38	21	114
	US_East	184	145	48	377
	SECA Subtotal	844	503	176	1,523
International Container Trade	US_Great_Lakes				
	US_Gulf	204	175	27	406
	US_North_Pacific	76	129	15	220
	US_South_Pacific	551	454	72	1,078
	US_East	859	738	115	1,712
	SECA Subtotal	1,690	1,497	229	3,416
International Trade Subtotal	US_Great_Lakes	98	33	17	149
	US_Gulf	628	417	95	1,141
	US_North_Pacific	159	173	36	368
	US_South_Pacific	606	492	93	1,191
	US_East	1,043	884	162	2,089
	SECA Subtotal	2,533	2,001	404	4,938

Source: Authors’ calculations.

Table 7-4. 2020 SECA Fuel Consumption Estimates at 100/50 nm, All Ships

Commodity Group	Region	IFO380 (thousand tons)	IFO180 (thousand tons)	MDO/MGO (thousand tons)	Total (thousand tons)
International Trade Subtotal	US_Great_Lakes	98	33	17	149
	US_Gulf	628	417	95	1,141
	US_North_Pacific	159	173	36	368
	US_South_Pacific	606	492	93	1,191
	US_East	1,043	884	162	2,089
	SECA Subtotal	2,533	2,001	404	4,938
Domestic Fleet (Jones Act and Other Vessels)	US_Great_Lakes	102	58	240	399
	US_Gulf	426	86	336	849
	US_North_Pacific	340	70	337	747
	US_South_Pacific	250	52	548	850
	US_East	391	67	625	1,083
	SECA Subtotal	1,509	334	2,086	3,929
Total SECA	US_Great_Lakes	200	91	257	548
	US_Gulf	1,054	504	432	1,989
	US_North_Pacific	499	244	373	1,116
	US_South_Pacific	856	545	641	2,041
	US_East	1,434	951	787	3,172
	SECA Total	4,043	2,335	2,490	8,867

Source: Authors’ calculations.

7.5 200 nm SECA Fuel Consumption Estimates

Under the 200 nm scenario, a total of 8.2 million tons of fuel is consumed by international trading ships (Table 7-5) in 2012. Including the domestic fleet brings total fuel consumption to 13.5 million tons in 2012 (Table 7-6).

In 2020, international trading ships consume 10.7 million tons of fuel within the 100/50 nm SECA boundary (Table 7-7). Including domestic ships, total SECA fuel consumption amounts to 16.2 million tons (Table 7-8).

Table 7-5. 2012 SECA Fuel Consumption Estimates at 200 nm, International Trading Ships

Commodity Group	Region	IFO380 (thousand tons)	IFO180 (thousand tons)	MDO/MGO (thousand tons)	Total (thousand tons)
International Commodities Trade	US_Great_Lakes	96	33	17	145
	US_Gulf	1,421	331	176	1,928
	US_North_Pacific	115	42	28	185
	US_South_Pacific	129	46	37	212
	US_East	697	192	148	1,037
	SECA Subtotal	2,458	644	406	3,507
International Container Trade	US_Great_Lakes				
	US_Gulf	430	151	42	623
	US_North_Pacific	425	136	40	601
	US_South_Pacific	699	331	74	1,103
	US_East	1,570	616	157	2,343
	SECA Subtotal	3,124	1,234	313	4,670
International Trade Subtotal	US_Great_Lakes	96	33	17	145
	US_Gulf	1,851	482	218	2,551
	US_North_Pacific	539	178	69	786
	US_South_Pacific	828	377	111	1,315
	US_East	2,267	808	305	3,380
	SECA Subtotal	5,581	1,877	718	8,177

Source: Authors' calculations.

Table 7-6. 2012 SECA Fuel Consumption Estimates at 200 nm, All Ships

Commodity Group	Region	IFO380 (thousand tons)	IFO180 (thousand tons)	MDO/MGO (thousand tons)	Total (thousand tons)
International Trade Subtotal	US_Great_Lakes	96	33	17	145
	US_Gulf	1,851	482	218	2,551
	US_North_Pacific	539	178	69	786
	US_South_Pacific	828	377	111	1,315
	US_East	2,267	808	305	3,380
	SECA Subtotal	5,581	1,877	718	8,177
Domestic Fleet (Jones Act and Other Vessels)	US_Great_Lakes	125	60	241	427
	US_Gulf	688	104	340	1,132
	US_North_Pacific	598	123	732	1,452
	US_South_Pacific	366	71	591	1,028
	US_East	532	86	692	1,310
	SECA Subtotal	2,310	444	2,595	5,350
Total SECA	US_Great_Lakes	221	93	258	572
	US_Gulf	2,540	585	558	3,683
	US_North_Pacific	1,137	301	800	2,239
	US_South_Pacific	1,194	447	702	2,343
	US_East	2,800	895	996	4,691
	SECA Total	7,891	2,321	3,314	13,527

Source: Authors’ calculations.

Table 7-7. 2020 SECA Fuel Consumption Estimates at 200 nm, International Trading Ships

Commodity Group	Region	IFO380 (thousand tons)	IFO180 (thousand tons)	MDO/MGO (thousand tons)	Total (thousand tons)
International Commodities Trade	US_Great_Lakes	98	33	17	149
	US_Gulf	1,528	358	190	2,076
	US_North_Pacific	121	45	28	194
	US_South_Pacific	141	51	41	233
	US_East	748	207	159	1,114
	SECA Subtotal	2,636	693	435	3,765
International Container Trade	US_Great_Lakes				
	US_Gulf	630	222	61	914
	US_North_Pacific	573	183	54	810
	US_South_Pacific	1,089	514	115	1,719
	US_East	2,335	884	231	3,451
	SECA Subtotal	4,627	1,804	462	6,893
International Trade Subtotal	US_Great_Lakes	98	33	17	149
	US_Gulf	2,159	580	251	2,989
	US_North_Pacific	694	228	82	1,004
	US_South_Pacific	1,230	565	156	1,952
	US_East	3,083	1,091	390	4,564
	SECA Subtotal	7,264	2,497	897	10,658

Source: Authors’ calculations.

Table 7-8. 2020 SECA Fuel Consumption Estimates at 200 nm, All Ships

Commodity Group	Region	IFO380 (thousand tons)	IFO180 (thousand tons)	MDO/MGO (thousand tons)	Total (thousand tons)
International Trade Subtotal	US_Great_Lakes	98	33	17	149
	US_Gulf	2,159	580	251	2,989
	US_North_Pacific	694	228	82	1,004
	US_South_Pacific	1,230	565	156	1,952
	US_East	3,083	1,091	390	4,564
	SECA Subtotal	7,264	2,497	897	10,658
Domestic Fleet (Jones Act and Other Vessels)	US_Great_Lakes	129	61	252	443
	US_Gulf	707	107	401	1,214
	US_North_Pacific	578	119	722	1,419
	US_South_Pacific	369	71	607	1,046
	US_East	557	90	746	1,393
	SECA Subtotal	2,340	448	2,727	5,515
Total SECA	US_Great_Lakes	227	95	270	592
	US_Gulf	2,865	687	651	4,203
	US_North_Pacific	1,272	347	804	2,423
	US_South_Pacific	1,599	636	763	2,998
	US_East	3,639	1,181	1,136	5,957
	SECA Total	9,603	2,945	3,624	16,173

Source: Authors' calculations.

7.6 Fuel Consumption Comparison across SECA Scenarios

Figure 7-1 presents a comparison of SECA fuel consumption between the two mileage zone scenarios in 2012. Intra-SECA MDO and MGO fuel consumption is 44% greater, and IFO180 fuel consumption is 27% greater under the 200 nm scenario than under the 100/50 nm scenario. However, IFO380 fuel consumption more than doubles, from 3.4 million tons to 7.9 million tons. As such, total fuel consumption is nearly double under the 200 nm scenario.

Figure 7-2 presents a comparison of SECA fuel consumption between the two mileage zone scenarios in 2020. Intra-SECA MDO and MGO fuel consumption is 45% greater, and IFO180 fuel consumption is 26% greater under the 200 nm scenario than under the 100/50 nm scenario. However, IFO380 fuel consumption more than doubles, from 4.0 million tons to 9.6 million tons. As such, total fuel consumption is nearly double under the 200 nm scenario: 16.2 million tons versus 8.9 million tons.

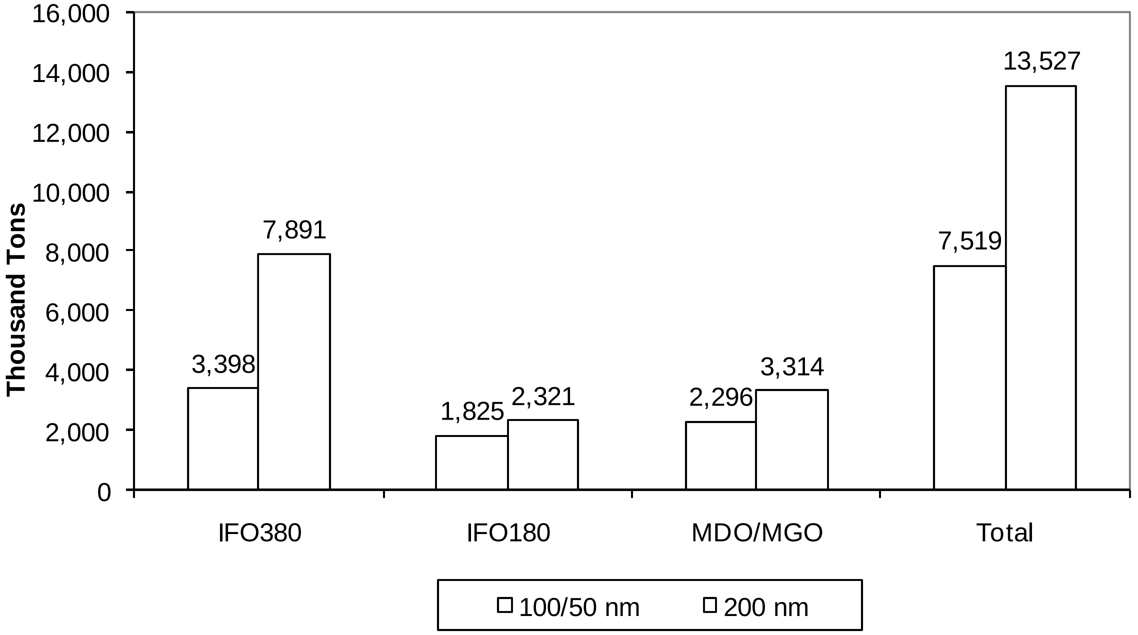

Figure 7-1. Comparison of SECA Fuel Consumption under Two Mileage Zone Scenarios, 2012

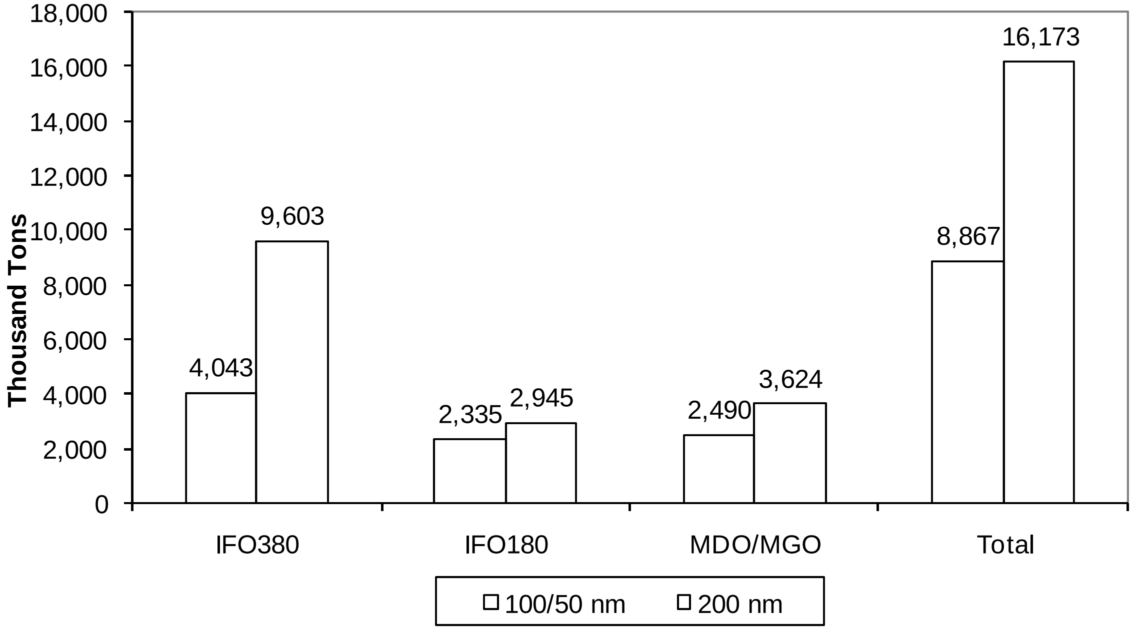

Figure 7-2. Comparison of SECA Fuel Consumption under Two Mileage Zone Scenarios, 2020

SECTION 8

SECA FUEL IMPACT ASSESSMENTS

This section presents the WORLD model results of the SECA designation under the two scenarios detailed in Section 7: (1) a SECA at 100 nm off the Pacific Coast and 50 nm off the Gulf and East Coasts and (2) a SECA at 200 nm off the Pacific, East, and Gulf Coasts. The WORLD model case runs were developed using the assessments of affected fuel volumes developed in Section 7 and EPA's scrubber penetration scenarios from Section 6.[1]

In addition, model run variants were undertaken for selected cases that added a Mexico SECA, with the same fuel-quality regulations that apply in the U.S. (including innocent passage in western Canada) cases. For the cases that include Mexico, we used a simplified approach. Rigorous route analysis was not conducted. The incremental affected fuel volume was taken as 10% of the fuel volume applying to the U.S. SECA cases. Seventy-five percent of the fuel was projected to come from the WORLD model's Greater Caribbean region (which includes Mexico), with the remaining 25% spread across the U.S. regions.

8.1 Summary

This subsection summarizes key results of the SECA fuel impact analysis; the rest of this section contains a more detailed discussion of the model cases and analytic results. As shown in Table 8-1, projected global marine bunker consumption for 2012 and 2020 is 406 million tons and 495 million tons, respectively. These projections correspond to an estimated demand of 358 million tons in 2007. Annual bunker demand growth rate through 2020 is just over 2.5%, which is appreciably higher than the growth rate for total global petroleum products projected by EIA when its 2006 Annual Energy Outlook is used as a reference case (1.4% per year) (EIA, 2006).

Global bunker consumption is composed of approximately 80% heavy IFO grades and 20% distillate grades (Figure 8-1). In 2012, the distillate grades are split between DMB-grade MDO (25%) and DMA-grade MGO (75%). Over time, the proportions of IFO and MDO are projected to increase moderately at the expense of MGO, reflecting increases in long-distance, large ship trade.

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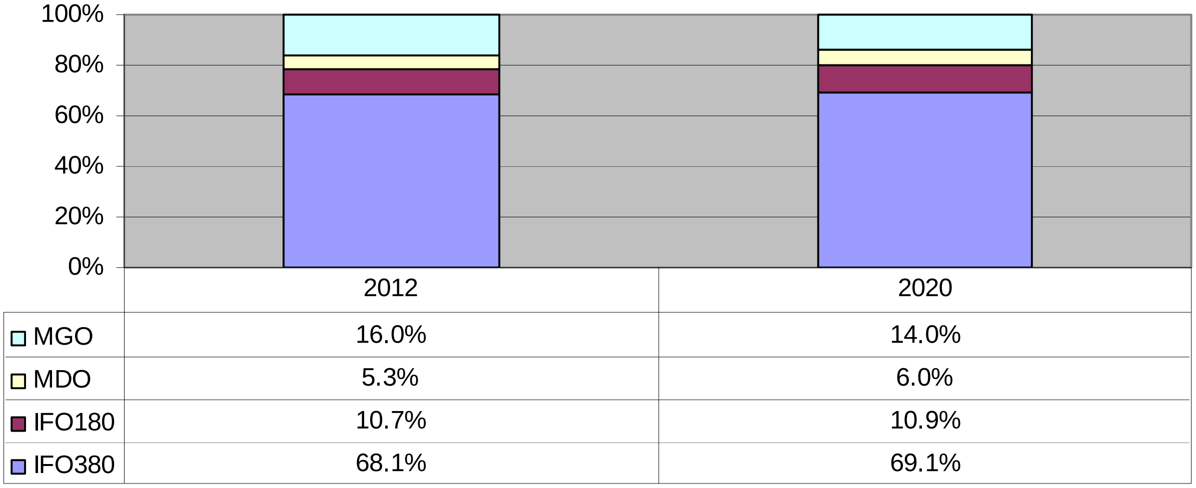
[1] This work was built on prior tasks undertaken for EPA, as well as assignments that EnSys and Navigistics performed for the American Petroleum Institute (API) and IMO. Those analyses, like this one for EPA, consider the refining investment, supply cost, and CO_2 emissions effects of potential marine fuels regulations. While the cases evaluated for API and IMO focused on global and multiple SECA scenarios, the cases evaluated here superimpose a range of potential North American SECA scenarios onto a base case that represents the status quo (i.e., current Annex VI regulations with SECAs at current standard in Northern Europe [Baltic and North Sea/Channel], plus the EU 0.1% sulfur rule on marine distillate). Insights gained through the API and IMO analyses were used mainly to set premises for base-case marine fuels qualities.

Table 8-1. Base Effects and Total Bunker Fuel Volumes

Total Marine Distillate Plus IFO—No Scrubbing				
	SECA-Affected Fuel Volumes			
	USA		USA/Canada/Mexico	Total Global Fuel Volumes
Year	100/50 nm	200 nm	200 nm	
	million tons/year	**million tons/year**	**million tons/year**	**million tons/year**
2007				357.9
2012	7.7	13.9	15.3	406.2
2020	9.6	16.6	18.2	495.3
	bpd	**bpd**	**bpd**	**bpd**
2012	143,000	255,900	281,300	7,428,800
2020	178,600	304,200	334,600	9,051,300
	percent	**percent**	**percent**	
2012	1.9%	3.4%	3.8%	
2020	1.9%	3.3%	3.7%	

Note: Includes innocent passage in western Canada.



	2012	2020
MGO	16.0%	14.0%
MDO	5.3%	6.0%
IFO180	10.7%	10.9%
IFO380	68.1%	69.1%

Figure 8-1. Makeup of Global Bunker Fuel, 2012 and 2020

The quantities of marine bunker fuels consumed in the United States are projected to be 34.9 million tons per year in 2012 and 40.9 million tons per year in 2020, corresponding to about 8.5% of the global fuel consumption total.

The SECA boundary scenarios, including an approximation for a Mexico SECA, yield a total fuel consumption ranging from 7.7 million tons per year (143,000 bpd) under the 2012 U.S. 100/50 nm scenario to 18.2 million tons per year (334,600 bpd) under the 2020 U.S. 200 nm plus

Mexico scenario. These levels equate to a range of 22% to 44% of U.S. bunker demand and approximately 1.9% to 3.8% of global bunker consumption.

Depending on the time horizon and SECA boundary scenario, approximately 68% to 80% of the affected fuel volume is projected to be consumed in the United States and Canada (Table 8-2). The proportions consumed in the United States are highest at the 100/50 nm zone and lowest at the 200 nm plus Mexico SECA zone. In addition, the proportions projected to be consumed in the United States decline slightly from 2012 to 2020. This shift reflects the increasing significance of international trade between the United States and other nations.

Table 8-2. Proportion of Affected Bunker Fuel Volumes in the United States and Canada

Total Marine Distillate Plus IFO—No Scrubbing			
	SECA-Affected Fuel Volumes		
	USA		USA/Canada/Mexico
Year	100/50 nm (percent)	200 nm (percent)	200 nm (percent)
2012	79.9%	74.9%	70.4%
2020	78.0%	72.0%	67.8%

Compliance with the projected North American SECA regulations will affect both distillate (MDO and MGO) and heavy (IFO) bunker fuels (unless scrubbers are used). All the model runs, save one, envisage conversion of MGO, MDO, and IFO grades at present-day standards to DMA MGO-quality at sulfur levels ranging from 0.5% to 0.1% (5,000 ppm to 1,000 ppm). Global MGO (DMA) base-case sulfur was set to 0.5% (5,000 ppm), and MDO (DMB) was set to 1.0% (10,000 ppm). As such, the primary effect of SECA standards with DMA at 0.5% (5,000 ppm), 0.2% (2,000 ppm), and 0.1% (1,000 ppm) sulfur relates to the cost of converting IFO to DMA. The costs attributable to sulfur reduction of MGO fuel already at DMA standard, or conversion of DMB-standard MDO at maximum 1.0% sulfur to DMA at lower levels, represent the minority of the conversion cost.[2] By far, the greater proportion of the total compliance cost will relate to conversion of the IFO bunker grades to DMA MGO standard. This will entail both upgrading and desulfurization; current global average IFO sulfur is around 2.7% (27,000 ppm). Percentage sulfur by weight is generally below 1% (10,000 ppm) for MDO and MGO.

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[2] Because MDO in the base cases is at DMB standard, there are some costs associated with the tighter viscosity, lower maximum density, and elimination of any carbon residue associated with a change to DMA. These are in addition to the costs of sulfur reduction.

Table 8-3 shows the volumes of IFO required to be upgraded to DMA-standard MGO under the different SECA scenarios analyzed and at the different scrubber-penetration levels used. For 2012, EPA advised a base level of scrubber penetration of 0% and a high level of 5%, implying that there is essentially no potential scrubber use until after 2012. For 2020, EPA advised a best estimate of 31% of fuel consumption used by ships outfitted with scrubbers, with a high estimate of 47% and a low of 0%. Thirty-one percent of fuel consumed by ships using scrubbers equates to a smaller proportion of all ships because it is expected that scrubbers would be fitted preferentially to larger ships with higher fuel consumption.

Table 8-3. Affected Bunker Fuel—IFO Shifted to Distillate

Alternative Mileage Zone and Scrubbing Scenarios				
		SECA-Affected Fuel Volumes		
		USA		USA/Canada/Mexico
Year	Scrubbing	1500/0 nm	200 nm	200/200 nm
		million tons/year	million tons/year	million tons/year
2012	0%	5.3	10.7	11.8
2012	5%	5.1	10.1	(11.2)
2020	0%	6.6	13.0	(14.4)
2020	31%	4.6	(9.0)	(10.0)
2020	47%	3.6	6.9	7.7
		bpd		
2012	0%	92,000	186,000	207,000
2012	5%	87,000	176,000	(196,700)
2020	0%	116,000	228,000	(256,600)
2020	31%	81,000	(157,300)	(177,000)
2020	47%	64,000	122,000	136,000

Notes: 1. Scrubbing usage level—percentage of fuel.
2. Figures in parentheses indicate WORLD case not run.

For 2012, the projected total volume of IFO to be converted to DMA-grade MGO is somewhat greater than 5 million tons per year (92,000 bpd) if the SECA boundary is set at 100/50 nm, essentially doubles at 200 nm, and increases by an additional 10% (to 11.8 million tons per year [207,000 bpd]) if Mexico is included.

For 2020, the range of IFO to be converted is estimated to be 6.6 million tons to 14.4 million tons per year (116,000 bpd to 256,600 bpd) if there is no use of scrubbers. However, this range drops to 4.6 million to 10.0 million tons per year (81,000 bpd to 196,700 bpd) under

EPA's "best estimate" of 31% scrubber use. Under the high estimate of 47% scrubber penetration, the range of IFO to be converted reduces to 3.6 million tons to 7.7 million tons per year (64,000 bpd to 136,000 bpd).

One implication of this finding is that, if scrubber use becomes significant by 2020, then the volumes of IFO that will need to be converted to MGO will potentially be no larger—and quite possibly smaller—in 2020 than in 2012. The analytic results show that the largest refining and cost effects potentially will occur in 2012, because scrubber penetration by 2020 reduces the fuel volumes to be converted, both in absolute terms and as a percentage of total global bunker and oil products demand.

Overall, it should be kept in mind that these analyses relate to a small proportion of total global oil demand of around 0.16% to 0.32% at 0% scrubbing, depending on SECA boundaries, dropping by up to half under 2020 high scrubber-use scenarios. In addition, the actual total volumes of future bunker fuel meeting SECA standards likely would be higher because other SECAs would come into effect.[3] The implementation of other SECAs or equivalent regulations would tend to raise costs for bunker fuel quality improvement or conversion to distillate.

Tables 8-4 through 8-6 summarize key results from the WORLD model cases.

Table 8-4 contains results from 2012 and 2020 cases at the 100/50 nm scenario for different sulfur levels, from 10,000 ppm to 1,000 ppm. Recall that all 2012 cases are at 0% scrubbing; for the 2020 cases at multiple sulfur levels, scrubbing penetration was assumed to be 47%.[4] As would be expected, costs increase with lower sulfur level and with use of DMA rather than IFO in 2012. The North American SECA affects fuel costs mainly in the United States and Canada. Marine fuel costs in these countries increase $1.16 to $1.35/barrel (bbl) in 2012 at 100/50 nm and increase $2.47 to $2.80/bbl at 200 nm.

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[3] The study was carried out with all regions outside North America at current 2007 regulations. Therefore, this study included the two Northern European SECAs and the EU 0.1% marine diesel rule, but excluded any other potential developments.

[4] Limits on the total number of cases mean that not all permutations of mileage zone, sulfur level, and scrubber use were run.

Table 8-4. Effects of the Bunker Fuel Standard and Sulfur Level

2012 and 2020 USA SECAs—100/50 nm							
Year	2012	2012	2012	2012	2020	2020	2020
Scrubber Penetration	0%	0%	0%	0%	47%	47%	47%
SECA Sulfur Level	**1.0%**	**0.5%**	**0.2%**	**0.1%**	**0.5%**	**0.2%**	**0.1%**
ppm	**10,000**	**5,000**	**2,000**	**1,000**	**5,000**	**2,000**	**1,000**
SECA Fuel	**IFO**	**DMA**	**DMA**	**DMA**	**DMA**	**DMA**	**DMA**
Cost and Investment Changes vs. Base Case							
Marine fuels global average cost ($/bbl)	$0.024	$0.126	$0.139	$0.148	$0.129	$0.150	$0.151
All products global average cost ($/bbl)	$0.005	$0.033	$0.037	$0.038	($0.003)	$0.003	$0.003
Marine fuels U.S. and Canada average cost ($/bbl)	$0.294	$1.164	$1.284	$1.353	$0.903	$0.952	$0.939
All products U.S. and Canada average cost ($/bbl)	$0.027	$0.069	$0.084	$0.090	$0.025	$0.029	$0.033
Global refining investment ($bn)	$0.14	$1.42	$1.36	$1.33	$0.98	$1.11	$1.38
Global Refinery and Marine Fuel CO_2 Emissions vs. Base Case							
Million tpa							
Global marine fuel	(0.47)	(1.18)	(0.51)	(0.37)	(0.64)	(0.15)	(0.28)
Global refinery	0.06	1.60	1.65	1.64	0.94	1.30	1.41
Combined	(0.41)	0.42	1.14	1.27	0.30	1.15	1.13
Combined—percentage change vs. base case	(0.02%)	0.02%	0.05%	0.06%	0.01%	0.04%	0.04%

For 2020, the increases at 0% scrubbing are $0.90 to $1.64/bbl at 100/50 nm and $1.64 to $3.02/bbl at 200 nm. At 47% scrubbing, the incremental U.S. marine fuel costs approximate $1.84/bbl. Marine fuels in other regions also are affected to a small degree, because part of the North American quality fuel is sourced outside the United States. Consequently, global marine fuels costs increase by around $0.13 to $0.29/bbl depending on the scenario, for both 2012 and 2020, except that the 2020 increase at 200 nm and 0% scrubbing is estimated at $0.39/bbl.

Enacting the North American SECA increases the proportion of distillates in the U.S., Canadian, and global product pools and reduces the proportion of residual-type fuels. Consequently, nonbunker distillate costs rise, costs of residual fuels drop slightly, and costs of other products are affected slightly. At 0.5% to 0.1% DMA standards, total U.S. petroleum product costs rise by $0.070/bbl to $0.240/bbl in 2012 and $0.023/bbl to $0.070/bbl (at 47% scrubbing) in 2020. Global total product costs also are affected.

In the 2020 cases, global refining investment is estimated to increase. In 2012, the reverse trend is found. *Prima facie*, this is contrary to expectation but, as mentioned elsewhere, the affected fuel volumes are a small proportion of global fuel demand. Thus, the model is incurring increasing product supply costs with lower sulfur in 2012, but is doing so by making small changes in blends and refining operations and capacity additions such that total investment decreases slightly.

Because only small proportions of global fuels are changing quality or type under the SECA scenarios, the effects on global marine fuel and refining emissions are small. Broadly, increases in refinery CO_2 emissions driven by increases in processing intensity are offset partially by reductions in the CO_2 emissions from marine fuels combustion, such that there are small net increases, mainly less than 0.10%, excluding the effects of petroleum coke.[5]

Table 8-5 indicates that switching from a 100/50 nm scenario to a 200 nm SECA boundary scenario approximately doubles incremental costs. For instance, 2012 U.S. marine fuel costs rise by $1.35/bbl at 100/50 nm and by $2.70/bbl at 200 nm. Incremental global refining investment also doubles from $1.33 billion to $2.55 billion, although these increases are against a base-case total investment from 2006 to 2012 of $219.6bn. At high scrubber-penetration levels, projected effects in 2020 are smaller than those in 2012.

Table 8-6 illustrates the effect of scrubber use in 2020. Incremental marine fuel costs and refining investments drop proportionately with the percentage of marine fuel that must meet the SECA standard. Thus, U.S. marine fuel costs drop from $1.63/bbl at 0% scrubbing to $0.94/bbl at 47% scrubbing.

8.2 Basis of WORLD Model Cases for SECA Fuels' Effects

The following summarizes the WORLD model cases run for 2012 and 2020, the projected affected volumes of marine fuels under the North American SECA scenarios, the methodology employed for iterating on bunker demand, and key premises for marine fuels' qualities.

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[5] The authors caution that the effects on CO_2 emissions, especially in some cases, are so small that they are approaching the limits of precision of the model.

Table 8-5. Effect of Mileage Zone and Mexico SECA

2012 and 2020 USA SECAs—100/50 and 200/200 nm						
Year	2012	2012	2012	2020	2020	2020
SECAs	U.S.	U.S.	U.S./ Can/Mex	U.S.	U.S.	U.S./ Can/Mex
Mileage Zone	100/50	200/200	200/200	100/50	200/200	200/200
Scrubber Penetration	0%	0%	0%	47%	47%	47%
SECA DMA Sulfur Level	**0.1%**	**0.1%**	**0.1%**	**0.1%**	**0.1%**	**0.1%**
ppm	**1,000**	**1,000**	**1,000**	**1,000**	**1,000**	**1,000**
Cost and Investment Changes vs. Base Case						
Marine fuels global average cost ($/bbl)	$0.15	$0.26	$0.29	$0.15	$0.24	$0.26
All products global average cost ($/bbl)	$0.04	$0.10	$0.11	$0.00	$0.01	$1.01
Marine fuels U.S. and Canada average cost ($/bbl)	$1.35	$2.70	$2.80	$0.94	$1.64	$1.77
All products U.S. and Canada average cost ($/bbl)	$0.09	$0.22	$0.23	$0.03	$0.07	$0.07
Global refining investment ($bn)	$1.33	$2.55	$2.86	$1.38	$2.63	$2.89
Global Refinery and Marine Fuel CO2 Emissions vs. Base Case						
Million tpa						
Global marine fuel	(0.37)	(0.45)	(0.97)	(0.28)	(1.80)	(0.18)
Global refinery	1.64	3.16	3.25	1.41	2.39	2.46
Combined	1.27	2.70	2.27	1.131	0.59	2.28
Combined—percentage change vs. base case	0.06%	0.12%	0.10%	0.04%	0.02%	0.09%

Table 8-6. Effect of Scrubber Penetration

2020 0.1% Sulfur DMA USA SECAs—100/50 nm			
Scrubber Penetration	**0%**	**31%**	**47%**
Cost and Investment Changes vs. Base Case			
Marine fuels global average cost ($/bbl)	$0.24	$0.19	$0.15
All products global average cost ($/bbl)	$0.008	$0.004	$0.003
Marine fuels U.S. and Canada average cost ($/bbl)	$1.63	$1.20	$0.94
All products U.S. and Canada average cost ($/bbl)	$0.07	$0.04	$0.03
Global refining investment ($bn)	$2.50	$1.70	$1.38
Global Refinery and Marine Fuel CO2 Emissions vs. Base Case			
Million tpa			
Global marine fuel	(1.6)	(1.1)	(0.3)
Global refinery	2.3	1.8	1.4
Combined	0.7	0.7	1.1
Combined—percentage change vs. base case	0.03%	0.03%	0.04%

8.2.1 *Cases Run*

Table 8-7 sets out the 26 cases that were analyzed in the WORLD model. Based on EPA guidance, 10,000 ppm cases (which retained the current IFO/MDO/MGO grade structure) were run only for 2012. The main emphasis was on cases requiring conversion of affected fuel volumes to medium- (5,000 ppm) or low-sulfur DMA standard fuel (2,000 ppm or 1,000 ppm). The differing sulfur levels were combined with permutations of nautical mileage zones, Mexico SECA designation, and scrubber penetration to probe sensitivity effects. Note that what would be the most costly case for 2020—at 1,000 ppm, 0% scrubbing, 200 nm (plus Mexico)—was not requested and has not been run; therefore, the results for 2020 should be considered in this light.

Table 8-7. Summary of WORLD Cases—Revised

Summary of Model Runs	Time Horizons (2012/2020)	Mileage Zones	Number of SECA Regions	Sulfur Levels	Scrubber Penetration Rates	Total WORLD Case Runs
High Sulfur—2012	2012	100/50	1	10,000	0%, 5%	2
Medium Sulfur—2012	2012	100/50	1	5,000	0%	1
Low Sulfur 2,000 ppm—2012	2012	100/50 200/200	1	2,000	0%	2
Low Sulfur 1,000 ppm—2012	2012	100/50 200/200	1	1,000	0%, 5%	4
Medium Sulfur—2020[a]	2020	100/50 200/200	1	5,000	0%, 31%, 47%	5
Low Sulfur 2,000 ppm—2020	2020	100/50 200/200	1	2,000	47%	2
Low Sulfur 1,000 ppm—2020[b]	2020	100/50 200/200	1	1,000	0%, 31%, 47%	4
Mexico Runs: 10% fuel increase to approx. Mexico						
Medium/Low Sulfurs—2012	2012	200/200	1	5,000 2,000 1,000	0%	3
Medium/Low Sulfurs—2012	2020	200/200	1	5,000 2,000 1,000	47%	3
Total Runs	—	—	—	—	—	26

[a] 31% penetration was run only at 100/50 nm.

[b] Only 47% penetration was run at 200 nm.

8.2.2 *Bunker Quality Premises*

The WORLD cases were run with the following bunker quality premises. These premises are the same as those used in parallel work undertaken by EnSys and Navigistics for the IMO:

1. Recent analyses of sample data undertaken by DNV, together with feedback from the bunker departments of major oil companies, have confirmed that (a) marine distillates are overwhelmingly either DMA or DMB, not DMC, and that (b) the majority of global distillate sold is at DMA standard. (This is doubtless driven, in part, by constraints in the oil companies' logistics/distribution systems.) The updated findings on marine distillates were incorporated into the base cases:
   - MGO fuel was kept universally as DMA grade and MDO set to DMB standard.
   - Based on findings from the IMO work, a 70:30 split of MGO:MDO was applied to the total distillate volumes in each region.
   - The volume of MGO was further increased—and that of MDO reduced—in the EU regions to reflect the EU 0.1% sulfur rule. Base-case MGO in the EU regions was thus already at 0.1% sulfur.

   The net effect was to arrive at an approximate **75:25 ratio globally of MGO (DMA) to MDO (DMB)** in the base cases.

2. Based on sample test results and commentary from DNV, **maximum density and viscosity specifications for DMA and DMB** were set based on allowing small increments over current reported worldwide averages (see Table 8-8).[6]

3. Base-case global average **sulfur levels for DMA and DMB** were set to 0.5% and 1.0% sulfur nominal, respectively. The same DNV sample results mentioned above show current average levels of 0.35% and 0.55% (Kassinger, 2007). These are well below the ISO 8217 specification limits for DMA and DMB of 1.5%. There are arguably conflicting forces that will be at play through 2020. Logistical constraints and the progressive reduction of sulfur levels in other diesel fuels and gas oils likely will constrain increases in DMA and DMB sulfur levels. Conversely, refiners can be expected to seek opportunities wherever possible to optimize against specifications, with the potential that DMA and DMB sulfur levels would therefore rise.[7] If marine fuel volumes increase and if price differentials versus other diesel/gas oil grades increase, refiners and blenders will have greater incentives to segregate marine fuels and produce them closer to their (sulfur) specifications. The view was taken to follow a middle path of allowing modest increases (i.e., to 0.5% and 1.0% nominal sulfur), to reflect both sets of factors.

4. **Carbon residue content** (MCR) **on DMB** was set to 0.05% by weight maximum. DNV reported a 0.1% global average but also reported that part of the fuel ordered as DMB is actually delivered as DMA, indicating that what is considered in WORLD as DMB (i.e., MDO in the base case) should have a lower MCR than 0.1%. Also, bunker fuel testing generally is assumed to take place at downstream stages in the bunkering supply system, where contamination may have occurred. Thus, the quality at the refinery or blender can be expected to be tighter than that tested. Allowing 0.05%

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[6] The maximum density for DMA was set at 0.860 versus 0.890 specification and 0.853 reported global average; the maximum density for DMB was set at 0.875 versus 0.900 specification and 0.865 global average. Maximum viscosities were set at 3.8 cSt and 4.5 cSt at 40°C versus global averages of 3.5 cSt and 4.2 cSt and ISO 8217 specifications of 6 cSt and 11 cSt at 40°C maximum.

[7] In the 2012 and 2020 base cases, current Annex VI (ISO 8217 2005) fuels regulations apply.

carbon residue in WORLD for DMB creates a situation where a proportion of (light) vacuum gas oil is allowed into the DMB blends. To meet sulfur and viscosity specifications, lighter (heavy kerosene) streams are also added to the blend. The authors believe such blends may not be in accord with current blending practice (i.e., that the appreciable vacuum gas oil content is not realistic). However, setting carbon residue at nil would have locked out vacuum gas oils totally and thus increased the costs for DMB in the base case, which would have raised the costs of the SECA cases versus the base cases.

5. The **EU 0.1% rule** was implemented by shifting MDO to MGO specification at 0.1% sulfur DMA standard. Based on data supplied by IMO, Cofala et al. (2000) data corresponded to approximately 50% of EU marine distillate being at the 0.1% sulfur standard. Consequently, 50% of the base MDO volume for Europe (North South and East) was reallocated and added to MGO. The remaining 50% stayed as MDO, of which, 70% was presumed to come under SECA standard (Europe North in the base case and all three European regions in the multiple SECA cases).
6. Maximum **sulfur level for the two IFO grades** was set to 3.5% nominal (3.4% actual limit). As for DMA and DMB, the rationale was based on comparison of the current specification (4.5%) with actual data. DNV data show regional average sulfur levels for IFO fuel in the range of 2.3% to 3.4%, with an overall global average of 2.7% (see Table 8-9). The authors believe that this average sulfur level can be expected to gradually move upward over time (under current regulations), as crude sulfur levels rise and pressure on sulfur grows, leading to high sulfur residual fuels being a convenient sink. Conversely, (a) there are logistical constraints on residual fuel supply such that IFO fuels are at times co-sold as high-sulfur inland fuels, which often have a 3.5% maximum sulfur, and (b) it is understood that the IMO would act to constrain any sharp increase in IFO sulfurs. However, it was not the intention to create base cases that would have required appreciable “on-purpose” residual desulfurization, which would have been the case had the current average of 2.7% been selected. As with the marine distillates, 3.4% was considered to represent a reasonable middle path.[8]

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[8] As discussed in Section 8.3, the selection of a 3.4% maximum led to a global average IFO in the 2020 base case of just over 3.2% sulfur. Also, the case lead to only a small increase (24,000 bpd) in residual desulfurization versus the API 2020 base case. That case, with a 4.5% nominal ±0.2% giveaway had IFO global average sulfur at 3.56%. The situation that resulted in the EPA 2020 base case was considered reasonable.

Table 8-8. DNV Petroleum Services Bunker Quality Report

	Sulfur % m/m			
	Average		Max	
Region	IFO180	IFO380	IFO180	IFO380
Northern Europe	1.9	2.3	2.8	4.3
Western Mediterranean	2.9	3.0	3.6	3.8
Central Mediterranean	2.6	2.6	3.5	3.6
Middle East	3.4	3.4	4.2	3.9
Eastern USA	2.7	2.4	3.9	4.3
USA Gulf	3.1	3.2	3.7	4.2
Western USA	2.6	2.4	3.4	3.1
Far East	2.8	3.1	4.1	4.5
Average	2.6	2.7	3.6	4.1

Note: Issued August 10, 2006.

8.2.3 Bunker Fuel Demand Projections

The RTI/Navigistics bunker demand projections originally developed in 2006 for EPA under Task 1 were adjusted to employ different MGO/MDO grade splits, as described above. We applied rigorous analysis of trade routes and volumes to assess volumes of marine fuel that would need to meet U.S./Canadian SECA standards. For 2012, this led to a projection of nearly 80% of the affected fuel being consumed in the United States and Canada, with the percentage somewhat lower in 2020. Table 8-10 provides an overview.

8.2.4 WORLD Model Weight/Volume Features and Bunker Methodology

Although WORLD was developed as a volume-based model, it also includes extensive weight-based features. Specifically, these features are as follows:

1. Every refinery unit processing vector is weight and sulfur balanced to within tight tolerances.
2. As well as drawing up a volume balance—which allows for process gain—a supply/demand weight-balance check is undertaken at the global level. This check uses static gravities for most products and supply streams, including major products. Crude gravities are a direct function of individual crude production volumes. The model is capable of accepting adjustments to the global average blend gravities used. Future extensions could lead to automation of this model based on the computed actual gravities of blended products.

Table 8-9. Comparison of Fuel Grade Specifications

			Category ISO-F-				Test Method Reference
Characteristic	**Unit**	**Limit**	**DMX**	**DMA**	**DMB**	**DMC**[a]	
Density at 15°C	kg/m^3	max	—	890,0	900,0	920,0	ISO 3675 or ISO 12185 (see also 7.1)
Viscosity at 40°C	mm^2/s [b]	min	1,40	1,50	—	—	ISO 3104
		max	5,50	6,00	11,0	14,0	ISO 3104
Flash point	°C	min	—	60	60	60	ISO 2719
		max	43	—	—	—	(see also 7.2)
Pour point (upper)[c]							
Winter quality	°C	max	—	−6	0	0	ISO 3016
Summer quality	°C	max	—	0	6	6	ISO 3016
Cloud point	°C	max	−16[d]	—	—	—	ISO 3015
Sulfur	% (*m/m*)	max	1,00	1,50	2,00[e]	2,00[e]	ISO 8754 or ISO 14596 (see also 7.3)
Cetane index	—	min	45	40	35	—	ISO 4264
Carbon residue on 10% (V/V) distillation bottoms	% (*m/m*)	max	0,30	0,30	—	—	ISO 10370
Carbon residue	% (*m/m*)	max	—	—	0,30	2,50	ISO 10370
Ash	% (*m/m*)	max	0,01	0,01	0,01	0,05	ISO 6245
Appearance[f]	—	—	Clear and bright		f	—	See 7.4 and 7.5
Total sediment, existent	% (*m/m*)	max	—	—	0,10[f]	0,10	ISO 10307-1 (see 7.5)
Water	% (V/V)	max	—	—	0,3[f]	0,3	ISO 3733
Vanadium	mg/kg	max	—	—	—	100	ISO 14597 or IP 501 or IP 470 (see 7.8)
Aluminum plus silicon	mg/kg	max	—	—	—	25	ISO 10478 or IP 501 or IP 470 (see 7.9)
Used lubricating oil (ULO)						The fuel shall be free of ULO[g]	
Zinc	mg/kg	max	—	—	—	15	IP 501 or IP 470
Phosphorus	mg/kg	max	—	—	—	15	IP 501 or IP 500
Calcium	mg/kg	max	—	—	—	30	IP 501 or IP 470 (see 7.7)

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[a] Note that although predominantly consisting of distillate fuel, the residual oil proportion can be significant.

[b] 1 mm^2/s = 1 cSt

[c] Purchasers should ensure that this pour point is suitable for the equipment on board, especially if the vessel operates in both the northern and southern hemispheres.

[d] This fuel is suitable for use without heating at ambient temperatures down to −16°C.

[e] A sulfur limit of 1.5% *(m/m)* will apply in SO$_x$ emission control areas designated by the International Maritime Organization, when its relevant protocol enters into force. There may be local variations, for example the EU requires that sulphur content of certain distillate grades be limited to 0.2% *(m/m)* in certain applications. See 8.3 and reference [7].

[f] If the sample is clear and with no visible sediment or water, the total sediment existent and water tests shall not be required. See 7.4 and 7.5.

[g] A fuel shall be considered to be free of used lubricating oils (ULOs) if one or more of the elements zinc, phosphorus, and calcium are below or at the specified limits. All three elements shall exceed the same limits before a fuel shall be deemed to contain ULOs.

Table 8-10. Affected and Total Fuel Volumes, Million Tons per Year

Affected and Total Fuel Volumes million tons per year			
	Affected Fuel Volumes under United States SECAs		
	100/50 nm	200nm	Total Fuel Volumes
2012	7.67	13.95	406.2
2020	9.56	16.58	495.3

3. A more rigorous methodology has been adopted for marine fuels, as described below.
4. The weight balances achieved at the global level are generally in the range of 0.2% weight to 0.5% weight.

Given the existence of bunker demand projections on a weight basis, and the need to account for the effects of bunker types changing from one class to another (notably IFO to DMB or DMA distillate), we applied a rigorous, iterative approach to computation of bunker demand tons, barrels, and related energy content.

There appears to be confusion regarding the fact that, when bunker demand is switched from IFO to distillate fuel type, the amount of fuel required on a weight basis drops, while the amount of fuel required on a volume basis rises. Table 8-11 illustrates this computation.

The lighter fuels have higher heating value per unit mass. Therefore, based on the specific gravities used for illustrative purposes in Table 8-11,[9] 0.936 tons of DMA delivers the same heating value as 1.000 tons of IFO380; in other words, fewer tons of DMA are needed. However, there are large differences in the specific gravities and, hence, in barrels per ton. Again, based on the specific gravities used, DMA has a specific volume of 7.44 bbl/ton as compared with 6.46 bbl/ton for IFO380, a factor of 1.152 to 1.000. Thus, DMA has a heating value of 5.909 million BTU/barrel compared with 6.373 million BTU/barrel for IFO380. Also, 1.0785 barrels of DMA are required deliver the same heating value as 1.0000 barrels of IFO380 (i.e., 6.3730/5.9090 = 1.0785). A similar rationale applies for other fuel conversions (e.g., for IFO180 to DMA, DMB to DMA).

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[9] The specific gravities shown here are not the precise gravities that evolved in the WORLD base case or other cases, but they are close. The values used here are intended to illustrate the effect and the typical volume factors that we obtained. Actual volume factors were developed and applied in each WORLD case through the iteration procedure to converge on consistent tons, barrels, and energy figures.

Table 8-11. Computation of Heating Values and Weight and Volume Factors for the Same Energy Content

Bunker Grade	Sulfur wt%	s.g. Estimated	API Gravity	HHV BTU/lb[a]	HHV million BTU/ton	Tonnes Required for Same HHV vs. IFO380	bbls/ ton	bbls/ tonne ratio	HHV million BTU/bbl	Barrels Required for Same HHV vs. IFO380
MGO DMA	0.20%	**0.845**	36.0	19,954	43,979	**0.936**	7.4426	1.1521	5.909	**1.0785**
MDO DMB	0.45%	**0.8606**	32.9	19,779	43,594	**0.944**	7.3077	1.1312	5.965	**1.0683**
MDO DMC	1.50%	**0.900**	25.7	19,364	42,679	0.965	6.9878	1.0817	6.108	1.0435
IFO 180	3.00%	**0.968**	14.7	18,728	41,276	0.997	6.4969	1.0057	6.353	1.0031
IFO 380	3.00%	**0.9735**	13.9	18,680	41,172	**1.000**	6.4602	1.0000	6.373	**1.0000**

[a] Basis as MEPC formulae.

All the relevant conversions to allow for energy content and density effects were built into WORLD. Unlike all the other fuels, the source data for bunker demand per RTI and Navigistics are in tons. An iterative procedure was consequently adopted. The bunker-tons figures by grade were multiplied by assumed gravities to give initial volumes (million bpd). A first-pass case was then run. Global average gravities for each bunker grade were extracted from the model case results and fed back into the input to adjust the bunker volumes derived from the initial figures in tons. If necessary, the iteration was repeated to ensure stable gravities. This procedure was used to establish a converged base case.

For subject cases, the iterative procedure with the MEPC energy content formulae enabled computation of volume factors for each shift (i.e., IFO180 and IFO380 to DMA, DMB to DMA), taking into account the energy effect on a BTU per barrel basis and which were based on fuel global average gravities.[10] Again, the case was iterated to ensure stable blend gravities. In this way, the main energy content effects of bunker grade shifts were captured by altering the volume demand and, at the same time, consistency was maintained between the bunker demand figures in tons and in barrels.

The effect of this situation is that partial or total conversion of IFO to distillate leads to a reduction in the total global tons of bunker fuel required but also leads to an increase in the barrels required. These effects are evident in the WORLD case results.

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[10] The global average gravities by bunker fuel type are built up from the barrels, gravities, and tons of demand in each region.

8.2.4.1 Model Reporting Extensions

Reporting extensions developed under the EnSys and Navigistics work for the IMO have been applied to the model reports here. Specifically, we applied the following:

1. bunker fuels' demand in weight, as well as in volume units
2. base 2006 capacities by major unit type by region and "allowed" project capacity additions by major unit by region (these are added in WORLD to the base refining capacities so that the model selects what is needed on top of base capacity plus known construction)
3. the total investment by region associated with the allowed projects, which then provides a picture—when added to the base-case investments selected by WORLD—of the total base-case investment needed over the 2006 base capacities and better enables the magnitude of the subject-case incremental investments to be put into context
4. regional reports on internal refinery energy consumptions and refinery CO_2 emissions

In addition, case results for the United States and Canada are broken out.

8.3 Case Results Details

The following is an itemization of results categorized into refining investments, refining capacity additions, marine fuel costs, and CO_2 emissions. These categorizations act to extend the discussion presented in Section 8.1. They are presented in conjunction with Tables 8-12 through 8-15, which provide comparisons with the respective 2012 and 2020 base cases of key WORLD model results. These categorizations also form the basis of the tables presented in Section 8.1.

8.3.1 Global Refinery Investments and Capacities

Refinery investment increases versus the base cases for 2012 and 2020, respectively, are as follows:

- 2012
  - 10,000 ppm (IFO) + $0.14bn
  - 5,000 ppm–1,000 ppm (DMA) $1.3bn$1.4bn at 100/50 nm, rising to $2.5bn at 200/200 nm and to more than $2.8bn at 200/200nm + Mexico. Essentially all results are at 0% scrubbing.

- 2020
  - 5,000 ppm–1,000 ppm (DMA) $1bn–$2bn at 100/50 nm, rising to $2bn–$4bn at 200/200 nm. Scrubber use is the main determinant of investment level. Raising use from 0% to 47% essentially halves investment. Adding in the Mexico SECA raises global investment by around $0.2bn–$0.4bn

Capacity additions in 2012 cases center on small increments in vacuum distillation and hydro-cracking (mainly resid), VGO/residual desulfurization plus associated hydrogen, and sulfur recovery plant. The 2020 cases present a slightly different picture: they present vacuum distillation, but also coking and hydro-cracking as the main addition (mainly ULS VGO type), with partially offsetting reductions in ULS gasoline and diesel desulfurization, again supported by additions to hydrogen and sulfur plant.

U.S./Canadian refinery investments increase in all subject cases, but the bulk of the investments occur outside the United States and Canada. These two countries generally represent around 10% to 30% of the total incremental investment. Especially in 2012, U.S./Canadian refinery throughputs are projected to drop (from 31,000 bpd to 161,000 bpd), partially offset by increases elsewhere. For the 2020 cases, the effect is still there, although it is smaller.

8.3.2 Crude Supply Cost/Price Differentials

In the 2012 cases, crude differentials (stated as WTI – Mayan) widen by around 14 c/bbl under 100/50 nm scenarios, rising to around 35 c/bbl at 200/200 nm and 36 c/bbl to 41 c/bbl at 200/200 nm plus Mexico. Projected 2020 impacts on differentials are smaller.

8.3.3 Product/Marine Fuels' Costs

- 2012
  - Under the 10,000 ppm IFO scenario, low-sulfur IFO380 costs rise by $2.64–$2.92/bbl on the U.S. Gulf and East Coasts and $4.20/bbl on the West Coast. There are also changes from –2 c/bbl on the West Coast to +7 c/bbl on the Gulf Coast in MGO/MDO supply costs.
  - Under the DMA scenarios, marine distillate costs rise by $1.53–$2.51/bbl on the East Coast, $1.28–$2.23/bbl on the Gulf Coast, and $1.20–$3.95/bbl on the West Coast, with the higher levels corresponding to lower sulfur (1,000 ppm) and a 200/200 nm scenario.
  - U.S./Canadian supply costs of other distillate fuels also rise by up to 60 c/bbl and gasoline prices by up to 10 c/bbl; the IFO380 HS price drops.
  - Prices in other world regions are also affected.

- 2020
  - Projected increases in U.S./Canadian supply costs for marine distillate vary with the scenario and region: \$1.67–\$2.32/bbl on the East Coast, \$1.05–\$1.71/bbl on the Gulf Coast, and \$3.28–\$5.58/bbl on the West Coast, again depending on the DMA sulfur level, scrubber penetration, and mileage zone.
  - Trends in the costs of other products are similar to those for 2012 except that, in 2020, there are slight projected price drops for U.S./Canadian gasoline grades.

8.3.4 Total Fuel Costs (All Products from LPG to Coke, Including Gasoline, Distillates, and Marine Fuels)

- U.S./Canadian total fuel cost is most affected under the 2012 200/200 nm scenario because there is little or no projected mitigating scrubber penetration. Total costs rise by 0.04% to 0.46%, depending on the specific case. For 2020, the corresponding increases are 0.04% to 0.19%.
- Effects on total global cost across all fuels are indicated at 1 c/bbl to 4 c/bbl for 2012 under 100/50 nm cases and 10 c/bbl to 11 c/bbl under 200/200 nm. For 2020, the indicated effects are around 1 c/bbl.

8.3.5 CO_2 Emissions

- U.S./Canadian refinery CO_2 emissions are projected to rise in 2012 by 0.13 million tons to 0.85 million tons per year—with larger increases in other regions, ranging from 1.05 million tons to 2.5 million tons per year.
- For 2020, the U.S./Canadian refinery CO_2 increments are indicated at 0.02 million tons to 0.35 million tons per year. Elsewhere, the CO_2 increases are indicated at 0.80 million tons to 2.73 million tons per year, leading to total global increments of 0.98 million tons to 3.08 million tons per year. The larger increases in 2020 potentially reflect a world that already has a higher proportion of distillates in the base-case scenario and, thus, where the processing and CO_2 effects for additional conversion of residual streams to distillate are higher.
- Across all cases, global refinery CO_2 emission increases with petroleum coke CO_2 added in generally lie in the range of 2.7 million tons to 6.7 million tons per year.
- The marine fuels tons demanded decrease under the DMA cases; this is because of DMA's higher energy content per ton than IFO. The effects are small though, around 0.2 million tons to 0.7 million tons per year out of global marine fuel totals of 406 million tons per year in 2012 and 495 million tons per year in 2020. There are small reductions in associated marine fuel CO_2 emissions.
- These reductions partially offset the refinery CO_2 increases, leading to net increases on the order of 0.1% to 0.2%.

We reiterate that many of the changes in these EPA cases are small on a global scale. Consequently, even with the rigorous iteration procedure used to converge marine fuels weight, volume, and energy (see below), the precision of some of these very small effects on CO_2

emissions is limited, and the reader is cautioned not to associate too much precision with these very small changes.

8.4 Tabulated Results

Tabulated results comparing subject cases with base cases are presented in Tables 8-12 through 8-15.

Table 8-12a. WORLD Model Results—Changes vs. 2012/2020 Base Cases

WORLD Model Results - Changes vs 2012 / 2020 Base Cases

Year	**2012**	**2012**	**2012**	**2012**	**2012**	**2012**	**2012**	**2012**	**2012**	**2012**	**2012**	**2012**
Case	compare 10L-1 vs 1BA	compare 15L-1 vs 1BA	compare 12L-1 vs 1BA	compare 11L-1 vs 1BA	compare 12L-2 vs 1BA	compare 11L-2 vs 1BA	compare 15M-2 vs 1BA	compare 12M-2 vs 1BA	compare 11M-2 vs 1BA	compare 10B-1 vs 1BA	compare 11B-1 vs 1BA	compare 11B-2 vs 1BA
Type	100nm	100nm	100nm	100nm	**200nm**	**200nm**	**200nm**	**200nm**	**200nm**	100nm	100nm	**200nm**
MGO Fuel Type - North America SECAs	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA
MDO Fuel Type - North America SECAs	DMB	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMB	DMA	DMA
MGO Sulfur Limit - North America SECAs	0.5%	0.5%	0.2%	0.1%	0.2%	0.1%	0.1%	0.1%	0.1%	0.5%	0.1%	0.1%
MDO Sulfur Limit - North America SECAs	**1.0%**	**0.5%**	**0.2%**	**0.1%**	**0.2%**	**0.1%**	**0.5%**	**0.2%**	**0.1%**	**1.0%**	**0.1%**	**0.1%**
IFO Sulfur - North America SECAs	**1.0%**	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	**1.0%**	n.a	n.a
SECA Basis	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	**US/Can/ Mexico**	**US/Can/ Mexico**	**US/Can/ Mexico**	US/Can	US/Can	US/Can
Scrubber Usage	0%	0%	0%	0%	0%	0%	0%	0%	0%	**5%**	**5%**	**5%**
Marine Fuels Demands million bpd												
Grand Total Bunkers - Global	(0.003)	0.010	0.010	0.013	0.020	0.023	0.021	0.019	0.022	(0.005)	0.014	0.025
Grand Total Bunkers - USA/Canada	0.001	0.006	0.006	0.006	0.012	0.012	0.013	0.013	0.013	(0.000)	0.007	0.012
Grand Total Bunkers - Caribbean	0.001	0.001	0.001	0.001	0.002	0.002	0.003	0.003	0.003	0.001	0.001	0.001
Grand Total Bunkers - Other Regions	(0.005)	0.003	0.003	0.005	0.006	0.009	0.005	0.003	0.007	(0.006)	0.007	0.011
IFO HS Shifted to Distillate - million tpa	5.2	5.3	5.3	5.3	10.7	10.7	11.9	11.8	11.8	5.0	5.1	10.1
IFO HS Shifted to Distillate - million bpd	0.091	0.093	0.092	0.091	0.187	0.186	0.207	0.207	0.206	0.087	0.087	0.176
IFO HS Shifted to LS IFO/MGO % of Global Total IF	1.62%	1.64%	1.63%	1.62%	3.31%	3.30%	3.67%	3.66%	3.65%	1.55%	1.55%	3.11%
Marine Fuels Demands million tpa												
Grand Total Bunkers - All Regions - mmtpa	(0.2)	(0.4)	(0.2)	(0.2)	(0.7)	(0.3)	(0.6)	(0.5)	(0.5)	(0.6)	(0.3)	(0.4)
IFO HS Shifted to LS IFO/MGO - million tpa	5.2	5.3	5.3	5.3	10.7	10.7	11.9	11.8	11.8	5.0	5.1	10.1
Refining Investment $bn												
Global	$ 0.14	$ 1.42	$ 1.36	$ 1.33	$ 2.50	$ 2.55	$ 2.82	$ 2.83	$ 2.86	$ 0.13	$ 1.27	$ 2.43
USA/Canada	$ 0.11	$ 0.47	$ 0.47	$ 0.38	$ 0.45	$ 0.39	$ 0.58	$ 0.35	$ 0.36	$ 0.10	$ 0.40	$ 0.39
Other Regions	$ 0.04	$ 0.95	$ 0.89	$ 0.96	$ 2.06	$ 2.16	$ 2.24	$ 2.48	$ 2.50	$ 0.03	$ 0.88	$ 2.04
Percent of Total Investment in USA/Canada	74%	33%	35%	28%	18%	15%	20%	12%	13%	76%	31%	16%
Refinery Throughputs million bpd												
Global	0.001	0.008	0.006	0.009	0.016	0.020	0.019	0.014	0.020	(0.001)	0.011	0.022
USA/Canada	(0.031)	(0.102)	(0.117)	(0.118)	(0.151)	(0.141)	(0.161)	(0.121)	(0.108)	(0.031)	(0.113)	(0.137)
Other Regions	0.031	0.111	0.123	0.127	0.167	0.161	0.180	0.135	0.128	0.030	0.124	0.158

Table 8-12b. WORLD Model Results—Changes vs. 2012/2020 Base Cases

WORLD Model Results - Changes vs 2012 / 2020 Base Cases

Year	2012	2012	2012	2012	2012	2012	2012	2012	2012	2012	2012	2012
Case	compare 10L-1 vs 1BA	compare 15L-1 vs 1BA	compare 12L-1 vs 1BA	compare 11L-1 vs 1BA	compare 12L-2 vs 1BA	compare 11L-2 vs 1BA	compare 15M-2 vs 1BA	compare 12M-2 vs 1BA	compare 11M-2 vs 1BA	compare 10B-1 vs 1BA	compare 11B-1 vs 1BA	compare 11B-2 vs 1BA
Type	100nm	100nm	100nm	100nm	**200nm**	**200nm**	**200nm**	**200nm**	**200nm**	100nm	100nm	**200nm**
MGO Fuel Type - North America SECAs	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA
MDO Fuel Type - North America SECAs	DMB	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMB	DMA	DMA
MGO Sulfur Limit - North America SECAs	0.5%	0.5%	0.2%	0.1%	0.2%	0.1%	0.1%	0.1%	0.1%	0.5%	0.1%	0.1%
MDO Sulfur Limit - North America SECAs	**1.0%**	**0.5%**	**0.2%**	**0.1%**	**0.2%**	**0.1%**	**0.5%**	**0.2%**	**0.1%**	**1.0%**	**0.1%**	**0.1%**
IFO Sulfur - North America SECAs	**1.0%**	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	**1.0%**	n.a	n.a
SECA Basis	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	**US/Can/ Mexico**	**US/Can/ Mexico**	**US/Can/ Mexico**	US/Can	US/Can	US/Can
Scrubber Usage	0%	0%	0%	0%	0%	0%	0%	0%	0%	**5%**	**5%**	**5%**
Product Prices / Supply Cost $/bbl												
SECA DMA - USEC	$ 0.02	$ 1.53	$ 2.01	$ 2.22	$ 2.23	$ 2.47	$ 1.77	$ 2.28	$ 2.51	$ 0.02	$ 2.22	$ 2.45
SECA DMA - USGC	$ 0.07	$ 1.28	$ 1.76	$ 1.97	$ 1.99	$ 2.23	$ 1.52	$ 2.03	$ 2.26	$ 0.07	$ 1.97	$ 2.21
SECA DMA - USWC	$ (0.02)	$ 1.20	$ 2.15	$ 2.89	$ 2.72	$ 3.95	$ 1.49	$ 2.87	$ 4.02	$ (0.02)	$ 2.89	$ 3.86
LSFO (IFO 380) USEC	$ 2.92	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	$ 2.92	n.a.	n.a.
LSFO (IFO 380) USGC	$ 2.64	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	$ 2.64	n.a.	n.a.
LSFO (IFO 380) USWC	$ 4.23	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	$ 4.20	n.a.	n.a.
HSFO (IFO 380) USEC	$ (0.38)	$ (0.62)	$ (0.63)	$ (0.61)	$ (1.32)	$ (1.40)	$ (1.35)	$ (1.43)	$ (1.48)	$ (0.38)	$ (0.59)	$ (1.30)
HSFO (IFO 380) USGC	$ (0.01)	$ (0.11)	$ (0.12)	$ (0.12)	$ (0.27)	$ (0.27)	$ (0.29)	$ (0.30)	$ (0.31)	$ (0.01)	$ (0.11)	$ (0.27)
HSFO (IFO 380) USWC	$ 0.03	$ (0.20)	$ (0.18)	$ (0.17)	$ (0.56)	$ (0.74)	$ (0.44)	$ (0.61)	$ (0.78)	$ 0.01	$ (0.17)	$ (0.74)
Marine Fuels Global Average Cost $/bbl	$ 0.02	$ 0.13	$ 0.14	$ 0.15	$ 0.26	$ 0.26	$ 0.27	$ 0.29	$ 0.29	$ 0.02	$ 0.14	$ 0.25
All Products Global Average Cost $/bbl	$ 0.01	$ 0.03	$ 0.04	$ 0.04	$ 0.11	$ 0.10	$ 0.10	$ 0.11	$ 0.11	$ 0.01	$ 0.04	$ 0.10
Marine Fuels US & Canada Average Cost $/bbl	$ 0.29	$ 1.16	$ 1.28	$ 1.35	$ 2.60	$ 2.70	$ 2.47	$ 2.70	$ 2.80	$ 0.26	$ 1.30	$ 2.55
All Products USA/Canada Average Cost $/bbl	$ 0.03	$ 0.07	$ 0.08	$ 0.09	$ 0.20	$ 0.22	$ 0.18	$ 0.21	$ 0.23	$ 0.02	$ 0.09	$ 0.20
Total Global / Regional Fuels Cost $ million / day												
Marine Bunkers Fuels - Global Supply Cost	$ 0.06	$ 1.42	$ 1.50	$ 1.69	$ 2.90	$ 3.01	$ 3.03	$ 3.02	$ 3.22	$ (0.08)	$ 1.75	$ 3.02
All Products - Global Supply Cost	$ 0.66	$ 4.24	$ 4.51	$ 4.77	$ 12.08	$ 12.04	$ 11.66	$ 12.72	$ 12.86	$ 0.52	$ 4.77	$ 11.56
Marine Bunkers Fuels - USA/Canada Supply Cost	$ 0.23	$ 1.04	$ 1.12	$ 1.17	$ 2.29	$ 2.36	$ 2.22	$ 2.37	$ 2.44	$ 0.17	$ 1.15	$ 2.24
All Products - USA/Canada Supply Cost	$ 0.70	$ 1.77	$ 2.16	$ 2.30	$ 5.16	$ 5.57	$ 4.68	$ 5.42	$ 5.81	$ 0.57	$ 2.24	$ 5.14
CO2 Emissions million tonnes / year												
Global Marine Fuel	(0.5)	(1.2)	(0.5)	(0.4)	(1.7)	(0.5)	(1.2)	(1.1)	(1.0)	(2.0)	(0.6)	(0.9)
Global Refinery	0.1	1.60	1.65	1.64	3.2	3.2	2.9	3.3	3.2	0.1	1.6	3.1
Combined Global Refinery + Marine Fuel												
Excl Petroleum Coke	(0.4)	0.4	1.1	1.3	1.4	2.7	1.7	2.2	2.3	(1.9)	1.0	2.2
Incl Petroleum Coke	0.5	1.9	2.3	2.5	3.8	5.7	4.4	4.9	5.7	(1.1)	2.2	4.9
Refinery CO2 Emissions Total USA+Canada	0.1	0.2	0.5	0.5	0.7	0.7	0.7	0.7	0.9	0.1	0.5	0.7
Refinery CO2 Emissions Total Other Regions	(0.1)	1.4	1.2	1.1	2.4	2.4	2.1	2.5	2.4	(0.1)	1.1	2.3

Table 8-12c.WORLD Model Results—Changes vs. 2012/2020 Base Cases

WORLD Model Results - Changes vs 2012 / 2020 Base Cases

Year	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020
Case	compare 25L-1 vs 2BA	compare 25H-1 vs 2BA	compare 25B-1 vs 2BA	compare 22B-1 vs 2BA	compare 21L-1 vs 2BA	compare 21H-1 vs 2BA	compare 21B-1 vs 2BA	compare 25L-2 vs 2BA	compare 25B-2 vs 2BA	compare 22B-2 vs 2BA	compare 21B-2 vs 2BA	compare 25M-2 vs 2BA	compare 22M-2 vs 2BA	compare 21M-2 vs 2BA
Type	100nm	100nm	100nm	100nm	100nm	100nm	100nm	**200nm**	**200nm**	**200nm**	**200nm**	**200nm**	**200nm**	**200nm**
MGO Fuel Type - North America SECAs	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA
MDO Fuel Type - North America SECAs	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA
MGO Sulfur Limit - North America SECAs	0.5%	0.5%	0.5%	0.2%	0.1%	0.1%	0.1%	0.5%	0.5%	0.2%	0.1%	0.2%	0.2%	0.2%
MDO Sulfur Limit - North America SECAs	**0.5%**	**0.5%**	**0.5%**	**0.2%**	**0.1%**	**0.1%**	**0.1%**	**0.5%**	**0.5%**	**0.2%**	**0.1%**	**0.5%**	**0.2%**	**0.1%**
IFO Sulfur - North America SECAs	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
SECA Basis	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	**US/Can/ Mexico**	**US/Can/ Mexico**	**US/Can/ Mexico**
Scrubber Usage	0%	**31%**	**47%**	**47%**	0%	**31%**	**47%**	0%	**47%**	**47%**	**47%**	**47%**	**47%**	**47%**
Marine Fuels Demands million bpd														
Grand Total Bunkers - Global	0.014	0.007	0.011	0.008	0.010	0.010	0.004	0.021	0.006	0.015	0.004	0.015	0.012	0.004
Grand Total Bunkers - USA/Canada	0.009	0.006	0.006	0.004	0.008	0.006	0.005	0.014	0.007	0.007	0.006	0.009	0.008	0.007
Grand Total Bunkers - Caribbean	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.002	0.001	0.001	0.001	0.002	0.002	0.002
Grand Total Bunkers - Other Regions	0.005	0.000	0.005	0.004	0.003	0.004	(0.001)	0.005	(0.002)	0.007	(0.003)	0.004	0.002	(0.005)
IFO HS Shifted to Distillate - million tpa	6.5	4.6	3.6	3.5	6.6	4.6	3.6	13.0	6.9	6.8	7.0	7.7	7.6	7.8
IFO HS Shifted to Distillate - million bpd	0.115	0.081	0.063	0.061	0.116	0.081	0.064	0.228	0.122	0.121	0.123	0.136	0.134	0.136
IFO HS Shifted to LS IFO/MGO % of Global Total IF	1.64%	1.15%	0.90%	0.87%	1.65%	1.16%	0.91%	3.26%	1.75%	1.72%	1.76%	1.93%	1.91%	1.95%
Marine Fuels Demands million tpa														
Grand Total Bunkers - All Regions - mmtpa	(0.4)	(0.4)	(0.2)	(0.1)	(0.6)	(0.4)	(0.2)	(0.6)	(0.7)	(0.2)	(0.7)	(0.4)	(0.3)	(0.2)
IFO HS Shifted to LS IFO/MGO - million tpa	6.5	4.6	3.6	3.5	6.6	4.6	3.6	13.0	6.9	6.8	7.0	7.7	7.6	7.8
Refining Investment $bn														
Global	$ 1.97	$ 1.20	$ 0.98	$ 1.11	$ 2.50	$ 1.70	$ 1.38	$ 3.96	$ 2.09	$ 2.52	$ 2.63	$ 2.51	$ 2.69	$ 2.89
USA/Canada	$ 0.18	$ 0.21	$ 0.16	$ 0.17	$ 0.24	$ 0.16	$ 0.12	$ 1.14	$ 0.16	$ 0.26	$ 0.23	$ 0.15	$ 0.28	$ 0.28
Other Regions	$ 1.79	$ 0.99	$ 0.82	$ 0.94	$ 2.26	$ 1.54	$ 1.26	$ 2.82	$ 1.93	$ 2.26	$ 2.39	$ 2.35	$ 2.41	$ 2.61
Percent of Total Investment in USA/Canada	9%	17%	17%	15%	10%	10%	9%	29%	8%	10%	9%	6%	10%	10%
Refinery Throughputs million bpd														
Global	0.014	0.009	0.014	0.008	0.001	0.007	0.001	0.014	0.004	0.008	(0.006)	0.011	0.004	(0.007)
USA/Canada	(0.031)	(0.008)	(0.011)	(0.026)	(0.019)	(0.011)	(0.020)	(0.020)	(0.041)	(0.036)	(0.029)	(0.061)	(0.041)	(0.026)
Other Regions	0.045	0.017	0.025	0.034	0.019	0.018	0.021	0.034	0.046	0.043	0.023	0.072	0.045	0.019

Table 8-12d. WORLD Model Results—Changes vs. 2012/2020 Base Cases

WORLD Model Results - Changes vs 2012 / 2020 Base Cases														
Year	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020
Case	compare 25L-1 vs 2BA	compare 25H-1 vs 2BA	compare 25B-1 vs 2BA	compare 22B-1 vs 2BA	compare 21L-1 vs 2BA	compare 21H-1 vs 2BA	compare 21B-1 vs 2BA	compare 25L-2 vs 2BA	compare 25B-2 vs 2BA	compare 22B-2 vs 2BA	compare 21B-2 vs 2BA	compare 25M-2 vs 2BA	compare 22M-2 vs 2BA	compare 21M-2 vs 2BA
Type	100nm	100nm	100nm	100nm	100nm	100nm	100nm	**200nm**	**200nm**	**200nm**	**200nm**	**200nm**	**200nm**	**200nm**
MGO Fuel Type - North America SECAs	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA
MDO Fuel Type - North America SECAs	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA	DMA
MGO Sulfur Limit - North America SECAs	0.5%	0.5%	0.5%	0.2%	0.1%	0.1%	0.1%	0.5%	0.5%	0.2%	0.1%	0.2%	0.2%	0.2%
MDO Sulfur Limit - North America SECAs	**0.5%**	**0.5%**	**0.5%**	**0.2%**	**0.1%**	**0.1%**	**0.1%**	**0.5%**	**0.5%**	**0.2%**	**0.1%**	**0.5%**	**0.2%**	**0.1%**
IFO Sulfur - North America SECAs	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
SECA Basis	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	US/Can	**US/Can/ Mexico**	**US/Can/ Mexico**	**US/Can/ Mexico**
Scrubber Usage	0%	**31%**	**47%**	**47%**	0%	**31%**	**47%**	0%	**47%**	**47%**	**47%**	**47%**	**47%**	**47%**
Product Prices / Supply Cost $/bbl														
SECA DMA - USEC	$ 1.68	$ 1.67	$ 1.67	$ 2.06	$ 2.32	$ 2.28	$ 2.28	$ 1.74	$ 1.68	$ 2.09	$ 2.32	$ 1.68	$ 2.10	$ 2.32
SECA DMA - USGC	$ 1.06	$ 1.06	$ 1.05	$ 1.44	$ 1.70	$ 1.67	$ 1.66	$ 1.12	$ 1.06	$ 1.48	$ 1.70	$ 1.07	$ 1.48	$ 1.71
SECA DMA - USWC	$ 3.60	$ 3.47	$ 3.28	$ 4.39	$ 5.15	$ 5.04	$ 5.03	$ 3.94	$ 3.61	$ 5.02	$ 5.15	$ 3.62	$ 5.06	$ 5.58
LSFO (IFO 380) USEC	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LSFO (IFO 380) USGC	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LSFO (IFO 380) USWC	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
HSFO (IFO 380) USEC	$ (0.13)	$ (0.11)	$ (0.10)	$ (0.15)	$ (0.25)	$ (0.19)	$ (0.18)	$ (0.40)	$ (0.14)	$ (0.20)	$ (0.27)	$ (0.17)	$ (0.25)	$ (0.31)
HSFO (IFO 380) USGC	$ (0.01)	$ 0.00	$ 0.00	$ 0.01	$ (0.02)	$ 0.01	$ 0.01	$ (0.07)	$ (0.01)	$ (0.03)	$ (0.04)	$ (0.03)	$ (0.05)	$ (0.05)
HSFO (IFO 380) USWC	$ (0.17)	$ (0.15)	$ (0.15)	$ (0.11)	$ (0.54)	$ (0.17)	$ (0.15)	$ (0.50)	$ (0.18)	$ (0.17)	$ (0.56)	$ (0.20)	$ (0.27)	$ (0.58)
Marine Fuels Global Average Cost $/bbl	$ 0.22	$ 0.15	$ 0.13	$ 0.15	$ 0.24	$ 0.19	$ 0.15	$ 0.39	$ 0.22	$ 0.26	$ 0.24	$ 0.25	$ 0.27	$ 0.26
All Products Global Average Cost $/bbl	$ 0.00	$ (0.00)	$ (0.00)	$ 0.00	$ 0.01	$ 0.00	$ 0.00	$ 0.01	$ 0.00	$ 0.01	$ 0.01	$ 0.01	$ 0.01	$ 0.01
Marine Fuels US & Canada Average Cost $/bbl	$ 1.64	$ 1.16	$ 0.90	$ 0.95	$ 1.63	$ 1.20	$ 0.94	$ 3.02	$ 1.66	$ 1.80	$ 1.64	$ 1.72	$ 1.84	$ 1.77
All Products USA/Canada Average Cost $/bbl	$ 0.05	$ 0.03	$ 0.02	$ 0.03	$ 0.07	$ 0.04	$ 0.03	$ 0.10	$ 0.05	$ 0.07	$ 0.07	$ 0.06	$ 0.07	$ 0.07
Total Global / Regional Fuels Cost $ million / day														
Marine Bunkers Fuels - Global Supply Cost	$ 2.67	$ 1.73	$ 1.70	$ 1.73	$ 2.67	$ 2.18	$ 1.56	$ 4.55	$ 2.28	$ 3.06	$ 2.34	$ 2.96	$ 3.00	$ 2.55
All Products - Global Supply Cost	$ 1.93	$ 0.93	$ 1.01	$ 1.38	$ 2.30	$ 1.73	$ 1.23	$ 3.60	$ 1.43	$ 2.92	$ 2.32	$ 2.37	$ 2.75	$ 2.46
Marine Bunkers Fuels - USA/Canada Supply Cost	$ 1.67	$ 1.18	$ 0.97	$ 0.91	$ 1.61	$ 1.21	$ 0.94	$ 2.98	$ 1.59	$ 1.71	$ 1.52	$ 1.74	$ 1.79	$ 1.68
All Products - USA/Canada Supply Cost	$ 1.31	$ 0.80	$ 0.64	$ 0.75	$ 1.72	$ 1.09	$ 0.85	$ 2.68	$ 1.22	$ 1.71	$ 1.76	$ 1.44	$ 1.92	$ 1.87
CO2 Emissions million tonnes / year														
Global Marine Fuel	(0.9)	(1.0)	(0.6)	(0.1)	(1.6)	(1.1)	(0.3)	(1.0)	(1.8)	(0.3)	(1.8)	(0.9)	(0.6)	(0.2)
Global Refinery	1.6	1.1	0.9	1.3	2.3	1.8	1.4	3.1	1.6	2.2	2.4	2.0	2.3	2.5
Combined Global Refinery + Marine Fuel														
Excl Petroleum Coke	0.7	0.1	0.3	1.2	0.7	0.7	1.1	2.1	(0.1)	1.8	0.6	1.1	1.7	2.3
Incl Petroleum Coke	3.1	2.1	2.0	2.8	2.9	2.8	2.8	5.7	2.3	4.2	3.0	3.7	4.2	4.7
Refinery CO2 Emissions Total USA+Canada	0.0	0.2	0.1	0.2	0.3	0.2	0.1	0.3	(0.1)	0.1	0.2	(0.2)	0.1	0.2
Refinery CO2 Emissions Total Other Regions	1.5	0.9	0.8	1.1	2.1	1.6	1.3	2.7	1.7	2.0	2.2	2.1	2.1	2.2

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APPENDIX A
REVIEW OF REFINERY PROCESS COSTS[1]

Task 1 called for an analysis of the potential technical and economic impacts of designating one or more SECAs along the North American Coastline, as provided by the MARPOL treaty, Annex VI, which places limits on both NO_x and SO_x emissions. Countries participating in the treaty must use a bunker fuel with a sulfur content at or below 4.5%. Countries participating in the treaty are also permitted to request designation of SECAs in which ships must treat their exhaust to 6.0 g of SO_2 per kWh or further reduce the sulfur level of their fuel to 1.5%.

The results obtained from this study will be primarily cost-of-production driven with respect to the different components of bunker fuel and the resulting fuel oil blend. These tie back directly to the investment and operating costs applied to the various refinery processes involved in their production as one of the key factors in determining economic impacts.

Not all refinery processes affect the results in equal measure. Obviously, those processes directed to producing residual fuel blend components are key, along with processes that produce blend stocks in the diesel fuel boiling range. Table A-1 illustrates a typical composition of bunker fuel oil, in this example blended to 380 centistokes for bunker grade RMG 35.

Table A-1. Bunker Fuel Composition

Stream	Quantity MT	Weight Percent	Viscosity cks@50 deg C	Density@ 15 deg C	Sulfur Wt Pct	Vanadium Mg/kg	AL+SI Mg/kg	Water Vol Pct
Residual	15000	43	1500	1.006	3	600	12	0.3
VGO	15000	43	100	0.979	1.5	10	5	0
MidDistillate	5000	14	3	0.85	0.2	0	0	0
Target	35000		380	0.991 max	4.5	300	250	0.5
Blend	35000	100	380	0.972	1.96	261	7.3	0.13

Source: Based on "Bunkers." Fisher, Christopher and Jonathon Lux. 2004. *Bunkers*, 3rd Edition. Banbury, England: Petrospot, Ltd. page 33.

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[1] The mention of certain Licensors and Companies in the text of this appendix and supporting references does not imply any preference for or endorsement of these processes or endorsement of operating practices as opposed to alternatives made available or employed by others. This is particularly so since there are several process alternatives available and several companies involved in any given area of refinery technology and any one may be more appropriate based on a specific refinery situation. Those processes cited are therefore cited for illustrative purposes only. The views and opinions of authors expressed herein do not necessarily reflect those of the United States Government or any agency thereof.

Using current and recognized sources, the following section provides base data on investment costs and operating requirements for a variety of refinery processes, with the stress on the “bottom of the barrel.” These are estimates based on current known refinery technology and do not include revolutionary technology breakthroughs, although these could occur in an extended 2010–2030 timeframe. They were used to review and guide any modifications required to cost and operating data in the WORLD model.

Recent progress in refinery technology development has been reported for several of the refinery process areas considered below. This progress reflects process unit potential for investment and operating cost reduction and capacity increase through technology advances and revamp experience, as well as by process product quality and yield improvement. These are described, again based on current and recognized sources and extend the time frame. In general, these refer to incremental improvements as opposed to revolutionary breakthroughs, with the exception of using ultrasound to reduce residual fuel sulfur, which is briefly described.

A.1 Atmospheric Residuals Desulphurization

Investment and Operating Costs

Basis 2nd Quarter 1995 U.S. Gulf Coast

Similar erected Chevron Units

Feed Rate 70,000 bpd AR 650+

Feed 11.8 API, 4.37% sulfur, 0.4 % 650+ product for RFCC feed

Investment Cost Summary, millions U.S. dollars:

Total On-Plot Cost	234.2
Total Off-Plot Cost	70.3 (30% of on-plot)
Catalyst Charge	8.8 per charge

Hydrogen and Utility Requirements:

Hydrogen	71.7 million SCFD
Fuel	272 BPD EFO
Power	27,000 kWh

Net Steam 94 klb/h

Cooling water 8200 gal/min

Net process & BOW −25 kgal/min

Catalyst 8.8 million dollars/year

Source: Robert A. Meyers Handbook of Petroleum Refining Processes, Third Edition, 2003, pg. 8.22–8.33

Using the latest technology catalysts and improved operational procedures, a large Middle East refinery has reported a 30% increase in the amount of feed processed in the first cycle. (NPRA Annual Meeting, March 13–15, 2005. NPRA Paper AM-05-54).

A.2 Vacuum Residual Hydro Cracking

Investment cost depending on feedstock properties and product requirements, typical investment costs range from $2000 to $ 5000 ISBL per BPSD. Basis 2002. This corresponds to 60–95% desulphurization.

Source: Robert A. Meyers *Handbook of Petroleum Refining Processes, Third Edition*, 2003, pg. 8.81–8.83—LC-Fining.

A.3 Ultra Sound Process to Reduce Heavy Sour Crude Sulfur

Patents awarded in 2005 and earlier describe the application of ultrasound to upgrade sour heavy crude oil into sweeter lighter crude (U.S. Patent No. 6,897,628, May 24, 2005). A 5,000 bpd commercial demonstration unit is planned with potential scale-up to 25,000 bpd and joint venture agreements have been entered into. It is anticipated that the technology could have upstream and downstream applications. A preliminary capital investment estimate of $1 million for a 2,000 bpd unit or $500 per bpd signals the potential for a dramatic reduction in the cost of desulphurization of residual fuel oil blend fractions (*Chemical Engineering*, March and June 2005). This process development is cited here because of its potential impact, but it must be realized that it is very much in the research and development stage (see www.Sulphco.com for additional information).Tracking of future progress is warranted.

A.4 Delayed Coking Process

Investment and Operating Requirements:

Investment costs may range from $45,000 to $95,000 per short ton of coke produced. This excludes the VRU unit and support facilities but includes the coke handling costs. The basis is 4th quarter 2002 and the Foster Wheeler process.

Operating requirements based on 1000 BPSD of fresh feed are as follows:

Fuel Liberated	5.1 mmBTU/h
Power consumed	150 kW
Steam exported	1700 lb/h
Boiler feed water consumed	2400 lb/h
Cooling water	5–25 gal/min
Raw water consumed	20–35 gal/day per short ton/day coke

Source: Robert A. Meyers Handbook of Petroleum Refining Processes, Third Edition, 2003, pg. 12.86–12.88.

A.5 Visbreaker Process

Investment and Operating Requirements:

Battery limits investment costs are $17 million for a 10,000 bpsd unit and $33 million for a 40,000 bpsd unit. This excludes the vacuum flasher and the gas plant. The basis is 4th quarter 2002 and the Foster Wheeler/UOP process.

Typical operating requirements per bpsd of fresh feed are as follows:

Fuel consumed	0.1195 million BTU
Power consumed	.0358 kW
Steam consumed	6.4 lb
Boiler feed water consumed	2400 lb/h
Cooling water	71 gal/min

Source: Robert A. Meyers Handbook of Petroleum Refining Processes, Third Edition, 2003, pg. 12.104–12.105.

A.6 Solvent Deasphalting Process (ROSE Process)

Investment and Operating Requirements:

The estimated installed cost for a 30,000 bpsd unit is $1,250 per bpsd. The basis is 2nd quarter 2002, U.S. Gulf Coast. Typical operating requirements per bbl of feed with propane deasphalting are as follows:

Process heat consumed 12 million BTU

Power consumed 1.5–2.1 kWh

Steam consumed 12 lb

Solvent loss, wt% of feed 0.05–0.10
Source: Robert A. Meyers Handbook of Petroleum Refining Processes, Third Edition, 2003, pg. 10.27–10.28.

A.7 Gas Oil Hydro Cracker

Investment and Operating Requirements:

Basis Jan 1, 2002 U.S. Gulf Coast

Similar projects executed for UOP Unicracking Process

VGO feed 22.2 API, 2.5% sulfur

Product 94% distillate vs.98% naphtha

Investment Cost Summary, millions U.S. dollars

Total Erected Cost $/bpsd

Distillate Mode 2500–3500

Naphtha Mode 2000–3000

Typical Utility Requirements, per 1,000 bpsd fresh feed

Fuel 2–6 million BTU/h

Power 200–400 kW

Net Steam 0.11–0.22 klb/h

Cooling water 40–120 gal/min

Net process & BFW 0.08 klb/h
Source: Robert A. Meyers Handbook of Petroleum Refining Processes, Third Edition, 2003, pg. 7.33.

A.8 Fluid Catalytic Cracking (FCC)

Investment and Operating Requirements:

Basis 1st Quarter 2002 U.S. Gulf Coast

Similar projects executed for KB RFCC Process

50,000 bpd VGO feed
Source: Robert A. Meyers Handbook of Petroleum Refining Processes, Third Edition, 2003, pg. 3.32.

Total installed cost $/ bpsd $2,250 to $2,500—Includes gas system (without power recovery), main fractionator, VRU, and amine treater.

Typical Utility Requirements, per bpsd fresh feed

Steam	40–200 lb Hp steam
Power	0.7 to 1.0 kWh

Residual cat cracking is significantly different than gas oil cracking with respect to feed properties and gasoline and distillate yields (conversion). As old FCC units are being replaced and new capacity is being added, up to 50% of the worldwide FCC capacity will become residual crackers.

Recent advances in RDS catalyst technology and integration with RFCC catalyst design have resulted in a 40% reduction on light cycle oil sulfur and a 50% reduction in RFCC sulfur along with allowing the FCC to process heavier feedstocks. Also a new RDS catalyst system developed allows substantially more 1,000 degF + material to be processed. (NPRA Annual Meeting, March 21–23, 2004. NPRA Paper AM-04-29).

Conversions approach 65% with recently tested FCC catalysts**.**

The heaviest residuals contain high levels of contaminant metals such as nickel, vanadium and iron. New FCC catalysts have been developed that improve the passivation of contaminant metals over previous residual matrix technologies. A typical feedstock is a mix of reduced crude, vacuum bottoms, deasphalted oil and bulk distillate, with feed properties typically 20 API (18–29), 7 wt% Conradson Carbon (0–9), 42 ppm nickel +vanadium(10–50), 2.0 wt% sulfur (0.2–2.4), and 0.3 wt% nitrogen(0.05–0.35). The values in parentheses are current commercial ranges. (NPRA Annual Meeting, March 21–23, 2004. NPRA Papers AM-04-16 and

AM-04-31). Robert A. Meyers Handbook of Petroleum Refining Processes, Third Edition, 2003, p 3.81.

A.9 FCC Stack Emission Reduction

Total 2002 dollar annualized (operating plus capital) costs range from $300 to 600 per ton of SO_2 removed depending on the specific type of SO_2 wet scrubbing system used.

Source: Robert A. Meyers Handbook of Petroleum Refining Processes, Third Edition, 2003, pg. 11.28

With the advent of consent decrees, SO_x and NO_x additives are being used increasingly to achieve ultra-low FCC stack emissions and reduce acid rain formation. With extensive research on how these additives work in the FCC regenerator, refiners have been able to reduce SO_x emissions to less than 25 ppm without the high capital cost of installing hardware. NO_x emission reduction poses a more difficult problem and results vary from unit to unit. Commercial examples demonstrate that NO_x reduction can be achieved in excess of 75%. In many units additives can reduce NO_x emissions to 35 ppm and at times below 25ppm of NO_x (NPRA Annual Meeting, March 13–15, 2005 NPRA Papers AM-05-21).

A.10 Low-Sulfur and Ultra Low-Sulfur Diesel Production

Operating Requirements for Hydro treating Diesel and Gas Oil Streams:

Units are per barrel feed

Stream	**Electric (KWh)**	**Fuel (Mmbtu)**	**Steam (Lb)**	**Hydrogen (Scf)**
Diesel	3.	0.15	8.	300.
Hvy. Gas Oil	6.	0.20	10.	600.

Investment Requirements for Hydro treating Diesel and Gas Oil Streams:

Basis: 1999 U.S. Gulf Coast, ISBL million of dollars, 30,000 bpsd

Diesel Feed	35.0
Heavy Gas Oil Feed	50.0

Source: Gary and Handwerk, Petroleum Refining Process Economics, Fourth Edition, 2001, pg. 182–183.

A.11 Ultra Low-Sulfur Diesel Processes

It is highly unlikely that ultraslow diesel production would be blended with residual fuel oil because of the high cost of production and the fact that its substitution for conventional diesel fuel does not exert sufficient leverage on the residual fuel blend sulfur content. It is more likely that it would be blended with the higher sulfur middle distillate components to produce the marine diesel fuel grades. Representative ultraslow diesel processes are described below:

Operating and Investment Requirements for the Phillips S Zorb Process

Feed rate, BPD	20,000	40,000
Feed sulfur wt ppm	2600	500
Product Sulfur wt ppm	6	6
Power kWh	2511	3698
Steam	nil	nil
Nitrogen, million scfd	807	332
Cooling water gpm	1835	1870
Fuel gas, million btu/h	46.5	109.6
Total hydrogen, million scfd	1.24	1.44
Sorbent makeup, lb per month	9970	19085
Erected Equipment, million dollars	20.85	30.60

Basis 2nd Quarter 2002 U.S. Gulf Coast
Source: Robert A. Meyers Handbook of Petroleum Refining Processes, Third Edition, 2003, pg. 11.56.

Operating and Investment Requirements for the UOP/Eni Oxidative Desulphurization Process

30% LCO, 70% straight run diesel

30,000 bpsd feed @400ppm sulfur and 10 ppm diesel product sulfur

U.S. Gulf Coast, 2nd quarter 2003

Capital cost, MM$	16.0
Hydrogen cost $MM/year	13.4
Utilities cost $, MM$/year	1.0
Catalyst cost $MM/year	1.3

Total cost $, MM$/year 15.7

Source: NPRA Annual Meeting, March 21–23, 2004, Paper AM-04-48.

A.12 Syntroleum Gas to Liquids (diesel)

Capital Cost of Plant $25,000 per bpd capacity

Operating Cost $5.00 per barrel excluding cost of natural gas

Product nil sulfur and aromatics, 74 cetane number

Basis 2001 U.S. Gulf Coast

Source: Robert A. Meyers Handbook of Petroleum Refining Processes, Third Edition, 2003, pg. 15.23.

A.13 Process Unit Revamping For Ultra Low-Sulfur Diesel Production

Claims have been made that revamping for ultra low-sulfur diesel production with countercurrent reactors can save up to 50% in Capex and 20% in OPEX based on recent pilot plant tests (NPRA Annual Meeting, March 21–23, 2005 NPRA Papers AM-04-22). Also, that integration of isotherming into an existing conventional unit is 60% of the total cost of a conventional revamp (NPRA Annual Meeting, March 21–23, 2005 NPRA Papers AM-04-40).

The estimated ISBL Investment Cost for (U.S. Gulf Coast, 1st Quarter 2005) for upgrading a 20,000 bpsd unit with light cycle oil (LCO) feed to produce 10 ppm ULSD at 45 cetane number is estimated at $36.4 million (NPRA Annual Meeting, March 13–15, 2005 NPRA Paper AM-05-53).