costs to reduce the sulphur content of diesel fuel

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on Costs to Reduce the Sulphur Content of Diesel Fuel
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ABSTRACT

This study examines the consequences to refineries of making step-wise reductions in the sulphur content of diesel fuel from 0.26 to 0.05% wt. The EC-12's 95 refineries have been grouped into four categories for the purposes of representing process configurations and studying changes using computer LP models.

With reduction of diesel fuel sulphur, increasing amounts of new high pressure (60+ bar) desulphurization capacity would be required. This would increase significantly in the region of 0.10% wt, although this break point differs for different countries and refineries.

To meet 0.05% wt sulphur in diesel fuel for EC-12 over the range of cases studied would require capital expenditure of 3000 to 4300 M$ and lead to an increase in total manufacturing costs of 12 to 18 $/t diesel fuel. Some 0.8 to 1 Mt/yr of additional refinery energy consumption would be required to meet the 0.05% rather than the 0.2% wt sulphur content level with a consequent increase in CO_2 emissions.

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SUMMARY

Concerns associated with particulate emissions from diesel exhausts and the connection between diesel fuel sulphur and particulate levels have increased pressure, resulting from developments in North America, to further reduce the sulphur content of diesel fuels in Europe significantly below the current 0.2/0.3% wt levels. As a result of this, CONCAWE has reviewed and extended the scope of its Report No. 11/84, Desulphurization of Gas Oils (Sept '84).

The study, based on a 1995 EC-12 forecast supply and demand situation, has examined the consequences of reducing step-wise the sulphur content of diesel fuel from 0.26 to 0.05% wt. Two sulphur levels have been used for the remaining gas oil pool, viz. 0.26% wt to represent the weighted average of the current EC regulatory limit and 0.2% wt to represent the likely upper limit after the unification of the two existing limits in the EC.

EC-12's 95 refineries have been grouped into four categories depending on their process configuration and each category represented in a LP model. The technical and economic data for the study have been compiled based on the replies to an extensive questionnaire sent to CONCAWE member companies and supplemented with published data.

With reduction of the sulphur limit of diesel fuel, increasing amounts of new high pressure (60+ bar) desulphurization (HDS) capacity would be required which would be largely dependent on existing capacity, diesel fuel demand and low sulphur crude availability. This need for additional capacity would increase significantly at a diesel sulphur level in the region of 0.10% wt. This break point would be different for different countries and at different refineries.

The various cost parameters for meeting a sulphur content of 0.05% wt in diesel fuel for EC-12, depending on diesel fuel demand and low sulphur crude availability, are:

- Capital Expenditure : 3000 to 4300 million USD
- Total Manufacturing Costs : 12 to 18 USD/t diesel
- Costs/Ton Sulphur Removed : 6000 to 9000 USD

Additional refinery energy consumption at the 0.05% wt sulphur level rather than at 0.2% wt will be 0.8 to 1 million t/yr (3 to 4% of EC-12 refinery energy consumption) which will lead to some 2.5 to 3 million t/yr additional CO_2 emission.

1. INTRODUCTION

In March 1987, the EC agreed to set new sulphur limits for gas oils in the Community. This limit was set to max. 0.3% wt with a possible lower limit of max. 0.2% wt if this is deemed necessary either for air quality or mass of sulphur emissions. The EC legislation came into force as of 1st January 1989. Germany, the Netherlands, Belgium and Denmark decided to implement the 0.2% wt limit. Outside the EC, Finland, Sweden and Switzerland also apply 0.2% wt while Austria has gone even lower to 0.15% wt.

The current EC directive (87/219/EEC) is due for review by April 1990 and the Commission shall submit a report to the Council accompanied by an appropriate proposal with a view to establishing a single value.

Meanwhile pressures in the US have been directed at reducing the sulphur level even further to 0.05% wt. The main drive of lowering the sulphur level is directed towards the reduction of particulate emissions from diesel engined vehicles via engine design changes rather than an overall reduction in sulphur emission.

In June 1988, API, NPRA, The Engine Manufacturers Association and The National Council of Farmer Cooperatives made a joint package of recommendations which included limiting the sulphur content of US diesel fuel to maximum 0.05% wt, cetane index to minimum of 40 and aromatics content at current levels. These limits would be applicable by 1st October 1993.

These US activities have attracted attention in Europe and have also been discussed within the Motor Vehicle Emissions Group (MVEG) of the EC. The Umweltbundesamt (UBA) in Germany commissioned A.D. Little (ADL) to study amongst other quality aspects, the costs of reduction in diesel fuel sulphur content and aromatics content for each EC member state.

The results were presented to MVEG. CONCAWE disagreed with some of the assumptions made and felt that a number of points demanded verification.

The last CONCAWE report on gas oil desulphurization No. 11/84 was issued in September 1984 and it covered the reduction of gas oil sulphur content down to 0.10% wt. In that report no discussion on the type of technology required for deep desulphurization was presented. Moreover the horizon year of 1990 then applied is now inappropriate. Furthermore, the situation on existing HDS capacity, operating severity, product demand and crude oil availability requires updating.

In the light of the above, CONCAWE decided to embark on a new study on the costs to reduce the sulphur content of diesel fuel step-wise down to 0.05% wt which would fully reflect the industry views. The study uses information on refinery capabilities, crude supply and product demand projections for the next decade compiled from replies to a questionnaire sent to CONCAWE member companies and supplemented with published information.

2. SCOPE AND METHODOLOGY

2.1 SCOPE

Supply and demand data for diesel fuel and heating oil were established for the base year 1990 and 1995 and a sensitivity included for the year 2000. Data generated by EC DG-XVII were used where applicable.

National petroleum product demand patterns were examined also paying attention to fuel oil and gasoline demand and the related crude oil quality available.

The EC refineries were grouped into categories depending on their configuration and the desulphurization studies using an LP model were based on these categories.

The study assessed how much additional desulphurization capacity would have to be constructed to meet, in the chosen years of 1990 and 1995, the various sulphur levels of diesel fuel in combination with two sulphur levels of heating oil. See Table 2.

Capital and operating cost were established for the various sulphur levels. A realistic degree of segregation between diesel fuel and heating oil, their respective demand forecasts and the quality (sulphur level) of the crudes processed were taken into account.

The cost data are presented showing the incremental cost for each step-wise decrease of the diesel fuel sulphur content.

2.2 METHODOLOGY

The cost of reducing the sulphur content in gas oil would vary from refinery to refinery within in the EC because of different configurations and supply/demand patterns. It would therefore not be realistic to study only average European refinery configurations since this would hide extremes. However, as there are almost 100 refineries in EC-12, each with different configuration, it would also not be practical to study each individual refinery.

Therefore, four typical refinery configurations have been defined according to the type of conversion process which predominates.

- Type 1: Hydroskimming (no conversion units)
- Type 2: Visbreaking and/or thermal cracking (no cat cracking)
- Type 3: Hydrocracking
- Type 4: Catalytic cracking (i.e. the other refineries)

Each of the refineries in the EC-12 was characterized as one of these four types, and the total processing capacities available in each category were defined as the aggregated capacities of the refineries allocated to that category.

For the purposes of the study, the EC-12 refining industry was modelled in terms of typically-sized modules of 5 million ton/year crude capacity. Four different configurations of module were developed, each with a ratio of downstream processing capacity (i.e. reforming, conversion, hydrotreating etc.) to crude capacity representative of one of the four refinery types described above.

Capacity utilizations of the refining modules were defined as follows:

- For types 3 and 4, crude runs were set to ensure full utilization of the key conversion units (cat cracking and hydrocracking).
- Balance of crude was distributed between types 1 and 2, assuming that these two configurations would each have the same level of crude unit utilization.

Input/output balances for the four categories of refinery module were adjusted to reflect realistic product yield patterns appropriate to the configuration type, which aggregated on a weight-averaged basis generated an overall material balance for the EC-12 consistent with supply/demand projections for the period under study.

Crude slates were allocated among the individual refinery modules - within the constraints set by the EC-12 supply forecast - to generate a base case consistent with current distillate sulphur qualities and existing installed process capacity.

Each refinery configuration was modelled in LOTUS 123 spreadsheet format on an IBM PS2/80 PC, and the economic optimum operation of each configuration at a number of distillate sulphur levels was determined with the help of a commercial LP optimization software programme.

The 1987 crude slate is taken to remain representative until 1990, after which the amount of low sulphur crude processed has been assumed to gradually reduce. The Middle East portion of the crude slate is represented by a 70/30% mixture of Arabian Light/Heavy and the low sulphur crudes by Brent and Forcados. Similarly, market demands, refinery production and deficits and surpluses for 1990 and 1995 are taken as about similar to 1987.

Since diesel fuel and heating oil are two similar products blended from components out of the same pool of medium cuts from crude distillation or conversion units, any definition of diesel fuel quality implies a quality constraint on heating oil. The study, therefore, modelled the sulphur level of heating oil as well as diesel.

The reduction of diesel fuel sulphur content was studied at five levels of specification, i.e. 0.26, 0.20, 0.15, 0.10 and 0.05% wt, with the heating oil specification at 0.26 and 0.20% wt giving a total of 10 cases. These cases are tabulated in Table 2.

The target sulphur content of the products as made is lower than specification, taking into account blending margins to reflect actual practices and imprecision in testing methods. See Table 2.

The sulphur removal capabilities of existing hydrotreating units were expressed as percentage hydrodesulphurization (% HDS) on feed sulphur. The model has the built-in flexibility to increase % HDS of existing units, within limits, at the expense of a capacity debit. This represents the real-world situation in which operating conditions (e.g. space velocity, reactor debottlenecking) of existing HDS would be adjusted to ensure optimum utilization of installed capacity before any investment in new units.

For new hydrodesulphurization capacity, HDS units with pressure of at least 60 bar are provided.

The following sensitivity cases have been run to cover the inevitable uncertainty of all forecast data:

- A 20 million t/yr switch in total European crude from low to high sulphur grades.

- An increase in diesel fuel production at the expense of heating oil of 12 million t/yr. This allows the assessment of the effects of underestimation of diesel fuel demand and/or the non-segregation of 15% of heating oil from diesel fuel.

Since segregation of refinery types by process configuration takes no account of any supply inefficiencies caused by location factors, the overall EC-12 balances which the model simulates may conceal a processing deficit at some location which is apparently compensated by spare capacity elsewhere. To test the degree of over-optimization, if any, inherent in the study results for this reason, "worst-case" and "best-case" country scenarios were also modelled.

3. REDUCTION OF SULPHUR CONTENT OF GAS OILS

3.1 SULPHUR CONTENT OF GAS OIL COMPONENTS

Diesel fuel and heating oil together constitute the gas oil pool of a refinery. The sulphur contents of the straight-run gas oil (SRGO) components of the gas oil pool depend on the crude source. For a given crude, the sulphur content increases with the boiling range of a cut. Light cycle oil (LCO) produced by catalytic cracking of heavy/vacuum cuts of crude has a higher sulphur content than straight-run gas oil from the same crude.

The average sulphur content of straight-run and cracked gas oil components from typical crudes of North Sea and Middle East origin are as follows:

Process Unit	North Sea Crude	Middle East Crude
Crude Distillation		
Kerosine (165-225°C)	0.02	0.13
Gas oil (225-370°C)	0.20	1.30
Catalytic Cracker		
Light cycle oil (LCO) (200-350°C)	0.72	2.80

The two main ways of reducing the sulphur content of the gas oil pool are by crude selection and desulphurization of gas oil components.

3.2 THE HYDRODESULPHURIZATION PROCESS

The main parameter by which the hydrodesulphurization process (HDS) is judged is the rate of desulphurization, defined as the ratio of sulphur removed/sulphur in feed.

The degree of sulphur removal attainable in a given HDS plant is critically dependent upon the quality and type of the feedstock as much as on the design and operational limits of the facility, i.e. pressure, space velocity and reaction temperature.

In the HDS process, some hydrogen is consumed depending on the amount of sulphur removed and the feedstock type. The variable operating costs of desulphurization can be considered to be built up from consumption of hydrogen, fuel and catalyst.

Feedstock Characteristics

The sulphur compounds in gas oil components belong to different chemical species according to where the S-atom is bonded. The main difference between straight-run and cracked components is in the type of prevailing sulphur compounds:

- In straight-run components, the S-atom is more often linked to aliphatic and to a lesser extent to simple thiophenic and benzothiophenic structures. Aliphatic and substituted benzothiophenic sulphur is easily removed under normal reaction conditions in a HDS unit.

- In LCO, the main sulphur containing molecules are substituted benzothiophenes and less reactive dibenzothiophenes.

By hydrodesulphurization, the more reactive sulphur compounds will be eliminated preferentially with the result that as the reaction proceeds, the remaining sulphur will on the average become more and more refractory. Therefore, it is generally economical to process those gas oil components having the highest sulphur content first. Consequently, good segregation of low and high sulphur feedstocks is of great importance although not always feasible.

Operating Variables

Information from pilot plant work contained in two articles recently published by American Cyanamid Co. (1,2) permits the formulation of a simple kinetic model for the hydrodesulphurization reaction. The feedstock used in (2) resembles in sulphur content and general characteristics a typical mixture of straight-run and LCO materials with a low cetane index, but its sulphur content is more representative of a 50/50 blend of North Sea and ME crudes.

$$(S_P^{1-n} - S_F^{1-n}) = \frac{(n-1)P^m}{LHSV} * K_o * e^{-E/RT}$$

where $E = 16\ 858$ and $K_o = 8.93 \times 10^6$, and the literature

quotes $n = 1.8$ and $m = 0.236$, and

E	-	Energy of activation
K_o	-	Frequency factor
m	-	Pressure exponent
n	-	Order of reaction
R	-	Universal Gas Constant
T	-	Reactor temperature (K)
P	-	Hydrogen pressure
LHSV	-	Liquid hourly space velocity, $V/V/h^{-1}$
S_F	-	Sulphur on feed wt fraction of 1
S_P	-	Sulphur on product wt fraction of 1

When the above formula is applied to an operation to produce 0.04% wt sulphur at 95% sulphur removal efficiency, for a 30 bar hydrogen pressure and LHSV of 2, a reactor inlet temperature of approx. 360°C is required. The maximum reactor inlet temperature before the onset of undesirable cracking reactions and catalyst deactivation may be bordering 360 - 370°C. With the average start-of-run temperatures in the neighbourhood of 360°C, the narrow temperature margin to compensate for the gradual activity decline to maintain on-specification product sulphur levels renders the whole operation infeasible. Higher maximum operating temperatures are required which in turn require higher hydrogen pressures to slow down catalyst deactivation by coke deposit.

Current and future components for blending gas oil and diesel fuel include a significant amount of cracked components with difficult to remove sulphur. The gas oil/diesel fuel pool at the 0.2-0.3% wt sulphur level has been achieved by removing the more accessible sulphur in present generation HDS units built for pressures below 60 bar and LHSV equal to or greater than 2. Further significant lowering of sulphur would require reducing the space velocity. Existing HDS plants cannot easily be revamped to lower space velocities through addition of a reactor. The increased hydrogen consumption would result in a large reduction in hydrogen partial pressure.

To meet much lower sulphur specifications will therefore require investments in plants designed for pressures of 60 bar minimum.

3.3 SEGREGATION OF GAS OIL GRADES

In the European market, several types of middle-distillate fuels are available ranging from diesel fuel and heating oil having marginally different specifications to heavy marine diesel oil. Furthermore, in several markets heating oil is used for off road automotive purposes, e.g. agricultural and construction low speed diesel engines.

Therefore, several locations find it economic to manufacture only one grade of gas oil meeting the automotive specifications which are the more stringent.

However, if the sulphur content of diesel fuel should become much lower than for heating oil, segregation, defined as separate handling and treating facilities, for the two products may then be required.

The gas oil components in a refinery can come from several production units, such as distillation and hydro/thermal/ catalytic cracking, with significantly different sulphur levels ranging from negligible in hydrocracked gas oils to levels in excess of 2% wt in cycle oils with furthermore a strong dependency on the sulphur level in the crude oil from which they originate.

When comparing diesel fuels with heating oils there are a number of different fuel performance characteristics and specifications. To economically blend the various grades it may be advantageous to segregate components on important quality characteristics other than sulphur.

Under such circumstances, the lowering of the sulphur specification would require:

- Crude segregation (i.e. low and high sulphur crudes). The capability is then created to select and blend the lowest sulphur containing gas oil components for the diesel fuel pool.

- Full segregation of the diesel fuel and heating oil pools. The allowable sulphur content of the heating oil pool is utilized.

Both might entail the construction of additional tankage for crude and gas oil components.

The CONCAWE questionnaire established that a high degree of segregation between diesel fuel and heating oil already exists today. As a consequence costs for increasing segregation have been considered only as a sensitivity in this study.

3.4 COSTS OF REDUCING SULPHUR CONTENT

The required amount of sulphur removal from the gas oil pool depends on the sulphur specifications of diesel fuel and heating oil, their relative production ratio and the sulphur content of components. The sulphur content of components in turn depends on the sulphur content of crude, refinery configuration, and cut points, among others.

When the overall gas oil pool sulphur specification is high, it is sufficient to desulphurize only high sulphur components and costs are relatively low. Therefore, good segregation of low/high sulphur feedstocks is of importance although not always feasible.

As the sulphur specification of diesel fuel and/or heating oil decreases, additional feeds with increasingly lower sulphur content have to be desulphurized and costs per ton sulphur removed increase. The first step is to use existing desulphurization capacity. This would depend on the availability of spare capacity and the efficiency of the existing capacity to achieve the required rate of desulphurization. If the existing capacity cannot meet the demand, then new capacity would have to be built.

In summary, the following factors can be identified as having a significant effect on the costs of reducing the sulphur level in diesel fuel with the overall rate of desulphurization being the prevailing factor:

- Sulphur levels and quantities of diesel fuel and heating oil

- Hydrodesulphurization unit characteristics (particularly rate of desulphurization and investment for new unit)

- Crude supply (quantities, qualities, particularly sulphur content)

- Refinery configuration

- Products demand and specification

- Segregation of diesel fuel and heating oil

From this, it is clear that the costs of reducing the sulphur level of diesel fuel will differ widely between refineries. For a given crude supply, and products demand and specifications, these costs will be mainly determined by HDS costs. Storage, mixing or pumping costs are not taken into account in the study although, in actual fact, some investments, e.g. HDS feed storage, may be necessary even before new HDS capacity is added.

4. TECHNICAL AND ECONOMIC DATA

A questionnaire was sent to CONCAWE member companies to collect the available data on European refineries, for present and future situations covering product demand, crude qualities, unit capacities, hydrogen availability, and characteristics (design and operational limits), available capacity and costs of hydrodesulphurization units. The technical and economic data for the study have, therefore, been compiled based on the replies to the questionnaire and supplemented with published data. The replies to the questionnaire covered 75% of the EC refineries.

4.1 PRODUCT SPECIFICATIONS AND MARGINS

The specifications of products used in this study have been selected to represent an up-to-date average European quality level.

Sulphur levels actually blended in the model are more stringent than the specification, i.e. they contain so-called blending margins. The reason is that experience has shown actual blends sometimes differ in qualities from the model forecast because of:

- Sulphur test method reproducibility
- Variation in blend composition due to measurement inaccuracies
- Variations in component qualities
- Limits in the accuracy of model formulae used to represent non-linear blending behaviour of some qualities

The quality parameters used in the model for the main products represented are:

Jet Fuel : A straight-run kerosine of 160-225°C cut with no quality limits imposed.

Gasoline : One grade is represented and unleaded Eurograde was chosen as this also covers the quality demands of 0.15 g/l Pb premium gasoline as well as itself representing a large and increasing share of the demand.

Gas Oil : A diesel fuel and a heating oil are represented, both with sulphur limits; diesel distillation and cetane characteristics are limited by blend restrictions of max. 15% kerosine and max. 25% cat. cracked gas oil. The base sulphur specification for diesel fuel and heating oil is taken as 0.26% wt, the current EC weighted average limit.

Fuel Oil : European refineries supply a large number of fuel oils to the inland and bunker market with different sulphur requirements. This multiplicity of grades is represented by one fuel grade.

The European crude mix is very much determined by the fuel oil sulphur level and the sulphur level produced by a European crude oil slate should automatically produce a typical European low/high sulphur fuel oil mix.

The fuel oil sulphur level was established in Reference Case 1 (see Table 2) at 2.8% wt and was considered to be consistent with the real situation. It was then maintained at this level throughout all the other cases.

The summary of the specifications and blending margins of the products are given in Table 3.

4.2 REFINERY CAPACITY DATA

The industry response to the CONCAWE questionnaire is summarized in Table 4 applying the various categories of refinery configurations as discussed in Section 2.2.

4.3 MARKET DEMAND AND REFINERY INTAKE

Projections of market demand and call on refinery capacity projections have been compiled using EC projections in combination with industry estimates. The data are given in Table 5.

4.4 HYDRODESULPHURIZATION DATA

The desulphurization rates used in the study which are typical industry figures are:

Reactor pressure (bar)		Rate of desulphurization (%)	
		LCO	SRGO
Less than	30	65	75
	30-60	80	90
Above	60	95	95

The HDS plant data are summarized in Table 6 for two sizes of units with design capacity of 1000 and 2000 t/cd.

The utilization factor of 80% takes into account a 10% allowance for routine maintenance shutdowns and another 10% allowance for seasonality, availability of feedstocks (sequential processing of higher and lower sulphur crude) and requirements of refinery flexibility.

An amine treating plant and sulphur recovery unit for handling the H_2S produced are also included in the cost estimates for each HDS unit.

4.5 HYDROGEN AVAILABILITY AND COST DATA

Hydrogen is consumed in the hydrodesulphurization process and a consumption figure of 0.5% wt on feed has been taken for the study.

Hydrogen in a refinery is normally produced by the catalytic reformers and is dependent on the operating conditions of the reformers. A shortfall in hydrogen availability can firstly be satisfied by hydrogen purification units. If this is still insufficient, hydrogen manufacturing units would have to be constructed. Refineries with hydrocrackers require large quantities of hydrogen and are normally equipped with hydrogen manufacturing facilities.

With desulphurization of gas oils to lower sulphur levels, increasing amounts of hydrogen will be required. It has been assumed that the hydrogen required by hydrocrackers is produced from hydrogen manufacturing units. Of the hydrogen produced by the catalytic reformers, some 65% is assumed to be normally available for use by hydrogen consuming processes. If the hydrogen required for reducing sulphur content of diesel fuel below the base case exceeds this figure, it is assumed that hydrogen purification units are installed to satisfy the excess demand. The maximum amount of hydrogen that can be recovered is assumed as 90%. Consumption exceeding this limit would have to be satisfied from new hydrogen manufacturing facilities.

The cost data, summarized in Table 7, for the hydrogen purification unit are based on a design capacity of 15 t/cd with a utilization factor of 80% for the same reasons as for desulphurization plants.

5. RESULTS

The HDS and hydrogen capacity utilization for the 10 cases described in Section 2.2 and for the sensitivity runs of increased diesel fuel demand and reduced availability of low sulphur crude, are given in Table 8-1 and 8-2.

The main points that can be seen from the results are:

- As the sulphur content of diesel fuel is lowered from 0.26 to 0.10% wt, there is a steady increase in the HDS capacity required. The HDS capacity requirement then increases significantly as the sulphur content is reduced further from 0.10 to 0.05% wt (refer also to Section 7).

- Only hydrogen purification units are required to cope with the increased desulphurization, the highest hydrogen recovery being 84% which is still within the assumed maximum possible rate of 90%.

- When the heating oil sulphur limit is set at 0.20% wt instead of 0.26% wt, the utilization of the HDS and hydrogen purification capacities is consistently greater.

- When the availability of low sulphur crude is decreased by 20 million t/yr or the diesel demand is increased by 12 million t/yr at the expense of heating oil, the utilization of the HDS and hydrogen purification capacities increases.

The increased utilization of existing and new HDS capacity must be allocated over most of the EC refineries. 85% of EC refineries (81) have reported that they would need new HDS capacity if very low sulphur diesel fuel would be required. The remaining refineries would in principle meet lower sulphur limits by a combination of utilization of spare HDS capacity and reallocation of crude oil.

Spreading the required new HDS capacity equally over 81 refineries gives unit capacities in the range of 200 - 1300 t/cd. Firstly, the low end of the range is unrealistically small and almost certainly units of this capacity would not be built. Secondly, the crude oil capacity range of refineries is from about 2.5 to 21 Mt/yr and clearly the larger refineries will need larger HDS units than small refineries. The net result would be that more new HDS capacity would be installed than calculated by the refinery model.

The following procedure has been followed to give the most reasonable representation of what would happen in practice:

- New HDS capacity is assumed at levels of 1000 and 2000 t/cd

- At the 0.05% wt sulphur level, 81 new HDS units (85% of EC-12 total) are assumed, the ratio between 1000 and 2000 t/cd being chosen to give the required overall capacity.

- At all sulphur levels above 0.05% wt, only new units of 1000 t/cd are assumed, to give the required overall capacity. In most cases, significantly less than 81 units are required.

The total manufacturing costs per ton of diesel fuel assuming that 12 million t/yr of heating oil cannot be segregated has also been calculated to give an indication of the sensitivity of limited segregation ability. In this case, the total costs of producing 90 million t/yr of diesel fuel are divided by 78 million t/yr of diesel oil since the additional 12 million t/yr of diesel fuel would be sold as heating oil.

The resulting costs for the various cases including the sensitivities are given in Table 9-1 and 9-2.

Another important aspect is that the results of the study represent the sum of EC averages in each of the four refinery categories. The cat. cracker category is relatively large covering 47 of the 95 EC refineries. This means that the model has assumed too much optimization compared with what is possible in practice.

An attempt has been made to quantify the over-optimization effect by analysing, within the categories of refineries, the regional variations in the most relevant factors, namely:

- Percentage of low sulphur crude
- Percentage of total gas oil demand on crude
- Ratio of existing HDS capacity to total gas oil demand

An example is given below of the extremes found between countries:

Country Type	A	B
Low sulphur crude (%)	32	76
Gas oil demand (% on crude)	34	25
Existing HDS capacity/gas oil demand	0.76	0.92

Running the LP model at these two extremes confirmed that country type A required significantly more new HDS capacity than country type B at each diesel fuel sulphur level. Moreover each situation resulted in more non-utilized existing HDS capacity in aggregation than in the base case. The results of the runs are tabulated in Table 10.

For country type A, the non-utilization increased with decreasing sulphur content. As increasingly deeper desulphurization is required due to the larger amount of high sulphur components, the low pressure HDS units had insufficient desulphurization efficiency and were left idle.

For country type B, there was a high HDS non-utilization at high sulphur level because it was not required by the larger amount of low sulphur components. At lower sulphur levels, the HDS units were activated as more sulphur is needed to be removed.

The above indicates that the model, by globally treating the four refinery categories, has underestimated the required amount of new HDS capacity because it assumes an even distribution of gas oil components, product demand and HDS capacity throughout the countries in the EC-12.

Some partial measure of the under-estimation can be obtained by taking the sum of the non-utilized HDS capacity shown in Table 10 and converting it to an equivalent of new high pressure HDS capacity required, using the following conversion:

- 1 t/yr low pressure HDS capacity to 0.74 t/yr new high pressure HDS capacity

- 1 t/yr medium pressure HDS capacity to 0.89 t/yr new high pressure HDS capacity.

The under-estimation of capacity and associated costs are tabulated in Table 11-1 and 11-2.

In the calculation of these costs, it has been assumed that the fixed and variable operating costs of the existing LP/MP HDS units not utilized would not be incurred in practice, i.e. units closed down, and have been subtracted. In both the cases where the diesel fuel sulphur limit is at 0.05% wt, the reference case has already assumed the maximum number of new HDS units in terms of 2000 t/cd and 1000 t/cd capacity. Additional capacity has been obtained therefore by assuming more 2000 t/cd units and less 1000 t/cd units. The costs for these two cases shown in Table 11-2 reflect a significant economy of scale effect.

The costs of the under-estimated capacity are plotted together with the costs in Table 9-1 and 9-2 in Figure 1, 2 and 3 and are assumed to be applicable to the sensitivity cases as well as the reference case.

6. DISCUSSION

The costs, as shown in Table 9-1, 9-2 and Figs. 1 to 3, are essentially proportional to new HDS capacity required. At the 0.05% wt sulphur level, there is a small economy of size effect where it is assumed that some 2000 t/cd units would be built instead of 1000 t/cd units, resulting in the following costs for EC-12 countries:

- Capital expenditure in the range of USD 2500 to 3800 million

- Total manufacturing costs including 25% capital charge in the range of USD 900 to 1400 million per year or USD 11 to 17 per ton diesel fuel

- Cost per ton sulphur removed in the range of USD 6000 to 9000.

Reporting costs per ton sulphur removed is meant to be indicative only, to allow comparison with other sulphur removal routes. Comparison of such costs between the cases is less meaningful since the various effects tend to mask each other.

In evaluating the overall results, it must be appreciated that the model used has represented EC-12 as four global refinery categories. While this is more realistic than assuming one global EC refinery, the large sizes of the individual categories still results in over-optimization which is difficult to assess. The attempt to quantify this effect by running country specific cases does take some account of the restricted area of action of an individual refinery.

Nevertheless some measure of the consequences have been calculated and accounting for over-optimization of the model would increase capital expenditure by USD 500 million and total manufacturing costs by USD 80 million per year or USD 1 per ton diesel fuel.

The study is based on a supply/demand situation deemed most likely to be valid for 1995. The differences between 1995 and 1987 are relatively small although for the particular study still significant, since there is an increasing demand for diesel fuel and a decreasing supply of low sulphur crude.

		1987	1995	2000
Diesel fuel demand	(10^6 t/yr)	70	78	88
Heating oil demand	(10^6 t/yr)	98	94	83
Low sulphur crude	(10^6 t/yr)	215	205	180

These trends are expected to continue in the same direction through year 2000 thus exacerbating industry expenditure due to reduced diesel fuel sulphur content.

The larger than proportional increase in new HDS capacity around and below the sulphur content of 0.10% wt level is due to the fact that at around this level a further reduction requires:

- The treatment of low sulphur feedstock
- The removal of sulphur compounds which are notoriously difficult to remove.

The 0.10% wt level is by no means a generally applicable break point. It is clear from the sensitivity runs that results are very dependent on a number of factors such as low sulphur crude percentage, and the ratio of existing HDS capacity to gas oil demand. These factors can vary significantly between countries and between refineries. A break-point in capacity requirement could therefore be below or above 0.10% wt sulphur depending upon circumstances.

This conclusion can also be drawn from diagrams (Figs. 1 to 3) where, based on sensitivity runs the shaded areas show the under-estimation at each sulphur level. Further, in line with expectations, increasing diesel fuel demand and/or decreasing low sulphur crude oil would increase the need even more for new high pressure HDS capacity.

An increased use of HDS capacity results in a direct increase in energy consumption and an indirect increase from hydrogen purification. Insofar as this energy in terms of gas and liquid fuel contains sulphur, there will be some additional refinery SO_2 and, of course, CO_2 emissions. These effects are shown in Table 12.

7. REFERENCES

1. Edgar, M.D. (1978) Hydrotreating compression focus pilot-plant study program. Oil & Gas Journal 76, 33, 102-106

2. McCulloch, D.C., Edgar, M.D., Pistorius, J.T. (1978) Higher severity HDT needed for low-sulfur diesel. Oil & Gas Journal 85, 15, 33-38

3. CONCAWE (1984) Desulphurization of gas oils. Report 11/84. The Hague: CONCAWE

4. CONCAWE (1986) Sulphur emissions from combustion of residual fuel oil based on EC energy demand and supply 1980 - 2000. Report 5/86. The Hague: CONCAWE

Table 1 Description of LP Model

1. Crudes and Feedstocks

In the model four crude types are used. Two are high-sulphur crudes: Arabian Light, Arabian Heavy; the two other are low sulphur crudes: Brent and Nigeria Forcados. Atmospheric residue import is of the Arabian Light type.

2. Units

- Crude Distillation
  - Crude cut points: LPG, naphtha FBP, kerosine FBP, middle distillate FBP (370°C)
- Vacuum Distillation
  - Vacuum gas oil: 370-565°C
- Catalytic Reformer
  - Feed cut points 70-160°C, severity 100 RON-0, high pressure (above 10 bar) and low pressure (below 10 bar) units, 80% of capacity are high-pressure units
- Hydrodesulphurization

  Category A : total reactor pressure below 30 bar
  Category B : total reactor pressure 30-60 bar
  Category C : total reactor pressure above 60 bar
- Catalytic Cracker
- Hydrocracker
- Visbreaker, Thermal Cracker
- Coker
- Alkylation
- Isomerization

3. Products

- LPG
- Light and Heavy Naphtha
- Jet Fuel
- Gasoline : RON 95, MON 85, unleaded (Eurograde)
- Diesel Fuel
- Heating Oil
- Fuel Oil : max. 40 cSt at 100°C,
max. 1.00 density at 15°C
- Coke

4. <u>Diesel Fuel and Heating Gas Oil Components</u>

- Kerosine
- Crude middle distillates
- Catalytic cracker middle distillates
- Visbreaker low sulphur middle distillates
- Visbreaker high sulphur middle distillates
- Thermal cracker vacuum gas oils
- Thermal cracker light gas oils
- Coker middle distillates
- Hydrocracker low sulphur middle distillates
- Hydrocracker high sulphur middle distillates
- Spare

Except for kerosine which is totally desulphurized, all components may be desulphurized at low, medium or high pressure.

Two gas oil properties are modelled: density and sulphur content.

5. <u>Hydrogen Balance</u>

Hydrogen balance was modelled - production, recovery, uses.

Table 2 LP Reference Case

SULPHUR LIMIT OF DIESEL FUEL AND HEATING OIL, % wt

CASE	NO.	DIESEL FUEL		HEATING OIL	
		TARGET	SPECS	TARGET	SPECS
26/26	1	0.24	0.26	0.24	0.26
20/26	2	0.18	0.20	0.24	0.26
15/26	3	0.13	0.15	0.24	0.26
10/26	4	0.09	0.10	0.24	0.26
05/26	5	0.04	0.05	0.24	0.26
26/20	6	0.24	0.26	0.18	0.20
20/20	7	0.18	0.20	0.18	0.20
15/20	8	0.13	0.15	0.18	0.20
10/20	9	0.09	0.10	0.18	0.20
05/20	10	0.04	0.05	0.18	0.20

Table 3 Product Specifications and Margins

	SPECIFICATION	BLENDING MARGIN	TARGET
GASOLINE			
RON	95 min	0.3	95.3
MON	85 min	0.5	85.5
VLI	1100 max	-	1100
DIESEL FUEL			
Sulphur, % wt	0.26 max	0.02	0.24
	0.20 max	0.02	0.18
	0.15 max	0.02	0.13
	0.10 max	0.01	0.09
	0.05 max	0.01	0.04
HEATING OIL			
Sulphur, % wt	0.26 max	0.02	0.24
	0.20 max	0.02	0.18
FUEL OIL			
Density	1.0 max	-	1.0
Visco @ 100°C, cSt	40 max	-	40
Sulphur, % wt			(a)

(a) Established at 2.8 based on crude slate

Table 4 Refinery Capacity

(All figures in million t/yr)

	Type 1 Hydrosk.	Type 2 VBU/TC	Type 3 HCC	Type 4 FCC	Total
Crude distillation (CDU)	37	81	85	384	587
Catalytic reformer (RFM)					
Pressure below 10 bar	0.4	0.9	3.6	10.0	14.9
Pressure above 10 bar	3.9	9.4	9.2	41.7	64.2
Total	4.3	10.3	12.8	51.7	79.1
Hydrodesulphurization					
Pressure below 30 bar	1.6	4.0	-	20.5	26.1
Pressure 30-60 bar	1.9	11.5	13.6	49.2	76.2
Pressure above 60 bar	0.6	1.4	1.4	7.1	10.5
Total	4.1	16.9	15.0	76.8	112.8
Isomerization (assumed)	0.4	2.1	1.5	3.3	7.3
Alkylation (assumed)	-	-	0.2	6.4	6.6
Conversion units					
Catalytic cracker (FCC)	-	-	2.6	85.4	88.0
Hydrocracker (HCC)	-	-	13.5	1.2	14.7
Thermal cracker (TC)	-	5.4	4.5	4.1	14.0
Visbreaker (VBU)	-	19.0	5.0	31.0	55.0
Coker (COK)	-	2.4	3.2	6.4	12.0

Table 5 Market Demand and Refinery Intake

(All figures in million t/yr)

	(a)(b) 1987	(a) 1990	(a) 1995	(c) 2000
Market Demand				
Gasoline	98	98	98	112
Kerosine	24	25	25	29
Diesel fuel	70	76	78	88
Heating oil	98	96	94	83
Bunker gas oil	7	7	7	7
Heavy fuel oil	72	72	70	59
Bunker fuel oil	22	22	22	24
Other products	81	80	78	80
Refinery fuel gas	19	19	19	20
Refinery liquid fuel	11	11	11	12
Total	502	506	502	514
Refinery Intake				
Low sulphur crude	215	215	205	180
Arabian light crude	)213	149	156	175
Arabian heavy crude	)	64	67	75
Feedstocks	44	44	45	50
Total	472	472	473	480
Product Deficit	30	34	29	34

(a) Data from COM (88) 491 Final, 23/09/88
(b) Included for reference purposes. Not used in the study
(c) Data from CONCAWE Report 5/86 (Ref. 4)

Note: 1) The surplus/deficit ex refinery for 1987 was as follows:

Surplus		Deficit	
Gasoline	5.6	LPG	5.5
Kerosine	6.0	Naphtha	9.8
Fuel Oil	3.5	Gas Oils	24.3
		Others	10.5

A similar pattern is forecast for the years 1990, 1995 and 2000.

2) It is assumed that diesel demand will be totally met by refineries and shortfalls in gas oils will be of heating oil quality.

Table 6 Costs of Proposed New 60 Bar HDS Unit

Location	Europe	
Year	1988	
Feedstock	Gas Oil/LCO (75/25%)	
Reactor pressure (bar)	60 - 80	
Rate of desulphurization (%)	95%	
Utilization ratio (%)	80	
Design capacity (t/cd)	1000	2000
Available capacity (t/cd)	800	1600
(Mt/yr)	0.292	0.584
Capex (USD x 10^6)		
Inside Plot	24.0	38.0
Outside Plot (20% inside plot)	4.8	7.6
Total	28.8	45.6
Capital Charge - 25% (USD x 10^6/yr)	7.2	11.4
Fixed Costs (USD x 10^6/yr)		
Manpower (7.5 man years)	0.30	0.30
Maintenance (2.5% capex)	0.72	1.14
Overheads (100% of manpower & maintenance)	1.02	1.44
Total	2.04	2.88
Variable Costs (USD x 10^6/yr)		
Catalyst (0.25 USD/t feed)	0.07	0.15
Energy (1.4% on intake, USD 100/t)	0.41	0.82
Hydrogen	(a)	(a)
Total	0.48	0.97
Total Manufacturing Costs(USD x 10^6/yr)	9.72	15.25
Unit Cost (USD/t gas oil) [(b)]	33.3	26.1

(a) Dependent on H_2 consumption and whether all-in or marginal costs are applicable.

(b) Based on 80% availability of capacity.

Table 7 Costs of Hydrogen Purification Plant

Design capacity (t/cd)	15.0
Utilization ratio (%)	80
Available capacity (t/cd)	12.0
(t/yr)	4380
Capex (USD x 10^6)	
Inside Plot	2.5
Outside Plot (20% inside plot)	0.5
Total	3.0
Capital Charge - 25% (USD x 10^6/yr)	0.75
Fixed Costs (USD x 10^6/yr)	
Manpower (0.6 man years)	0.025
Maintenance (2.5% capex)	0.075
Overheads (100% of manpower & maintenance)	0.10
Total	0.20
Variable Costs (USD x 10^6)	
Energy + Feed (2 t/t H_2)	0.09
Total Manufacturing Costs (USD x 10^6)	1.04
All-in Unit Costs (USD/t H_2) [(a)]	237 [(b)]

Note: (a) Unit costs are calculated based on 80% availability of capacity.

(b) The hydrogen produced is removed from the refinery fuel pool and has to be replaced by energy equivalent assumed to be 3 x USD 100 = 300 USD/t H_2 which has to be added to purification costs. Therefore, total cost of hydrogen via purification is 537 USD/t H_2.

TABLE 8-1

HDS AND HYDROGEN CAPACITY UTILIZATION TO MEET REDUCED DIESEL SULPHUR LIMITS

(HEATING OIL SULPHUR LIMIT AT 0.26% WT)

		ADDITIONAL CAPACITY ABOVE BASE CASE											
	0.26/0.26	0.26/0.20			0.26/0.15			0.26/0.10			0.26/0.05		
	BASE CASE	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B
HDS Capacity Utilization, 10^6 t/yr													
Existing :													
Less than 30 bar	25.8	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
30 - 60 bar	76.2	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
More than 60 bar	3.4	5.5	6.6	6.6	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
New :													
More than 60 bar	NIL	NIL	1.4	3.3	5.0	6.3	8.8	8.9	11.1	13.2	26.2	33.1	31.1
H_2 Purification Capacity Utilization, 10^3 t/yr	NIL	NIL	9	28	41	53	72	75	95	115	108	132	125
H_2 Recovery, %	65	65	66	67	68	69	71	71	73	75	74	76	76

NOTE : Ref. Case - See Table 2
Case A - Plus 12 Mt/yr diesel fuel
Case B - Minus 20 Mt/yr low sulphur crude

TABLE 8-2

HDS AND HYDROGEN CAPACITY UTILIZATION TO MEET REDUCED DIESEL SULPHUR LIMITS

(HEATING OIL SULPHUR LIMIT AT 0.20% WT)

		ADDITIONAL CAPACITY ABOVE BASE CASE											
	0.20/0.26	0.20/0.20			0.20/0.15			0.20/0.10			0.20/0.05		
	BASE CASE	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B
HDS Capacity Utilization, 10^6 t/yr													
Existing :													
Less than 30 bar	26.1	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	Min. 20.3	Min. 6.0
30 - 60 bar	76.2	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
More than 60 bar	8.9	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
New :													
More than 60 bar	NIL	5.8	5.8	8.1	10.8	11.6	14.3	14.8	16.1	19.5	30.5	46.3	36.5
H_2 Purification Capacity Utilization, 10^3 t/yr	NIL	49	49	71	93	100	124	130	142	169	146	219	170
H_2 Recovery, %	65	69	69	71	73	74	76	76	77	79	77	84	79

NOTE : Ref. Case - See Table 2
Case A - Plus 12 Mt/yr diesel fuel
Case B - Minus 20 Mt/yr low sulphur crude

TABLE 9-1

COSTS OF REDUCING DIESEL FUEL SULPHUR LIMIT

(HEATING OIL SULPHUR LIMIT AT 0.26% WT)

	0.26/0.20			0.26/0.15			0.26/0.10			0.26/0.05		
	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B
CAPEX ($ x 10^6)												
New HDS	Nil	144	317	490	634	864	893	1094	1296	2484	2870	2770
New H_2 Purification	Nil	6	18	27	33	48	51	63	78	75	96	90
TOTAL	Nil	150	335	517	667	912	944	1157	1374	2559	2966	2860
MANUFACTURING COSTS ($ x 10^6/yr)												
Existing HDS (a)	10	11	11	12	12	12	12	12	12	12	12	12
New HDS	Nil	49	107	165	214	292	301	369	437	837	964	931
New H_2 Purification	Nil	5	14	21	26	38	40	49	61	59	75	71
TOTAL	10	65	132	198	252	342	353	430	510	908	1051	1014
- $/t Diesel Fuel	0.1	0.7 0.8*	1.7	2.5	2.8 3.2*	4.4	4.5	4.8 5.5*	6.5	11.6	11.7 13.5*	13.0
- $/t S Removed	-	-	-	5100	4800	8800	5000	4900	7300	8300	7900	9300

NOTE : (a) Variable operating costs
Ref. Case - See Table 2
Case A - Plus 12 Mt/yr diesel fuel
Case B - Minus 20 Mt/yr low sulphur crude
Case * - Assuming 12 Mt/yr heating oil cannot be segregated

TABLE 9-2

COSTS OF REDUCING DIESEL FUEL SULPHUR LIMIT

(HEATING OIL SULPHUR LIMIT AT 0.20% WT)

	0.20/0.20			0.20/0.15			0.20/0.10			0.20/0.05		
	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B	REF. CASE	CASE A	CASE B
CAPEX ($ x 10^6)												
New HDS	576	576	806	1066	1152	1411	1469	1584	1930	2736	3660	3072
New H_2 Purification	33	33	45	63	69	84	90	99	117	99	150	117
TOTAL	604	609	851	1129	1221	1495	1559	1683	2047	2835	3810	3189
MANUFACTURING COSTS ($ x 10^6/yr)												
EXISTING HDS (a)	3	3	3	3	3	3	3	3	3	3	- 31	- 7
New HDS	194	194	272	360	389	476	496	535	651	920	1224	1031
New H_2 Purification	26	26	35	50	54	66	71	78	92	78	118	92
TOTAL	223	223	310	413	446	545	570	616	746	998	1311	1116
- $/t Diesel Fuel	2.8	2.5 2.8*	4.0	5.3	4.9 5.7*	7.0	7.3	6.8 7.9*	9.5	12.8	14.6 16.8*	14.3
- $/t S Removed	4700	4700	6600	4800	4800	6300	4900	4800	6400	6400	7600	7200

NOTE : (a) Variable operating costs

Ref. Case - See Table 2

Case A - Plus 12 Mt/yr diesel fuel

Case B - Minus 20 Mt/yr low sulphur crude

Case * - Assuming 12 Mt/yr heating oil cannot be segregated

TABLE 10

EFFECT OF EXTREME COUNTRY TYPE CONDITIONS ON NEW HDS AND NON-UTILIZED HDS CAPACITY

COUNTRY TYPE	A		B	
HDS CAPACITY, 10^6 T/YR	NEW	NON-UTILIZED	NEW	NON-UTILIZED
HEATING OIL - 0.26% WT S				
DIESEL FUEL, % WT S				
0.20	3.3	4.2	0.6	5.0
0.15	4.1	4.2	0.7	3.5
0.10	4.8	6.0	0.8	2.6
0.05	11.6	9.0	0.9	1.5
HEATING OIL - 0.20% WT S				
DIESEL FUEL, % WT S				
0.20	4.3	4.4	0.8	3.0
0.15	5.4	4.2	1.3	1.9
0.10	11.6	8.5	1.9	0.9
0.05	13.0	9.7	2.3	NIL

NOTE : Country Type A - Low HDS Capacity and Low % Low Sulphur Crude
Country Type B - High HDS Capacity and High % Low Sulphur Crude

TABLE 11-1

ASSESSMENT OF POSSIBLE UNDER-ESTIMATION OF REQUIRED NEW HDS CAPACITY TO REDUCE DIESEL FUEL SULPHUR LIMIT

CAPACITY, 10^6 T/YR	NON-UTILIZED HDS, COUNTRY TYPE A + B	EQUIVALENT NEW HIGH PRESSURE HDS (a)	NON-UTILIZED HDS, EC-12 MODEL OPTIMIZED	ASSESSED UNDER-ESTIMATION OF NEW HDS
HEATING OIL - 0.26% WT S				
DIESEL FUEL, % WT S				
0.20	9.2	7.6	1.6	6.0
0.15	7.7	6.3	NIL	6.3
0.10	8.6	7.0	NIL	7.0
0.05	10.5	8.4	NIL	8.4
HEATING OIL - 0.20% WT S				
DIESEL FUEL, % WT S				
0.20	7.4	6.1	NIL	6.1
0.15	6.1	5.2	NIL	5.2
0.10	9.4	7.6	NIL	7.6
0.05	9.7	7.8	NIL	7.8

(a) : 1 ton low pressure HDS capacity equivalent to 0.74 t high pressure HDS capacity
1 ton medium pressure HDS capacity equivalent to 0.89 t high pressure HDS capacity

TABLE 11-2

ASSESSMENT OF POSSIBLE UNDER-ESTIMATION OF COSTS TO REDUCE DIESEL FUEL SULPHUR LIMIT

NEW HDS + H_2 PURIFICATION	CAPEX $\$ \times 10^6$	MANUFACTURING COSTS	
		$\$ \times 10^6$ /YR (c)	$/T DIESEL
HEATING OIL - 0.26% WT S			
DIESEL FUEL, % WT S			
0.20 (b)	638	146	1.9
0.15 (b)	669	167	2.1
0.10 (b)	730	180	2.3
0.05 (a)	485	80	1.0
HEATING OIL - 0.20% WT S			
DIESEL FUEL, % WT S			
0.20 (b)	640	160	2.0
0.15 (b)	549	139	1.8
0.10 (b)	795	198	2.5
0.05 (a)	470	82	1.1

NOTE :
(a) Costs are benefited by assumption that additional capacity is in terms of 2000 t/cd HDS units replacing 1000 t/cd units in the reference case.
(b) Costs are based on additional 1000 t/cd HDS units.
(c) It has been assumed that fixed and variable costs of existing LP/MP HDS which is not utilized are not incurred.

TABLE 12

SULPHUR REMOVED, ENERGY CONSUMPTION AND RESULTING SULPHUR DIOXIDE AND CARBON MONOXIDE EMISSIONS IN REFINERIES

	S REMOVED ABOVE REF. CASE (1000 T/YR)	ENERGY ABOVE REF. CASE (1000 T/YR)	RESULTING (a) SO_2 EMISSION (1000 T/YR)	RESULTING (b) CO_2 EMISSION (1000 T/YR)
HEATING OIL - 0.26% WT S				
DIESEL FUEL, % WT S				
0.20	-	-	-	-
0.15	39	256	5	750
0.10	70	447	9	1320
0.05	109	821	16	2420
HEATING OIL - 0.20% WT S				
DIESEL FUEL, % WT S				
0.20	47	300	6	880
0.15	86	546	11	1610
0.10	117	750	15	2210
0.05	156	1035	21	3050

NOTE : (a) - Sulphur content of energy assumed at 1%
(b) - CO_2 emission factor assumed at 2.95

Figure 1

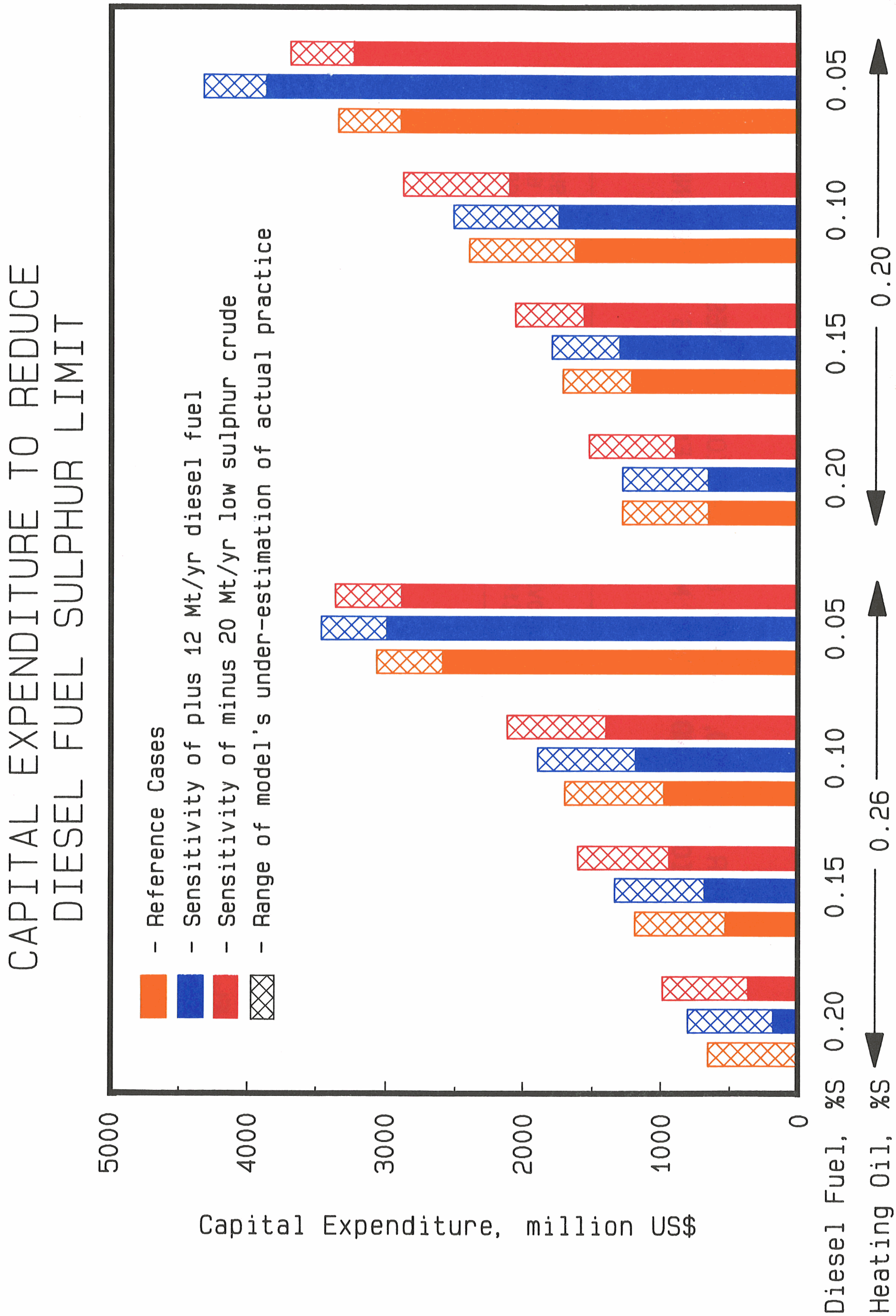
CAPITAL EXPENDITURE TO REDUCE
DIESEL FUEL SULPHUR LIMIT
- Reference Cases
- Sensitivity of plus 12 Mt/yr diesel fuel
- Sensitivity of minus 20 Mt/yr low sulphur crude
- Range of model's under-estimation of actual practice
Capital Expenditure, million US$
5000
4000
3000
2000
1000
0
Diesel Fuel, %S
0.20
0.15
0.10
0.05
0.20
0.15
0.10
0.05
Heating Oil, %S
0.26
0.20

Figure 2

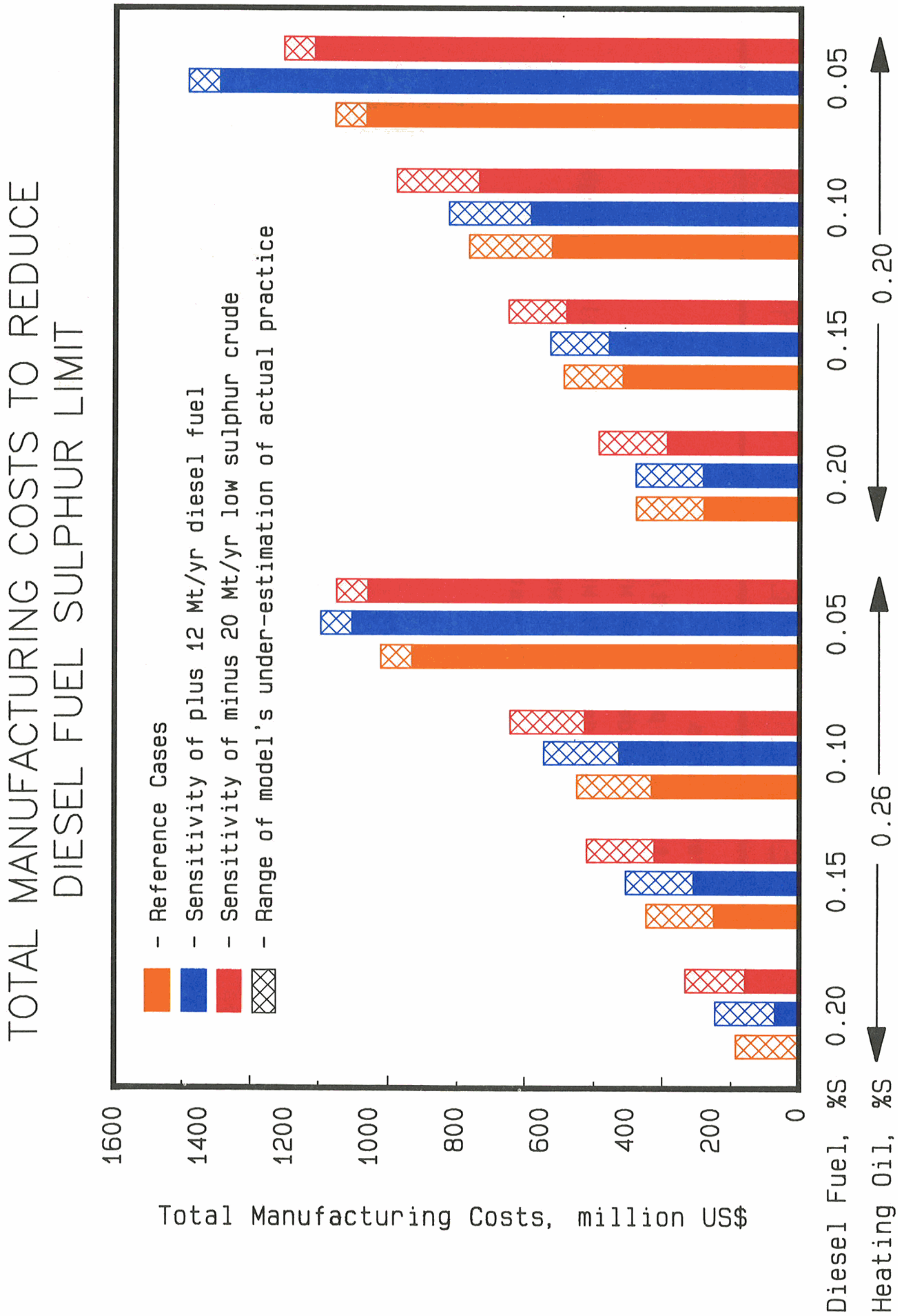
TOTAL MANUFACTURING COSTS TO REDUCE
DIESEL FUEL SULPHUR LIMIT
- Reference Cases
- Sensitivity of plus 12 Mt/yr diesel fuel
- Sensitivity of minus 20 Mt/yr low sulphur crude
- Range of model's under-estimation of actual practice
Total Manufacturing Costs, million US$
1600
1400
1200
1000
800
600
400
200
0
Diesel Fuel, %S
0.20
0.15
0.10
0.05
0.20
0.15
0.10
0.05
Heating Oil, %S
0.26
0.20

Figure 3

TOTAL MANUFACTURING COSTS PER TON DIESEL FUEL TO REDUCE DIESEL FUEL SULPHUR LIMIT