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Cost of Diesel Fuel Desulphurisation for Different Refinery Structures Typical of the Asian Refining Industry

(Prepared for the Asian Development Bank)

FINAL REPORT

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CONTENTS

Abbreviations and Acronyms		**Page 3**
Executive Summary		**Page 4**
Background		**Page 13**
Study Objectives		**Page 14**
Chapter 1		**Page 15**
1.1	**Analysis of the current structure of the Major Refineries in South East Asia, People's Republic of China and Indian Sub-Continent**	**Page 15**
1.1.1	**Average refinery size**	**Page 17**
1.1.2	**Average refinery complexity by country**	**Page 18**
1.1.3	**Refinery ability to manufacture low sulphur diesel fuel blending components.**	**Page 19**
Chapter 2		**Page 21**
2.1	**Identification of Typical Configurations Representative of the Major Refineries of South East Asia, People's Republic of China and Indian Sub-Continent.**	**Page 21**
2.1.1	**Definition of Refinery Categories**	**Page 21**
2.1.2	**Calculation of the Diesel Sulphur Content of the Base Case**	**Page 23**
Chapter 3		**Page 31**
3	**Cost Calculation of Diesel Fuel Sulphur Reduction**	**Page 31**
3.1	**Cost Calculation Methodology**	**Page 31**
3.2	**Cost Inputs**	**Page 32**
3.3	**Product Yields with High & Low Sulphur Crude Oils**	**Page 34**
3.4	**Cost of Meeting a 3,000 ppm Maximum Limit of the Gas Oil Pool**	**Page 34**
3.5	**Cost of Meeting a 1,000 ppm Maximum Limit of the Gas Oil Pool**	**Page 37**
3.6	**Cost of Meeting a 500 ppm Maximum Limit of the Gas Oil Pool**	**Page 40**
3.7	**Cost of Meeting a 350 ppm Maximum Limit of the Gas Oil Pool**	**Page 43**
3.8	**Cost of Meeting a 250 ppm Maximum Limit of the Gas Oil Pool**	**Page 45**
3.9	**Cost of Meeting a 50 ppm Maximum Limit of the Gas Oil Pool**	**Page 47**
3.10	**Cost of Meeting a 10 ppm Maximum Limit of the Gas Oil Pool**	**Page 51**
4	**Conclusive Remarks**	**Page 54**
Appendix 1 – Refinery Data Base of Asian Countries		**Page 57**
Appendix 2 – Brief Description of Refinery Processes		**Page 82**
Appendix 3 – Summary of Refinery Structures in Asia		**Page 84**
Appendix 4 – Analysis of Refinery Configurations		**Page 89**
Appendix 5 – Summary of diesel fuel Desulphurisation Costs		**Page 110**

ABBREVIATIONS AND ACRONYMS

ADB	Asian Development Bank
bpd	barrels per day
FCC	Fluid Catalytic Cracking
LPG	Liquefied Petroleum Gas
NOx	Nitrogen Oxides
ppm	parts per million
RETA	Regional Technical Assistance
SOx	Sulphur Oxides

EXECUTIVE SUMMARY

Introduction

Rapid economic development in Asia has resulted in a dramatic increase in the number of motor vehicles and motorcycles. Data show that, in several Asian countries, the size of vehicle fleets is doubling every five to seven years, and this trend is expected to continue for the next ten to fifteen years at least.

However this increased mobility comes with a price. Vehicles have in fact become one of the major sources of pollution in most cities across Asia.

Most Asian countries, having successfully phased out lead from their gasoline, are now beginning to impose stricter maximum allowable limits to the sulphur level of the diesel fuel. The rationale for this approach is twofold: a) lower diesel fuel sulphur results in a direct reduction of the emissions of both sulphate particles and SOx emissions; b) lower sulphur levels of the diesel fuel are necessary to enable the use of those advanced engine technologies, which are essential to achieve reductions of NOx and particulate matter above 70% to 80%, and hence reverse the growing pollution trend due to the continuing growth of the vehicle fleets in Asia.

However, regulations to reduce sulphur levels in diesel fuels have usually been linked to claims about high investments needed to install new refinery desulphurisation units. To date, only limited information is available on the capital investment required to install diesel fuel desulphurisation plants in Asia. Therefore ADB deemed necessary and commissioned this study on the cost of diesel fuel desulphurisation for different refinery structures typical of the Asian refining industry.

Study Objectives

(i) Analyse and summarise the current structure of the major refineries in South East Asia, People's Republic of China, India and Pakistan, with emphasis on the type, severity and complexity of the diesel fuel desulphurisation units. Compare with representative benchmarks in Japan, Australia, Europe and the USA.

(ii) Identify a minimum of five typical refinery configurations that would represent the vast majority of the Asian refineries;

(iii) Calculate, for each configuration, capital investments and additional product cost data for each of the following diesel fuel sulphur levels: 3,000 ppm (parts per million), 1,000 ppm, 500 ppm, 350 ppm, 250 ppm, 50 ppm, and 10 ppm. The basis for this calculation will be published information by major refinery process vendors and petroleum industries;

(iv) Calculate, for each Asian country included in the study, indicative investment and product costs (based on the refinery structure of each country), for each of the above diesel fuel sulphur levels, for a nominal refinery producing 2,000,000 t/y of diesel fuel;

(v) Report the conclusions to the Asian Development Bank.

Analysis of the current structure of the Major Refineries in South East Asia, People's Republic of China and Indian Sub-Continent.

A good understanding of the current state of the refining industry and the capabilities of the units, which are already installed, is an essential part of this project. A total of 145 Asian refineries were assessed in terms of their fundamental structure, and their ability to control the sulphur level of the diesel fuel they manufacture. The following number of refineries was examined for each country:

Number of Refineries by Country

Countries	Number of Refineries
Singapore	3
Malaysia	6
Thailand	4
Philippines	3
Indonesia	8
Myanmar	2
Brunei	1
India	17
Pakistan	4
Bangladesh	1
Sri Lanka	1
People's Republic of China	95

In Appendix 1 of this report, the following information is reported for each of the 145 refineries: name, location, size, major conversion processes and major processes capable of reducing the sulphur content of the diesel fuel. All these processes are briefly described in Appendix 2. The information of Appendix 1, on each individual refinery, is summarised by country and by configuration in Appendix 3.

This summary information is indicative of the progress already made in each country towards diesel fuel sulphur reduction, and of the size of the task ahead, should additional sulphur reductions be required. The average refinery configuration of the 12 Asian countries listed in the above table is compared to that of some benchmark countries, which have already achieved very substantial diesel fuel sulphur reductions. The list of these benchmark countries is shown in the following table, together with the corresponding current diesel fuel sulphur limit.

Benchmark Countries/States

Countries/States	Current Diesel Fuel Sulphur Limit, ppm max
Japan	500 (1)
Australia	1,500 (2)
UK	350 (3)
Germany	350 (3)
Italy	350 (3)
Netherlands	350 (3)
USA	500 (4)
California	500 (4)

(1) There are plans under discussion to reduce the limit to 50 ppm in 2007.
(2) The limit will be reduced to 500 ppm in 2003, with plans for a further reduction to 50 ppm in 2006.
(3) The limit will be reduced to 50 ppm in 2005. In the mean time, a significant proportion of the diesel fuel supplied into the market has already a sulphur content of 50 ppm max (through tax incentives). The European Union will introduce a limit of 10 ppm max beginning from 2008/2009.
(4) The US EPA published the final rule for highway diesel sulphur control in Jan. 2001. The sulphur content will be reduced to 15 ppm in 2006 (to be enforced on about 80% of the total fuel supply).

- The US refineries have a configuration aiming at the maximization of gasoline production (very high catalytic cracking capacity). The lack of visbreaking units, associated with a fairly high hydro-cracking capacity, gives these refineries the ability to meet also advanced diesel fuel specifications.
- The refineries of the 12 Asian countries, together with most of the European refineries, rely on relatively high visbreaking units for converting heavy fuel oils into naphtha and gas oil. This approach generates a distillate component with a particularly high sulphur content.
- In these countries, the capacity of the catalytic cracking units is lower than in the USA, reflecting the higher ratio of diesel to gasoline demands versus the USA.
- Regarding the production of very low Sulphur streams (and hence the ability to blend very low sulphur diesel fuel grades), many Asian countries have some hydro cracking capacity, albeit at levels lower than that of the majority of the benchmark countries.
  - Only the refineries of Singapore and Thailand have capacities of hydro-treating and hydro-cracking units comparable to the size of some benchmark countries.
  - In the Philippines, the refineries have large hydro-treating capacities, but no hydro-crackers. This situation gives these refineries the ability of meeting intermediate sulphur grades, but the very low grades, that are made possible through the use of hydro-cracked gas oils, are not feasible.
  - The refineries of Malaysia, Indonesia, India and the People’s Republic of China have the capability of blending small amounts of lower sulphur fuel grades, if the low sulphur streams (produced by either the hydro-treating or the hydro-cracking units) are segregated.

Identification of Typical Configurations Representative of the Major Refineries of South East Asia, People's Republic of China and Indian Sub-Continent.

There are 145 refineries in the Asian countries, which are the object of this study, and it is impractical, within the limited scope of this project, to assess each one individually. Therefore, two approaches were used to study the implications of reducing the diesel fuel sulphur content of the products manufactured in the 145 Asian refineries:

1) As a first step, the refineries were grouped by country, aggregating the process unit capacities for each country.
2) However the refineries are all different, and, within the same country, each type of refinery will encounter different problems in meeting tighter sulphur specifications. Therefore, regardless of the country where they are, all 145 refineries have been classified in 10 broad categories. The objective was to identify a range of problems (and hence a range of solutions) representative of countries with a large number of refineries, having different configurations.

In Appendix 3, the grouping of the refineries by country (approach 1) is shown in details, including the number of refineries in each country, their total crude oil capacities, and their aggregated process unit capacities for conversion and diesel sulphur control processes.

As regards approach 2), the refineries of each country, which are included in the 10 refinery configuration mentioned before, are listed in details in Appendix 4. The definition of the 10 configuration categories is summarised in the following table:

Selected Refinery Configurations
(Capacity of units shown as % of crude throughput)

Configuration Number	Number of refineries	Crude Throughput, bpd	Thermal Cracking & Coking	Vis- -breaking	Catalytic Cracking	Hydro-treating	Hydro-cracking
1	80	2,564,850	--	--	--	--	--
2	12	1,078,900	--	--	35.1	--	--
3	15	1,590,000	6.9	3.6	20.0	--	--
4	6	271,200	20.2	--	--	--	--
5	8	1,142,700	--	--	17.2	17.5	--
6	4	327,500	18.6	3.1	--	--	29.7
7	5	686,100	14.6	0.9	24.7	--	11.7
8	4	612,000	3.6	11.9	--	10.5	--
9	5	1,135,700	4.8	6.9	12.5	14.9	11.5
10	3	368,000	8.7	5.6	34.5	17.1	--

Calculation of the Diesel Sulphur Content of the Base Case

As the first step for the calculation of the level and type of new process units needed for achieving the target sulphur levels, the sulphur content of the base case conditions were calculated for:

- the average refinery configuration of each country,
- each of the 10 individual refinery configurations summarised in the previous table both for high sulphur and low sulphur crude slates.

The assumptions made for these calculations are discussed in section 2.1.2.1 of this report. The results of these calculations for the 12 countries under study are shown in the following table, together with the current diesel fuel sulphur limits:

Base Case Sulphur Content of Total Gas Oil Pool by Country, ppm

Country	High Sulphur Crude Oil	Low Sulphur Crude Oil	Sulphur Limits Max, ppm	Notes
Singapore	3,975	2,413	500	
Malaysia	6,451	3,877	2,000	
Thailand	5,202	3,137	500	
Philippines	3,690	2,236	2,000	
Indonesia	6,922	4,148	5,000	
Myanmar	8,901	5,323	3,000	
Brunei	8,500	5,100	2,500	
India	8,136	4,876	2,500	500 in metropolitan areas
Pakistan	8,500	5,100	10,000	5,000 from Dec. 2002
Bangladesh	9,355	5,575	5,000	
Sri Lanka	9,198	5,493	10,000	5,000 from 2003
People's Republic of China	8,198	4,899	5,000 to 10,000	2,000 for the Premium Grade

In trying to reconcile the calculated values of this table with the diesel fuel sulphur limits of each country, the following must be taken into account:

- all distillate blending streams are included in the calculated data of the above table, including those refinery streams, that, in most cases, are used for blending fuels aimed at marketing outlets different from the high speed automotive diesel engines (e.g. railways, off-road and industrial applications, etc.).
- usually the gas oil components used for blending these other diesel fuel grades have higher sulphur contents, as the specification limits for these grades tend to be higher than the limit for the automotive diesel fuel.
- in most countries, the infrastructure exists for segregating the automotive diesel fuels from the gas oils used for other applications. However, in other countries, these segregating facilities do not exist.

A detailed reconciliation between calculated data and local sulphur limits would require detailed studies for each country, including the precise sulphur content of the crude run in each refinery, the detailed severity of the various refinery units employed and the precise capacity of each unit, the capability of the refining and marketing distribution systems to segregate gas oil streams as required, the importation of low sulphur blending components and/or finished diesel fuel. This detailed analysis goes beyond the scope of this study.

However, as an example, a hypothetical blending study was made for the average refineries of Singapore, simulating the production of 2 or 3 different diesel fuel sulphur grades, instead of blending the streams all together in the same gas oil pool. This blending study has been made for both the High and Low Sulphur crude oil cases. The results show that, while the calculated sulphur content of the gas oil pool ranges between 2,400 and 3,900 ppm (according to the different crude slates), the refineries of Singapore would have the capability of producing significant amounts of low sulphur diesel fuel grades, down to 500 and/or 50 ppm of sulphur.

Similar considerations could be made for all countries with refineries having hydro-treating and/or hydro-cracking facilities in the base case.

Cost Calculation of Diesel Fuel sulphur Reduction for Each Study Country and Each Selected Refinery Configuration.

The additional refinery investments and diesel fuel costs, consequent to the reduction of the maximum sulphur content of the diesel fuel to 3,000 ppm, 1,000 ppm, 500 ppm, 350 ppm, 250 ppm, 50 ppm and 10 ppm, was calculated for:

a) The average refinery structure of each of the 12 Asian countries included in this study;

b) Each of the 10 refinery configurations, selected as being representative of the 145 refineries currently in operation in the above 12 countries.

Cost Calculation Methodology

The case studies are presented and discussed in increasing order of complexity and cost of refinery investments and operations, both for high and low sulphur crude oils, as follows:

- reduction of the sulphur content of the diesel fuel pool to 3,000 ppm maximum, assuming to invest in new or expanded low to medium pressure hydro-treating units.
- reduction of the sulphur content of the diesel fuel pool to 1,000 ppm, 500 ppm, 350 ppm, and 250 ppm maximum, assuming to invest in new or expanded high pressure (above 70 bar) hydro-treating units.
- reduction of the sulphur content of the diesel fuel pool to 50 ppm and 10 ppm maximum, assuming to invest in new or expanded hydro-cracking units.
- run sensitivity cases to ensure that the above approach, rather than combinations of sulphur reduction processes, leads to lower cost solutions.

For each individual case, the following detailed information are given:

1) Capital investment costs
2) Fixed operating costs and variable operating costs associated to the investments in 1)
3) Other operating costs due to the use of low sulphur crude oils.
4) For all cases involving the use of low sulphur crude oils, the credits for the higher yields of naphtha and distillate and the lower yields of heavy fuel oil are calculated.
5) Additional cost of the diesel fuel, consequent to the costs incurred in 1), 2), 3), 4). For this calculation, it is assumed that the additional costs 1), 2), 3), 4) are incurred only because of the need to improve the quality of the diesel fuel; therefore these costs are only allocated to the diesel fuel. They are expressed in cents of US dollar per litre of fuel.

An industry standard linear programming model was used to calculate the yields of the various processes. Diesel fuel sulphur quality mass balances and costs of each case study were calculated through the use of spreadsheets. All calculations were made for product pools (i.e. no attempts were made to identify and separate possible product grades). The refinery investments have been estimated on the assumption that the refinery would always be run to the limitation of the crude distillation unit.

The capital costs for the processes that are considered in this study are those quoted by major international process vendors for Western Europe and the U.S. Gulf Coast. Therefore they are corrected through the use of a location factor, with an average value of 1.5. This value is consistent with the usual practice in Asian countries. These costs have been also compared to costs adopted in similar studies world-wide, to ensure relative consistency. In particular, a consistent set of cost data used in the European Union Auto-Oil II programme proved quite useful. This study was performed for Directorate General XVII of the European Union by independent consultants. The process cost data for this study were extensively searched and came from a variety of sources, among which: UOP, IFP, AKZO NOBEL, CRITERION Catalyst UK, HALDOR TOPSOE Denmark, STRATCO USA, Sud-Chemie Germany, CONCAWE and several petroleum industries. Detailed costs are listed in Section 3.2 of this report.

For the calculation of the costs of the processes included in the present study (and of their implications in terms of product cost) the following assumptions were made:

- Location Factor: 1.5 across all processes
- Scaling Factor (for calculating the capital cost of units having a size different from that of plants for which the actual cost is available): power of 0.6. This is standard practice in the petroleum and chemical industries.
- Annualization of capital costs: the capital costs were annualised over 10 years, with a discount factor of 7%. This factor is consistent with fact that cost calculations are made in U.S. dollars.
- Operating costs associated with the investment: 10 % of the annualised capital costs.
- Cost of additional tankage, pumps, pipes, utilities, infrastructure, etc.: 20% on top of total local capital cost.
- It is assumed that, in the base case there is no excess hydrogen available. Therefore, to all new hydro-treating and hydro-cracking units, the cost of a hydrogen plant of adequate capacity was added.
- In order to compare the investments and product cost results relative to the 12 study countries and the 10 refinery configurations, the cost calculations were made, in all cases, assuming a constant diesel fuel production of 2,000,000 t/y.

Conclusive Remarks

In Chapter 3, the capital investments and the additional diesel fuel product costs, relative to the enforcement of diesel fuel sulphur limits from 3,000 to 10 ppm, are calculated and discussed for each of the average refinery structures of the 12 countries under study and the 10 typical refinery configurations of the Region. The major conclusions of this study are summarised below.

As already discussed, there are important differences in the current average refinery structure of the countries considered in this study, regarding both the cracking capacity and the ability to manufacture diesel fuels with low sulphur content. On one extreme, there are countries which refineries have very little cracking capacity and essentially no flexibility to reduce the sulphur content of the diesel fuel blending components produced by their refineries, apart from the use of lower sulphur crude oils. Examples are Pakistan, Myanmar and Brunei. On the other extreme, there are countries which refineries have already invested in very significant conversion facilities (both thermal and catalytic cracking processes), as well as units to reduce the sulphur content of the diesel fuel, such as hydro-treating and/or hydro-cracking units. However, among these countries, there are big differences in terms of the relative capacity installed for these plants, and hence of their ability to produce low sulphur distillates in large amounts. For example, countries like Singapore, Thailand, Malaysia and the Philippines have, today, refineries with units capable of producing lower sulphur distillates in significant quantities, while, on average, in other countries, these units have a much smaller capacity, as summarised in the following table:

Currently Installed Average Hydro-treating and Hydro-cracking Capacity

Country	Hydro-treating Capacity, %	Hydro-cracking Capacity, %
Singapore	16.2	7.4
Malaysia	6.1	5.5
Thailand	14.3	2.9
Philippines	23.7	--
Indonesia	1.2	10.0
India	3.8	2.6
Bangladesh	--	3.6
Sri Lanka	4.2	--
People's Republic of China	1.1	2.8

However, it is important to note that, apart from Singapore and, to a lesser extent Thailand, no other country has average refinery structures that are approaching those of the countries which have already implemented severe diesel fuel sulphur specifications, as shown in the following table:

Currently Installed Average Hydro-treating and Hydro-cracking Capacity in some Benchmark Countries

Country	Hydro-treating Capacity, %	Hydro-cracking Capacity, %
USA	14.4	8.7
California	23.4	21.4
Japan	31.8	3.3
Germany	24.2	7.3

The refineries of these countries have, on average, significantly higher levels of hydro-treating plus hydro-cracking capacity; furthermore, some of the hydro-treating units operate at higher severity, hence with a higher capability to reduce the diesel fuel sulphur content to lower limits at or below 500 ppm.

The just described different base case situations of the refineries of the countries under study is reflected in the calculated capital and diesel fuel costs, relative to the implementation of stricter diesel fuel sulphur limits. In fact the data of Appendix 5 show, for refineries representing the average country structure, and manufacturing 2,000,000 t/y of diesel fuel:

- The existence of Low/Medium Pressure Hydro-treating units in the base case is predicted to significantly reduce the need for capital investments mainly for diesel fuel sulphur limits above 500 ppm.
- For sulphur limits at or below 500 ppm, the presence of High Pressure Hydro-treating units and/or hydro-crackers becomes more important.
- Sulphur limits down to 50 or 10 ppm can only be satisfied through the deployment of hydro-cracking units of high capacity. Therefore only refineries with existing hydro-cracking capacity in the base case require sizeably lower investments to achieve these sulphur targets.
- The use of low sulphur crude oils has an important impact in reducing the necessary capital investment, only for diesel fuel sulphur levels above 500 ppm. At or below this value, the delta between the investments required with high and low sulphur crude oils becomes smaller, and

the use of low sulphur crude oils becomes economically unattractive. This point is emphasised by the calculated diesel fuel cost increase, which is higher in the low sulphur crude cases.

- In the diesel fuel sulphur range between 500 and 250 ppm, the incremental capital costs, relative to the 250 ppm limit versus the 500 ppm limit, are 10% to 20% higher for the countries which refineries already include large hydro-treating and/or hydro-cracking capacity in the base case, but only 2% to 4% for the other countries. This is due to the fact that the refineries of the first group of countries could meet the 500 ppm diesel fuel sulphur limit with a lower level of new investments.
- Reducing the diesel fuel sulphur limit from 250 to 50 ppm represents a major change in terms of refinery processes required and capital investments. In fact the 50 ppm limit requires sizeable hydro-cracking capacities. As a consequence, the calculated investment costs for the refinery structures representative of the average conditions of the countries under study increased from a range of $ 150M to $ 185M, for the 250 ppm limit, to a range of $ 375M to $ 450M (i.e. by a factor of 2.5 about). The countries with refineries that have already invested in hydro-cracker units in the base case are predicted to require the lowest investments.
- These higher investment costs are reflected in the additional diesel fuel product costs, which are predicted to increase from a range of 0.95 to 1.58 cents per litre, for the 250 ppm case, to a range of 2.36 to 3.24 cents per litre, for the 50 ppm case (i.e. by a factor of 2.0 to 2.5).
- The investment required to satisfy a diesel fuel sulphur limit of 10 ppm is calculated to be up to 10% higher than that required to meet the 50 ppm limit.
- The data show that, for diesel fuel sulphur limits below 350 ppm, all refinery structures and configurations tend to converge towards a uniform approach, in order to achieve the sulphur target. For these severe sulphur limits, also the investment costs of the various refinery configurations considered in this study tend to become of the same order of magnitude.
- Overall, finding the capital funds necessary to invest in the severe diesel fuel desulphurisation units, which are needed to meet severe sulphur limits, appears to be the biggest obstacle to achieving low sulphur diesel fuel in the short range. However, for the most severe limits, also diesel fuel cost increases of the order of 3.0 cents of US dollar per litre or above cannot be ignored.

BACKGROUND

Asia is experiencing a rapid urbanization process, and, within the next twenty years, it is expected that the majority of Asia's population will live in an urban environment. Furthermore, rapid economic development in the Region has also resulted in a dramatic increase in the number of motor vehicles and motorcycles. Data show that, in several Asian countries, the size of vehicle fleets is doubling every five to seven years, and this trend is expected to continue for the next ten to fifteen years at least.

However this increased mobility comes with a price. Vehicles have in fact become one of the major sources of pollution in most cities across Asia.

In this situation, the Asian Development Bank (ADB) has implemented a programme aimed at providing assistance to its member countries, through lending and technical assistance grants. As in the case of automotive air pollution the problem is shared by several countries, ADB provides a specific Regional Technical Assistance grant, or RETA. This specific RETA is called RETA No. 5937 – Action Plans for Reducing Vehicle Emissions. Within this RETA, actions are identified that, when implemented, would significantly reduce the emissions of the pollutants that are most dangerous for the human health, and would help the Asian countries in their processes of moving towards the use of cleaner fuels.

Most Asian countries, having successfully phased out lead from their gasoline, are now beginning to impose stricter maximum allowable limits to the sulphur level of the diesel fuel. The rationale for this approach is twofold: a) lower diesel fuel sulphur results in a direct reduction of the emissions of both sulphate particles and SOx emissions; b) lower sulphur levels of the diesel fuel are necessary to enable the use of those advanced engine technologies, which are essential to achieve reductions of NOx and particulate matter above 70% to 80%, and hence reverse the growing pollution trend due to the continuing growth of the vehicle fleets in Asia.

However, regulations to reduce sulphur levels in diesel fuels have usually been linked to claims about high investments needed to install new refinery desulphurisation units. To date, only limited information is available on the capital investment required to install diesel fuel desulphurisation plants in Asia. Therefore ADB deemed necessary and commissioned this study on the cost of diesel fuel desulphurisation for different refinery structures typical of the Asian refining industry.

Study Objectives

The objectives of this study are the following:

(i) Analyse and summarise the current structure of the major refineries in South East Asia, People's Republic of China, India and Pakistan, with emphasis on the type, severity and complexity of the diesel fuel desulphurisation units. Do the same analysis for representative benchmarks in Japan, Australia, Europe and the USA, and comment on the differences between these benchmarks (where significant investments for low sulphur diesel fuels have already been implemented) and the Asian refineries, that are the object of this study.

(ii) Identify a minimum of five typical refinery configurations that would represent the vast majority of the Asian refineries;

(iii) Calculate, for each configuration, capital investments and additional product cost data for each of the following diesel fuel sulphur levels: 3,000 ppm (parts per million), 1,000 ppm, 500 ppm, 350 ppm, 250 ppm, 50 ppm, and 10 ppm. The basis for this calculation will be published information by major refinery process vendors and petroleum industries;

(iv) Calculate, for each Asian country included in the study, indicative investment and product costs (based on the refinery structure of each country), for each of the above diesel fuel sulphur levels, for a nominal refinery producing 2,000,000 t/y of diesel fuel;

(v) Report the conclusions to the Asian Development Bank.

Chapter 1

1.1 Analysis of the current structure of the Major Refineries in South East Asia, People's Republic of China and Indian Sub-Continent.

A good understanding of the current state of the refining industry and the capabilities of the units, which are already installed, is an essential part of this project. A total of 145 Asian refineries were assessed in terms of their fundamental structure, and their ability to control the sulphur level of the diesel fuel they manufacture. The following number of refineries was examined for each country:

Table 1.1.1 Number of Refineries by Country

Countries	Number of Refineries
Singapore	3
Malaysia	6
Thailand	4
Philippines	3
Indonesia	8
Myanmar	2
Brunei	1
India	17
Pakistan	4
Bangladesh	1
Sri Lanka	1
People's Republic of China	95

In Appendix 1, the following information is shown for each of the above refineries:

a) Country
b) Name of the refinery
c) Location
d) Crude throughput
e) Size of thermal cracking units
f) Size of visbreaking units
g) Size of coking units
h) Size of catalytic cracking units
i) Size of distillate hydro-treating units
j) Size of hydro-cracking units

The above information is giving an impression of the following features of each refinery:

- the size of the refinery is given by the data in d);
- the data in e), f), g) and h) represent the complexity of the plant and its ability to convert heavy fuel oil and other heavy refinery fuel steams into lighter products such as naphtha and distillates. As the distillates produced from conversion units have sulphur contents different from the one of the virgin gas oil (coming from the primary distillation), the above four data points provide some very useful indications on the sulphur content of the distillate before it is treated in other units to reduce its sulphur content;

- the data in i) and j) give indications on the refinery's capability to reduce the sulphur content of the distillates produced.

All processes mentioned above are briefly described in Appendix 2.

Because of the limited scope of this project, it has not been possible to do the fieldwork that would have been necessary to contact and/or visit each of the 145 refineries of Appendix 1, and collect direct and detailed information about the capacity and severity of each unit. Therefore, the data summarised in Appendix 1 is derived from published information, particularly from the Oil & Gas Journal publications, which include information updated to the middle of 2001.

The information of Appendix 1, on each individual refinery, is summarised by country and by configuration in Appendix 3. This summary information is indicative of the progress already made in each country towards diesel fuel sulphur reduction, and of the size of the task ahead, should additional sulphur reductions be required. The average refinery configuration of the 12 Asian countries listed in Table 1.1.1 is compared to that of some benchmark countries, which have already achieved very substantial diesel fuel sulphur reductions. The list of these benchmark countries is shown in the following Table 1.1.2, together with the corresponding current diesel fuel sulphur limit.

Table 1.1.2 Benchmark Countries/States

Countries/States	**Current Diesel Fuel Sulphur Limit, ppm max**
Japan	500 (1)
Australia	1,500 (2)
UK	350 (3)
Germany	350 (3)
Italy	350 (3)
Netherlands	350 (3)
USA	500 (4)
California	500 (4)

(1) There are plans under discussion to reduce the limit to 50 ppm in 2007.
(2) The limit will be reduced to 500 ppm in 2003, with plans for a further reduction to 50 ppm in 2006.
(3) The limit will be reduced to 50 ppm in 2005. In the mean time, a significant proportion of the diesel fuel supplied into the market has already a sulphur content of 50 ppm max (through tax incentives). The European Union will introduce a limit of 10 ppm max beginning from 2008/2009.
(4) The US EPA published the final rule for highway diesel sulphur control in Jan. 2001. The sulphur content will be reduced to 15 ppm in 2006 (to be enforced on about 80% of the total fuel supply).

A good understanding of the current state of industry and its current capability of reducing the diesel fuel sulphur content is an essential part of this exercise. Therefore, the following comments are worth noting, regarding the information reported in Appendix 3:

1.1.1 Average refinery size

As fuel specifications become tighter, it is increasingly difficult for small, simple refineries to satisfy the new fuel specifications, because of the economies of scale involved in constructing new processing units. This general concept is particularly valid in the case of the relatively high investments needed for drastically reducing the diesel fuel sulphur content. Some small refineries would not be able to supply low sulphur diesel fuel at a competitive price. Therefore it is probable that, for economic reasons, small/simple refineries would have to shut down, while the complex refineries would expand to continue to satisfy global market demand. The average refinery throughput for the plants of the 12 Asian countries of Table 1.1.1, as well as the benchmark countries, are listed in the next Table 1.1.1.1:

Table 1.1.1.1 Average Refinery Throughput by Country, bpd

Study Country	Throughput	Benchmark Country	Throughput
Singapore	423,333	Japan	141,714
Malaysia	85,600	Australia	84,700
Thailand	170,438	UK	161,000
Philippines	139,833	Germany	132,882
Indonesia	124,175	Italy	138,765
Myanmar	16,000	Netherlands	200,500
Brunei	8,600	USA	108,809
India	124,229	California	90,455
Pakistan	59,625		
Bangladesh	33,000		
Sri Lanka	50,000		
People’s Republic of China	45,692		

- Singapore’ s refineries are among the largest and, as it will be discussed later, also fairly complex. Their aim is clearly the export market, as their production is much higher than the market demand.
- The average size of the refineries in Thailand, Philippines, Indonesia and India is consistent with that of most benchmark countries, which have already invested in units producing low sulphur diesel fuels at competitive prices.
- In Malaysia, while the average size of the six refineries is below 100,000 bpd of crude throughput, Appendix 1 sows that 1 refinery has a size of 155,000 bpd, 3 can process between 80,000 and 95,000 bpd of crude, and only 2 have a crude distillation capacity below 50,000 bpd.
- All refineries of Myanmar, Brunei, Pakistan, Bangladesh and Sri Lanka have crude distillation capacities below 100,000 bpd, with the exception of a refinery in Pakistan.

- The situation of the 95 Chinese refineries is quite complex, and the average crude throughput value is not very meaningful, as it can be seen from a more detailed analysis of the information in Appendix 1. In fact, 21 Chinese refineries have crude throughputs above 100,000 bpd, 20 between 50,000 and 100,000 bpd, and 54 refineries are below 50,000 bpd.

1.1.2 Average refinery complexity by country

In the next Table 1.1.2.1 the average refinery complexity for each country is expressed in terms_of the refinery's capability to convert heavy fuel oil and/or other heavy refinery streams into lighter products such as LPG, naphtha, kerosene and gas oils. In the table, this capability is represented by the refinery installed capacity of the following units: thermal cracking, coking, visbreaking, catalytic cracking and hydro-cracking. The refinery installed capacity is expressed in terms of % of the crude throughput. Similar data for the benchmark countries is shown in Table 1.1.2.2.

Table 1.1.2.1 Average Refinery Complexity by Country – 12 Asian Study Countries (Capacity -- % of crude throughput)

Country	Thermal Cracking	Coking	Visbreaking	Catalytic Cracking	Hydro Cracking
Singapore	2.4	--	14.0	5.1	7.4
Malaysia	--	3.7	--	--	5.5
Thailand	--	--	2.6	11.8	2.9
Philippines	5.2	--	--	5.8	--
Indonesia	0.9	3.3	5.0	10.2	10.0
Myanmar	--	16.3	--	--	--
Brunei	--	--	--	--	--
India	--	2.1	4.4	7.9	2.6
Pakistan	--	--	--	--	--
Bangladesh	--	--	30.3	--	3.6
Sri Lanka	--	--	26.7	--	--
People's Republic of China	--	6.7	--	20.5	2.8

Table 1.1.2.2 Average Refinery Complexity by Country – Benchmark Countries (Capacity -- % of crude throughput)

Country	Thermal Cracking	Coking	Visbreaking	Catalytic Cracking	Hydro Cracking
Japan	--	1.8	--	16.1	3.3
Australia	--	--	--	27.2	--
UK	2.3	3.8	3.1	25.1	1.8
Germany	1.2	5.6	8.3	15.2	7.3
Italy	4.5	1.9	13.2	12.9	11.3
Netherlands	0.7	3.0	9.3	8.4	13.5
USA	0.1	12.7	0.1	33.8	8.7
California	--	23.8	0.5	32.7	21.4

- The refineries of most benchmark countries have a higher level of complexity than the 12 Asian countries under study. This implied the production of more high sulphur components in the pool. For achieving the low sulphur limits of the automotive diesel fuels, these refineries had to take a combination of the following measures:
  - Segregation of high sulphur streams for blending non-automotive gas oil grades
  - Running more low sulphur crude oils
  - Investing in refinery units capable of producing low and/or very low sulphur gas oil streams, such as hydro-treating plants at medium or high pressure and hydro-crackers.
- The US refineries have a configuration aiming at the maximization of gasoline production (very high catalytic cracking capacity). The lack of visbreaking units, associated with a fairly high hydro-cracking capacity, gives these refineries the ability to meet also advanced diesel fuel specifications.
- The refineries of the 12 Asian countries, together with most of the European refineries, rely on relatively high visbreaking units for converting heavy fuel oils into naphtha and gas oil. This approach generates a distillate component with a particularly high sulphur content (from about 6,000 ppm, up to 15,000 ppm, depending on the type of crude oil processed). Because of this high sulphur content, the visbreaker gas oil is usually further processed, instead of being blended directly into the diesel fuel.
- In these countries, the capacity of the catalytic cracking units is lower than in the USA, reflecting the higher ratio of diesel to gasoline demands versus the USA.
- Regarding the production of very low Sulphur streams (and hence the ability to blend very low sulphur diesel fuel grades), many Asian countries have some hydro cracking capacity, albeit at levels lower than that of the majority of the benchmark countries.

1.1.3 Refinery ability to manufacture low sulphur diesel fuel blending components.

The next Table 1.1.3.1 presents a summary, by country, of the average capability to produce low sulphur blending streams. This capability is indicated by the reefing hydro-treating and hydro-cracking capacities.

Table 1.1.3.1 Average Hydro-treating and Hydro-cracking Capacity (Capacity -- % of crude throughput)

Study Country	Hydro-treating	Hydro-cracking	Benchmark	Hydro-treating	Hydro-cracking
Singapore	20.7	7.4	Japan	31.8	3.3
Malaysia	6.1	5.5	Australia	12.5	--
Thailand	14.3	2.9	UK	20.6	1.8
Philippines	23.7	--	Germany	24.2	7.3
Indonesia	1.2	10.0	Italy	15.3	11.3
Myanmar	--	--	Netherlands	9.7	13.5
Brunei	--	--	USA	14.4	8.7
India	3.8	2.6	California	23.4	21.4
Pakistan	--	--			
Bangladesh	--	3.6			
Sri Lanka	4.2	--			
People's Republic Of China	1.1	2.8			

- Only the refineries of Singapore and Thailand have capacities of hydro-treating and hydro-cracking units comparable to the size of some benchmark countries.
- In the Philippines, the refineries have large hydro-treating capacities, but no hydro-crackers. This situation gives these refineries the ability of meeting intermediate sulphur grades, but the very low grades, that are made possible through the use of hydro-cracked gas oils, are not feasible.
- The refineries of Malaysia, Indonesia, India and the People's Republic of China have the capability of blending small amounts of lower sulphur fuel grades, if the low sulphur streams (produced by either the hydro-treating or the hydro-cracking units) are segregated.

Chapter 2

2.1 Identification of Typical Configurations Representative of the Major Refineries of South East Asia, People's Republic of China and Indian Sub-Continent.

2.1.1 Definition of Refinery Categories

1) There are 145 refineries in the Asian countries, which are the object of this study, and it is impractical, within the limited scope of this project, to assess each one individually. Therefore, two approaches were used to study the implications of reducing the diesel fuel sulphur content of the products manufactured in the 145 Asian refineries:
3) As a first step, the refineries were grouped by country, aggregating the process unit capacities for each country.
4) However the refineries are all different, and, within the same country, each type of refinery will encounter different problems in meeting tighter sulphur specifications. Therefore, regardless of the country where they are, all 145 refineries have been classified in 10 broad categories. The objective was to identify a range of problems (and hence a range of solutions) representative of countries with a large number of refineries, having different configurations.

In Appendix 3, the grouping of the refineries by country (approach 1) is shown in details, including the number of refineries in each country, their total crude oil capacities, and their aggregated process unit capacities for conversion and diesel sulphur control processes.

As regards approach 2), the refineries of each country, which are included in the 10 refinery configuration mentioned before, are listed in details in Appendix 4. The definition of the 10 configuration categories is summarised in the following Table 2.1.1.1:

Table 2.1.1.1 Selected Refinery Configurations
(Capacity of units -- % of crude throughput)

Configuration Number	Number of refineries	Crude Throughput, bpd	Thermal Cracking & Coking	Vis- -breaking	Catalytic Cracking	Hydro-treating	Hydro-cracking
1	80	2,564,850	--	--	--	--	--
2	12	1,078,900	--	--	35.1	--	--
3	15	1,590,000	6.9	3.6	20.0	--	--
4	6	271,200	20.2	--	--	--	--
5	8	1,142,700	--	--	17.2	17.5	--
6	4	327,500	18.6	3.1	--	--	29.7
7	5	686,100	14.6	0.9	24.7	--	11.7
8	4	612,000	3.6	11.9	--	10.5	--
9	5	1,135,700	4.8	6.9	12.5	14.9	11.5
10	3	368,000	8.7	5.6	34.5	17.1	--

A detailed list of every refinery included in each configuration category is reported in Appendix 4. The 10 categories can be defined as follows:

Configuration 1 – it includes the simplest refineries, with no conversion units and also without diesel fuel hydro-treating capability. Eighty of the 145 refineries are represented by this category, for a total crude oil capacity of 2,564,850 bpd, or 132,292,500 t/y. The only possibility to reduce the diesel fuel sulphur content is, for these refineries, the use of lower sulphur crude oils.

Configuration 2 – it includes the refineries which have only a catalytic cracking unit, for the conversion of heavier into lighter products. In general, these refineries maximise naphtha, and therefore gasoline production. Twelve of the 145 refineries are represented by this category, for a total crude oil capacity of 1,078,900 bpd, or 53,945,000 t/y. Also these refineries have the use of lower sulphur crude oils, as the only option for reducing the diesel fuel sulphur content.

Configuration 3 – the refineries with both thermal and catalytic cracking are represented in this category. The average sulphur content of the pool of distillates produced by the refineries in this category is usually higher than that produced by the refineries of Configuration 1, particularly because of the visbreaker and the thermally cracked and coking gas oils. In this category there are 15 refineries, for a total crude throughput capacity of 1,590,000 bpd, or 79,500,000 t/y. Like the refineries of Configurations 1 and 2, also these refineries have little or no flexibility for the reduction of the diesel fuel sulphur content, except the use of low sulphur crude oils.

Configuration 4 – this configuration includes the refineries with significant levels of thermal cracking and coking. Therefore these refineries cannot produce low sulphur diesel fuel grades. The total capacity of this type of refineries is not high: only 271,200 bpd of crude capacity, equivalent to 13,560,000 t/y.

Configuration 5 – it concerns with the refineries with catalytic crackers and a level of hydro-treating capacity of the same magnitude of the catalytic crackers. The hydro-treaters give these refineries the possibility to segregate a diesel fuel grade with sulphur levels ranging from 2,000 to 1,000 ppm, depending on the crude being run and the severity of the hydro-treater.

The total capacity of this type of refineries is 1,142,700 bpd, equivalent to 57,135,000 t/y of crude capacity.

Configuration 6 – this category includes the 4 refineries with a combination of thermal cracking, coking and visbreaking, plus almost 30% of hydro-cracking capacity. The latter unit gives these refineries the ability to segregate a diesel grade with sulphur level as low as required; the volume of this grade is dictated by the hydro-cracker capacity. The total capacity of this type of refineries is fairly small: only 327,500 bpd of crude capacity, equivalent to 16,375,000 t/y.

Configuration 7 – this is a variant of the previous configuration, the difference being the presence of a substantial catalytic cracking capacity (in addition to the thermal cracking, coking and visbreaking), and a reduced hydro-cracking capacity (only about 11% to 12%, versus the previous 30%). The total crude capacity of these refineries is 686,100 bpd, equivalent to 34,305,000 t/y.

Configuration 8 – this configuration includes refineries with the same type of thermal conversion units of Configuration 6. However, this category of refineries does not include any catalytic-cracking units, and the only way to produce diesel fuel grade(s) with low sulphur is through the fairly modest hydro-treating capacity (only about 10%). The total crude capacity of these refineries is 612,000 bpd, equivalent to 30,600,000 t/y.

Configuration 9 – it includes the most complex refineries in the region, with substantial capacities of each of the following units: most types of thermal cracking, catalytic cracking, hydro-cracking and diesel fuel hydro-treating. These refineries have a high degree of flexibility in meeting a range of diesel fuel sulphur specifications. There are 5 large refineries in this group, for a total crude distillation capacity of 1,135,700 bpd, equivalent to 52,785,000 t/y.

Configuration 10 – this category is similar to the previous Configuration 9, with the difference that the 3 refineries in this small group do not have a hydro-cracking unit. Hence, these refineries cannot produce very low sulphur diesel fuel grades. The three refineries in this group have a crude capacity of 368,000 bpd, equivalent to 18,400,000 t/y.

2.1.2 Calculation of the Diesel Sulphur Content of the Base Case

As the first step for the calculation of the level and type of new process units needed for achieving the target sulphur levels, the sulphur content of the base case conditions were calculated for:

- the average refinery configuration of each country, as represented in Tables 1.1.2.1 and 1.1.3.1
- each of the 10 individual refinery configuration groups, described in Section 2.1.1 of this report, and summarised in Table 2.1.1.1.

2.1.2.1 Assumptions for the Calculation of the Sulphur Content of Base Case and Variant Cases

These base case calculations have been based on the following assumptions:

- the investments already in place in each country and refinery configuration have cost zero.
- all gas oil components produced by the various refinery units are all in one pool. No attempt was made to study quantitatively the possibility to divide the components of the pool into different grades. Qualitative comments are made for each country, and a quantitative evaluation of some possible alternatives has been made for Singapore, as an example. Detailed studies for each country would require an in depth analysis of the diesel fuel marketing approach, the available and planned fuel distribution infrastructures, etc., which are outside the scope of this study.
- Within each country and configuration, distillate components are freely exchanged among the refineries of each group. This assumption makes the average sulphur values directionally low, and the cost of the variant cases directionally low. One alternative to this assumption would be to study each of the 145 refineries individually, which would go beyond the limited scope of this study. However, in reality, there are formidable obstacle to the exchange of components among refineries. In fact, while for transfers between refineries in the same company the issue is often easy to resolve, the transfer of intermediates among different companies is usually more difficult to arrange, as this is not a common feature of normal operation.

- In all cases (both country and configuration groups), the crude run capacity was adjusted to obtain a total diesel fuel production of 2,000,000 t/y. In this way, it will be easier to compare the relative investments for the various combinations of countries, refinery configurations and diesel fuel sulphur levels, separating the impact of the total crude distillation capacity from the effect of the units that are needed to reduce the diesel sulphur level.
- When sulphur reduction investments are made (i.e. low/medium pressure hydro-treating units, high pressure hydro-treating units, gas oil hydro-crackers), it is assumed to treat first the highest sulphur refinery streams, and subsequently the others, in the following order: visbreaker gas oil, thermally cracked gas oil, coking gas oil, catalytically cracked gas oil, straight-run gas oil.

Crude oil quality is an important factor for refineries, because more complex and expensive facilities are required to process high sulphur crude oils for the production of low sulphur diesel fuel grades. Therefore, both the country and the configuration refinery cases have been assessed with two different types of crude oil. As it would have been impractical to calculate the impact of the about 75 types of crude oils, normally processed by refineries worldwide, the following two crude types were selected: a) one representative of mixtures of Arab Light and Iranian Light crude oils. These mixtures have sulphur contents ranging between 1.5% and 2.0%, and are representative of medium to high sulphur crude oils (They will be called **High Sulphur Crude Oils** in this study); b) one representative of mixtures of medium to lower sulphur crude oils, with sulphur a content around 1.0% (They will be called **Low Sulphur Crude Oils** in this study).

A careful examination of refining literature allowed to identify the following set of sulphur contents for the two above crude oils and for the range of processes of interest:

Table 2.1.2.1.1 Sulphur Content of Refinery Streams with High & Low Sulphur Crude Oils

	Sulphur Content, ppm	**Sulphur Content, ppm**
Gas Oil Type	**High Sulphur Crude**	**Low Sulphur Crude**
Straight run	8,500	5,100
Thermally cracked & Coker	11,200	6,600
Visbreaker	13,100	7,700
Catalytically cracked	7,400	4,350
MP Hydro-treated straight run and Catalytically cracked (*)	2,300	1,400
MP Hydro-treated Thermally Cracked and Coker (*)	3,000	1,900
MP Hydro-treated Visbreaker (*)	3,800	2,400
HP Hydro-treated (**)	200	200
Hydro-cracked	10	10

(*) MP stands for Medium Pressure **(**)** HP stands for High Pressure

The above assumptions have been made with the objective to obtain an acceptably accurate, albeit simplified, representation of the very complex and diverse refining industry in Asia.

2.1.2.2 Base Case Diesel Fuel Sulphur Content by Country

Using this set of assumptions, the base case sulphur contents were predicted for the gas oil pools of the refinery categories, grouped both by country and by configuration, for the high sulphur and the low sulphur crude oils. The results for each country are summarised in the following Table 2.1.2.2.1.

Table 2.1.2.2.1 Base Case Sulphur Content of Total Gas Oil Pool by Country, ppm

Country	High Sulphur Crude	Low Sulphur Crude
Singapore	3,975	2,413
Malaysia	6,451	3,877
Thailand	5,202	3,137
Philippines	3,690	2,236
Indonesia	6,922	4,148
Myanmar	8,901	5,323
Brunei	8,500	5,100
India	8,136	4,876
Pakistan	8,500	5,100
Bangladesh	9,355	5,575
Sri Lanka	9,198	5,493
People's Republic of China	8,198	4,899

It is interesting to compare the data of this table to the current diesel fuel sulphur limits of the same countries, which are shown in the following Table 2.1.2.2.2:

Table 2.1.2.2.2 Current Diesel Fuel Sulphur Limits

Country	Sulphur Limits max, ppm	Notes
Singapore	500	
Malaysia	2,000	
Thailand	500	
Philippines	2,000	
Indonesia	5,000	
Myanmar	3,000	
Brunei	2,500	
India	2,500	500 in metropolitan areas
Pakistan	10,000	5,000 from Dec. 2002
Bangladesh	5,000	
Sri Lanka	10,000	5,000 from 2003
People's Republic of China	5,000 to 10,000	2,000 for the Premium Gra

In trying to reconcile the calculated values of Table 2.1.2.2.1 with the diesel fuel sulphur limits of each country, the following comments must be taken into account:

- all distillate blending streams are included in the calculated data of Table 2.1.2.2.1, including those refinery streams, that, in most cases, are used for blending fuels aimed at marketing outlets different from the high speed automotive diesel engines (e.g. railways, off-road and industrial applications, etc.).
- usually the gas oil components used for blending these other diesel fuel grades have higher sulphur contents, as the specification limits for these grades are usually higher than the limit for the automotive diesel fuel.
- in most countries, the infrastructure exists for segregating the automotive diesel fuels from the gas oils used for other applications. However, in other countries, these segregating facilities do not exist.

A detailed reconciliation between calculated data and local sulphur limits would require detailed studies for each country, including the precise sulphur content of the crude run in each refinery, the detailed severity of the various refinery units employed and the precise capacity of each unit, the capability of the refining and marketing distribution systems to segregate gas oil streams as required, the importation of low sulphur blending components and/or finished diesel fuel. This detailed analysis goes beyond the scope of this study. However, the following qualitative comments can be made:

Singapore:

As an example, a hypothetical blending study was made, simulating the production of 2 or 3 different diesel fuel sulphur grades, instead of blending the streams all together in the same gas oil pool. This simple blending study has been made for both the High and Low Sulphur crude oil cases. The results show:

Table 2.1.2.2.3 Blending Study – High Sulphur Crude Oil

	Sulphur, ppm	**Production, t/y**
Pool	3,975	2,000,000
Alternative One		
Grade A, 50 ppm max	49	329,655
Grade A, 500 ppm max	499	212,242
Grade A, 5500 ppm max	5,369	1,458,103
Alternative Two		
Grade A, 50 ppm max	49	0
Grade A, 500 ppm max	499	624,397
Grade A, 6000 ppm max	5,553	1,375,603

Table 2.1.2.2.4 Blending Study – Low Sulphur Crude Oil

	Sulphur, ppm	Production, t/y
Pool	2,413	2,000,000
Alternative One		
Grade A, 50 ppm max	49	329,655
Grade A, 500 ppm max	499	242,442
Grade A, 5500 ppm max	5,434	1,427,903
Alternative Two		
Grade A, 50 ppm max	49	0
Grade A, 500 ppm max	499	736,897
Grade A, 6000 ppm max	5,843	1,263,103

The results of this hypothetical blending study show that, in the base case, the three refineries of Singapore have the capability of producing significant quantities of low sulphur diesel fuel grades, with a sulphur level of both 50 and 500 ppm max. Obviously, the production of these grades is limited by the capacities of the hydro-cracking and hydro-treating units. The lower sulphur crude allows producing more of the 500 ppm sulphur grade, but it has essentially no impact on the production of the 50 ppm grade, which is only limited by the capacity of the hydro-crackers.
Similar considerations could be made for all groups of refineries considered in this study (grouped either by country or by configuration), where gas oil sulphur reduction units are installed, i.e. hydro-crackers and/or hydro-treaters.

Malaysia:
Of the total gas oil blending components manufactured in Malaysia, about 18% are hydro-treated, and about 11% are hydro-cracked. This allows the production of enough automotive diesel fuel with a sulphur content ranging from 1,000 to 2,000 ppm. However, the higher sulphur blending components should be segregated and used for blending other gas oil grades.

Thailand:
Of the total gas oil blending components manufactured in Thailand, about 41% are hydro-treated, and about 6% are hydro-cracked. This allows the production of enough automotive diesel fuel with a sulphur content below 500 ppm, particularly if fairly low sulphur crude slates are used.

Philippines:
Of the total gas oil blending components manufactured in the Philippines, about 74% are hydro-treated. This allows the production of enough automotive diesel fuel with a sulphur content below 2,000 ppm, particularly if fairly low sulphur crude slates are used.

Indonesia:
Of the total gas oil blending components manufactured in the refineries of Indonesia, about 3% are hydro-treated, and about 17% are hydro-cracked. This

should allow the production of automotive diesel fuels with sulphur contents below 5,000 ppm. Going below this level, would require a combination of lower sulphur crude slates and some refinery investments.

Myanmar:
No gas oil desulphurisation units currently exist in the Myanmar refineries. The only ways of reducing the diesel fuel sulphur content are: a) reducing the sulphur content of the crude slate, and/or b) importing lower sulphur diesel fuel blending components.

Brunei:
No gas oil desulphurisation units currently exist in the Brunei refinery. The only ways of reducing the diesel fuel sulphur content are: a) reducing the sulphur content of the crude slate, and/or b) importing lower sulphur diesel fuel blending components.

India:
Of the total gas oil blending components manufactured in India, about 3.5% are hydro-treated, and about 2.4% are hydro-cracked. These components are likely to be used (eventually complemented by importations of low sulphur diesel fuels) to blend the diesel for the Metropolitan areas. Significant volumes of the higher sulphur blending components should be segregated and used for blending fuels for the rest of the country and for non-automotive applications.

Pakistan:
No gas oil desulphurisation units currently exist in the refineries of Pakistan. The only ways of reducing the diesel fuel sulphur content are: a) reducing the sulphur content of the crude slate, and/or b) importing lower sulphur diesel fuel blending components.

Bangladesh:
Of the total gas oil blending components manufactured in Bangladesh, about 2.8% are hydro-cracked. This allows blending some automotive diesel fuels with sulphur contents below 5,000 ppm max, the total amount depending on the level of sulphur of the crude used locally. However, the refinery of Bangladesh is also producing large volumes of high sulphur visbreaker gas oil (about 30% of the total distillate pool).

Sri Lanka:
Of the total gas oil blending components manufactured in Sri Lanka, about 3.5% are hydro-treated. This allows blending enough automotive diesel fuel with a sulphur content meeting the local specification.

People’s Republic of China:
The refining situation of this country is very complex. As shown in the detailed analysis of Appendix 1, some refineries are quite complex and sophisticated,

while others are simple and inflexible. However, on a global basis, of the total gas oil blending components manufactured in China, about 1% are hydro-treated, and about 2.3% are hydro-cracked. This limits the volume of Premium Grade that can be manufactured, without investing in additional refinery units. Of course, the volume of Premium Grade that can be produced is also a function of the sulphur content of the crude oils run in the local refineries.

2.1.2.3 Base Case -- Diesel Fuel Sulphur Content by Refinery Configuration

In each country, there are, in most cases, several refineries with different structures. Therefore each individual refinery may have peculiar problems and difficulties in meeting stricter diesel fuel sulphur specifications. Regarding the base case, each refinery will have, for both the High Sulphur and Low Sulphur crude oils, diesel fuel sulphur values that are a function of the conversion facilities and the desulphurisation units already existing in the refinery. The diesel fuel sulphur values predicted for the base case are reported in Table 2.1.2.3.1 for each of the refinery configurations described in section 2.1.1 of this report.

Table 2.1.2.3.1 Base Case – Diesel Fuel Sulphur Content by Refinery Configuration

Configuration	Therm. Cracking (*)	Catalytic Cracking	Hydro-treating	Hydro-cracking	High S Crude	Low S Crude
1	--	--	--	--	8,500	5,100
2	--	x	--	--	7,888	4,683
3	x	x	--	--	8,725	5,181
4	x	--	--	--	9,632	5,729
5	--	x	x	--	6,100	3,667
6	x	--	--	x	6,136	3,649
7	x	x	--	x	7,462	4,426
8	x	--	x	--	7,737	4,656
9	x	x	x	x	5,572	3,352
10	x	x	x	--	6,854	4,096

(*) In this table, with thermal cracking, it is meant the conventional thermal cracking, coking and visbreaking

Keeping in mind the capacities of the units of each configuration (listed in Table 2.1.1.1), the following comments are worth noting:

- The diesel fuel sulphur content for all configurations are relative to the total pool of distillate streams.
- Configurations 1, 2, 3 and 4 do not include any units producing low sulphur blending components, and therefore are predicted to produce a pool of distillate with the highest sulphur content. The configurations including thermal cracking units have the highest sulphur levels.

- Configuration 5, with catalytic cracking and hydro-treating units, can produce fairly low distillate sulphur pool levels, particularly when low sulphur crude oils are processed.
- Configuration 8, on the contrary, with thermal cracking and hydro-treating units, would need a much higher hydro-treating capacity to achieve the same sulphur levels of configuration 5.
- Configurations 6 and 9, in spite of the presence of thermal cracking units, can produce fairly low sulphur distillate pool levels, because of the presence of some hydro-cracking capacity.
- Configuration 9 is a demonstration that complex refineries can produce amounts of low sulphur diesel fuels. However, even these refineries do not have enough capacity to produce low sulphur distillates for their entire production (see the Singapore blending study data of Tables 2.1.2.2.3 and 2.1.2.2.4 as an example).
- In the base case conditions, the distillate pools manufactured with low sulphur crude oils are predicted to have a sulphur content about 40% lower than that produced with high sulphur crude oils.
- Overall, there are potentially big differences between the severities of the problems encountered by the Asian refineries, when tackling the issue of reducing the sulphur content of the diesel fuel. In fact, a refinery with some hydro-treating and/or hydro-cracking capacity, and running a low sulphur crude slate, is predicted to produce, in the base case, a distillate pool with a sulphur content which can be up to 65% lower than that produced by a refinery with thermal cracking units, and running a high sulphur crude slate.

Chapter 3

3. Cost Calculation of Diesel Fuel sulphur Reduction for Each Study Country and Each Selected Refinery Configuration.

The additional refinery investments and diesel fuel costs, consequent to the reduction of the maximum sulphur content of the diesel fuel to 3,000 ppm, 1,000 ppm, 500 ppm, 350 ppm, 250 ppm, 50 ppm and 10 ppm, was calculated for:

a) The average refinery structure of each of the 12 Asian countries included in this study;

b) Each of the 10 refinery configurations, selected as being representative of the 145 refineries currently in operation in the above 12 countries.

3.1 Cost Calculation Methodology

The case studies are presented and discussed in increasing order of complexity and cost of refinery investments and operations, both for high and low sulphur crude oils, as follows:

- reduction of the sulphur content of the diesel fuel pool to 3,000 ppm maximum, assuming to invest in new or expanded low to medium pressure hydro-treating units.
- reduction of the sulphur content of the diesel fuel pool to 1,000 ppm, 500 ppm, 350 ppm, and 250 ppm maximum, assuming to invest in new or expanded high pressure (above 70 bar) hydro-treating units.
- reduction of the sulphur content of the diesel fuel pool to 50 ppm and 10 ppm maximum, assuming to invest in new or expanded hydro-cracking units.
- run sensitivity cases to ensure that the above approach, rather than combinations of sulphur reduction processes, leads to lower cost solutions.

The results of each of these case studies are presented individually, and discussed according to logical groupings, i.e. discussing together, for each sulphur level, the implications both on a country basis and on a refinery configuration basis. For each individual case, the following detailed information are given:

1) Capital investment costs
2) Fixed operating costs and variable operating costs associated to the investments in 1)
3) Other operating costs due to the use of low sulphur crude oils.
4) For all cases involving the use of low sulphur crude oils, the credits for the higher yields of naphtha and distillate and the lower yields of heavy fuel oil are calculated.
5) Additional cost of the diesel fuel, consequent to the costs incurred in 1), 2), 3), 4). For this calculation, it is assumed that the additional costs 1), 2), 3), 4) are incurred only because of the need to improve the quality of the diesel fuel; therefore these costs are only allocated to the diesel fuel. They are expressed in cents of US dollar per litre of fuel.

An industry standard linear programming model was used to calculate the yields of the various processes. Diesel fuel sulphur quality mass balances and costs of each case study were calculated through the use of spreadsheets. All calculations were made for product pools (i.e. no attempts were made to identify and separate possible product grades). The refinery investments have been estimated on the assumption that the refinery would always be run to the limitation of the crude distillation unit.

The capital costs for the processes that are considered in this study are those quoted by major international process vendors for Western Europe and the U.S. Gulf Coast. Therefore they are corrected through the use of a location factor, with an average value of 1.5. This value is consistent with the usual practice in Asian countries. These costs have been also compared to costs adopted in similar studies world-wide, to ensure relative consistency. In particular, a consistent set of cost data used in the European Union Auto-Oil II programme proved quite useful. This study was performed for Directorate General XVII of the European Union by independent consultants. The process cost data for this study were extensively searched and came from a variety of sources, among which: UOP, IFP, AKZO NOBEL, CRITERION Catalyst UK, HALDOR TOPSOE Denmark, STRATCO USA, Sud-Chemie Germany, CONCAWE and several petroleum industries.

For the calculation of the costs of the processes included in the present study (and of their implications in terms of product cost) the following assumptions were made:

- Location Factor: 1.5 across all processes
- Scaling Factor (for calculating the capital cost of units having a size different from that of plants for which the actual cost is available): power of 0.6. This is standard practice in the petroleum and chemical industries.
- Annualization of capital costs: the capital costs were annualised over 10 years, with a discount factor of 7%. This factor is consistent with fact that cost calculations are made in U.S. dollars.
- Operating costs associated with the investment: 10 % of the annualised capital costs.
- Cost of additional tankage, pumps, pipes, utilities, infrastructure, etc.: 20% on top of total local capital cost.
- It is assumed that, in the base case there is no excess hydrogen available. Therefore, to all new hydro-treating and hydro-cracking units, the cost of a hydrogen plant of adequate capacity was added.
- In order to compare the investments and product cost results relative to the 12 study countries and the 10 refinery configurations, the cost calculations were made, in all cases, assuming a constant diesel fuel production of 2,000,000 t/y.

3.2 Cost Inputs

The spreadsheet cost and diesel fuel sulphur content calculations were based on the following data, which was common for each case:

a) Capital Costs -- the capital costs of new processes for low/medium pressure and high pressure hydro-treating units, and for distillate hydro-crackers are summarised in the next table, together with the impact of the implications of the assumptions listed in section 3.1 of this report.

Table 3.2.1 Capital Cost of New Processes

Process Unit	Capacity, t/y	1999 Cost $ M	Location Factor	1999 Local Cost, $M	2002(*) Local Cost, $M	Hydrogen Unit, % of Total Cost	2002 Total Local (**) Cost, $M
MP Hydro treating	250,000	17.5	1.5	26.3	30.4	8%	39.4
HP Hydro treating	500,000	34.0	1.5	51.0	59.0	10%	77.9
Hydro Cracking	500,000	65.0	1.5	97.5	112.9	14%	154.4
Hydro Cracking	1,000,000	98.5	1.5	147.8	171.0	14%	234.0

(*) cost increase – 5% per year
(**) including hydrogen balance unit and utilities, tankage, infrastructures, etc.

The costs indicated in this table are average total installed costs of the plant. In the actual situation of any of the 145 Asian refineries under consideration, these costs would be subject to variation depending on site conditions. In particular, it must be pointed out that the accuracy of the results obtained from an exercise of this nature is intrinsically subject to a number of uncertainties. These arise from the assumptions that have had to be made. Among the more important are those related to:

- refinery units: capacities, availabilities, performance, operating costs
- crude oils: sulphur content and prices
- oil product prices

Because of all these elements, levels have been selected for the above elements which would generally be regarded as reasonable, and command a consensus amongst experts of the sector.

However, it must be emphasised that the accuracy of the cost figures calculated in this study are only offered for conceptual planning purposes. In particular, such figures should not be used as a basis for local investment decisions. This would require a much more detailed local study, which would take into account all the necessary local petroleum products refining and marketing data and conditions.

b) Petroleum Product Prices

The prices used to calculate the diesel fuel price increase, due to tighter sulphur specifications, are shown in Table 3.2.2. The prices of these commodities are all related to the price of crude oil, and this has shown great volatility. However, as all prices are linked to crude oil prices, their relative values tend to remain fairly constant. The approach taken in this report was to use current Singapore prices – third quarter 2002 – for petroleum product commodities.

Table 3.2.2 Petroleum Product Prices

Product	Cost, $/barrel	Cost, $/tonne
High Sulphur Crude	26.0	189.9
Additional Price of Low Sulphur Crude	1.1	8.1
Heavy Fuel Oil	--	165.0
Full Range Naphtha	27.4	242.7
Gas oil – 1.0% S	29.0	210.1
Gas oil – 0.5% S	29.7	216.2
Gas oil – 0.3% S	30.0	219.7
Gas oil – 0.05% S	30.6	225.6
Gas oil – 0.005% S	34.3	253.8

3.3 Product Yields with High and Low Sulphur Crude Oils

On average, low sulphur crude oils are lighter than the high sulphur ones. Therefore, when running low sulphur crude oils, the naphtha and distillate yields tend to be higher, and the heavy fuel oil yields tend to be lower. For this study, the following average crude distillation unit yields were assumed, for high and low sulphur crude oils respectively:

Table 3.3.1 Light Product Yields (from Distillation Unit)

	High Sulphur Crude	Low Sulphur Crude
Full Range Naphtha	16	20
Gas Oil	28	35

The higher yields of more valuable lighter products are partly compensating for the higher cost of running low sulphur crude oils. This has been taken into account in the calculation of the costs of implementing the variant cases that will be presented in the subsequent sections of this report.

3.4 Cost of Meeting a 3,000 ppm Maximum Limit of the Gas Oil Pool

The cost of meeting a 3,000 ppm maximum limit of the gas oil pool was calculated for each average country refinery structure, and for each of the refinery configurations under study, versus the base case. This calculation was made for both the high and low sulphur crude oil. The results, in terms of capital investments and additional diesel fuel costs, are reported in the next set of tables. The costs were calculated according to the methodology described in section 3.1, and using the input data listed in section 3.2 of this report. It is worth remembering that, consistently with the assumptions of this study, all costs in the following Table 3.4.1 are relative to an average refinery, with a configuration including the key units at the average capacity of each country, and producing, in every case, 2,000,000 t/y of diesel fuel.

Table 3.4.1 Capital Costs and Product Incremental Cost – 3,000 ppm Maximum Sulphur Limit of the Gas Oil Pool – 12 Study Asian Countries.

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	Low S Crude	High S crude	Low S Crude
Singapore	46.1	0.0	0.29	0.31
Malaysia	98.3	59.0	0.62	0.73
Thailand	83.9	21.9	0.53	0.49
Philippines	37.5	0.0	0.24	0.38
Indonesia	106.4	70.0	0.67	0.74
Myanmar	131.5	101.6	0.83	1.00
Brunei	130.0	99.5	0.82	1.05
India	125.1	93.7	0.79	0.94
Pakistan	130.0	99.5	0.82	1.05
Bangladesh	131.6	102.1	0.83	0.95
Sri Lanka	131.6	102.1	0.83	0.97
People's Republic of China	127.0	96.0	0.80	0.92

The following remarks are worth noting:

- in all cases, the sulphur reduction has been achieved through the installation of additional Medium Pressure hydro-treating capacity.
- with low sulphur crude oils, the refineries representative of the average configurations of Singapore and the Philippines could meet the 3,000 ppm sulphur target without any additional investments. Even in the high sulphur crude oil case, these refineries would have to make relatively low investments, in the range of US $ 46 million and US $ 37 million respectively. This is due to the high hydro-treating and hydro-cracking capacities of the base case conditions in Singapore, and to the very high hydro-treating capacity of the base case in the Philippines (for more details, see section 1.1.2 "Average Refinery Complexity by Country", and more specifically Table 1.1.3.1). Because of these favourable base case conditions, these two countries are predicted to incur the lowest incremental diesel fuel cost (in the range of 0.25 to 0.38 cents of US $ per litre of product.
- In all cases, with the exception of Thailand, the incremental product cost is higher when running low sulphur crude oils, as the impact of the higher crude oil price is larger than the impact of the annualised capital cost difference between the investments with high and low sulphur crude oils.
- a detailed comparison of Tables 1.1.3.1 and 3.4.1 shows that the capital investment is low when the base case includes significant levels of hydro-treating and/or hydro-cracking capacity. On the contrary, the required capital investment is high, when the base case capacity of thermal cracking units in general, and of visbreakers in particular, is high.
- In all cases, running low sulphur crude oils can remarkably reduce the level of capital investments required. This is quite important, as, in most cases, the fairly high capital

investments required are one of the major obstacles to the implementation of low sulphur diesel fuel projects.

Similar calculations have been made for the 10 refinery configurations, which represent the conditions of most of the individual 145 refineries analysed in this study. The results of these calculations are shown in the following Table 3.4.2:

Table 3.4.2 Capital Costs and Incremental Product Cost – 3,000 ppm Maximum Sulphur Limit of the Gas Oil Pool – 10 Refinery Configurations.

Configuration	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
1	130.0	99.4	0.82	1.05
2	127.8	87.4	0.80	0.74
3	130.9	95.5	0.82	0.80
4	134.1	105.3	0.84	0.91
5	92.2	50.0	0.58	0.57
6	81.9	41.7	0.51	0.41
7	113.7	76.5	0.71	0.63
8	114.8	82.0	0.72	0.79
9	85.4	39.1	0.54	0.43
10	112.3	77.2	0.71	0.64

In order to understand the data of this table, it should be examined together with the information of Table 2.1.1.1, where the type and capacity of each relevant refinery unit is reported. Also in this case, it is assumed that each refinery configuration produces 2,000,000 t/y of diesel fuel, and that the sulphur reduction of the gas oil pool is achieved through additional medium pressure hydro-treating capacity. The following messages emerge:

- configurations 1, 2, 3 and 4 do not include any hydro-treating or hydro-cracking capacity. Therefore they require the highest investments. Configuration 4 requires the highest investment, as it includes the highest thermal cracking capacity, hence producing gas oil components with high sulphur contents.
- Regarding the incremental product costs of the first four configurations, the high sulphur cases present very similar values, as these mainly reflect the capital costs, which are very similar. On the contrary, the low sulphur cases present quite different values, ranging from 0.74 to 1.05 cents of US $ per litre. Configuration 1 shows the highest product cost increase, as, in this case, there are no conversion units. Therefore all the distillate must be produced in the distillation unit, which implies running the highest amount of crude oil (hence incurring the highest cost debit due to the high price of the low sulphur crude oils), in order to produce the target of 2,000,000 t/y of diesel fuel.
- Configurations 5, 8 and 10 already include hydro-treating units in the base case, with significant capacities, ranging from 10.5% to 17.5% of the crude distillation capacity. The investment costs and the incremental product costs are therefore lower than the first four configurations. In fact the predicted capital cost are between 15% and 30% lower for

the high sulphur crude oils, and between 20% and 50% lower for the low sulphur crude oils.

- Similar considerations can be made for configurations 6 and 7 (with substantial hydro-cracking capacity) and configuration 9, which includes both hydro-treating and hydro-cracking units.

3.5 Cost of Meeting a 1,000 ppm Maximum Limit of the Gas Oil Pool

The cost of meeting a 1,000 ppm maximum limit of the gas oil pool was calculated for each average country refinery structure, and for each of the refinery configurations under study, versus the base case. The introductory comments made about the 3,000 ppm limit case apply also to this section of the report. The results, in terms of capital investments and additional diesel fuel costs, are reported in the next set of tables.

Table 3.5.1 Capital Costs and Product Incremental Cost – 1,000 ppm Maximum Sulphur Limit of the Gas Oil Pool – 12 Study Asian Countries.

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	Low S Crude	High S crude	Low S Crude
Singapore	104.3	88.1	0.66	0.87
Malaysia	144.4	135.0	0.91	1.21
Thailand	123.5	113.0	0.78	1.06
Philippines	123.7	81.3	0.78	0.89
Indonesia	151.7	142.7	0.95	1.19
Myanmar	174.9	167.0	1.10	1.47
Brunei	174.9	167.0	1.10	1.47
India	169.7	161.7	1.07	1.37
Pakistan	174.9	167.0	1.10	1.47
Bangladesh	171.5	163.5	1.08	1.34
Sri Lanka	172.6	164.7	1.09	1.36
People’s Republic of China	171.5	163.5	1.08	1.35

Remarks:

- in all cases, the sulphur reduction was achieved through the installation of High Pressure (above 70 bar) hydro-treating capacity, as the Low/Medium pressure hydro-treating units cannot achieve consistently 1,000 ppm maximum distillate sulphur content, particularly for refineries with thermal conversion units, and running high sulphur crude oils.
- In all cases, both the capital costs and the incremental product costs have increased substantially, versus the 3,000 ppm limit case, as shown in the following table:

Table 3.5.2 Capital Costs and Product Incremental Cost – Increase of 1,000 ppm Maximum Sulphur Case versus the 3,000 ppm Maximum Sulphur Case – 12 Study Asian Countries

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
Singapore	58.2	88.1	0.37	0.55
Malaysia	46.1	76.1	0.29	0.48
Thailand	39.7	91.1	0.25	0.57
Philippines	86.2	81.3	0.54	0.51
Indonesia	45.3	72.9	0.28	0.46
Myanmar	43.4	65.4	0.27	0.41
Brunei	44.9	67.5	0.28	0.42
India	44.6	68.0	0.28	0.43
Pakistan	44.9	67.5	0.28	0.42
Bangladesh	39.8	61.4	0.25	0.39
Sri Lanka	40.9	62.6	0.26	0.39
People's Republic of China	44.5	67.5	0.28	0.42

This table shows that, when the stricter limit of 1,000 ppm (versus 3,000 ppm) is imposed, the impact of the benefit of the low sulphur crude is de- emphasised, as the cost increase of the low sulphur crude cases are higher than the cost increases of the high sulphur crude cases. For the refineries representing the average conditions of Singapore, Thailand and the Philippines, the cost increases are higher than the average, as, for the 1,000 ppm limit, the base case hydro-treating capacity (which is quite relevant for the refineries of these countries) becomes less important towards meeting the more severe sulphur target of 1,000 ppm.

- A sensitivity study was made to explore if a combination of low/medium pressure and high pressure hydro-treating units would have been less costly than achieving the 1,000 ppm sulphur target with high pressure hydro-treating only.
- This sensitivity analysis was done for the following cases: Singapore – low sulphur crude, Malaysia – low and high sulphur crude oils, Indonesia – low and high sulphur crude oils. The results of this analysis are reported in the following table.

Table 3.5.3 Cost Implications of Meeting 1,000 ppm Sulphur Target with Low/Medium And High Pressure Hydro-Treaters Rather than High Pressure Hydro-Treaters Only

Hydro-Treater	**High Pressure only**	**High Pressure only**	**High Pressure only**	**High Pressure only**	**Med & High Pressure**	**Med & High Pressure**	**Med & High Pressure**	**Med & High Pressure**
Cost	Capital, $ M	Capital, $ M	Product, US c/l	Product, US c/l	Capital, $ M	Capital, $ M	Product, US c/l	Product, US c/l
Crude	High S	Low S	High S	Low S	High S	Low S	High S	Low S
Singapore	--	88.1	--	0.87	--	101.4	--	0.95
Malaysia	144.4	135.0	0.91	1.21	176.9	167.5	1.11	1.41
Indonesia	151.7	142.7	0.95	1.19	189.2	178.5	1.19	1.42

In all cases, achieving the diesel fuel sulphur target with a combination of low/medium and high pressure hydro-treating units is more costly than investing, from the outset, in high pressure hydro-treating units only. This finding reinforces the desirability of avoiding intermediate sulphur specification levels, which may be achieved through the deployment of relatively less advanced refining technologies, which may become ineffective or partly obsolete, if subsequently stricter sulphur limits are going to be mandated.

Also in this case, similar calculations have been made for the 10 refinery configurations, which represent the conditions of most of the individual 145 refineries analysed in this study. The results of these calculations are shown in the following Table 3.5.4:

Table 3.5.4 Capital Costs and Incremental Product Cost – 1,000 ppm Maximum Sulphur Limit of the Gas Oil Pool – 10 Refinery Configurations.

Configuration	**Capital Cost, $ million**	**Capital Cost, $ million**	**Incremental Product Cost, US cents/litre**	**Incremental Product Cost, US cents/litre**
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
1	174.9	167.0	1.10	1.47
2	173.2	163.4	1.09	1.21
3	173.1	163.4	1.09	1.23
4	174.9	167.0	1.10	1.29
5	139.4	129.0	0.88	1.07
6	125.7	114.8	0.79	0.87
7	156.8	148.1	0.99	1.08
8	159.8	150.5	1.00	1.22
9	132.7	123.0	0.83	0.96
10	171.7	167.0	1.08	1.20

Remarks:

- only the configurations with significant levels of hydro-treating and/or hydro-cracking capacities in the base case (number 5, 6, 9, and, to a lesser extent 7, 8) are predicted to be able to meet the 1,000 ppm maximum sulphur limit with investment and incremental diesel fuel costs lower than the other configurations.

- In particular, the three configurations which have hydro-cracking units in the base case (number 6, 7 and 9) are predicted to achieve the sulphur target with investment costs between 10% and 30% lower than the other configurations.
- In this case – 1,000 ppm – the difference between the capital costs required with high sulphur and low sulphur crude oils is much lower than for the 3,000 ppm case. In fact, while the differences in capital requirements (between the high and low sulphur cases) which are needed to meet the 3,000 ppm sulphur target range between $ 30 M and $ 45 M, the equivalent differences to meet the 1,000 ppm sulphur target are only $ 5 M to $ 10 M. This trend has been experienced in several refinery applications, where the deployment of more advanced sulphur reduction technologies (due to the need to meet severe diesel fuel sulphur limits), made the low sulphur crude oils economically less appealing as: a) the advanced desulphurisation technologies (high pressure hydro-treating and hydro-cracking units) reduce the sulphur levels of the desulphurised streams to very low levels, almost regardless of the sulphur content of the feed, and b) the higher cost of low sulphur crude oils impacts on all products manufactured by the refineries.

3.6 Cost of Meeting a 500 ppm Maximum Limit of the Gas Oil Pool

The cost of meeting a 500 ppm maximum limit of the gas oil pool was calculated for each average country refinery structure, and for each of the refinery configurations under study, versus the base case. The introductory comments made about the 3,000 ppm limit case apply also to this section of the report. The results, in terms of capital investments and additional diesel fuel costs, are reported in the next set of tables.

Table 3.6.1 Capital Costs and Product Incremental Cost – 500 ppm Maximum Sulphur Limit of the Gas Oil Pool – 12 Study Asian Countries

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	Low S Crude	High S crude	Low S Crude
Singapore	135.5	118.8	0.85	1.06
Malaysia	154.8	148.7	0.97	1.29
Thailand	146.5	131.6	0.92	1.18
Philippines	155.8	142.0	0.98	1.27
Indonesia	159.3	155.9	1.00	1.28
Myanmar	181.8	178.9	1.14	1.48
Brunei	181.8	178.9	1.14	1.54
India	176.8	173.9	1.11	1.45
Pakistan	181.8	178.9	1.14	1.54
Bangladesh	178.5	175.5	1.12	1.41
Sri Lanka	179.5	176.7	1.13	1.44
People’s Republic of China	178.5	175.5	1.12	1.42

Remarks:

- In all cases, the sulphur reduction was achieved through the installation of High Pressure (above 70 bar) hydro-treating units.
- In all cases, both the capital costs and the incremental product costs have increased, versus the previous 1,000 ppm limit case, as shown in the following table. However, this increase is significantly lower than that of Table 3.5.2, which was showing the difference between the costs of the 3,000 ppm limit and the 1,000 ppm limit.

Table 3.6.2 Capital Costs and Product Incremental Cost – Increase of 500 ppm Maximum Sulphur Case versus the 1,000 ppm Maximum Sulphur Case – 12 Study Asian Countries

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
Singapore	31.2	30.6	0.20	0.19
Malaysia	10.4	13.6	0.07	0.09
Thailand	23.0	18.6	0.14	0.12
Philippines	32.1	60.6	0.20	0.38
Indonesia	7.6	13.2	0.05	0.08
Myanmar	6.9	11.9	0.04	0.07
Brunei	6.9	11.9	0.04	0.07
India	7.0	12.2	0.04	0.08
Pakistan	6.9	11.9	0.04	0.07
Bangladesh	7.0	12.1	0.04	0.08
Sri Lanka	7.0	12.0	0.04	0.08
People's Republic of China	7.0	12.1	0.04	0.08

This table shows that, when the stricter limit of 500 ppm (versus 1,000 ppm) is imposed, the impact of the benefit of the low sulphur crude is even more de- emphasised, as the cost increase of the low sulphur crude cases are higher than the cost increases of the high sulphur crude cases.

- Also for the 500 ppm sulphur target limit, a sensitivity study was made to explore if a combination of low/medium pressure and high pressure hydro-treating units would have been less costly than achieving the 500 ppm sulphur target with high pressure hydro-treating only.
- This sensitivity analysis was done for the following cases: Malaysia – low sulphur crude, Indonesia – low and high sulphur crude oils. The results of this analysis are reported in the following table.

Table 3.6.3 Cost Implications of Meeting 500 ppm Sulphur Target with Low/Medium And High Pressure Hydro-Treaters Rather than High Pressure Hydro-Treaters Only

Hydro-Treater	**High Pressure only**	**High Pressure only**	**High Pressure only**	**High Pressure only**	**Med & High Pressure**	**Med & High Pressure**	**Med & High Pressure**	**Med & High Pressure**
Cost	Capital, $ M	Capital, $ M	Product, US c/l	Product, US c/l	Capital, $ M	Capital, $ M	Product, US c/l	Product, US c/l
Crude	High S	Low S	High S	Low S	High S	Low S	High S	Low S
Malaysia	--	148.7	--	1.29	--	171.7	--	1.44
Indonesia	159.3	155.9	1.00	1.28	187.2	190.7	1.18	1.50

Also for the 500 ppm sulphur limit, achieving the diesel fuel sulphur target with a combination of low/medium and high pressure hydro-treating units is more costly than investing, from the outset, in high pressure hydro-treating units only.
Also in this case, similar calculations have been made for the 10 refinery configurations, which represent the conditions of most of the individual 145 refineries analysed in this study. The results of these calculations are shown in the following Table 3.6.4:

Table 3.6.4 Capital Costs and Incremental Product Cost – 500 ppm Maximum Sulphur Limit of the Gas Oil Pool – 10 Refinery Configurations

Configuration	**Capital Cost, $ million**	**Capital Cost, $ million**	**Incremental Product Cost, US cents/litre**	**Incremental Product Cost, US cents/litre**
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
1	181.8	178.9	1.14	1.54
2	181.1	177.7	1.14	1.30
3	181.1	177.6	1.14	1.32
4	181.8	178.9	1.14	1.37
5	169.4	156.4	1.06	1.24
6	134.2	129.9	0.84	0.96
7	164.2	160.9	1.03	1.16
8	176.4	170.2	1.11	1.34
9	148.6	140.6	0.93	1.07
10	181.8	178.9	1.14	1.28

Remarks:

- only the configurations with significant levels of hydro-treating and/or hydro-cracking capacities in the base case (number 6, 9, and, to a lesser extent 5, 7, 8) are predicted to be able to meet the 500 ppm maximum sulphur limit with investment and incremental diesel fuel costs lower than the other configurations.
- In particular, configuration 6, which has hydro-cracking units with the highest capacity (almost 30%) in the base case, is predicted to achieve the sulphur target with investment costs between 20% and 30% lower than the other configurations, except configuration 9. This configuration is predicted to require investments only about 10%

higher than configuration 6, as it includes, in the base case, not only a hydro-cracker unit with a capacity of 11.5%, but also an additional hydro-treating capacity of almost 15%.

- In this case – 500 ppm – the difference between the capital costs required with high sulphur and low sulphur crude oils is very low (between $ 2 M and $ 5 M, which represent about 1% to 3% of the total investment required). This makes the low sulphur crude oils economically even less appealing than for the 1,000 ppm sulphur limit. This trend will continue as the sulphur targets will become lower.

3.7 Cost of Meeting a 350 ppm Maximum Limit of the Gas Oil Pool

The cost of meeting a 350 ppm maximum limit of the gas oil pool was calculated for each average country refinery structure, and for each of the refinery configurations under study, versus the base case. The introductory comments made about the 3,000 ppm limit case apply also to this section of the report. The results, in terms of capital investments and additional diesel fuel costs, are reported in the next set of tables.

Table 3.7.1 Capital Costs and Product Incremental Cost – 350 ppm Maximum Sulphur Limit of the Gas Oil Pool – 12 Study Asian Countries

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
Singapore	145.0	136.7	0.91	1.17
Malaysia	163.3	155.8	1.03	1.22
Thailand	155.7	148.4	0.98	1.29
Philippines	164.6	158.1	1.03	1.37
Indonesia	161.5	159.7	1.02	1.30
Myanmar	183.8	182.4	1.16	1.50
Brunei	183.8	182.4	1.16	1.57
India	178.9	177.4	1.12	1.47
Pakistan	183.8	182.4	1.16	1.57
Bangladesh	180.5	179.1	1.13	1.43
Sri Lanka	181.6	180.2	1.14	1.46
People's Republic of China	180.5	179.1	1.13	1.44

Remarks:

- In all cases, the sulphur reduction was achieved through the installation of High Pressure (above 70 bar) hydro-treating units.
- In all cases, both the capital costs and the incremental product costs have increased, versus the previous 500 ppm limit case, as shown in the following table. However, this increase is significantly lower than that of Tables 3.5.2 and 3.6.2, which were showing the difference between the costs of the 3,000 ppm limit and the 1,000 ppm limit, and the difference between the costs of the 1,000 ppm limit and the 500 ppm limit respectively.

Table 3.7.2 Capital Costs and Product Incremental Cost – Increase of 350 ppm Maximum Sulphur Case versus the 500 ppm Maximum Sulphur Case – 12 Study Asian Countries

Country	**Capital Cost, $ million**	**Capital Cost, $ million**	**Incremental Product Cost, US cents/litre**	**Incremental Product Cost, US cents/litre**
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
Singapore	9.5	17.9	0.06	0.11
Malaysia	8.5	7.2	0.05	0.04
Thailand	9.1	16.8	0.06	0.11
Philippines	8.8	16.1	0.06	0.10
Indonesia	2.2	3.8	0.01	0.02
Myanmar	2.0	3.5	0.01	0.02
Brunei	2.0	3.5	0.01	0.02
India	2.1	3.5	0.01	0.02
Pakistan	2.0	3.5	0.01	0.02
Bangladesh	2.1	3.5	0.01	0.02
Sri Lanka	2.0	3.5	0.01	0.02
People's Republic of China	2.1	3.5	0.01	0.02

This table shows that, when the stricter limit of 350 ppm is imposed, the impact of the benefit of the low sulphur crude on the capital costs is reduced even more.

- Also for the 350 ppm sulphur target limit, a sensitivity study was made to explore if a combination of low/medium pressure and high pressure hydro-treating units would have been less costly than achieving the 500 ppm sulphur target with high pressure hydro-treating only.
- Also for the 350 ppm sulphur limit, achieving the diesel fuel sulphur target with a combination of low/medium and high pressure hydro-treating units is more costly than investing, from the outset, in high pressure hydro-treating units only.

Also in this case, similar calculations have been made for the 10 refinery configurations, which represent the conditions of most of the individual 145 refineries analysed in this study. The results of these calculations are shown in the following Table 3.7.3:

Table 3.7.3 Capital Costs and Incremental Product Cost – 350 ppm Maximum Sulphur Limit of the Gas Oil Pool – 10 Refinery Configurations

Configuration	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	Low S Crude	High S crude	Low S Crude
1	183.8	182.4	1.16	1.57
2	183.5	181.8	1.15	1.33
3	183.5	181.8	1.15	1.34
4	183.8	182.4	1.16	1.39
5	177.8	171.6	1.12	1.34
6	136.7	134.1	0.86	0.99
7	166.4	164.6	1.05	1.18
8	181.2	178.2	1.14	1.39
9	155.3	149.6	0.98	1.10
10	183.8	182.4	1.16	1.30

Remarks:

- only the configurations with hydro-cracking units in the base case (number 6, 7 and 9) are predicted to be able to meet the 350 ppm maximum sulphur limit with investment and incremental diesel fuel costs lower than the other configurations.
- The impact of low/medium pressure hydro-treating units in the base case is very modest (numbers 5, 8, 10), when the aim is meeting diesel fuel oil sulphur limits of 350 ppm maximum or below.
- In this case – 350 ppm – the difference between the capital costs required with high sulphur and low sulphur crude oils is very low (between $ 1 M and $ 5 M, which represent about 1% to 2% of the total investment required). This makes running low sulphur crude oils economically unattractive. This trend will continue as the sulphur targets will become lower.

3.8 Cost of Meeting a 250 ppm Maximum Limit of the Gas Oil Pool

The cost of meeting a 250 ppm maximum limit of the gas oil pool was calculated for each average country refinery structure, and for each of the refinery configurations under study, versus the base case. The introductory comments made about the 3,000 ppm limit case apply also to this section of the report. The results, in terms of capital investments and additional diesel fuel costs, are reported in the next set of tables.

Table 3.8.1 Capital Costs and Product Incremental Cost – 250 ppm Maximum Sulphur Limit of the Gas Oil Pool – 12 Study Asian Countries

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
Singapore	151.1	147.7	0.95	1.24
Malaysia	169.1	166.0	1.06	1.40
Thailand	161.6	158.9	1.02	1.35
Philippines	170.3	168.2	1.07	1.44
Indonesia	163.4	162.2	1.03	1.32
Myanmar	185.2	184.7	1.16	1.52
Brunei	185.2	184.7	1.16	1.58
India	181.5	180.4	1.14	1.49
Pakistan	185.2	184.7	1.16	1.58
Bangladesh	181.9	181.4	1.14	1.45
Sri Lanka	184.3	183.3	1.16	1.48
People's Republic of China	181.9	181.4	1.14	1.46

Remarks:

- the refineries representing the average conditions of countries, which, among their refineries, include some hydro-cracking units, would need investment costs $ 20 M to $ 30 M, out of a total of about $ 180 – 185 M.
- the capital costs calculated for the high sulphur and low sulphur crude oils have essentially the same order of magnitude. In fact, the calculated difference ranges between $ 0.5 M and $ 3.4 M, out of a total $ 150 –180 M.
- refineries representing the average country conditions of this study, and producing a constant amount of diesel fuel of 2,000,000 t/y, are predicted to have to invest between $ 150 M and $ 185 M, to meet a diesel fuel sulphur limit of 250 ppm maximum.
- In these conditions, the incremental diesel fuel cost is about 1.0 to 1.2 cents of US $ per litre (when running high sulphur crude oils), and about 1.2 to 1.6 cents of US $ per litre (when running low sulphur crude oils). In these situations, running low sulphur crude oils is not economically attractive.

Also in this case, similar calculations have been made for the 10 refinery configurations, which represent the conditions of most of the individual 145 refineries analysed in this study. The results of these calculations are shown in the following Table 3.8.2:

Table 3.8.2 Capital Costs and Incremental Product Cost – 250 ppm Maximum Sulphur Limit of the Gas Oil Pool – 10 Refinery Configurations

Configuration	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
1	185.2	184.7	1.16	1.58
2	185.1	184.5	1.16	1.35
3	185.0	184.5	1.16	1.36
4	185.2	184.7	1.16	1.41
5	183.2	181.3	1.15	1.40
6	138.3	137.0	0.87	1.01
7	167.9	167.1	1.06	1.20
8	184.3	183.3	1.16	1.42
9	160.0	157.1	1.01	1.17
10	185.2	184.7	1.16	1.31

Remarks:

- only the configurations with hydro-cracking units in the base case (number 6, 7 and 9) are able to meet the 250 ppm maximum sulphur limit with investment and incremental diesel fuel costs lower than the other configurations.
- In particular, the calculated investments of configuration 6 (with a hydro-cracking unit with a capacity of almost 30% of the crude distillation capacity) are about $ 45 – 50 M lower than the configurations without hydro-cracking capacity.
- In this case – 250 ppm – the difference between the capital costs required with high sulphur and low sulphur crude oils is very low (between $ 2 M or less). This makes running low sulphur crude oils economically unattractive.

3.9 Cost of Meeting a 50 ppm Maximum Limit of the Gas Oil Pool

The cost of meeting a 50 ppm maximum limit of the gas oil pool was calculated for each average country refinery structure, and for each of the refinery configurations under study, versus the base case. The introductory comments made about the 3,000 ppm limit case apply also to this section of the report. The results, in terms of capital investments and additional diesel fuel costs, are reported in the next set of tables.

Table 3.9.1 Capital Costs and Product Incremental Cost – 50 ppm Maximum Sulphur Limit of the Gas Oil Pool – 12 Study Asian Countries

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
Singapore	375.7	374.4	2.36	2.67
Malaysia	415.1	411.9	2.61	2.95
Thailand	398.5	397.2	2.51	2.85
Philippines	417.7	416.4	2.63	3.00
Indonesia	400.1	398.4	2.52	2.80
Myanmar	449.7	448.9	2.83	3.18
Brunei	449.7	448.9	2.83	3.24
India	443.3	442.4	2.79	3.14
Pakistan	449.7	448.9	2.83	3.24
Bangladesh	442.0	441.2	2.78	3.08
Sri Lanka	448.2	446.5	2.82	3.13
People's Republic of China	442.0	441.2	2.78	3.09

Remarks:

- the refineries representing the average conditions of countries, which, among their refineries, include some hydro-cracking units, would need investment costs $ 50 M to $ 75 M, out of a total of about $ 420 – 450 M.
- In all cases, the sulphur reduction was achieved through the installation of hydro-cracking units.
- the capital costs calculated for the high sulphur and low sulphur crude oils have essentially the same order of magnitude. In fact, the calculated difference ranges between $ 0.8 M and $ 3.2 M, out of a total $ 375 –450 M.
- refineries representing the average country conditions of this study, and producing a constant amount of diesel fuel of 2,000,000 t/y, are predicted to have to invest between $ 375 M and $ 450 M, to meet a diesel fuel sulphur limit of 50 ppm maximum.
- In these conditions, the incremental diesel fuel cost is about 2.4 to 2.85 cents of US $ per litre (when running high sulphur crude oils), and about 2.7 to 3.25 cents of US $ per litre (when running low sulphur crude oils). In these situations, running low sulphur crude oils is not economically attractive.
- In all cases, both the capital costs and the incremental product costs have increased, versus the previous 250 ppm limit case, as shown in the following table.

Table 3.9.2 Capital Costs and Product Incremental Cost – Increase of 50 ppm Maximum Sulphur Case versus the 250 ppm Maximum Sulphur Case – 12 Study Asian Countries

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
Singapore	224.5	226.7	1.41	1.43
Malaysia	246.0	245.9	1.55	1.55
Thailand	236.9	238.3	1.49	1.50
Philippines	247.4	248.2	1.56	1.56
Indonesia	236.7	236.2	1.49	1.48
Myanmar	264.6	264.2	1.68	1.68
Brunei	264.6	264.2	1.66	1.66
India	261.8	262.0	1.65	1.65
Pakistan	264.6	264.2	1.66	1.66
Bangladesh	260.1	259.8	1.64	1.63
Sri Lanka	263.9	263.2	1.66	1.65
People's Republic of China	260.1	259.8	1.64	1.63

Or, expressed as percent increase:

Table 3.9.3 Capital Costs and Product Incremental Cost – % Increase of 50 ppm Maximum Sulphur Case versus the 250 ppm Maximum Sulphur Case – 12 Study Asian Countries

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
Singapore	149%	153%	149%	115%
Malaysia	146%	145%	148%	110%
Thailand	147%	147%	150%	111%
Philippines	145%	145%	148%	109%
Indonesia	145%	146%	145%	113%
Myanmar	143%	143%	143%	109%
Brunei	143%	143%	143%	105%
India	144%	144%	145%	111%
Pakistan	143%	143%	143%	105%
Bangladesh	143%	143%	143%	113%
Sri Lanka	143%	143%	144%	112%
People's Republic of China	143%	143%	143%	112%

Remarks:

- decreasing the diesel fuel sulphur limit from 250 ppm to 50 ppm, represents a very important change, as essentially all refineries must invest in large hydro-cracking units, and , as a consequence, the capital costs are predicted to become more than double of the already substantial investments required to meet the 250 ppm limit.
- the required level of capital investments is usually the biggest obstacle for the implementation of diesel fuel sulphur levels of 50 ppm or below. However, also the incremental cost of the diesel fuel becomes significant at these sulphur levels. In fact, for a sulphur limit of 50 ppm, the diesel fuel cost is calculated to increase by 1.4 to 1.7 cents of US $ (or 110 to 150%), versus the fairly high incremental cost of the 250 ppm limit.
- Also for the 50 ppm sulphur target limit, a sensitivity study was made to explore if a combination of high pressure hydro-treating and of hydro-cracking units would have been less costly than achieving the 50 ppm sulphur target with hydro-cracking units only.
- This sensitivity analysis was done for the following cases: low and high sulphur crude cases for Singapore, Thailand and Indonesia. The results of this analysis are reported in the following table.

Table 3.9.4 Cost Implications of Meeting the 50 ppm Sulphur Target with High Pressure Hydro-Treaters and Hydro-crackers Rather than Hydro-crackers only

Hydro-Treater	**Hydro-Cracker only**	**Hydro-Cracker only**	**Hydro-Cracker only**	**Hydro-Cracker only**	**Hydro-Treaters, Hydro-Crackers**	**Hydro-Treaters, Hydro-Crackers**	**Hydro-Treaters, Hydro-Crackers**	**Hydro-Treaters, Hydro-Crackers**
Cost	Capital, $ M	Capital, $ M	Product, US c/l	Product, US c/l	Capital, $ M	Capital, $ M	Product, US c/l	Product, US c/l
Crude	High S	Low S	High S	Low S	High S	Low S	High S	Low S
Singapore	375.7	374.4	2.36	2.67	393.6	393.6	2.47	2.79
Thailand	398.5	397.2	2.51	2.85	417.5	417.5	2.62	2.98
Indonesia	400.1	398.4	2.52	2.80	411.9	411.8	2.59	2.89

For the 50 ppm sulphur limit, achieving the diesel fuel sulphur target with a combination of high pressure hydro-treating units and hydro-crackers is more costly than investing, from the outset, in hydro-cracking units only.

Also for the 50 ppm sulphur limit, investment and product cost calculations have been made for the 10 refinery configurations, which represent the conditions of most of the individual 145 refineries analysed in this study. The results of these calculations are shown in the following Table 3.9.5:

Table 3.9.5 Capital Costs and Incremental Product Cost – 50 ppm Maximum Sulphur Limit of the Gas Oil Pool – 10 Refinery Configurations

Configuration	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
1	449.7	448.9	2.83	3.24
2	449.5	448.5	2.83	3.01
3	449.6	448.6	2.83	3.02
4	449.7	448.9	2.83	3.07
5	446.3	443.4	2.81	3.05
6	**338.9**	**338.0**	**2.13**	**2.27**
7	**408.8**	**407.9**	**2.57**	**2.71**
8	448.2	446.6	2.82	3.08
9	**391.3**	**392.0**	**2.46**	**2.65**
10	449.7	448.9	2.83	2.98

Remarks:
- only the configurations with hydro-cracking units in the base case (number 6, 7 and 9) are able to meet the 50 ppm maximum sulphur limit with investment and incremental diesel fuel costs lower than all the other configurations, which all need essentially the same level of investment.
- In particular, the calculated investments of configuration 6 (with a hydro-cracking unit with a capacity of almost 30% of the crude distillation capacity) are about $ 110 M lower than the configurations without hydro-cracking capacity in the base case.
- In this case – 50 ppm – running low sulphur crude oils is economically unattractive.

3.10 Cost of Meeting a 10 ppm Maximum Limit of the Gas Oil Pool

The cost of meeting a 10 ppm maximum limit of the gas oil pool was calculated for each average country refinery structure, and for each of the refinery configurations under study, versus the base case. The introductory comments made about the 3,000 ppm limit case apply also to this section of the report. The results, in terms of capital investments and additional diesel fuel costs, are reported in the next set of tables.

Table 3.10.1 Capital Costs and Product Incremental Cost – 10 ppm Maximum Sulphur Limit of the Gas Oil Pool – 12 Study Asian Countries

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
Singapore	414.4	414.4	2.61	2.92
Malaysia	419.9	419.9	2.64	3.00
Thailand	435.1	435.1	2.74	3.09
Philippines	451.0	451.0	2.84	3.21
Indonesia	403.4	403.4	2.54	2.83
Myanmar	451.0	451.0	2.84	3.19
Brunei	451.0	451.0	2.84	3.26
India	444.6	444.6	2.80	3.15
Pakistan	451.0	451.0	2.84	3.26
Bangladesh	443.3	443.3	2.79	3.10
Sri Lanka	451.0	451.0	2.84	3.16
People's Republic of China	444.8	444.8	2.80	3.11

Remarks:

- in order to achieve a diesel fuel sulphur limit of 10 ppm maximum, essentially all diesel fuel blending components must be hydro-cracked, regardless of the sulphur level of the processed crude oil.
- Therefore, the investment level of each of the above cases is only a function of the hydro-cracking capacity already existing in the base case.
- However, in all cases, the capital costs, for each of the above hypothetical refineries (which produce 2,000,000 t/y of diesel fuel), exceed $ 400 M. The corresponding incremental diesel fuel costs are in the range of 3 cents of US $ per litre.
- In all cases, both the capital costs and the incremental product costs have increased, versus the previous 50 ppm limit case, as shown in the following table.

Table 3.10.2 Capital Costs and Product Incremental Cost – Increase of 10 ppm Maximum Sulphur Case versus the 50 ppm Maximum Sulphur Case – 12 Study Asian Countries

Country	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
Singapore	38.8	40.0	0.24	0.25
Malaysia	4.8	8.0	0.03	0.05
Thailand	36.5	37.8	0.23	0.24
Philippines	33.3	34.6	0.21	0.22
Indonesia	3.3	5.0	0.02	0.03
Myanmar	1.3	2.1	0.01	0.01
Brunei	1.3	2.1	0.01	0.01
India	1.3	2.1	0.01	0.01
Pakistan	1.3	2.1	0.01	0.01
Bangladesh	1.2	2.1	0.01	0.01
Sri Lanka	2.8	4.5	0.02	0.03
People's Republic of China	2.8	3.6	0.02	0.02

Remark:

The marginal cost of decreasing the diesel fuel sulphur limit from 50 ppm to 10 ppm, represents only a small increase versus the very large capital costs, which are predicted to be needed to achieve the 50 ppm limit.

Also for the 10 ppm sulphur limit, investment and product cost calculations have been made for the 10 refinery configurations, which represent the conditions of most of the individual 145 refineries analysed in this study. The results of these calculations are shown in the following Table 3.10.3:

Table 3.10.3 Capital Costs and Incremental Product Cost – 10 ppm Maximum Sulphur Limit of the Gas Oil Pool – 10 Refinery Configurations

Configuration	Capital Cost, $ million	Capital Cost, $ million	Incremental Product Cost, US cents/litre	Incremental Product Cost, US cents/litre
	High S crude	**Low S Crude**	**High S crude**	**Low S Crude**
1	451.0	451.0	2.84	3.26
2	451.0	451.0	2.84	3.02
3	451.0	451.0	2.84	3.04
4	451.0	451.0	2.84	3.08
5	451.0	451.0	2.84	3.10
6	**340.5**	**340.5**	**2.14**	**2.29**
7	**410.1**	**410.1**	**2.58**	**2.73**
8	451.0	451.0	2.84	3.11
9	**400.2**	**400.2**	**2.52**	**2.70**
10	451.0	451.0	2.84	2.99

Remarks:

- As for the 50 ppm case, only the configurations with hydro-cracking units in the base case (number 6, 7 and 9) are able to meet the 10 ppm maximum sulphur limit with investment and incremental diesel fuel costs lower than all the other configurations, which all need essentially the same level of investment.
- In particular, the calculated investments of configuration 6 (with a hydro-cracking unit with a capacity of almost 30% of the crude distillation capacity) are about $ 110 M lower than the configurations without hydro-cracking capacity in the base case.
- Also in the 10 ppm case, running low sulphur crude oils is economically unattractive
- The data show that, for diesel fuel sulphur limits below 350 ppm, all refinery structures and configurations tend to converge towards a uniform approach, in order to achieve the sulphur target.

4. Conclusive Remarks

By examining all together the data discussed in the previous chapter, some general conclusions can be drawn. To help this overall analysis of the calculated data, all calculated values for the capital investments and the additional diesel fuel costs have been reported together in Appendix 5, for each of the study countries and the refinery configurations.

There are important differences in the current average refinery structure of the countries considered in this study, regarding both the cracking capacity and the ability to manufacture diesel fuels with low sulphur content. On one extreme, there are countries which refineries have very little cracking capacity and essentially no flexibility to reduce the sulphur content of the diesel fuel blending components produced by their refineries, apart from the use of lower sulphur crude oils. Examples are Pakistan, Myanmar and Brunei. On the other extreme, there are countries which refineries have already invested in very significant conversion facilities (both thermal and catalytic cracking processes), as well as units to reduce the sulphur content of the diesel fuel, such as hydro-treating and/or hydro-cracking units. However, among these countries, there are big differences in terms of the relative capacity installed for these plants, and hence of their ability to produce low sulphur distillates in large amounts. For example, countries like Singapore, Thailand, Malaysia and the Philippines have, today, refineries with units capable of producing lower sulphur distillates in significant quantities, while, on average, in other countries, these units have a much smaller capacity, as summarised in the following table:

Table 4.1 Currently Installed Average Hydro-treating and Hydro-cracking Capacity by Country.

Country	Hydro-treating Capacity, %	Hydro-cracking Capacity, %
Singapore	16.2	7.4
Malaysia	6.1	5.5
Thailand	14.3	2.9
Philippines	23.7	--
Indonesia	1.2	10.0
India	3.8	2.6
Bangladesh	--	3.6
Sri Lanka	4.2	--
People's Republic of China	1.1	2.8

However, it is important to note that, apart from Singapore and, to a lesser extent Thailand, no other country has average refinery structures that are approaching those of the countries which have already implemented severe diesel fuel sulphur specifications, as shown in the following table:

Table 4.2 Currently Installed Average Hydro-treating and Hydro-cracking Capacity in some Benchmark Countries

Country	**Hydro-treating Capacity, %**	**Hydro-cracking Capacity, %**
USA	14.4	8.7
California	23.4	21.4
Japan	31.8	3.3
Germany	24.2	7.3

The refineries of these countries have, on average, significantly higher levels of hydro-treating plus hydro-cracking capacity; furthermore, some of the hydro-treating units operate at higher severity, hence with a higher capability to reduce the diesel fuel sulphur content to lower limits at or below 500 ppm.

The just described different base case situations of the refineries of the countries under study is reflected in the calculated capital and diesel fuel costs, relative to the implementation of stricter diesel fuel sulphur limits. In fact the data of Appendix 5 show, for refineries representing the average country structure, and manufacturing 2,000,000 t/y of diesel fuel:

- The existence of Low/Medium Pressure Hydro-treating units in the base case is predicted to significantly reduce the need for capital investments mainly for diesel fuel sulphur limits above 500 ppm.
- For sulphur limits at or below 500 ppm, the presence of High Pressure Hydro-treating units and/or hydro-crackers becomes more important.
- Sulphur limits down to 50 or 10 ppm can only be satisfied through the deployment of hydro-cracking units of high capacity. Therefore only refineries with existing hydro-cracking capacity in the base case require sizeably lower investments to achieve the sulphur target.
- The use of low sulphur crude oils has an important impact in reducing the necessary capital investment, only for diesel fuel sulphur levels above 500 ppm. At or below this value, the delta between the investments required with high and low sulphur crude oils becomes relatively smaller, and the use of low sulphur crude oils becomes economically unattractive. This point is emphasised by the calculated diesel fuel cost increase, which is higher in the low sulphur crude cases.
- In the diesel fuel sulphur range between 500 and 250 ppm, the incremental capital costs, relative to the 250 ppm limit versus the 500 ppm limit, are 10% to 20% higher for the countries which refineries already include large hydro-treating and/or hydro-cracking capacity in the base case, but only 2% to 4% for the other countries. This is due to the fact that the refineries of the first group of countries could meet the 500 ppm diesel fuel sulphur limit with a lower level of new investments.
- Reducing the diesel fuel sulphur limit from 250 to 50 ppm represents a major change in terms of refinery processes required and capital investments. In fact the 50 ppm limit

requires sizeable hydro-cracking capacities. As a consequence, the calculated investment costs for the refinery structures representative of the average conditions of the countries under study increased from a range of $ 150M to $ 185M, for the 250 ppm limit, to a range of $ 375M to $ 450M (i.e. by a factor of 2.5 about). The countries with refineries that have already invested in hydro-cracker units in the base case are predicted to require the lowest investments.

- These higher investment costs are reflected in the additional diesel fuel product costs, which are calculated to increase from a range of 0.95 to 1.58 cents per litre, for the 250 ppm case, to a range of 2.36 to 3.24 cents per litre, for the 50 ppm case (i.e. by a factor of 2.0 to 2.5).
- The investment required to satisfy a diesel fuel sulphur limit of 10 ppm is calculated to be up to 10% higher than that required to meet the 50 ppm limit.
- The data show that, for diesel fuel sulphur limits below 350 ppm, all refinery structures and configurations tend to converge towards a uniform approach, in order to achieve the sulphur target. For these severe sulphur limits, also the investment costs of the various refinery configurations considered in this study tend to become of the same order of magnitude.
- Overall, finding the capital funds necessary to invest in the severe diesel fuel desulphurisation units, which are needed to meet severe sulphur limits, appears to be the biggest obstacle to achieving low sulphur diesel fuels in the short range. However, for the most severe limits, also diesel fuel cost increases of the order of 3.0 cents of US dollar per litre or above cannot be ignored.

APPENDIX 1

Refinery Data Base of Asian Countries

Data Base Content

Geographical Areas	South East Asia	Indian Sub-continent	P. R. China
Countries	Singapore	India	P. R. China
	Malaysia	Pakistan	
	Thailand	Bangladesh	
	Philippines	Sri Lanka	
	Indonesia		
	Myanmar		
	Brunei		

Refinery Configurations

(Situation Updated in mid. 2001)

SINGAPORE

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Exxon/Mobil Corp	Jurong/Pulau Ayer Chawan	580,000	0	0	118,000
Shell Eastern Petroleum Ltd.	Pulau Bukom	405,000	30,000	0	30,000
Singapore Petr. Co. Ltd.	Pulau Merlimau	285,000	0	0	30,400
Total Capacities		1,270,000	30,000	0	178,400
% of Throughput			2.4%	0%	14.0%

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Exxon/Mobil Corp	Jurong/Pulau Ayer Chawan	0	107,750	34,000
Shell Eastern Petroleum Ltd.	Pulau Bukom	34,000	77,600	30,000
Singapore Petr. Co. Ltd.	Pulau Merlimau	31,000	78,000	30,300
Total Capacities		65,000	263,350	94,300
% of Throughput		5.1%	20.7%	7.4%

Refinery Configurations
(Situation Updated in mid. 2001)

MALAYSIA

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Esso Malaysia Berhad	Port Dickson	83,600	0	0	0
Petronas	Kertih	40,000	0	0	0
Petronas	Melaka I	95,000	0	0	0
Petronas	Melaka II	95,000	18,900	0	0
Sarawak Shell Berhad	Lutong	45,000	0	0	0
Shell Refining Co. Berhad	Port Dickson	155,000	0	0	0
Total Capacities		513,600	18,900	0	0
% of Throughput			3.7%	0%	0%

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Esso Malaysia Berhad	Port Dickson	0	0	0
Petronas	Kertih	0	0	0
Petronas	Melaka I	0	0	0
Petronas	Melaka II	0	31,500	28,500
Sarawak Shell Berhad	Lutong	0	0	0
Shell Refining Co. Berhad	Port Dickson	0	0	0
Total Capacities		0	31,500	28,500
% of Throughput		0%	6.1%	5.5%

Refinery Configurations
(Situation Updated in mid. 2001)

THAILAND

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Esso Standard Thailand Ltd.	Sriracha	160,000	0	0	0
Petroleum Authority of Thailand	Bangchack Bangkok	61,750	0	0	0
Refinery Company (RefCo)	Map Ta Phut Rayong	275,000	0	0	0
Thai Oil Co. Ltd.	Sriracha	185,000	0	0	17,400
Total Capacities		681,750	0	0	17,400
% of Throughput			0%	0%	2.6%

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Esso Standard Thailand Ltd.	Sriracha	36,000	68,000	0
Petroleum Authority of Thailand	Bangchack Bangkok	0	0	0
Refinery Company (RefCo)	Map Ta Phut Rayong	33,300	25,200	0
Thai Oil Co. Ltd.	Sriracha	11,200	4,100	19,900
Total Capacities		80,500	97,300	19,900
% of Throughput		11.8%	14.3%	2.9%

Refinery Configurations
(Situation Updated in mid. 2001)

PHILIPPINES

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Caltex (Philippines) Inc.	Batangas	86,500	0	0	0
Petron Corp.	Limay, Bataan	180,000	0	0	0
Philipinas Shell Petr. Corporation	Tabango	153,000	22,000	0	0
Total Capacities		419,500	22,000	0	0
% of Throughput			5.2%	0%	0%

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Caltex (Philippines) Inc.	Batangas	12,500	16,000	0
Petron Corp.	Limay, Bataan	12,000	36,000	0
Philipinas Shell Petr. Corporation	Tabango	0	47,300	0
Total Capacities		24,500	99,300	0
% of Throughput		5.8%	23.7%	0%

Refinery Configurations

(Situation Updated in mid. 2001)

INDONESIA

Refinery Name	**Refinery Location**	**Crude Throughput bpd**	**Thermal Cracking bpd**	**Coking bpd**	**Vis-Breaking bpd**
Pertamina	Balikpapan Kalimantan	241,000	0	0	0
Pertamina	Balongan	125,000	0	0	0
Pertamina	Cepu	3,400	0	0	0
Pertamina	Cilacap Central Java	348,000	0	0	50,040
Pertamina	Dumai Central Sumatra	114,000	0	32,580	0
Pertamina	Musi, South Sumatra	110,000	8,820	0	0
Pertamina	Pangakalan Brandan	5,000	0	0	0
Pertamina	Sungai Pakning	47,000	0	0	0
Total Capacities		993,400	8,820	32,580	50,040
% of Throughput			0.9%	3.3%	5.0%

Refinery Configurations

(Situation Updated in mid. 2001)

INDONESIA (cont.d)

Refinery Name	**Refinery Location**	**Catalytic Cracking bpd**	**Distillate Hydro-treating bpd**	**Hydro-Cracking bpd**
Pertamina	Balikpapan Kalimantan	0	0	49,500
Pertamina	Balongan	83,000	0	0
Pertamina	Cepu	0	0	0
Pertamina	Cilacap Central Java	0	12,000	0
Pertamina	Dumai Central Sumatra	0	0	50,220
Pertamina	Musi, South Sumatra	18,450	0	0
Pertamina	Pangakalan Brandan	0	0	0
Pertamina	Sungai Pakning	0	0	0
Total Capacities		101,450	12,000	99,720
% of Throughput		10.2%	1.2%	10.0%

<u>Refinery Configurations</u>

(Situation Updated in mid. 2001)

MYANMAR

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Myanmar Petrochemical Enterprise	Chauk	6,000	0	0	0
Myanmar Petrochemical Enterprise	Thanlyin	26,000	0	5,200	0
Total Capacities		32,000	0	5,200	0
% of Throughput			0%	16.3%	0%

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Myanmar Petrochemical Enterprise	Chauk	0	0	0
Myanmar Petrochemical Enterprise	Thanlyin	0	0	0
Total Capacities		0	0	0
% of Throughput		0%	0%	0%

Refinery Configurations
(Situation Updated in mid. 2001)

BRUNEI

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Brunei Shell Petroleum Co.	Seria	8,600	0	0	0
Total Capacities		8,600	0	0	0
% of Throughput			0%	0%	0%

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Brunei Shell Petroleum Co.	Seria	0	0	0
Total Capacities		0	0	0
% of Throughput		0%	0%	0%

Refinery Configurations
(Situation Updated in mid. 2001)

INDIA

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Bharat Petr. Co. Ltd.	Mahul Bombay	120,000	0	0	0
Bharat Petr. Co. Ltd.	Numaligarh Assam	60,000	0	8,400	0
Bongaigaon Ref & Petr Ltd	Bongaigaon Assam	27,000	0	9,675	0

Kochin Refineries Ltd	Ambalamugal	150,000	0	0	19,000
Hindustan Petr Corp Ltd	Bombay	110,000	0	0	0
Hindustan Petr Corp Ltd	Visakhapatnam	164,000	0	0	20,580
Indian Oil Co. Ltd.	Bihar	66,000	0	20,000	0
Indian Oil Co. Ltd.	Digboi Assam	11,700	0	850	0
Indian Oil Co. Ltd.	Gawahati Assam	20,000	0	6,000	0
Indian Oil Co. Ltd.	Koyali Gujarat	185,000	0	0	19,500
Indian Oil Co. Ltd.	Haldia West Bengal	61,000	0	0	9,600
Indian Oil Co. Ltd.	Mathura Uttar Pradesh	156,000	0	0	18,000
Indian Oil Co. Ltd.	Panipat	120,000	0	0	6,500
Madras Ref. Ltd.	Cauvery Basin	10,000	0	0	0
Chennai Ref. Ltd	Madras	130,700	0	0	0
Mangalore Ref & Petr Ltd	Mangalore	180,000	0	0	0
Reliance Pet. Ltd.	Jamnagar	540,000	0	0	0
Total Capacities		2,111,900	0	44,925	93,180
% of Throughput			0%	2.1%	4.4%

Refinery Configurations
(Situation Updated in mid. 2001)

INDIA

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Bharat Petr. Co. Ltd.	Mahul Bombay	28,755	0	0
Bharat Petr. Co. Ltd.	Numaligarh Assam	0	0	22,000
Bongaigaon Ref & Petr Ltd	Bongaigaon Assam	0	0	0

Kochin Refineries Ltd	Ambalamugal	27,000	0	0
Hindustan Petr Corp Ltd	Bombay	14,000	25,890	0
Hindustan Petr Corp Ltd	Visakhapatnam	32,900	47,104	0
Indian Oil Co. Ltd.	Bihar	0	0	0
Indian Oil Co. Ltd.	Digboi Assam	0	0	0
Indian Oil Co. Ltd.	Gawahati Assam	0	0	0
Indian Oil Co. Ltd.	Koyali Gujarat	20,000	0	0
Indian Oil Co. Ltd.	Haldia West Bengal	0	3,100	0
Indian Oil Co. Ltd.	Mathura Uttar Pradesh	20,000	0	0
Indian Oil Co. Ltd.	Panipat	13,400	0	32,600
Madras Ref. Ltd.	Cauvery Basin	0	0	0
Chennai Ref. Ltd	Madras	11,250	5,100	0
Mangalore Ref & Petr Ltd	Mangalore	0	0	0
Reliance Pet. Ltd.	Jamnagar	0	0	0
Total Capacities		167,305	81,194	54,600
% of Throughput		7.9%	3.8%	2.6%

Refinery Configurations
(Situation Updated in mid. 2001)

PAKISTAN

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Attock Refinery Ltd.	Rawalpindi	30,500	0	0	0
National Refinery Ltd	Korangi Karachi	62,000	0	0	0
Pakistan Refinery Ltd	Karachi	46,000	0	0	0
Pak-Arab Refinery (PARCO)	Punjab	100,000	0	0	0
Total Capacities		238,500	0	0	0
% of Throughput			0%	0%	0%

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Attock Refinery Ltd.	Rawalpindi	0	0	0
National Refinery Ltd	Korangi Karachi	0	0	0
Pakistan Refinery Ltd	Karachi	0	0	0
Pak-Arab Refinery (PARCO)	Punjab	0	0	0
Total Capacities		0	0	0
% of Throughput		0%	0%	0%

Refinery Configurations
(Situation Updated in mid. 2001)

BANGLADESH

Refinery Name	**Refinery Location**	**Crude Throughput bpd**	**Thermal Cracking bpd**	**Coking bpd**	**Vis-Breaking bpd**
Eastern Refinery Ltd.	Chittagong	33,000	0	0	10,000
Total Capacities		33,000	0	0	10,000
% of Throughput			0%	0%	30.3%

Refinery Name	**Refinery Location**	**Catalytic Cracking bpd**	**Distillate Hydro-treating bpd**	**Hydro-Cracking bpd**
Eastern Refinery Ltd.	Chittagong	0	0	1,200
Total Capacities		0	0	1,200
% of Throughput		0%	0%	3.6%

<u>Refinery Configurations</u>

(Situation Updated in mid. 2001)

SRI LANKA

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Ceylon Petr. Co.	Sapugaskanda	50,000	0	0	13,350
Total Capacities		50,000	0	0	13,350
% of Throughput			0%	0%	26.7%

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Ceylon Petr. Co.	Sapugaskanda	0	2,100	0
Total Capacities		0	2,100	0
% of Throughput		0%	4.2%	0%

<u>Refinery Configurations</u>

(Situation Updated in mid. 2001)

PEOPLE' s REPUBLIC of CHINA

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
China National Petrol. Corp.	Anshan	50,000	0	0	0
	Dalian	142,600	0	0	0
	Dandong	6,000	0	0	0
	Daqing	70,000	0	13,000	0
	Daqing	120,500	0	13,000	0
	Dushanzi	120,500	0	14,000	0
	Fushun	184,800	0	35,000	0
	Golmud	20,000	0	0	0
	Harbin	30,000	0	1,000	0
	Heilongjiang	7,000	0	0	0
	Heilongjiang	7,000	0	0	0
	Heilongjiang	10,000	0	0	0
	Heilongjiang	2,000	0	0	0
	Huhhot	20,000	0	0	0
	Jilin	6,000	0	0	0
	Jilin	90,400	0	0	0
	Jilin	4,000	0	0	0
	Jilin	4,000	0	0	0
	Jilin	3,000	0	0	0
	Jinxi	100,000	0	1,000	0
	Jinzhou	110,500	0	20,000	0
	Lanzhou	110,500	0	15,000	0
	Lanzhou	20,000	0	0	0
	Liaohe	50,000	0	0	0
	Liaoning	2,000	0	0	0
	Liaoyang	80,000	0	0	0
	Linyuan	50,000	0	0	0
Total Capacities		1,420,800	0	112,000	0
% of Throughput			0%	7.9%	0%

<u>Refinery Configurations</u>

(Situation Updated in mid. 2001)

PEOPLE' s REPUBLIC of CHINA

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
China National Petrol. Corp.	Anshan	2,000	0	0
	Dalian	70,000	0	0
	Dandong	0	0	0
	Daqing	14,000	0	8,000
	Daqing	0	0	0
	Dushanzi	12,000	0	0
	Fushun	66,000	0	8,000
	Golmud	0	0	0
	Harbin	6,000	0	0
	Heilongjiang	0	0	0
	Heilongjiang	0	0	0
	Heilongjiang	0	0	0
	Heilongjiang	0	0	0
	Huhhot	0	0	0
	Jilin	0	0	0
	Jilin	0	0	0
	Jilin	0	0	0
	Jilin	0	0	0
	Jilin	0	0	0
	Jinxi	24,000	0	0
	Jinzhou	16,000	0	0
	Lanzhou	24,000	0	0
	Lanzhou	0	0	0
	Liaohe	0	0	0
	Liaoning	0	0	0
	Liaoyang	0	0	0
	Linyuan	17,000	0	0
Total Capacities		251,000	0	16,000
% of Throughput		17.7%	0%	1.1%

Refinery Configurations

(Situation Updated in mid. 2001)

PEOPLE' s REPUBLIC of CHINA (Cont.d 1)

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
China National Petrol. Corp.	Qianguo	50,000	0	0	0
	Qinghai	27,000	0	0	0
	Shaanxi	2,000	0	0	0
	Shaanxi	6,000	0	0	0
	Sichuan	3,000	0	0	0
	Urumqi	50,000	0	8,000	0
	Xianyang	50,000	0	0	0
	Yanchang	2,000	0	0	0
	Yumen	80,000	0	0	0
	Zepu	3,000	0	0	0
Sinopec	Anqing	56,200	0	8,000	0
	Baling	100,000	0	12,000	0
	Baoding	10,000	0	0	0
	Beihai	10,000	0	0	0
	Binzhou	8,000	0	0	0
	Boxing	2,000	0	0	0
	Boxing	2,000	0	0	0
	Cangzhou	20,000	0	0	0
	Changyi	3,000	0	0	0
	Dagang	60,000	0	0	0
	Dongming	6,000	0	0	0
	Fujian	80,000	0	0	0
	Gaoqiao	150,600	0	10,000	0
	Guangrao	6,000	0	0	0
	Guangzhou	104,000	0	20,000	0
	Hangzhou	6,000	0	0	0
	Henan	2,400	0	0	0
Total Capacities		899,200	0	58,000	0
% of Throughput			0%	6.5%	0%

Refinery Configurations

(Situation Updated in mid. 2001)

PEOPLE' s REPUBLIC of CHINA (Cont.d 1)

Refinery Name	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
China National Petrol. Corp.	Qianguo	24,000	0	0
	Qinghai	0	0	0
	Shaanxi	0	0	0
	Shaanxi	0	0	0
	Sichuan	0	0	0
	Urumqi	16,000	0	0
	Xianyang	0	0	0
	Yanchang	0	0	0
	Yumen	0	0	0
	Zepu	0	0	0
Sinopec	Anqing	24,000	0	0
	Baling	50,000	11,000	0
	Baoding	0	0	0
	Beihai	0	0	0
	Binzhou	0	0	0
	Boxing	0	0	0
	Boxing	0	0	0
	Cangzhou	9,000	0	0
	Changyi	0	0	0
	Dagang	0	0	0
	Dongming	0	0	0
	Fujian	16,000	0	0
	Gaoqiao	38,000	0	0
	Guangrao	0	0	0
	Guangzhou	44,000	5,000	0
	Hangzhou	0	0	0
	Henan	0	0	0
Total Capacities		221,000	16,000	0
% of Throughput		24.6%	1.8%	0%

<u>Refinery Configurations</u>

(Situation Updated in mid. 2001)

PEOPLE’ s REPUBLIC of CHINA (Cont.d 2)

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Sinopec.	Huabei	4,000	0	0	0
	Jianghan	6,000	0	0	0
	Jianhu	2,000	0	0	0
	Jinan	6,000	0	0	0
	Jinan	80,000	0	0	0
	Jingmen	100,000	0	8,000	0
	Jinling	140,600	0	28,000	0
	Juijiang	50,000	0	8,000	0
	Karamay	66,300	0	0	0
	Kenli	8,000	0	0	0
	Lijin	3,000	0	0	0
	Linyi	4,000	0	0	0
	Luoyang	100,000	0	0	0
	Luoyang	4,000	0	0	0
	Maoming	170,700	0	24,000	0
	Nandagang	2,000	0	0	0
	Nanyang	12,500	0	0	0
	Qilu	160,700	0	16,000	0
	Qingdao	50,000	0	0	0
	Qingdao	4,000	0	0	0
	Shanghai	106,400	0	0	0
	Shengli	50,000	0	0	0
	Shengli	3,000	0	0	0
	Shijiazhuang	50,000	0	0	0
	Shouguang	3,000	0	0	0
	Taizhou	6,000	0	0	0
	Tianjin	120,500	0	0	0
Total Capacities		1,312,700	0	84,000	0
% of Throughput			0%	6.4%	0%

Refinery Configurations

(Situation Updated in mid. 2001)

PEOPLE' s REPUBLIC of CHINA (Cont.d 2)

Refinery Name	**Refinery Location**	**Catalytic Cracking bpd**	**Distillate Hydro-treating bpd**	**Hydro-Cracking bpd**
Sinopec.	Huabei	0	0	0
	Jianghan	0	0	0
	Jianhu	0	0	0
	Jinan	0	0	0
	Jinan	22,000	0	0
	Jingmen	20,000	4,000	8,000
	Jinling	44,000	0	16,000
	Juijiang	24,000	0	0
	Karamay	0	0	0
	Kenli	0	0	0
	Lijin	0	0	0
	Linyi	0	0	0
	Luoyang	40,000	5,000	0
	Luoyang	0	0	0
	Maoming	32,000	0	16,000
	Nandagang	0	0	0
	Nanyang	0	0	0
	Qilu	46,000	5,000	42,000
	Qingdao	0	0	0
	Qingdao	0	0	0
	Shanghai	0	0	0
	Shengli	0	0	0
	Shengli	0	0	0
	Shijiazhuang	24,000	0	0
	Shouguang	0	0	0
	Taizhou	0	0	0
	Tianjin	35,000	0	0
Total Capacities		287,000	14,000	82,000
% of Throughput		21.9%	1.1%	6.2%

<u>Refinery Configurations</u>

(Situation Updated in mid. 2001)

PEOPLE' s REPUBLIC of CHINA (Cont.d 3)

Refinery Name	Refinery Location	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
Sinopec.	Wuhan	50,000	0	8,000	0
	Wuxi	3,000	0	0	0
	Xi'an	3,000	0	0	0
	Yan'an	20,000	0	0	0
	Yancheng	2,000	0	0	0
	Yangzhou	3,000	0	0	0
	Yangzi	120,500	0	20,000	0
	Yanshan	190,800	0	0	0
	Yongping	6,000	0	0	0
	Zhanjiang	20,000	0	0	0
	Zhenhai	160,700	0	8,000	0
	Zhongyuan	26,000	0	0	0
	Zhongjie	3,000	0	0	0
Wepec	Dallan	100,000	0	0	0
Total Capacities		708,000	0	36,000	0
% of Throughput			0%	5.1%	0%

Refinery Configurations
(Situation Updated in mid. 2001)

PEOPLE' s REPUBLIC of CHINA (Cont.d 3)

Refinery Name	**Refinery Location**	**Catalytic Cracking bpd**	**Distillate Hydro-treating bpd**	**Hydro-Cracking bpd**
Sinopec.	Wuhan	20,000	0	0
	Wuxi	0	0	0
	Xi'an	0	0	0
	Yan'an	0	0	0
	Yancheng	0	0	0
	Yangzhou	0	0	0
	Yangzi	0	0	24,000
	Yanshan	48,000	0	0
	Yongping	0	0	0
	Zhanjiang	0	0	0
	Zhenhai	28,000	0	0
	Zhongyuan	0	0	0
	Zhongjie	0	0	0
Wepec	Dallan	37,000	19,000	0
Total Capacities		133,000	19,000	24,000
% of Throughput		18.8%	2.7%	3.4%

Refinery Configurations

(Situation Updated in mid. 2001)

SUMMARY

Geographical Area	Crude Throughput bpd	Thermal Cracking bpd	Coking bpd	Vis-Breaking bpd
South East Asia	3,918,850	60,820	56,680	245,840
% of Throughput		1.6%	1.4%	6.3%
Indian Sub-Continent	2,433,400	0	44,925	116,530
% of Throughput		0.0%	1.8%	4.8%
People Republic of China	4,340,700	0	290,000	0
% of Throughput		0.0%	6.7%	0.0%

Geographical Area	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
South East Asia	271,450	503,450	242,420
% of Throughput	6.9%	12.8%	6.2%
Indian Sub-Continent	167,305	83,294	55,800
% of Throughput	6.9%	3.4%	2.3%
People Republic of China	892,000	49,000	122,000
% of Throughput	20.5%	1.1%	2.8%

Appendix 2

Brief Description of Process Plants Considered in this Study

Atmospheric Crude Distillation Unit
The crude blend is heated and flashed into the crude distillation tower for fractionation into Light Hydrocarbons, Naphtha, Jet Fuel, Gas Oil and Atmospheric Residue. Kerosene and Gas Oil are drawn from the tower and sent to side strippers where volatile components are removed. The gas Oil component can go either to fuel blending (diesel fuel or other distillate products) or to hydro-treating for sulphur reduction. This Gas Oil is commonly called Straight-run Gas Oil.
The Gas Oil plus Kerosene yields of a crude distillation unit range typically between 20% and 50%, depending on the crude processed. Typical yields for some commonly used crude oils are:

Crude Type	Gas Oil plus Kerosene Yields, wt%
Arabian Light	33.1
Nigerian (Forcados)	47.2
Brent	35.5
Maya	23.1

Thermal Cracking
Conventional thermal cracking is now virtually obsolete, since there are several other superior cracking processes available. However some units are still in operation. The process requires the feed (generally heavy fuel oil and/or heavy gas oils) to be heated to around 500 deg.C at a pressure of up to 70 bars. Then it is passed into a soaking chamber, where the cracking reactions take place. The gas oil yields are about 30% (up to 60% is naphtha) of a fairly high sulphur and low cetane product.

Coking
This is a severe form of thermal cracking designed to convert residual products, such as heavy fuel oils, into gas, naphtha, gas oils and coke. It is a particularly valuable conversion process, when the market for heavy fuel oil is not attractive, compared to the markets for naphtha and gas oils. Light gas oil from this unit is usually stabilised in a hydro-treating unit. The heavy gas oil is often used as a feed for catalytic crackers or for hydro-crackers.

Visbreaking
It is a low severity form of thermal cracking, originally developed to reduce the viscosity of residual fuel oils, thereby minimising the amount of higher value distillates needed as fuel oil fluxants. Nowadays it is most often used as a cheap process for converting some of the excess fuel oil into the more profitable distillate. In principle, the process is similar to the conventional thermal cracking, using temperatures up to about 500 deg.C, but lower pressures of about 20 bars. The yield of gas oil can vary between 15% and 25%, when using atmospheric residuum as feed. The visbreaker gas oil has usually a high sulphur content.

Fluid Catalytic Cracking (FCC)

This is the most important and widely used process for converting heavy refinery streams into lighter products, and it is the most popular method of increasing the ratio of light to heavy products from crude oil. It has superseded conventional thermal cracking because of its higher yields, better product quality (particularly for gasoline blending components) and superior economics. The gas oils produced through this process (usually called cycle oils) are poor diesel fuel blending components, because of their high sulphur content and particularly for their very low cetane numbers.

Distillate Hydro-treating

Gas oil streams from the Atmospheric Crude Oil Distillation Unit, the various conversion units, and cycle oil from the FCC Unit can all be desulphurised by hydrogen treatment in Distillate Hydro-treating Units. There are many variations of this process, but they all use hydrogen, albeit at different pressures and with different catalysts. By far the largest fraction of distillate hydro-treating capacity world wide operates at low to medium hydrogen pressure, i.e. below 60 bars. At this level of pressures, hydro desulphurisation units can reduce the sulphur level of straight-run distillates from Middle East crude oils down to 1,000 to 2,500 ppm, while the sulphur level of thermally cracked distillates (including visbreaker distillates) can be reduced to values ranging from 3,000 to 5,500 ppm.

High Pressure Hydro-treating units, operating with hydrogen pressures above 60 to 70 bars, can reduce the sulphur content of the treated gas oil down to about 200 ppm. The capital and operating costs of the high pressure units are significantly higher.

Hydro-cracking

The mechanism of hydro-cracking is similar to that of catalytic cracking, but with hydrogenation superimposed. A dual-function catalyst is needed which performs satisfactorily both cracking and hydrogenation reactions. Hydro-cracking is used mainly to produce low boiling fractions from heavier feed stocks, such as heavy gas oils, waxy distillates, etc. The degree of cracking depends greatly on the feed stock, and, in general, the heavier the feed the more middle distillate is produced.

The hydrogen requirement of these units is extremely high, so that, in general, it is necessary to have a hydrogen production plant as part of the hydro-cracker complex. The yields and product quality achieved depend on the feed and the severity of operation. However, in most cases, the units are run to maximise middle distillate production. In these cases, the distillate yields can be as high as 60% to 70%, the other products being saturated LPG, naphtha and Kerosene. The distillate produced by these units is characterised by a very low sulphur content (typically 10 ppm or even lower) and overall high quality.

APPENDIX 3

Summary of Refinery Configurations of Asian Countries and Benchmark Countries

Refinery Configurations

(Situation Updated in mid. 2001)

ASIAN COUNTRIES

Country	Number of Refineries	Throughput Per Refinery bpd	Total Crude Throughput bpd	Thermal Cracking bpd	Coking bpd
Singapore	3	423,333	1,270,000	30,000	0
% of throughput				2.4%	0.0%
Malaysia	6	85,600	513,600	0	18,900
% of throughput				0.0%	3.7%
Thailand	4	170,438	681,750	0	0
% of throughput				0.0%	0.0%
Philippines	3	139,833	419,500	22,000	0
% of throughput				5.2%	0.0%

Refinery Name	Vis-Breaking bpd	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Singapore	178,400	65,000	263,350	94,300
% of throughput	14.0%	5.1%	20.7%	7.4%
Malaysia	0	0	31,500	28,500
% of throughput	0.0%	0.0%	6.1%	5.5%
Thailand	17,400	80,500	97,300	19,900
% of throughput	2.6%	11.8%	14.3%	2.9%
Philippines	0	24,500	99,300	0
% of throughput	0.0%	5.8%	23.7%	0.0%

Refinery Configurations

(Situation Updated in mid. 2001)

ASIAN COUNTRIES (Cont.d 1)

Country	Number of Refineries	Throughput Per Refinery bpd	Total Crude Throughput bpd	Thermal Cracking bpd	Coking bpd
Indonesia	8	124,175	993,400	8,820	32,580
% of throughput				0.9%	3.3%
Myanmar	2	16,000	32,000	0	5,200
% of throughput				0.0%	16.3%
Brunei	1	8,600	8,600	0	0
% of throughput				0.0%	0.0%
India	17	124,229	2,111,900	0	44,925
% of throughput				0.0%	2.1%

Refinery Name	Vis-Breaking bpd	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Indonesia	50,040	101,450	12,000	99,720
% of throughput	5.0%	10.2%	1.%	10.0%
Myanmar	0	0	0	0
% of throughput	0.0%	0.0%	0.0%	0.0%
Brunei	0	0	0	0
% of throughput	0.0%	0.0%	0.0%	0.0%
India	93,180	167,305	81,194	54,600
% of throughput	4.4%	7.9%	3.8%	2.6%

Refinery Configurations

(Situation Updated in mid. 2001)

ASIAN COUNTRIES (Cont.d 2)

Country	Number of Refineries	Throughput Per Refinery bpd	Total Crude Throughput bpd	Thermal Cracking bpd	Coking bpd
Pakistan	4	59,625	238,500	0	0
% of throughput				0.0%	0.0%
Bangladesh	1	33,000	33,000	0	0
% of throughput				0.0%	0.0%
Sri Lanka	1	50,000	50,000	0	0
% of throughput				0.0%	0.0%
P. R. China	95	45,692	4,340,700	0	290,000
% of throughput				0.0%	6.7%

Refinery Name	Vis-Breaking bpd	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Pakistan	0	0	0	0
% of throughput	0.0%	0.0%	0.0%	0.0%
Bangladesh	10,000	0	0	1,200
% of throughput	30.3%	0.0%	0.0%	3.6%
Sri Lanka	13,350	0	2,100	0
% of throughput	26.7%	0.0%	4.2%	0.0%
P. R. China	0	892,000	49,000	122,000
% of throughput	0.0%	20.5%	1.1%	2.8%

Refinery Configurations

(Situation Updated in mid. 2001)

BENCHMARK COUNTRIES

Country	**Number of Refineries**	**Throughput Per Refinery bpd**	**Total Crude Throughput bpd**	**Thermal Cracking bpd**	**Coking bpd**
Japan	35	141,714	4,960,000	0	88,500
% of throughput				0.0%	1.8%
Australia	10	84,700	847,000	0	0
% of throughput				0.0%	0.0%
UK	11	161,000	1,771,000	40,000	68,000
% of throughput				2.3%	3.8%
Germany	17	132,882	2,259,000	28,000	126,275
% of throughput				1.2%	5.6%

Refinery Name	**Vis-Breaking bpd**	**Catalytic Cracking bpd**	**Distillate Hydro-treating bpd**	**Hydro-Cracking bpd**
Japan	0	799,145	1,579,000	161,800
% of throughput	0.0%	16.1%	31.8%	3.3%
Australia	0	230,000	106,000	0
% of throughput	0.0%	27.2%	12.5%	0.0%
UK	54,700	444,500	364,000	31,500
% of throughput	3.1%	25.1%	20.6%	1.8%
Germany	188,000	343,500	547,000	164,700
% of throughput	8.3%	15.2%	24.2%	7.3%

Refinery Configurations

(Situation Updated in mid. 2001)

BENCHMARK COUNTRIES (Cont.d 1)

Country	Number of Refineries	Throughput Per Refinery bpd	Total Crude Throughput bpd	Thermal Cracking bpd	Coking bpd
Italy	17	138,765	2,359,000	106,000	45,000
% of throughput				4.5%	1.9%
Netherlands	6	200,500	1,203,000	9,000	36,660
% of throughput				0.7%	3.0%
USA	152	108,809	16,539,000	18,000	2,098,000
% of throughput				0.1%	12.7%
California	22	90,455	1,990,000	0	474,100
% of throughput				0.0%	23.8%

Refinery Name	Vis-Breaking bpd	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Italy	311,000	305,100	362,000	265,900
% of throughput	13.2%	12.9%	15.3%	11.3%
Netherlands	112,000	101,400	117,000	162,500
% of throughput	9.3%	8.4%	9.7%	13.5%
USA	22,000	5,588,100	2,382,000	1,441,000
% of throughput	0.1%	33.8%	14.4%	8.7%
California	10,000	650,700	465,000	425,500
% of throughput	0.5%	32.7%	23.4%	21.4%

APPENDIX 4

Analysis of Configurations of Asian Refineries

Summary of Configurations

Configuration Number	Thermal Cracking, Visbreaking, Coking	Catalytic Cracking	Distillate Hydro Treating	Hydro Cracking
1	--	--	--	--
2	--	x	--	--
3	x	x	--	--
4	x	--	--	--
5	--	x	x	--
6	x	--	--	x
7	x	x	--	x
8	x	--	x	--
9	x	x	x	X
10	x	x	x	--

Asian Refineries with Configuration 1

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
Malaysia	Port Dickson (Esso)	83,600	0	0
	Kertih	40,000	0	0
	Melaka I	95,000	0	0
	Lutong	45,000	0	0
	Port Dickson (Shell)	155,000	0	0
Thailand	Bangchak, Bongkok	61,750	0	0
Indonesia	Cepu	3,400	0	0
	Pangakalan Brandan	5,000	0	0
	Sungai Pakning	47,000	0	0
Myanmar	Chauk	6,000	0	0
Brunei	Seria	8,600	0	0
India	Cauvery Basin	10,000	0	0
	Mangalore	180,000	0	0
	Jamnagar	540,000	0	0
Pakistan	Rawalpindi	30,500	0	0
	Korangi, Karachi	62,000	0	0
	Karachi	46,000	0	0
	Punjab	100,000	0	0

Country	**Refinery Location**	**Catalytic Cracking bpd**	**Distillate Hydro-treating bpd**	**Hydro-Cracking bpd**
Malaysia	**Port Dickson (Esso)**	0	0	0
	Kertih	0	0	0
	Melaka I	0	0	0
	Lutong	0	0	0
	Port Dickson (Shell)	0	0	0
Thailand	**Bangchak, Bongkok**	0	0	0
Indonesia	**Cepu**	0	0	0
	Pangakalan Brandan	0	0	0
	Sungai Pakning	0	0	0
Myanmar	**Chauk**	0	0	0
Brunei	**Seria**	0	0	0
India	**Cauvery Basin**	0	0	0
	Mangalore	0	0	0
	Jamnagar	0	0	0
Pakistan	**Rawalpindi**	0	0	0
	Korangi, Karachi	0	0	0
	Karachi	0	0	0
	Punjab	0	0	0

Asian Refineries with Configuration 1 (cont.d 1)

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
P.R. China	**Dandong**	6,000	0	0
	Golmud	20,000	0	0
	Heilongjiang	7,000	0	0
	Heilongjiang	7,000	0	0
	Heilongjiang	10,000	0	0
	Heilongjiang	2,000	0	0
	Huhhot	20,000	0	0
	Jilin	6,000	0	0
	Jilin	90,400	0	0
	Jilin	4,000	0	0
	Jilin	4,000	0	0
	Jilin	3,000	0	0
	Lanzhou	20,000	0	0
	Liaohe	50,000	0	0
	Liaoning	2,000	0	0
	Liaoyang	80,000	0	0
	Qinghai	27,000	0	0
	Shaanxi	2,000	0	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
P.R. China	**Dandong**	0	0	0
	Golmud	0	0	0
	Heilongjiang	0	0	0
	Heilongjiang	0	0	0
	Heilongjiang	0	0	0
	Heilongjiang	0	0	0
	Huhhot	0	0	0
	Jilin	0	0	0
	Jilin	0	0	0
	Jilin	0	0	0
	Jilin	0	0	0
	Jilin	0	0	0
	Lanzhou	0	0	0
	Liaohe	0	0	0
	Liaoning	0	0	0
	Liaoyang	0	0	0
	Qinghai	0	0	0
	Shaanxi	0	0	0

Asian Refineries with Configuration 1 (cont.d 2)

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
P.R. China	**Shaanxi**	6,000	0	0
	Sichuan	3,000	0	0
	Xianyang	50,000	0	0
	Yanchang	2,000	0	0
	Yumen	80,000	0	0
	Zepu	3,000	0	0
	Baoding	10,000	0	0
	Beihai	10,000	0	0
	Binzhou	8,000	0	0
	Boxing	2,000	0	0
	Boxing	2,000	0	0
	Changyi	3,000	0	0
	Dagang	60,000	0	0
	Dongming	6,000	0	0
	Guangrao	6,000	0	0
	Hangzhou	6,000	0	0
	Henan	2,400	0	0
	Huabei	4,000	0	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
P.R. China	**Shaanxi**	0	0	0
	Sichuan	0	0	0
	Xianyang	0	0	0
	Yanchang	0	0	0
	Yumen	0	0	0
	Zepu	0	0	0
	Baoding	0	0	0
	Beihai	0	0	0
	Binzhou	0	0	0
	Boxing	0	0	0
	Boxing	0	0	0
	Changyi	0	0	0
	Dagang	0	0	0
	Dongming	0	0	0
	Guangrao	0	0	0
	Hangzhou	0	0	0
	Henan	0	0	0
	Huabei	0	0	0

Asian Refineries with Configuration 1 (cont.d 3)

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
P.R. China	Jianghan	6,000	0	0
	Jianhu	2,000	0	0
	Jinan	6,000	0	0
	Karamay	66,300	0	0
	Kenli	8,000	0	0
	Lijin	3,000	0	0
	Linyi	4,000	0	0
	Luoyang	4,000	0	0
	Nandagang	2,000	0	0
	Nanyang	12,500	0	0
	Qingdao	50,000	0	0
	Qingdao	4,000	0	0
	Shanghai	106,400	0	0
	Shengli	50,000	0	0
	Shengli	3,000	0	0
	Shouguang	3,000	0	0
	Taizhou	6,000	0	0
	Wuxi	3,000	0	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
P.R. China	Jianghan	0	0	0
	Jianhu	0	0	0
	Jinan	0	0	0
	Karamay	0	0	0
	Kenli	0	0	0
	Lijin	0	0	0
	Linyi	0	0	0
	Luoyang	0	0	0
	Nandagang	0	0	0
	Nanyang	0	0	0
	Qingdao	0	0	0
	Qingdao	0	0	0
	Shanghai	0	0	0
	Shengli	0	0	0
	Shengli	0	0	0
	Shouguang	0	0	0
	Taizhou	0	0	0
	Wuxi	0	0	0

Asian Refineries with Configuration 1 (cont.d 4)

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
P.R. China	**Xi'an**	3,000	0	0
	Yan'an	20,000	0	0
	Yancheng	2,000	0	0
	Yangzhou	3,000	0	0
	Yongping	6,000	0	0
	Zhanjiang	20,000	0	0
	Zhongyuan	26,000	0	0
	Zhongjie	3,000	0	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
P.R. China	**Xi'an**	0	0	0
	Yan'an	0	0	0
	Yancheng	0	0	0
	Yangzhou	0	0	0
	Yongping	0	0	0
	Zhanjiang	0	0	0
	Zhongyuan	0	0	0
	Zhongjie	0	0	0

Summary of Configuration 1

Capacity of Refineries with this Configuration (bpd): 2,564,850
% of Total Capacity of Asian Refineries: 24.0%
Number of Refineries with this Configuration: 80
Average Throughput per Refinery (bpd): 32,061

Asian Refineries with Configuration 2

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
Indonesia	Balongan	125,000	0	0
India	Mahul, Bombay	120,000	0	0
P.R. China	Anshan	50,000	0	0
	Dalian	142,600	0	0
	Linyuan	50,000	0	0
	Qianguo	50,000	0	0
	Cangzhou	20,000	0	0
	Fujian	80,000	0	0
	Jinan	80,000	0	0
	Shijiazhuang	50,000	0	0
	Tianjin	120,500	0	0
	Yanshan	190,800	0	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Indonesia	Balongan	83,000	0	0
India	Mahul, Bombay	28,755	0	0
P.R. China	Anshan	2,000	0	0
	Dalian	70,000	0	0
	Linyuan	17,000	0	0
	Qianguo	24,000	0	0
	Cangzhou	9,000	0	0
	Fujian	16,000	0	0
	Jinan	22,000	0	0
	Shijiazhuang	24,000	0	0
	Tianjin	35,000	0	0
	Yanshan	48,000	0	0

Summary of Configuration 2

Capacity of Refineries with this Configuration (bpd):	**1,078,900**
% of Total Capacity of Asian Refineries:	**10.1%**
Number of Refineries with this Configuration:	**12**
Average Throughput per Refinery (bpd):	**89,908**
Catalytic Cracking Capacity (% of Throughput):	**35.1%**

Asian Refineries with Configuration 3

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
Indonesia	Musi, South Sumatra	110,000	8,820	0
India	Ambalamugal	150,000	0	19,000
	Koyali, Gujarat	185,000	0	19,500
	Mathura, Uttar Pradesh	156,000	0	18,000
P.R. China	Dushanzi	120,500	14,000	0
	Harbin	30,000	1,000	0
	Jinzi	100,000	1,000	0
	Jinzhou	110,500	20,000	0
	Lanzhou	110,500	15,000	0
	Urumqi	50,000	8,000	0
	Anqing	56,200	8,000	0
	Gaoqiao	150,600	10,000	0
	Juijiang	50,000	8,000	0
	Wuhan	50,000	8,000	0
	Zhenhai	160,700	8,000	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Indonesia	Musi, South Sumatra	18,450	0	0
India	Ambalamugal	27,000	0	0
	Koyali, Gujarat	20,000	0	0
	Mathura, Uttar Pradesh	20,000	0	0
P.R. China	Dushanzi	12,000	0	0
	Harbin	6,000	0	0
	Jinzi	24,000	0	0
	Jinzhou	16,000	0	0
	Lanzhou	24,000	0	0
	Urumqi	16,000	0	0
	Anqing	24,000	0	0
	Gaoqiao	38,000	0	0
	Juijiang	24,000	0	0
	Wuhan	20,000	0	0
	Zhenhai	28,000	0	0

Summary of Configuration 3

Capacity of Refineries with this Configuration (bpd):	**1,590,000**
% of Total Capacity of Asian Refineries:	**14.9%**
Number of Refineries with this Configuration:	**15**
Average Throughput per Refinery (bpd):	**106,000**
Catalytic Cracking Capacity (% of Throughput):	**20.0%**
Thermal Cracking & Coking Capacity (% of Throughput):	**6.9%**
Visbreaking Capacity (% of Throughput):	**3.6%**

Asian Refineries with Configuration 4

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
Myanmar	Thanlyin	26,000	5,200	0
India	Bongaigaon, Assam	27,000	9,675	0
	Bihar	66,000	20,000	0
	Digboi, Assam	11,700	850	0
	Gawahati, Assam	20,000	6,000	0
P.R. China	Daqing	120,500	13,000	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Myanmar	Thanlyin	0	0	0
India	Bongaigaon, Assam	0	0	0
	Bihar	0	0	0
	Digboi, Assam	0	0	0
	Gawahati, Assam	0	0	0
P.R. China	Daqing	0	0	0

Summary of Configuration 4

Capacity of Refineries with this Configuration (bpd): **271,200**
% of Total Capacity of Asian Refineries: **2.5%**
Number of Refineries with this Configuration: **6**
Average Throughput per Refinery (bpd): **45,200**
Thermal Cracking & Coking Capacity (% of Throughput): **20.2%**

Asian Refineries with Configuration 5

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
Thailand	Sriracha (Esso)	160,000	0	0
	Map Ta Phut, Rayong	275,000	0	0
Philippines	Batangas	86,500	0	0
	Limay, Bataan	180,000	0	0
India	Bombay	110,500	0	0
	Madras	130,700	0	0
P.R. China	Luoyang	100,000	0	0
	Dallan	100,000	0	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Thailand	Sriracha (Esso)	36,000	68,000	0
	Map Ta Phut, Rayong	33,300	25,200	0
Philippines	Batangas	12,500	16,000	0
	Limay, Bataan	12,000	36,000	0
India	Bombay	14,000	25,890	0
	Madras	11,250	5,100	0
P.R. China	Luoyang	40,000	5,000	0
	Dallan	37,000	19,000	0

Summary of Configuration 5

Capacity of Refineries with this Configuration (bpd): 1,142,700
% of Total Capacity of Asian Refineries: 10.7%
Number of Refineries with this Configuration: 8
Average Throughput per Refinery (bpd): 142,838
Catalytic Cracking Capacity (% of Throughput): 17.2%
Distillate Hydro-Treating Capacity (% of Throughput): 17.5%

Asian Refineries with Configuration 6

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
Indonesia	**Dumai, Central Sumatra**	114,000	32,580	0
India	**Numaligarh, Assam**	60,000	8,400	0
Bangladesh	**Chittagong**	33,000	0	10,000
P.R. China	**Yangzi**	120,500	20,000	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Indonesia	**Dumai, Central Sumatra**	0	0	50,220
India	**Numaligarh, Assam**	0	0	22,000
Bangladesh	**Chittagong**	0	0	1,200
P.R. China	**Yangzi**	0	0	24,000

Summary of Configuration 6

Capacity of Refineries with this Configuration (bpd): 327,500
% of Total Capacity of Asian Refineries: 3.1%
Number of Refineries with this Configuration: 4
Average Throughput per Refinery (bpd): 81,875
Thermal Cracking & Coking Capacity (% of Throughput): 18.6%
Visbreaking Capacity (% of Throughput): 3.1%
Distillate Hydro Cracking Capacity (% of Throughput): 29.7%

Asian Refineries with Configuration 7

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
India	Panipat	120,000	0	6,500
P.R. China	Daqing	70,000	13,000	0
	Fushun	184,800	35,000	0
	Jinling	140,600	28,000	0
	Maoming	170,700	24,000	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
India	Panipat	13,400	0	32,600
P.R. China	Daqing	14,000	0	8,000
	Fushun	66,000	0	8,000
	Jinling	44,000	0	16,000
	Maoming	32,000	0	16,000

Summary of Configuration 7

Capacity of Refineries with this Configuration (bpd): 686,100
% of Total Capacity of Asian Refineries: 6.4%
Number of Refineries with this Configuration: 5
Average Throughput per Refinery (bpd): 137,220
Thermal Cracking & Coking Capacity (% of Throughput): 14.6%
Catalytic Cracking Capacity (% of Throughput): 24.7%
Visbreaking Capacity (% of Throughput): 0.9%
Distillate Hydro Cracking Capacity (% of Throughput): 11.7%

Asian Refineries with Configuration 8

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
Philippines	Tabango	153,000	22,000	0
Indonesia	Cilacap, Central Java	348,000	0	50,040
India	Haldia, West Bengal	61,000	0	9,600
Sri Lanka	Sapugaskanda	50,000	0	13,350

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Philippines	Tabango	0	47,300	0
Indonesia	Cilacap, Central Java	0	12,000	0
India	Haldia, West Bengal	0	3,100	0
Sri Lanka	Sapugaskanda	0	2,100	0

Summary of Configuration 8

Capacity of Refineries with this Configuration (bpd): 612,000
% of Total Capacity of Asian Refineries: 5.7%
Number of Refineries with this Configuration: 4
Average Throughput per Refinery (bpd): 153,000
Thermal Cracking & Coking Capacity (% of Throughput): 3.6%
Visbreaking Capacity (% of Throughput): 11.9%
Distillate Hydro Treating Capacity (% of Throughput): 10.5%

Asian Refineries with Configuration 9

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
Singapore	Pulau Bukom	405,000	30,000	30,000
	Pulau Merlimau	285,000	0	30,400
Thailand	Sriracha, Thai Oil Co. Ltd.	185,000	0	17,400
P.R. China	Jingmen	100,000	8,000	0
	Qilu	160,700	16,000	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
Singapore	Pulau Bukom	34,000	77,600	30,000
	Pulau Merlimau	31,000	78,000	30,300
Thailand	Sriracha, Thai Oil Co. Ltd.	11,200	4,100	19,900
P.R. China	Jingmen	20,000	4,000	8,000
	Qilu	46,000	5,000	42,000

Summary of Configuration 9

Capacity of Refineries with this Configuration (bpd): 1,135,700
% of Total Capacity of Asian Refineries: 10.6%
Number of Refineries with this Configuration: 5
Average Throughput per Refinery (bpd): 227,140
Catalytic Cracking Capacity (% of Throughput): 12.5%
Thermal Cracking & Coking Capacity (% of Throughput): 4.8%
Visbreaking Capacity (% of Throughput): 6.9%
Distillate Hydro Treating Capacity (% of Throughput): 14.9%
Distillate Hydro Cracking Capacity (% of Throughput): 11.5%

Asian Refineries with Configuration 10

Country	Refinery Location	Crude Throughput bpd	Thermal Cracking & Coking bpd	Vis-Breaking bpd
India	Visakapatnam	164,000	0	20,580
P.R. China	Baling	100,000	12,000	0
	Guangzhou	104,000	20,000	0

Country	Refinery Location	Catalytic Cracking bpd	Distillate Hydro-treating bpd	Hydro-Cracking bpd
India	Visakapatnam	32,900	47,104	0
P.R. China	Baling	50,000	11,000	0
	Guangzhou	44,000	5,000	0

Summary of Configuration 10

Capacity of Refineries with this Configuration (bpd):	**368,000**
% of Total Capacity of Asian Refineries:	**3.4%**
Number of Refineries with this Configuration:	**3**
Average Throughput per Refinery (bpd):	**122,667**
Catalytic Cracking Capacity (% of Throughput):	**34.5%**
Thermal Cracking & Coking Capacity (% of Throughput):	**8.7%**
Visbreaking Capacity (% of Throughput):	**5.6%**
Distillate Hydro Treating Capacity (% of Throughput):	**17.1%**

APPENDIX 5

Summary of Diesel Fuel De-sulphurisation Costs

Costs relative to the average Refinery structures of each Country

SINGAPORE

	Capital Investment US$ million	**Capital Investment US$ million**	**Incremental Product Cost USc/Litre**	**Incremental Product Cost USc/Litre**
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	46.1	0.0	0.29	0.31
1,000	104.3	88.1	0.66	0.87
500	135.5	118.8	0.85	1.06
350	145.0	136.7	0.91	1.17
250	151.1	147.7	0.95	1.24
50	375.7	374.4	2.36	2.67
10	414.4	414.4	2.61	2.92

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

MALAYSIA

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	98.3	59.0	0.62	0.73
1,000	144.4	135.0	0.91	1.21
500	154.8	148.7	0.97	1.29
350	163.3	155.8	1.03	1.34
250	169.1	166.0	1.06	1.40
50	415.1	411.9	2.61	2.95
10	419.9	419.9	2.64	3.00

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

THAILAND

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	83.9	21.9	0.53	0.49
1,000	123.5	113.0	0.78	1.06
500	146.5	131.6	0.92	1.18
350	155.7	148.4	0.98	1.29
250	161.6	158.9	1.02	1.35
50	398.5	397.2	2.51	2.85
10	435.1	435.1	2.74	3.09

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

PHILIPPINES

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	37.5	0.0	0.24	0.38
1,000	123.7	81.3	0.78	0.89
500	155.8	142.0	0.98	1.27
350	164.6	158.1	1.03	1.37
250	170.3	168.2	1.07	1.44
50	417.7	416.4	2.63	3.00
10	451.0	451.0	2.84	3.21

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

INDONESIA

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	106.4	70.0	0.67	0.74
1,000	151.7	142.7	0.95	1.19
500	159.3	155.9	1.00	1.28
350	161.5	159.7	1.02	1.30
250	163.4	162.2	1.03	1.32
50	400.1	398.4	2.52	2.80
10	403.4	403.4	2.54	2.83

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

MYANMAR

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	131.5	101.6	0.83	1.00
1,000	174.9	167.0	1.10	1.41
500	181.8	178.9	1.14	1.48
350	183.8	182.4	1.16	1.50
250	185.2	184.7	1.16	1.52
50	449.7	448.9	2.83	3.18
10	451.0	451.0	2.84	3.19

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

BRUNEI

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	130.0	99.5	0.82	1.05
1,000	174.9	167.0	1.10	1.47
500	181.8	178.9	1.14	1.54
350	183.8	182.4	1.16	1.57
250	185.2	184.7	1.16	1.58
50	449.7	448.9	2.83	3.24
10	451.0	451.0	2.84	3.26

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

INDIA

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	125.1	93.7	0.79	0.94
1,000	169.7	161.7	1.07	1.37
500	176.8	173.9	1.11	1.45
350	178.9	177.4	1.12	1.47
250	181.5	180.4	1.14	1.49
50	443.3	442.4	2.79	3.14
10	444.6	444.6	2.80	3.15

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

PAKISTAN

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	130.0	99.5	0.82	1.05
1,000	174.9	167.0	1.10	1.47
500	181.8	178.9	1.14	1.54
350	183.8	182.4	1.16	1.57
250	185.2	184.7	1.16	1.58
50	449.7	448.9	2.83	3.24
10	451.0	451.0	2.84	3.26

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

BANGLADESH

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	131.6	102.1	0.83	0.95
1,000	171.5	163.5	1.08	1.34
500	178.5	175.5	1.12	1.41
350	180.5	179.1	1.13	1.43
250	181.9	181.4	1.14	1.45
50	442.0	441.2	2.78	3.08
10	443.3	443.3	2.79	3.10

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

SRI LANKA

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	131.6	102.1	0.83	0.97
1,000	172.6	164.7	1.09	1.36
500	179.5	176.7	1.13	1.44
350	181.6	180.2	1.14	1.46
250	184.3	183.3	1.16	1.48
50	448.2	446.5	2.82	3.13
10	451.0	451.0	2.84	3.16

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

P. R. CHINA

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	127.0	96.0	0.80	0.92
1,000	171.5	163.5	1.08	1.35
500	178.5	175.5	1.12	1.42
350	180.5	179.1	1.13	1.44
250	181.9	181.4	1.14	1.46
50	442.0	441.2	2.78	3.09
10	444.8	444.8	2.80	3.11

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

Costs relative to the ten typical refinery configurations identified in this study

CONFIGURATION 1

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	130.0	99.4	0.82	1.05
1,000	174.9	167.0	1.10	1.47
500	181.8	178.9	1.14	1.54
350	183.8	182.4	1.16	1.57
250	185.2	184.7	1.16	1.58
50	449.7	448.9	2.83	3.24
10	451.0	451.0	2.84	3.26

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

CONFIGURATION 2

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	127.8	87.4	0.80	0.74
1,000	173.2	163.4	1.09	1.21
500	181.1	177.7	1.14	1.30
350	183.5	181.8	1.15	1.33
250	185.1	184.5	1.16	1.35
50	449.5	448.5	2.83	3.01
10	451.0	451.0	2.84	3.02

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

CONFIGURATION 3

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	130.9	95.5	0.82	0.80
1,000	173.1	163.4	1.09	1.23
500	181.1	177.6	1.14	1.32
350	183.5	181.8	1.15	1.34
250	185.0	184.5	1.16	1.36
50	449.6	448.6	2.83	3.02
10	451.0	451.0	2.84	3.04

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

CONFIGURATION 4

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	134.1	105.3	0.84	0.91
1,000	174.9	167.0	1.10	1.29
500	181.8	178.9	1.14	1.37
350	183.8	182.4	1.16	1.39
250	185.2	184.7	1.16	1.41
50	449.7	448.9	2.83	3.07
10	451.0	451.0	2.84	3.08

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

CONFIGURATION 5

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	92.2	50.0	0.58	0.57
1,000	139.4	129.0	0.88	1.07
500	169.4	156.4	1.06	1.24
350	177.8	171.6	1.12	1.34
250	183.2	181.3	1.15	1.40
50	446.3	443.4	2.81	3.05
10	451.0	451.0	2.84	3.10

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

CONFIGURATION 6

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	81.9	41.7	0.51	0.41
1,000	125.7	114.8	0.79	0.87
500	134.2	129.9	0.84	0.96
350	136.7	134.1	0.86	0.99
250	138.3	137.0	0.87	1.01
50	338.9	338.0	2.13	2.27
10	340.5	340.5	2.14	2.29

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

CONFIGURATION 7

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	113.7	76.5	0.71	0.63
1,000	156.8	148.1	0.99	1.08
500	164.2	160.9	1.03	1.16
350	166.4	164.6	1.05	1.18
250	167.9	167.1	1.06	1.20
50	407.9	407.9	2.57	2.71
10	410.1	410.1	2.58	2.73

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

CONFIGURATION 8

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	114.8	82.0	0.72	0.79
1,000	159.8	150.5	1.00	1.22
500	176.4	170.2	1.11	1.34
350	181.2	178.2	1.14	1.39
250	184.3	183.3	1.16	1.42
50	448.2	446.6	2.82	3.08
10	451.0	451.0	2.84	3.11

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

CONFIGURATION 9

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	85.4	39.1	0.54	0.43
1,000	132.7	123.0	0.83	0.96
500	148.6	140.6	0.93	1.07
350	155.3	149.6	0.98	1.10
250	160.0	157.1	1.01	1.17
50	391.3	392.0	2.46	2.65
10	400.2	400.2	2.52	2.70

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.

CONFIGURATION 10

	Capital Investment US$ million	Capital Investment US$ million	Incremental Product Cost USc/Litre	Incremental Product Cost USc/Litre
Crude Slate	**High Sulphur**	**Low Sulphur**	**High Sulphur**	**Low Sulphur**
Diesel Fuel Sulphur, ppm				
3,000	112.3	77.2	0.71	0.64
1,000	171.7	167.0	1.08	1.20
500	181.8	178.9	1.14	1.28
350	183.8	182.4	1.16	1.30
250	185.2	184.7	1.16	1.31
50	449.7	448.9	2.83	2.98
10	451.0	451.0	2.84	2.99

Basic Study Assumption: all distillate production is de-sulphurised to the levels shown above.