economic consequences of limiting benzene/aromatics in gasoline

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ABSTRACT

This report records the economic consequences to four different types of refineries in Europe if the benzene content of gasoline is required to be limited to 3% vol or 1% vol. The consequences of also setting limits on aromatics content are also investigated. The study utilized refining planning computer models optimized by linear programming techniques.

European gasoline currently contains on average 2.6% vol benzene and 34% vol aromatics. These levels would increase to 3.2% vol and 43% vol, respectively, if all gasoline were to be supplied as 95 octane unleaded grade; depending on individual refinery configuration, the production would range from 2.3 to 5% vol benzene and 35 to 56% vol aromatics, with the highest levels resulting from simple refineries (hydroskimming/thermal cracking) processing Brent-type crude oils. The levels also depend on the amount of oxygenates and isomerization capacity available.

A restriction of benzene in gasoline to 3% vol would mainly affect the simple refineries (still representing 40% of the number of refineries and 20% of the capacity in EC), which would need benezene extraction facilities, and isomerization capacity if not already installed. The investment for the refining sector in EC would be USD 1100 million. The manufacturing cost increase would range from a minor increase for complex refineries (catcracking/hydrocracking/coking) up to USD 10-12/ton gasoline for simple refineries.

Further reduction of benzene below 3% vol would need benzene extraction facilities also in complex refineries. A 1% vol benzene limit would require an investment of USD 1750 million in EC. The manufacturing cost increase would go up to USD 8-12/ton for complex refineries and to USD 16-20/ton gasoline for simple refineries.

About 2 million t/yr of benzene would have to be extracted and disposed of in a European market of 5 million t/yr, as a result of a 1% vol benzene limit.

The aromatic content of gasoline from simple refineries could only be reduced by some 5 percentage points through the additional use of oxygenates and isomerization, resulting in average aromatics levels still exceeding 40% vol. Further aromatics reduction in simple refineries would result in yield losses of up to half or more of the gasoline production. Complex refineries could achieve aromatics levels generally in the range of 30 to 35% vol through the wide use of oxygenates as well as additional isomerization.

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SUMMARY

Following the phasing out of lead from gasoline, continuing environmental and health concerns have led some countries to focus attention on the hydrocarbon composition of gasoline; specifically, further reduction of the benzene content and a limitation of the total aromatics content are being discussed.

A study group was set up by CONCAWE to investigate the technical and economic consequences for the EC refining industry of reducing benzene and aromatics in gasoline. The study addressed the cost and feasibility of meeting various combinations of specifications for four different refinery configurations, representing the EC situation. The cost for the refining industry were calculated on the basis of the EC-12 low demand scenario developed by the EC Commission. The reported cost would have been higher, if the study had been based on the EC Commission's high demand scenario.

Other CONCAWE study groups are investigating alternative ways to reduce overall gasoline emissions, including benzene and aromatics, in order to establish the most cost-effective solutions for reducing emissions. These alternatives involve a closing of the gasoline system by using vapour recovery techniques to control evaporative losses from the distribution and use of gasoline.

European gasoline currently contains on average 2.6% vol benzene and 34% vol aromatics. It is calculated that these levels would increase to 3.2% vol and 43% vol, respectively, if all gasoline were to be supplied as 95 octane unleaded grade. Depending on individual refinery configurations, the production would range from 2.3 to 5% vol benzene, and 35 to 56% vol aromatics, with the highest levels resulting from simple refineries (hydroskimming/thermal cracking) processing Brent-type crude oils.

A benzene limit of 3% vol in gasoline would have the greatest impact on simple refineries (still representing 40% of the number of refineries and 20% of the capacity in EC), which would need benzene extraction facilities, as well as additional isomerization capacity where this would limit the extent of benzene extraction required. The investment for the refining sector in the EC, would be USD 1100 million. The manufacturing cost increase would range from USD 10-12/ton gasoline for simple refineries to a much smaller increase for complex refineries (catcracking/hydrocracking/ coking) for the cases studied. Use of oxygenates, as an alternative to benzene extraction in simple refineries, would create problems with naphtha surplus, making the economics worse.

Further reduction of benzene below 3% vol would need installation of additional isomerization and benzene extraction facilities also in complex refineries. A 1% vol benzene limit would require an

investment of USD 1750 million for the EC refining industry. The manufacturing cost increase would go up to USD 16-20/ton gasoline for simple refineries and to USD 8-12/ton for complex refineries.

The amount of benzene necessary to extract as a result of a 1% vol benzene limit would be about 2 million t/yr, to be disposed of in a European market of 5 million t/yr. The impact on the petrochemical industry is presently the subject of a separate study by the CEFIC Aromatic Sector Group. A full assessment of the economic consequences of a reduction of benzene in gasoline should take into account both the CONCAWE and CEFIC studies.

The aromatic content of gasoline from simple refineries could only be reduced by some 5 percentage points through the use of oxygenates and isomerization, resulting in average aromatics levels still exceeding 40% vol. Further aromatics reduction in simple refineries would result in large surpluses of naphtha and high losses in gasoline yield. Complex refineries could achieve aromatics levels generally in the range of 30 to 35% vol through the wide use of oxygenates; the economic penalty would be around USD 7-17/ton gasoline depending on whether the benzene content would have to be limited as well.

The energy penalty resulting from a reduction of the gasoline benzene content has not been evaluated in this study. However, calculations made by one CONCAWE member company indicate a significant increase in crude oil demand to meet a gasoline benzene limit of 1%. Additional work is underway to quantify this energy debit.

The supply of gasoline in the Atlantic basin has tightened because of the growing demand for unleaded gasoline in Europe and the reduction of gasoline vapour pressure limits in the USA. A further loss in octane manufacturing capability through reduced benzene/aromatics levels would not only result in significantly higher manufacturing costs, but could constrain supplies.

1. INTRODUCTION

1.1 BACKGROUND

The increasing production of unleaded gasoline in a number of European countries, due to the implementation of EC Directive 85/210 (see Section 1.3), has already changed refinery process and blending operations. The typical European premium gasoline will, in future, require a different balance of components to meet the necessary octane quality. This will lead to increased benzene and aromatics contents in motor gasoline. The effects on health of exposure to these compounds from motor gasoline are a matter of discussion and concern in some EC countries. The health effects of exposure to benzene are covered in CONCAWE Report No. 8/89.

This report summarizes the results of a CONCAWE study into the effects of refining changes, and discusses the available processing options and the associated costs to cope with lower levels of both benzene and aromatics in gasoline marketed within the EC-12 countries.

The implications for the European oil and chemical industries of a benzene/aromatics reduction in gasoline should be taken into account in assessing the cost-effectiveness of other alternative options for reducing benzene emissions to the atmosphere. Parallel CONCAWE studies on Stage I/Stage II systems for terminals and service stations, and on-board carbon canisters and exhaust catalysts for vehicles will provide the necessary information to identify the options which can control benzene/aromatics emissions at the lowest possible cost to the consumer and with a minimum energy penalty.

1.2 RELATIONSHIP WITH PREVIOUS CONCAWE REPORT

An earlier CONCAWE Report No. 84/57 - "Consequences of limiting the Benzene Content of Gasoline" (1), has already dealt with the cost to the refining industry of reducing benzene levels in gasoline. However, a number of changes have occurred which prompted a further review of the subject.

- changes to processing configurations
- process development outlook
- availability of oxygenates
- crude oil prices
- product demand pattern
- unleaded gasoline specifications
- concerns about total aromatics content of gasoline

Particular attention has been paid to defining typical European refinery configurations, and an overall EC picture has been obtained by aggregating the specific configurations, rather than by modelling a single average refining operation.

1.3 CURRENT RELEVANT LEGISLATION

The EC Directive 85/210, which requires the introduction of unleaded gasoline, specifies a maximum benzene content of 5% vol for all gasolines from October 1, 1989. This limit has already been widely introduced into many national specifications (2). The Directive also requires that "Reduction or elimination of lead must not have the effect of significantly increasing other pollutants contained in the exhaust gases of motor vehicles as a consequence of modifications in the composition of petrol".

The use of oxygenates as blending components in gasoline is covered by EC Directive 85/536, which specifies the maximum level for each type of oxygenate which member states must permit (column A of the appropriate technical annex) and the maximum level which can be permitted by local legislation without the need for marking of the pumps at filling stations (column B of the same annex). These requirements are shown in detail in Appendix 1 Table 5.

1.4 CURRENT BENZENE AND AROMATICS CONTENTS OF EUROPEAN MOTOR GASOLINES

Comprehensive information was collected for each European country in order to assess benzene and aromatics contents of the gasoline grades which are presently marketed. Table 1 summarizes the evidence obtained by analyzing and grouping more than 1900 sets of analytical data for 16 countries.

The survey shows:

- Current benzene and total aromatics contents vary widely, even within a given grade of gasoline.

- For example, lowest and highest reported benzene contents of leaded Premium differ by 8% vol while the spread on aromatics in leaded regular is 44%. These ranges are caused by local factors like process configuration, oxygenates utilization, exchange of blendstocks and specific circumstances of the day-by-day operations.

- Weight-averaging of the results on the basis of the estimated 1987 gasoline market grade ratios indicates that the present gasoline pool has an average benzene content of about 2.6% vol, and an aromatics content of about 34% vol.

- The unleaded Premium gasoline at 95 RON/85 MON presently has benzene and aromatics contents of about 3.3 and 41% vol respectively; these figures do not differ too much from the study estimates (3.2 and 43% vol, see Section 3.2.1) if it is duly taken into account that the 1986 production was rather low and allowed for a flexible selection of the blending components.

Based on this analysis the future unleaded Eurograde pool would therefore be characterized by an average increase in benzene contents of about 0.6-0.7% vol and in aromatics contents of some 7 to 9% vol. It should be noted that marketing of a "Super-plus" (98/88) unleaded grade (which has not been considered in this study) would likely lead to further increases in the cost of controlling benzene and aromatics contents in the European gasoline pool.

The accuracy of these predictions depends on various influencing factors like:

- future process development;
- product demand structure;
- number of unleaded gasoline grades (e.g. wider use of "Super-plus");
- oxygenates availability;
- evolution of local or EC gasoline specifications;
- market trends for crude and product prices.

The present study is based on specific assumptions for the above reported variables.

2. METHODOLOGY

2.1 OVERALL APPROACH

Gasoline benzene content is critically dependent upon the quality of the refinery feedstock, the processing configuration, and the way in which the facilities are operated, e.g. cut points of intermediate feed streams and blendstocks, reformer operating severity, etc. required to meet demand pattern on the refinery. It was apparent at the start of this study that the usual approach of modelling the average European refinery operation would not give a true representation of the high cost burden encountered by the simple refineries. Hence, CONCAWE decided to base its study on individual refinery configurations and to aggregate results into a European industry average. Details of this approach are summarized in the following section.

Each refinery configuration was computer modelled and economically optimized using linear programming techniques. Cases studied covered a range of feedstock qualities, and a range of potential gasoline benzene and aromatics specifications, as discussed below. The results are discussed in Section 3.

2.2 BASIS FOR MODELLING EUROPEAN REFINING

2.2.1 Individual Refinery Configurations

European refineries were divided into four categories based on equipment complexity, and the results are summarized in Tables 7 to 23 of Appendix 3. Configurations selected were:

(i) hydroskimming, i.e. no conversion facilities (hydroskimming refineries)
(ii) visbreaking/thermal cracking (thermal conversion refineries)
(iii) catcracking/hydrocracking (complex I conversion refineries)
(iv) catcracking/hydrocracking/coking/alkylation (complex II conversion refineries)

In the following, category (i) and (ii) and category (iii) and (iv) are sometimes grouped together and called simple and complex refineries, respectively.

For the purpose of investigating refinery configurations, the operations were each based on 100 kB/SD of crude, with sufficient reforming capacity, as appropriate, to process the available feedstock.

Each type of refinery configuration was modelled with two extreme feedstocks (see Section 2.2.2), with and without naphtha isomerization capacity and at various benzene and aromatics levels (Section 2.3.2). The results from the individual configurations were combined and scaled up to provide a total EC-12 picture. For this purpose, the capacity of each refinery type was used to get the appropriate contribution to total gasoline production, and the contribution was used as a multiplier to aggregate the individual configurations into a European industry average.

It was assumed that 45% of the naphtha reforming capacity operates at low pressure, with a resulting higher reformate yield, and the balance representing older units operating at higher pressures. These assumptions are consistent with CONCAWE Report No. 84/57 (1). Light cracked naphtha (LCN) splitting and reforming was used as required to upgrade the pool octane level. The catcracking units were assumed to accept up to 30% low sulphur atmospheric residue.

It was further assumed that approximately 5 Mt/yr of light naphtha isomerization capacity (recycle type) will be available in the late 1990s, located at simple as well as complex refineries. In evaluating the scope for reducing benzene and aromatics levels, it was necessary to assume future expansion of this capacity: at the simple refineries the capacity will be required to avoid excessive naphtha surplus and unacceptable loss of gasoline production, whilst in complex configurations additional capacity will be required to meet low benzene contents by diluting the gasoline pool. It was assumed that 40% of complex refineries and all of the hydroskimming and thermal conversion refineries will make use of isomerization. Sensitivity cases assuming full availability of isomerization units at all of the EC-12 refineries were also considered (see Tables 24 and 25 of Appendix 3). Costs of the new isomerization capacity were included in the economic calculations.

2.2.2 Refinery Demands and Feedstock

The estimated refinery product demands for the year 2000 are summarized below, with the corresponding feedstock requirements. These data have also been used in other previous CONCAWE reports. In this study the EC-12 low demand estimate developed by the EC Commission has been used but with one exception: the light naphtha demand was increased above the level shown below (1 Mt/yr) as it was not possible to absorb all the naphtha in gasoline. Instead, 6 to 11 Mt/yr of light naphtha demand was assumed which is considered consistent with potential future chemical feedstock requirements.

Note: Total costs for reducing benzene and aromatics contents in gasoline on the basis of the EC-12 high demand scenario (3) would exceed those given later in this study.

Crude slates were selected to reflect the range of feed sources experienced across Europe, i.e. mainly North Sea crudes in Scandinavia and the North-West, and significant proportions of Arabian crudes in the Mediterranean area. The distinction is important, since reformer feedstocks derived from Brent contain significantly higher proportions of benzene precursors than most other crudes commonly processed in Europe, especially those from the Middle East area. The typical range was reflected by using two representative crude slates - 20% Brent/80% Arabian Light, and 80% Brent/20% Arabian Light (All figures in % vol).

To provide a total EC-12 picture the results of the individual configurations were aggregated by maintaining the high sulphur/low sulphur crude feed ratio predicted for the EC-12 (see Table below).

Refinery Demands and Feedstock (3)

Units: Mt/yr

Demands:	
LPG	17
Naphtha	1
Gasoline	89
Kerosine	22
Gasoil/Diesel	119
Inland Fuel Oil	52
Bunker Fuel Oil	11
Lube Oil	6
Bitumen	11
Coke	4
Refinery Fuel and Loss	25
TOTAL	357
Feedstocks:	
Crude Oil - Low Sulphur	143
- Medium Sulphur	132
- High Sulphur	57
Atmospheric Residue	25
TOTAL	357

2.2.3 Crude and Product Pricing Basis

Typical product prices in 1987 and a corresponding Arab. Light marker price of around 18 $/Bbl have been used in assessing future years economics. The assumed prices are shown below:

Crude and Product Price Basis (1987 money)

Arabian Light Crude	18 USD/Bbl
LPG	135 USD/ton
LDF (Light Distillate Fuel)	165 USD/ton
Premium Gasoline	190 USD/ton
Jet/Kerosine	175 USD/ton
Gasoil/Diesel	160 USD/ton
Fuel Oil	100 USD/ton
LS Fuel Oil	110 USD/ton
MTBE	247 USD/ton
Benzene	213 USD/ton

Economic sensitivity calculations were carried out for various price differentials in order to test the conclusions in critical situations. For example, the conclusions were checked against lower LDF prices (naphtha/mogas differentials of 35 and 45, in addition to 25 USD/ton) of any naphtha surplus with respect to the base case production.

The quoted MTBE price corresponds to an oxygenate/mogas price ratio of 1.3. However, since the MTBE demand could reach or exceed the predicted availability of 2.8 Mt/yr in the mid 1990s (see Appendix 2), the economics were also checked against a 1.5 price ratio. It is, however, also recognized that MTBE production is increasing, and new butane feedstock sources and new plants at complex refineries could boost availability significantly. Alternative oxygenates were not evaluated, for the reasons discussed in Section 2.3.3.

The benzene price shown above is 12% above that of premium gasoline which is an average between current price and a minimum level based on heating value. As a sensitivity case, a price of 0.53 times that of gasoline was used for the heating value of benzene, a situation where the market would become saturated (no alternative sales outlet available) or additional costs would have to be borne by refiners for additional processing to saleable petrochemical derivatives of benzene.

2.3 GASOLINE QUALITY & BLENDING BASIS

2.3.1 General Quality Specifications

All gasoline has been blended to a single unleaded specification of 95 RON/85 MON, assumed to represent the long-term European gasoline production. This grade is similar in composition to and meets the general quality requirements of the typical 98 RON, 0.15 g/l leaded Premium grade currently produced in many countries.

A low octane (91 RON) unleaded grade has not been included, since it is expected to represent only a small proportion of the future European gasoline pool. "Super plus" (98 RON) unleaded gasoline has been introduced in some European countries but this new development was too recent to be covered by this study. It is apparent, however, that the cost and the energy penalty for any reduction of the benzene and aromatics content in the EC-12 gasoline pool would further increase once "Super plus" gains a significant market share.

The following critical product quality limits were assumed:

Gasoline

Octane - 95 RON, 85 MON minimum at zero lead, with no front end octane quality requirement.

Volatility - Vapour Lock Index (VLI): maximum 1100 with no separate RVP or E_{70} limit.
VLI = RVP (millibars) + $7E_{70}$ (% evaporated at 70°C)

Distillation - E_{100} (% evaporated at 100°C): 45% to 70%
FBP (Final Boiling Point): max. 215°C

Density (15°C): 0.73 to 0.78 g/ml

Middle Distillates

Sulphur : Maximum 0.2% wt

Cetane : Not constrained, as not critical in this study

Fuel Oils

Sulphur : Maximum 2.5% wt for inland sales, maximum 4.0% wt for bunkers

Viscosity : Maximum 40 cS at 100°C for all grades.

2.3.2 Benzene & Aromatics Limitations

A number of benzene and aromatics reductions from current levels were considered in various combinations to cover the proposals under discussion in some EC countries and to determine the associated costs. Current gasoline production contains 0.3-8.6% vol benzene (averaging about 2.6%), and 14-58% vol aromatics (averaging 34%), as discussed in Section 1.4 and detailed in Table 1.

In order to achieve a reasonable balance between the time and effort required for the study and the amount of information obtainable from the results, the number of cases investigated was originally limited to:

Base Current operation with no limitations

(i) Maximum 5% vol benzene and no aromatics limit (the same as the base case for most refineries).

(ii) Maximum 3% vol benzene and no aromatics limit.

(iii) Maximum 3% vol benzene and 30% vol aromatics.

(iv) Maximum 1% vol benzene and no aromatics limit.

(v) Maximum 1% vol benzene and 30% vol aromatics.

When it became evident that most of the refinery configurations will not be able to achieve an aromatics reduction to 30% vol under the normal range of operational constraints, restrictions of max. 35 and max. 40% vol aromatics were also investigated and reported. Some of these results were determined by interpolation between the cases described above.

2.3.3 Use of Oxygenates

Several oxygenates are available for use as gasoline octane-enhancers, including MTBE, GTBA, Oxinol, etc. However, estimates of future oxygenate availability by the European Fuels Oxygenates Association (EFOA) and others (see Section 2.2.3 and Appendix 2), suggest that MTBE will be the major oxygenate compound in the future. This is supported by press announcements of planned constructions of new MTBE production plants and the conversion of some existing GTBA plants into MTBE production facilities.

In order to simplify the refinery modelling exercise, MTBE was selected to represent all oxygenates (Section 4.5). In the modelling of the various refinery configurations, MTBE was used as economically required in the optimized pool up to the EC "A" limit of 10% vol.

2.4 METHODS FOR REDUCING BENZENE & AROMATICS

2.4.1 Reformer Feed Initial Cut Point

The most effective method of reducing reformate benzene content is by increasing the reformer feed initial boiling point (IBP).

For example, an increase in IBP to 95°C would remove almost all of the benzene precursors. However, a number of problems would result:

- Reformer feed availability would be significantly reduced. This could be offset at least to some extent by increasing the final boiling point (FBP) of the feed, although this would increase the coking tendency of the feed, shorten the reformer cycle length, and reduce capacity.

- The straight-run gasoline fraction (LDF) would be heavier, changing chemicals feedstock quality and causing operational problems in steamcrackers.

- The proportion of straight-run material in the gasoline pool would increase, causing a reduction in pool octane quality which could not be readily offset by a higher amount of reformate due to the feed shortage referred to above.

This last effect is of particular importance, and refiners have two possible though costly methods for dealing with the problem:

- Increase production of chemical feedstock and rebalance octane quality by using higher reformer severities (if feasible) or by reformate or gasoline imports. This will lead to a significant cost penalty, as referred to in Section 4.1.

- Split the straight-run gasoline into a light C5/C6 stream, which could be isomerized prior to gasoline blending (see below), and a heavier fraction for direct blending.

Study cases were based on a 66°C cut point, assumed to be typical for a refinery operating an isomerization plant. Some refineries will operate at higher IBPs but the majority is likely to be below the range were a noticeable effect on reformate benzene levels occurs. Thus the chosen IBP was not seen as resulting in a significantly higher benzene level than that experienced at a typical European refinery.

2.4.2 Isomerate Dilution

Light naphtha isomerization increases both the Research and Motor Octane Numbers of the LDF stream. Moreover, introduction of isomerate into the gasoline pool reduces benzene and aromatics levels by the following mechanisms:

- Any increase in the octane level of the straight-run portion of the pool permits a reduction in reformer severity and/or in the percentage of reformate in the finished gasoline

- Addition of a new aromatics-free component to the gasoline reduces the benzene and aromatic concentrations in the gasoline

Appendix 4 contains details of the capital investment and operating costs of grass-roots naphtha isomerization units based on 1987 costs. A scaling factor of 0.6 was used to adjust the capital costs for different unit sizes. The operating cost calculation assumes an on-stream time of 8000 hours/yr, and a utilization factor of 89%.

Further details on the isomerization process and the blending behaviour of isomerate are discussed in Section 4.2.

2.4.3 Addition of MTBE

MTBE addition lowers aromatics levels in gasoline by partially replacing the reformate (the major high-octane component in gasoline) thereby allowing a reduction of the quantity of reformate in the gasoline pool and/or a lower severity reformer operation.

MTBE was assumed to be representative of the various oxygenates which are used in gasolines, for the reasons summarized in Section 2.3.3 and discussed in Section 4.5.

2.4.4 Debenzenization of Reformate

The method selected for reducing the benzene level of gasoline is direct extraction. Straight distillation alone, or the combination of solvent extraction and rich solvent distillation, would have the disadvantages of a limited selectivity. Extractive distillation would require a predistillation step to obtain a selected cut and a final distillation of the rich solvent, while the raffinate stream would still have a relatively high benzene content; moreover, it would be economically attractive only at high benzene concentrations in the feed. Overall, it is considered that solvent extraction of the benzene and other aromatics, followed by extractive distillation of the enriched solvent to separate the remaining non-aromatics, and a final distillation for aromatics recovery, would be the optimum combination of processes most likely to be applied in European refineries.

It is realized that further technological developments could offer potentially attractive alternatives which in combination with other petrochemical processes could produce saleable benzene derivatives, even at the refinery location, from the benzene which cannot be contained in the gasoline pool.

Nevertheless, the selected process scheme is considered to be representative for the purposes of this study of the future impact of a benzene restriction on refinery operations and economics.

Appendices 5 and 6 include a schematic process diagram and stream balances for the extraction of benzene from reformate, as well as the basic investment and operating costs. The scaling and utilization assumptions are similar to those summarized in Section 2.4.2 for the isomerization process.

3. RESULTS

3.1 INDIVIDUAL REFINERY CONFIGURATIONS

Summarized below (Section 3.1) are the results of the computer modelling studies which are tabulated in detail in Tables 7 to 23 of Appendix 3. Key conclusions for the selected benzene/aromatics scenarios are given in summary tables at the end of individual sections. It should be noted that the total costs in these tables do not consider possible MTBE, LDF and benzene market price variations from the base prices assumed in Section 2.2.3. Results on simple refineries and complex II refineries have been chosen to cover the extreme scenarios.

3.1.1 Meeting the unleaded Eurograde gasoline specifications

Once the unleaded Eurograde (assumed at 95 RON/85 MON - see Section 2.3.1) has achieved complete market penetration and replaced all of the other gasoline grades according to the assumptions of this study, yields and properties of gasoline produced by individual refineries will still vary widely in view of different process configurations; this applies particularly to benzene and aromatics contents.

Hydroskimming and thermal conversion refineries, which presently still represent some 40% of the number of EC refineries, would probably produce levels of 5% vol benzene and up to 56% vol aromatics respectively if mainly fed with Brent-type crudes and not equipped with light ends isomerization facilities; at the other extreme levels of 2.3% vol benzene and 35% vol aromatics should be attainable at the complex II refineries with isomerization facilities and Ar.Light-type crudes (see Table 2).

Isomerization, if available at all the refineries, could significantly contribute to reduce the expected levels of benzene and aromatics contents and to avoid losses of gasoline yield due to the naphtha surplus. Simple refinery configurations would benefit most, with benzene content reductions by some 0.7 - 1.4% vol and aromatics content being kept below 50% vol (see Table 2).

The effect would decrease at complex refineries: benzene reduction could range from 0.2% vol to 1.1% vol depending on crude type, aromatics could be reduced by about 4 - 5% vol. Details are reported in Table 2 and in Table 7 of Appendix 3.

Blending oxygenates to the gasoline pool would mainly help to reduce the aromatics content with minor effects on benzene; specific results would however depend on the oxygenate type/blending properties as well as on actual availabilities and allowed concentrations (see Appendix 1). Adding other oxygenates in addition to MTBE could actually lead to a further reduction in aromatics contents. The best results would in theory be obtained if oxygenates could be selectively utilized at the most critical locations, like in simple refineries mainly fed with naphthenic crudes. Benefits resulting from MTBE addition can be reasonably scaled up to identify the maximum aromatics reduction of any feasible alternative (see Section 4.5).

Larger benzene reductions than those predicted could occur at those refineries which might be able to operate at high reformer feed IBP and to market the large naphtha surplus at an economical price. The reported range of expected benzene concentrations is likely to cover such local occurrences.

Relevant information from Table 2 is summarized in the following Table.

Effect of Isomerization on Benzene/Aromatics Contents - No Oxygenate Addition

	Simple Refineries Isomerization:		Complex II Refineries Isomerization:	
	With	Without	With	Without
Benzene Cont. % vol	2.6-4.2	3.6-5.1	2.3-2.4	2.6-3.5
Aromat. Cont.	44-47	51-56	35-37	39-42

3.1.2 Meeting 3% vol benzene content

This target could be met by all process configurations if paraffinic crudes were prevailing in the feed and simple refineries were sufficiently equipped with isomerization facilities (see Table 2 and Table 7 of Appendix 3). Isomerization would also provide complex II configurations with the opportunity of improving gasoline yields and reducing aromatics content by about 4% vol. Difficulties would however arise at both hydroskimming and thermal conversion refineries which manufacture reformer feed mainly from naphthenic crudes (higher benzene precursors content), as in the case of Northern European refineries using Brent-type crudes.

Complex refineries would have minor or no problems in achieving the desired gasoline quality at 3% vol benzene without any oxygenates addition but could need isomerization to meet required gasoline yields.

Among the available options for meeting the benzene 3% target with both selected crude slates with an adequate safety margin (see Appendix 3 - Table 9 and 11), simple refineries would have to choose whether to make use of oxygenates or to extract benzene from reformates, as other ways would cause a high loss in gasoline production. Benzene extraction would in this case be a marginally less costly option and would not imply the need to rely on a very large oxygenates availability.

Relevant information from Tables 7, 9, 11, 16, 17 of Appendix 3 for the 3% benzene case is summarized below (Note: indicated ranges are mainly due to different crude slates).

Process Options and Costs for Meeting 3% vol Benzene Content

	Simple Refineries		Complex II Refineries	
Base Case				
Ref. Config.	With Isom.	No Isom.	With Isom.	No Isom.
Benzene % vol.	2.6-4.2	3.6-5.1	2.3-2.4	2.6-3.5
3% Benzene Unrestricted Aromatics Case				
Aromatics % vol	<-----37 to 47----->		<------ 35 to 37 ---->	
MTBE % vol	<----- 0 or 10----->		<-------- 0 ------>	
Benzene Prod. kt/yr	<----- 0 to 16----->		<-------- 0 ------>	
Cost/Refinery (M USD/yr)	0-5.0	7.2-13.2	0	0-6.6
Cost/t gasoline (USD/t)	0-4.9	8.0-12.9	0	0-3.9
Investment Cost:				
Isom. M USD	0	24-27	0	20-22
Benz. Ext. M USD	0-7	0-7	0	0
Total M USD	0-7	24-34	0	20-22

3.1.3 Meeting 1% vol benzene content

This target could be met only by extracting benzene from reformates for all the investigated process configurations (see Appendix 3 - Tables 8 to 15). Isomerization facilities could significantly reduce the extent of required benzene extraction while minimizing loss in gasoline yields (see Section 3.1.1).

Depending on crude type, simple refineries would each have to extract benzene in the range of 18-42 kt/yr if MTBE is not used as a blending component. The effect of MTBE addition on the reduction of benzene content is only small as indicated by the marginally reduced benzene extraction requirement (being lowered from 18-42 to 17-40 kt/yr). However, adding MTBE at a concentration of 6-9% in simple refineries reduces aromatics contents by about 5-7% and improves gasoline yields.

In comparison with simple refineries, complex refineries produce higher gasoline yields usually with lower benzene and aromatics contents. This leads to a benzene extraction requirement of 21-38 kt/yr (without MTBE addition) which is about equivalent to that required in simple refineries.

Meeting the 1% benzene target in both types of refineries would cost each refinery up to about 15-16 M USD, including isomerization facilities but without oxygenate addition. About 2 M USD/yr could be saved for simple refineries by adding MTBE at the above reported concentrations; complex II refineries would save less than 1 M USD/yr. Costs to the refinery could exceed 19 or even 20 M USD/yr if the large benzene production should reduce the market price (see Section 2.2.3); any savings from MTBE addition would be completely offset if the oxygenate market price would be higher than 1.3 times that of gasoline.

The economic penalty per ton of gasoline could ultimately range between 8 to 12 USD for complex refineries and up to 16 to 20 USD for simple refineries. Depending on the crude type, all the process configurations would require a capital investment of 34 to 40 M USD at refineries where isomerization is not already installed.

Details on the economic evaluation are reported in Appendix 3 - Tables 20 and 21. Table 20 also reports the case of a complex I refinery without isomerization which could meet the target at lower capital and operating costs; a valid comparison of this case with the other ones should take into account that this refinery, while meeting the Eurograde gasoline specifications, would have a yield penalty with respect to the alternative of using isomerization (see Appendix 3 - Table 7).

Relevant information from Tables 8, 9, 10, 11, 14, 15, 20, 21 of Appendix 3 for the 1% benzene case is summarized below.

Process Options and Costs for Meeting 1% Benzene Content

	Simple Refineries		Complex II Refineries	
Base Case				
Ref. Config.	With Isom.	No Isom.	With Isom.	No Isom.
Benzene % vol.	2.6-4.2	3.6-5.1	2.3-2.4	2.6-3.5
1% Benzene, Unrestricted Aromatics Case				
Aromatics % vol	<-----37 to 46----->		<-----32 to 34----->	
MTBE % vol	<----- 0 or 6-9--->		<----- 0 or 1-4--->	
Benzene Prod. kt/yr	<-----17 to 42----->		<-----17 to 38----->	
Cost/Refinery[(a)] (M USD/yr)	3.3-7.5	11.0-15.7	5.2-7.4	12.7-15.7
Cost/t gasoline[(a)] (USD/t)	3.1-7.2	~10 - ~14	3.7-5.2	~8 - ~10
Investment Cost:				
Isom. M USD	0	25-27	0	25-28
Benz. Ext. M USD	9-13	9-13	9-12	9-12
Total M USD	9-13	34-40	9-12	34-40

Note

(a) Case requires about 2 Mt/yr of benzene to be disposed of in a European market of 5 Mt/yr.

3.1.4 Meeting 3% vol benzene and 40% vol aromatics contents

Hydroskimming and thermal conversion refineries could not meet 3% vol benzene and 40% vol aromatics content under the normal range of operational constraints without experiencing a high loss in gasoline production. The problem could only in theory be solved by adding large amounts of oxygenates to gasoline up to an equivalent MTBE concentration of 10% vol. Simple refineries would for instance require from 100 to 120 kt/yr of MTBE to achieve an average 3% vol benzene and 37 to 38% vol aromatics with a 20/80 Arabian Light/Brent crude feed ratio; the naphtha surplus would exceed 145 kt/yr (see Appendix 3 - Table 9 and 11). Potential problems related to the large oxygenate requirement and naphtha surplus would increase even more if refineries had to use lighter crudes, for part of the time as might happen during normal operations.

The economic penalty for a 20/80 Arabian Light/Brent crude feed ratio would be about 20 M USD/yr, including cost of the isomerization facilities and allowances for possible oxygenate and naphtha market price variations (see Section 2.2.3); a capital investment of about 27 M USD would be required and costs of gasoline production would ultimately increase by 16 to 20 USD/ton. Details on these economics are reported in Appendix 3 - Table 17.

Complex I refineries with predominantly Arabian Light type crude slates could meet on average the above contents if adequate isomerization facilities were installed. In the case of Brent type crude slates oxygenate addition would allow to meet the aromatics target. Investment in isomerization of about 24 to 28 M USD to achieve a 40% aromatics limit could increase costs of gasoline production by up to 5 USD/ton (about 7 to 8 M USD/year) (see Appendix 3 - Table 7).

Complex II refineries with isomerization facilities are the only configuration able to meet the restrictions with adequate flexibility margins to cope with most of the operational constraints. Investments in isomerization units (if not previously available) would cost the refinery 6 to 7 M USD/yr and 4 USD/ton gasoline; capital investment would range between 20 M USD and 22 M USD (see Appendix 3 - Table 7).

3.1.5 Meeting 3% vol benzene and 35% vol aromatics contents

As described in the previous section, simple refineries could not even achieve aromatics contents of 40% vol under realistic operating conditions. Facing a reduction to even 35% aromatics, hydroskimming refineries might lose 400 to 520 kt/yr of gasoline and produce up to 620 kt/yr of naphtha surplus; problems would be similar at thermal conversion refineries, as gasoline loss and naphtha surplus would still exceed 380 and 450 kt/yr respectively if Brent-type crudes were prevailing in the feed (see Appendix 3 - Tables 8 to 11). Moreover these compositional restrictions would cost refineries where isomerization is not already installed up to 40 to 50 USD/ton gasoline (see Appendix 3 - Table 18).

Complex I refineries without isomerization would not yield better results as loss of gasoline and naphtha surplus could exceed 320 and 470 kt/yr respectively with Brent type crude slates even at an MTBE concentration of 10% vol in gasoline. The restrictions would cost the refineries about 25 M USD/yr with the assumed 20/80 Arabian Light/Brent feed ratio and gasoline production costs could increase by about 23 USD/ton (see Appendix 3 - Tables 12, 13 and 18). These cost penalties could be somewhat reduced by investing about 24-28 M USD in isomerization facilities and relying on a still large oxygenate availability.

By interpolating the reported cases with no restrictions and 3% vol benzene/30% vol aromatics contents (see Appendix 3 - Tables 7 and 13), it can be estimated that levels of 3% vol and 35% vol would imply a gasoline loss and a naphtha surplus of about 110 kt/yr and 220 kt/yr respectively while 90 kt/yr of MTBE would be required to allow for an oxygenate content of about 6% vol. The economic penalty could likely exceed 28 M USD and 16 USD/ton of gasoline respectively.

Complex II refineries could meet the target if isomerization facilities were available and some oxygenates were added to gasoline produced from Brent-type crude (see Appendix 3 - Tables 14 and 15). Isomerization would cost refineries up to about 8 M USD/yr and 6 to 7 USD/ton of gasoline; a capital investment of about 25 to 28 M USD would be required (see Appendix 3 - Table 18).

3.1.6 Meeting 3% vol benzene and 30% vol aromatics contents

Only complex II refineries with isomerization facilities could keep the average aromatics content of gasoline around the level of 30% vol if large amounts of oxygenates were available to reduce gasoline loss. All other process configurations would incur high yield penalties even at 10% vol MTBE content as shown in the summary table below.

About 120 kt/yr of MTBE would be required per refinery to meet the compositional targets with a crude feed composition of 20% Arabian Light/80% Brent (see Appendix 3 - Table 15); the oxygenate content of gasoline would be about 7% vol. On the other hand MTBE requirement and MTBE content would be 65 kt/yr and 4% vol respectively if Arabian Light-type crudes were prevailing in the feed (see Appendix 3 - Table 14). In fact the actual oxygenate demand would largely depend on crude type as related to the gasoline yield and the naphthenes and aromatics content of the reformer feed. For instance, it can be estimated that 100% Brent-type crude would require more than 140 kt/yr of MTBE, which would correspond to an oxygenate content of 8 to 9% vol in gasoline; requirements could further increase with crudes lighter than Brent.

In conclusion, refineries would hardly be able to meet the target under all operational circumstances and some flexibility margin above the 30% vol aromatics level would be required. Depending on the crude type, restrictions could cost the refineries from about 12 to 21 M USD/yr; capital investment in isomerization units would be about 25 to 28 M USD and cost of gasoline production would increase by 8 to 12 USD/ton (see Appendix 3 - Table 19).

Key conclusions from Section 3.1.5 to 3.1.6 are summarized below:

Process Options and Costs for Meeting 3% Benzene and Aromatics Contents of 35% and 30% - Some Examples

	Simple Refineries	Complex II Refineries	
	Isomerization + MTBE Addition	Isomeriz.	Isomeriz. + MTBE Add.
Benzene % vol	<------------------------- 3	------------------------>	
Aromatics % vol	34-35	30	30
MTBE % vol	10	-	4-7
Gasoline loss (kt/yr)	24-518	168-434	(72)-(78)(1)
Naphtha surplus (kt/yr)	188-622	190-399	0-57
Total cost (2) (M USD/yr)	12-24	11-20	10-15
Investment cost (3) Isomerization M USD	25-27	25-28	25-28

Notes (1): Increase in gasoline production
(2): Capital charge and operating cost of isomerization included
(3): Isomerization costs apply to refineries where isomerization is not already installed.

3.1.7 Meeting 1% vol benzene and 35% vol aromatics contents

Benzene extraction from reformate would not significantly reduce the problems of meeting 35% vol aromatics content (see Section 3.1.5).

Hydroskimming refineries would still incur high gasoline loss and naphtha surplus even with an MTBE content in gasoline of higher than 10% vol; moreover the economic penalty could exceed 18-24 M USD/yr while requiring a capital investment of 31 M to 35 M USD. Cost to the refiner could even approach 40 M USD/yr and 57 USD/ton gasoline if the large benzene production should reduce the market price and the MTBE price should increase beyond the assumed level. Details are reported in Appendix 3 - Tables 8, 11 and 22.

Thermal conversion refineries would also need a very large MTBE addition; loss of gasoline yield and naphtha surplus could still exceed 80 kt/yr and 210 kt/yr respectively even if Brent-type crudes were limited to 80% of feed and the oxygenate content of gasoline could be kept at least at 10% vol.

Restrictions, if applied, could cost the refineries in the case of the low benzene/high MTBE price scenario up to 30 M USD/yr and up to 30 USD/ton of gasoline; a capital investment of 36 to 38 M USD would be required. Details are reported in Appendix 3 - Tables 10, 11 and 22.

The situation would not be better for complex I refineries since not less than 10% vol of MTBE would have to be added to gasoline and very large yield penalties would occur if Brent-type crudes were prevailing in the feed. In this case refineries would be forced to reduce gasoline production by more than 400 kt/yr to meet a 35% vol aromatics content without exceeding the already unrealistically high 10% vol MTBE addition; the reformer should consequently be operated at high feed IBP and naphtha surplus would probably exceed 550 kt/yr. Benzene production could be lower than 5 kt/yr owing to the lower content of benzene precursors in the reformer feed. The compositional restrictions would imply severe drawbacks and would cost the refineries up to 28 M USD/yr and 28 USD/ton of gasoline (see details in Appendix 3 - Tables 12, 13 and 22).

However problems could be significantly eased if further isomerization facilities were installed; with reference to the above considerations on the 3% vol benzene and 35% vol aromatics case (see Section 3.1.5) it can be estimated that refineries would incur much lower gasoline loss and naphtha surplus while keeping the oxygenate requirement within more reasonable limits.

Complex II refineries with isomerization facilities could meet the target by only extracting benzene from reformates; minor MTBE addition would help to keep acceptable gasoline yields and would be particularly useful for meeting normal operation at a 35% vol aromatics content with proper flexibility margins (see Appendix 3 - Tables 14, 15 and 22).

3.1.8 Meeting 1% vol benzene and 30% vol aromatics contents

Only complex II refineries with isomerization facilities would in theory be able to keep the average aromatics content of gasoline around the level of 30% vol by using oxygenates (see Section 3.1.6); the target of 1% vol benzene would imply benzene extraction from reformates.

Depending on whether Arabian Light or Brent-type crudes were prevailing in the feed the MTBE content of gasoline would range between 4 and 6% vol and up to 110 kt/yr of oxygenates would be required; benzene production would range between 19 and 34 kt/yr (see Appendix 3 - Tables 14 and 15).

Restrictions would cost the refineries from 20 to 30 M USD/yr including an allowance of 4 to 8 M USD/yr for possible MTBE and benzene market price variations; with these assumptions cost of gasoline production would increase by 13 to 17 USD/ton and up to 39 M USD would have to be invested in isomerization and benzene extraction facilities (see Appendix 3 - Table 23). As the MTBE requirement could be much higher with crudes lighter than Brent, proper flexibility margins should be applied to the limit of 30% vol aromatics content in view of the uncertainties of the future oxygenates availability.

Key conclusions from Section 3.1.7 and 3.1.8 are summarized below:

Process Options and Costs for Meeting 1% Benzene and Aromatics contents of 35% and 30% - Some Examples

	Simple Refineries	Complex II Refineries	
	Isomeriz. + MTBE Addition	Isomeriz.	Isomeriz. + MTBE Addition
Benzene % vol	<------------------------------ 1 ------------------------------>		
Aromatics % vol	34-35	30	30
MTBE % vol	10	-	4-6
Benzene prod. (kt/yr)	14-30	16-26	19-34
Gasoline loss (kt/yr)	(149)-513 (1)	144-423	(51)-(57)(1)
Naphtha Surplus (kt/yr)	0-599	148-347	0-22
Total cost (2) (M USD/yr)	17-24	16-25	15-20
Investment cost (3)			
Isomerization M USD	25-27	25-28	25-38
Benzene extr. M USD	6-10	9-10	9-11
TOTAL M USD	31-38	34-38	35-39

General Note: All processing options used in addition to benzene extraction

Note(1): Figures in parentheses denote increase in gasoline production
(2): Capital charge and operating cost of isomerization included
(3): Isomerization costs apply to refineries where isomerization is not already installed.

3.2 EC REFINING INDUSTRY

Results worked out for the EC refining industry are detailed in Tables 24 and 25 of Appendix 3.

3.2.1 Meeting Unleaded Eurograde Gasoline Specifications

Computer modelling shows that wide differences of benzene and aromatics contents have to be expected among the individual refineries once the unleaded Eurograde gasoline (95 RON, 85 MON) has achieved complete market penetration.

It is estimated that the whole EC gasoline production would be characterized by average contents of 3.2% vol benzene and 43% vol aromatics if isomerization capacity and crude feed composition are in line with the assumptions in Section 2.2.1 and 2.2.2 and gasolines are produced without oxygenates addition.

These figures, which were obtained by interpolating the data of Table 3, could in practice result in somewhat lower levels depending on the amount of oxygenates which could be selectively added to gasoline at each individual refinery configuration.
The average RON level could be higher than 95 RON because complex refineries, which contribute the highest share to the total gasoline production, would limit costs of splitting/reforming the low MON cracked naphtha by blending it in the pool as far as possible; MON level could slightly exceed the 85 specification as gasoline from hydroskimming and thermal conversion refineries would mainly contain the high MON reformates. Vapour pressure could be reduced below the 80 kPa average level by removing butane from gasoline; however MON would slightly decrease and balancing with reformate would ultimately tend to provide higher benzene and aromatics contents in gasoline.

Additional isomerization capacity would appreciably contribute to reduce the differences of benzene and aromatics contents among the individual refinery productions. If isomerization capacity would be increased to about 9.6 Mt/yr and such facilities would be available at all the simple refineries, then aromatics contents would range between 35 to 47% vol (see Table 2). The EC gasoline production would in this case be characterized by average benzene and aromatics contents of about 3.1% vol and 40.2% vol, respectively (see Appendix 3 Table 24).

Some differences from the above reported figures could be expected if the possible influence of variables like operational constraints, trend of oxygenates utilization and crude types other than those assumed were taken into account.

With respect to the basic assumption of an available 5 Mt/yr isomerization capacity in the late 1990s this would cost the EC refining industry about 240 M USD/yr and would require a capital investment of about 800 M USD (see Appendix 3 Table 25) to meet the base case unleaded gasoline demand.

Increasing isomerization capacity even up to a level of 14 Mt/yr would not further reduce the differences of benzene/aromatics contents among the individual refinery productions. Average benzene and aromatics contents of the EC gasoline would not be lower than 2.9 and 39% vol respectively. This case would cost the EC refining industry about 350 M USD/yr and 1400 M USD as capital investment.

3.2.2 Meeting 3% vol Benzene Content (No Restrictions on Aromatics)

Meeting this target would require benzene extraction from reformates or oxygenates utilization at the hydroskimming and thermal conversion refineries to avoid unacceptable high losses of gasoline production. An additional isomerization capacity at these refineries of about 5 Mt/yr would be needed to limit naphtha surplus, benzene production and oxygenates requirement.

Blending of oxygenates would require about 1 Mt/yr of MTBE to be selectively distributed among the simple refineries; extraction would require new process facilities for treating about 2.5 Mt/yr of reformates and producing about 200 kt/yr of benzene. This solution, which would be the less costly one, would imply an economic penalty of 300 M USD/yr and a capital investment of about 1100 M USD for the whole EC refining industry; a large part of these costs would be borne by simple refineries (see Section 3.1.2). Aromatics would still range between 35 and 47% vol and the average content would be about 40% vol. These levels could be somewhat lower if both oxygenates addition and benzene extraction were applied simultaneously. However the normal operation constraints as well as the influence of other factors, like crude feed composition and oxygenates distribution among the refineries, would actually limit the achievable results.

3.2.3 Meeting 1% vol Benzene Content (No Restriction on Aromatics)

Meeting this target would imply up to 2.2 Mt/yr of benzene extraction from reformates. About 10 Mt/yr of isomerization capacity should be available to avoid unacceptably low gasoline yields and large benzene and naphtha productions. Total crude oil feed would increase by 13 Mt/yr (case without MTBE addition); aromatics would range between 32 and 46% vol (see Section 3.1.3) with an average content of about 38 to 39% vol.

This benzene restriction could cost the EC refining industry from about 1200 M USD/yr to more than 1400 M USD/yr depending on benzene market price (see Section 2.2.3) while costs of gasoline production could at the same time increase by 13 to 16 USD/ton and reach 20 USD/ton at hydroskimming refineries; about 1800 M USD should be invested in isomerization and benzene extraction facilities, the latter being needed up to a reformate feed capacity of 48 Mt/yr. Benzene production and economic penalty could be even larger if actual crude types should yield naphthas with benzene precursors contents higher than expected from the assumed crude slate.

Blending oxygenates would mainly result in better gasoline yields and a reduction of the average aromatics content, with a minor influence on benzene extraction requirement. Aromatics would range between 32 and 41% vol if MTBE could be added from 6 to 9% vol at hydroskimming and thermal conversion refineries and from 1 to 4% vol at the complex II configurations.

The EC refining industry would require about 2.2 Mt/yr of MTBE with the assumed crude types and would reach an average aromatics content of 38% vol in gasoline; in this case extraction facilities are required for 44 Mt/yr of reformates and 1.9 Mt/yr of benzene would be produced. This case could cost the EC about 1250 M USD/yr or even up to 1560 M USD/yr depending on MTBE and benzene market prices; cost of gasoline production could at the same time increase by up to 18 USD/ton and about 1700 M USD would still be required as capital investment in isomerization and benzene extraction facilities. Naphtha surplus would not change appreciably with respect to the base case.

3.2.4 Reducing Aromatics Content

The achievable extent of aromatics reduction would mainly depend on types and amounts of oxygenates available for blending into the gasoline pool. Light ends isomerization would significantly contribute and would be particularly effective at the complex I refinery configurations where gasoline is mainly composed of highly aromatic reformates. However, the EC refining industry could not meet a target of 40% vol or less as only complex refineries with isomerization facilities could comply without major yield penalties and unrealistically high oxygenates requirements. Hydroskimming and thermal conversion refineries would have to add oxygenates at equivalent MTBE contents even higher than 10% vol in gasoline and could not avoid a large naphtha surplus (see Section 3.1.4).

Among the explored alternatives of aromatics reduction, the case of meeting 1% vol benzene content and using 2.2 Mt/yr of MTBE would lead to an average aromatics content of about 38% vol with individual refinery levels ranging between 32 and 41% vol (see Section 3.1.3).

The oxygenate requirement is based on the assumption that MTBE utilization might be unevenly distributed among the refineries as simple configurations would need up to 9% vol MTBE contents whilst levels even lower than 2% vol could be suitable for the complex II refineries. This case, if feasible, would represent the most optimistic scenario for the EC refining industry; additional amounts of oxygenates, if available, would allow for further reductions at the complex II refineries and could ultimately result in an average content below 38% vol for the whole EC production. On the other hand it has to be taken into account that operational constraints, crude types lighter than assumed and possible concerns about high oxygenates requirements at simple refineries would necessitate a proper flexibility margin leading to a generally acceptable legal restriction beyond 41% vol maximum content.

The reported case would cost the EC refining industry up to 1560 M USD/yr and 1700 M USD as capital investment; benzene production would be 1.9 Mt/yr and cost of gasoline production would increase by up to 18 USD/ton.

Alternatives for meeting 35% vol aromatics content were evaluated with the main purpose of checking feasibilities and economic consequences for each refinery configuration (see Section 4.2). Relevant results, which show that only complex II refineries could meet the target with proper flexibility margin, were nevertheless aggregated to provide consistent EC scenarios and to allow for general comparisons with the above reported cases (see Section 3.2.1 to 3.2.4); details are included in Tables 24 and 25 of Appendix 3.

4. DISCUSSION OF METHODS TO REDUCE BENZENE/AROMATICS

4.1 THE ROLE OF THE CATALYTIC REFORMER FEED IBP

The benzene content of gasoline can be reduced appreciably by increasing the reformer feed initial boiling point (IBP). For example, setting the (true boiling) end point of the straight-run light naphtha at 90-95°C would remove most of the benzene precursors from the reformer feed; with respect to a reference cut point of 70°C the benzene content of reformate could be reduced by about 0.9-1.2% vol when feeding 150°C end point naphtha from Arabian Light or Brent type crudes. Reductions can be larger with other crudes and different cut points as it mainly depends, for a given reformer severity, on the naphthenes plus aromatics contents of the naphtha and the benzene precursors distribution over its distillation curve (1). Actual effects on benzene content of gasoline would ultimately depend on the volume percentage of reformate in the finished gasoline pool. In this respect hydroskimming and thermal conversion refineries would get the highest benefit; complex processing configurations would be less influenced due to the availability of other components with low or no benzene content, like cracked naphtha, isomerate, alkylate, etc.

The disadvantages of this mode of operation, which increases the yields of light and low octane fractions (see Section 2.4.1), can be summarized as follows:

- Chemical feedstock production would have to be increased if the octane loss could not be readily balanced by further upgrading facilities (low pressure reformers, isomerization, light cracked naphtha splitting/reforming etc.);

- Refineries could be forced to blend the light naphtha into the gasoline pool and to meet the octane requirements by using more reformate; this mode of operation, which would imply higher reformer feed end points and increased gasoline production, could in practice be limited by the types of crudes processed, the reformer operational constraints and the structure of local product demand patterns;

- Another processing option would be to compensate the octane loss due to an increased reformer feed IBP by an increase in reformer severity.

For example, reforming at 98 severity, topping of the feed at 85°C and blending the unreformed light front end back into the reformate has the following effect:

Feed type	Feed cut	Initial operation severity/RON	Initial operation benzene	New severity	RON	Blend benzene
Ekofisk	66 to 180°C	98	5.4% wt	99	98	4.2% wt
Kuwait	55 to 180°C	98	4.8% wt	102	95.5	3.1% wt

- The above numbers suggest that some benzene reduction can be achieved by topping cat.reformer feed especially when the light end share is small as with Ekofisk (4.3% of feed). With a higher proportion a problem arises for maintaining the RON level. The Kuwait did not maintain the overall RON despite maximum reforming severity.

- Light naphtha surplus, if unavoidable, would impact on the costs of products supply and distribution as local market demand would have to be balanced by importing gasoline or gasoil and finding new outlets for the light naphtha with associated quality (high distillation end point) and freight penalties; the latter could likely exceed 10 or even 15 USD/ton depending on distances and transportation.

Some of the EC refineries could in practice increase the light naphtha cut point.

For instance, this could apply to those refinery configurations which do not use isomerization in the first place to produce Eurograde unleaded gasoline. Other refineries would not be able to do that at all or will prefer to cut at a lower reformer feed IBP in order to obtain a proper isomerization feed quality.

The EC refining industry could ultimately operate with an average cut point somewhat higher than the 66°C TBP level on which most of the evaluations were based. It is however important to realize that any legal benzene content restriction has to be met by all of the refineries and under all circumstances of the day-to-day operation.

This aspect suggests avoiding the approach of evaluating the achievable benzene contents on the basis of average European process conditions. Nevertheless benzene extraction from reformates would not be lower than estimated (see Table 24 in Appendix 3) because hydroskimming and thermal conversion refineries might not have the assumed isomerization facilities available. The EC low pressure reforming capacity, if ultimately larger than foreseen, could allow for blending higher FBP light naphthas into the gasoline pool and balancing the octane loss by increasing reformer operation severities. On the other hand, isomerization of higher FBP light naphthas, which in principle would yield better results, might still require very high reforming severities (see above) whilst existing isomerization/reforming facilities might not be suitable for such a mode of operation.

Attention has been paid to not overestimating the economic consequences of limiting the benzene content: neither any investment costs for the required process capacities (other than for isomerization and benzene extraction) nor extra charges on imports/exports for balancing local market demands (see above) were included in the reported figures.

4.2 THE ROLE OF LIGHT ENDS ISOMERIZATION

In principle light ends isomerization does not represent a compulsory step on the way to meet the Eurograde gasoline specifications; however it allows for flexible operations as it makes available a new blending component of appreciable quality (89-91 RON clear, low sensitivity, free of benzene and aromatics) instead of a low octane light naphtha fraction. Isomerization may offer the refinery some attractive options like:

- blending light naphtha surplus into the gasoline pool and being more flexible in meeting market products demands within a wider range of crude types;

- reducing the reformer severity to obtain better yields under less operational constraints;

- increasing the percentage of full range cracked naphtha in the gasoline pool to save capital and operating costs needed for splitting/reforming the heart cut of this low octane fraction;

- improving the gasoline front end octane characteristics and lowering density.

Isomerization facilities would also contribute to reduce benzene and aromatics content of gasoline when the Eurograde will have achieved a complete market penetration.

Section 2.4.2 deals with the effect of isomerate on reducing the reformer severity and/or diluting benzene and aromatics contents in the gasoline pool; the combined effect is described in Section 3.1.1 and summarized in Table 4, which includes an estimate of what might be expected for the EC gasoline production if all the refineries had full access to isomerization instead of the assumed 5 Mt/yr overall capacity.

Hydroskimming refineries are expected to get the largest benefit as the isomerate/reformate ratio would be higher than in other process configurations.

Benzene and aromatics reduction would be lower at thermal conversion refineries due to the combined effect of somewhat higher gasoline yields and octane requirements from reformates; this aspect is likely to be more noticeable if visbroken distillates are recycled for further conversion and thermally cracked light naphtha is blended as such into the pool.

Complex refineries would get the lowest benefits as the isomerate volume would be small in proportion to the volume of the other available blending components. However benzene and aromatics reductions could even exceed 1% vol and 5% vol, respectively, if Brent type crudes were prevailing in the feed.

Isomerization by itself would allow for a reduction of the average benzene and aromatics contents of the EC gasoline to levels even lower than 3% vol and 39% vol if the refining industry could rely on a total capacity of about 14 Mt/yr (see Table 24 in Appendix 3). All the alternative cases were consequently evaluated by including isomerization as an operational tool which could help the refineries to meet the targets.

The results show that the assumed 5 Mt/yr capacity would allow for meeting average benzene and aromatics contents of about 3.2% vol and 43% vol if isomerization was mainly available at hydroskimming refineries; contents of individual refinery productions could however be as high as 5% vol benzene and 56% vol aromatics depending on the crude feed type and the day-by-day operational constraints. Further significant reductions would be achievable if the EC isomerization capacity would be increased and all the complex refineries could have it available. This case was evaluated on the basis of a total 9.6 Mt/yr capacity, which would also cover some 40% of the cracking refineries: benzene and aromatics contents of individual gasoline productions could mostly be kept below 4.5% vol and 50% vol respectively while the average EC gasoline pool would meet levels of about 3.1% vol and 40.2% vol respectively. Increasing isomerization capacity up to a level of 14 Mt/yr would reduce the average benzene and aromatics contents even below 3% vol and 39% vol (see above) respectively but would not change the upper limits still expected for simple configurations.

4.3 LDF PRODUCTION LEVEL

The EC is currently a net importer of naphtha. Indigenous production is likely to increase with the growth of the unleaded gasoline market demand. In principle, the refining industry could place on the market all the light distillate fuel (LDF) required to balance the gasoline pool octane. But local market situations might force individual refineries to blend LDF into the gasoline pool thus requiring increased reformer severity and possibly investment in new octane upgrading facilities. However such occurrences would not modify the overall trend of a larger LDF production and the EC as a whole would have to balance the market demand through a change in the import/export pattern.

Problems could probably arise if refineries would have to meet a benzene restriction by increasing the reformer feed IBP or limiting aromatics contents below those levels achievable by the addition of the predicted future volumes of oxygenates. Any attempts to avoid or to limit benzene extraction from reformates would increase LDF production significantly whenever refineries would have no adequately sized isomerization and/or low pressure reforming facilities. Simple refinery configurations would have to deal with the largest LDF surplus but even complex II refineries could face serious problems.

A typical example of a 5 Mt/yr complex refinery is reported hereafter assuming the less critical case of Arabian Light crude prevailing in the refinery feed. The data shown are differences from a base case with 65°C reformer feed IBP and no benzene restrictions in place:

Ar. Light/Brent feed ratio	(wt/wt)	80/20
Naphtha surplus	(kt/yr)	+163
Gasoline	(kt/yr)	-209
Reformer feed IBP/FBP	(°C TBP)	+15/-10
Reformer severity	(RON Clear)	-0.5
Cracked naphtha to reformer	(kt/yr)	-25
Total reformer feed	(kt/yr)	-189
Gasoline - Density	(g/ml)	+0.02
- RON/MON		+0.8/-
- Benzene content	(% vol)	-1.4
- Aromatics content	(% vol)	-0.9
- RVP	(kPa)	+2.7
- VLI		+20

A reduction of the aromatics content would be by far the most difficult problem as the LDF surplus would be much larger and unevenly distributed among the individual refinery configurations (see Appendix 3 - Tables 8 to 24). Even if the total LDF production could be absorbed within the EC import/export pattern, individual refineries would have to deal with an unacceptable large surplus and might be forced to export it at a freight penalty of at least 10 to 15 USD/ton. Moreover refineries might be faced with an even more serious economic burden resulting from the fact that the LDF surplus will impact on the gasoline yield, which would be so low that compensation by a higher crude intake could not be economically justified. This aspect cannot be properly addressed if considering only the average situation of the EC as a whole. In this case the severe problems encountered in hydroskimming and thermal conversion configurations would be camouflaged by the flexible operations of complex II refineries. The consequences of meeting for instance a 35% vol aromatics content in the EC scenario would lead to an LDF production ranging between 16 and 20 Mt/yr, a crude throughput increase of 25 to 40 Mt/yr and an economic penalty in terms of investment costs of 1 to 2 billion USD (see Table 24 and 25 in Appendix 3). On the other hand, simple refineries, even with access to large quantities of oxygenates might lose more than 50% of the potential gasoline production and produce up to 500-600 kt/yr of LDF surplus. Overall, aromatics restrictions might cost simple refineries up to 40 M USD/yr and an additional penalty of 10 to 20 M USD/yr would probably burden supply and distribution.

4.4 THE ROLE OF THE CRUDE FEED TYPE

Alternative routes for reducing benzene and aromatics contents of gasoline were evaluated on the basis of Arabian Light and Brent as the only reference crudes for each individual refinery configuration.

This choice was made for two major reasons, namely to take into account two typical but different crude types and to achieve consistency with previous CONCAWE reports (1,3). Computer modelling as used in this study could not cover the wide ranges of different crude types available to European refineries which influence the achievable benzene/aromatics reductions.

An important role is played for instance by the actual naphthenes and aromatics contents of the reformer feed which have a direct influence on the benzene content of reformate (1); other crude characteristics, like distribution of benzene precursors across the naphtha distillation curve as well as light and heavy naphtha yields, might affect operations significantly.

In fact the crude type may influence the reformer severity, the (highly aromatic) reformate content of gasoline and the LDF amount exceeding the pool octane balance. Hence, refineries may find that achieving required benzene and aromatics reductions would be more difficult and costly than shown by the study results. This would be the case for those refineries use Nigerian type crudes or some North Sea crudes other than Brent. A relevant set of characteristics is reported hereafter to allow for comparisons with the data resulting from the basic assumptions. It is important to note that benzene and/or aromatics restrictions, if legally applied, should include proper flexibility margins with respect to the minimum contents achievable with any average or defined crude feed composition.

Characteristics of some typical naphthenic crudes

	Brent	Ninian	Forties	Nigerian Brass
API gravity	38.5°	36.2°	37.3°	43.5°
Naphtha yields				
C5-66°C fraction (%wt)	4.3	4.2	5.1	5.6
C5-70°C fraction (%wt)	4.9	4.5	5.5	6.2
70-180°C fraction (%wt)	20.4	17.7	20.1	27.2
66-180°C fraction (%wt)	21.0	18.0	20.5	27.8
$\frac{\text{C5-70°C}}{\text{70-180°C}}$ yield ratio (wt/wt)	0.24	0.28	0.27	0.23
Characteristics				
Light naphtha				
- FBP (°C)	66	70	70	66
- Benzene content (%wt)	3.0	2.8	4.8	1.9
- Total C6 " (%wt)	40.8	41.2	63.3	40.1
Heavy naphtha				
- Naphthenes " (% vol)	38.0	39.1	40.1	48.0
- Aromatics " (% vol)	13.6	13.6	14.5	12.2

4.5 THE ROLE OF OXYGENATES AS GASOLINE BLENDING COMPONENTS

Most of the oxygenates available on the market will help refiners to reduce benzene and aromatics contents of gasoline. These compounds are characterized by blend octane numbers which largely exceed the unleaded European gasoline specifications and might consequently allow for reducing the reformer severity and diluting the reformate in the pool. However the extent of achievable benzene and aromatics reductions also depends on other characteristics like vapour pressure and oxygen content, which can limit oxygenate utilization. Blending properties of typical compounds, as reported hereafter, clearly show large octane and RVP differences for given % vol oxygenate contents in gasoline. EC maximum concentration limits for each individual oxygenate in gasoline are reported in Appendix 1.

Typical blending properties of common oxygenates (5)

	RON	MON	RVP (kPa)	% Vol in blend
Ethanol	125	97	172	7
GTBA	108	94	152	7
MTBE	115	101	90	10
Methanol/Ethanol (1)	125	96	310	7
Methanol/GTBA (2)	117	95	324	6

Note (1): 40/60 blend Note (2): 50/50 blend

MTBE was selected as the reference oxygenate for this study because it has the highest potential of all the commercially available oxygenates to reduce benzene and aromatics contents in gasoline within the refineries' operational constraints. MTBE is particularly attractive due to its low vapour pressure, high MON and allowed concentration of max. 10% vol content in gasoline (see Column A of Appendix 1). Low vapour pressure and oxygen content allow high blending rates while the high blend MON can significantly contribute to increase the full range, low octane cracked naphtha content of gasoline. Cracked naphtha as such is charactarized by benzene and aromatics contents much lower than those of typical reformate. Addition of MTBE would minimize the need to split and reform this component in view of its low MON.

MTBE availability in 1995 is not expected to exceed 2.8 Mt/yr in Western Europe as a whole (see Appendix 2). The study results show that this amount should satisfy the expected EC requirement for the explored alternatives of benzene reduction. A reduction of the average aromatics content of the EC gasoline by 3 to 5% vol might however require more than 4 to 6 Mt/yr of MTBE and would hence imply a large utilization of other oxygenate compounds. The achievable reduction would ultimately depend on the above mentioned EC limits on oxygenate but would most probably not exceed the values as reported in Section 3.2.4.

4.6 BENZENE CONTENT OF GASOLINE AND EXTRACTION FROM REFORMATES

The benzene content of individual refinery productions is expected to range between 2.3 and 4.3% vol with the assumed crude feed types and octane upgrading capacities; the average content of the EC unleaded gasoline would be around 3.2 % vol or somewhat lower if oxygenates were used as blending components. MTBE could for instance allow for reducing benzene content by 0.2 to 0.3% vol if added at 2.5% vol on average; however it would not have an appreciable effect on the above range which would still predominantly depend on the widely varying circumstances of the operation at individual refineries.

In fact the benzene contents of future EC gasolines will not be much higher than those of the current 97 RON/0.15 g/l lead production, which already has an average content of about 2.8% vol. Meeting a 3% vol benzene content under all the operational circumstances would require additional process facilities like light naphtha isomerization or even benzene extraction from reformates, the latter being an option for hydroskimming and thermal conversion refineries if local market situations would prevent marketing of naphtha surplus. This case would imply only a minor benzene production, which would not exceed about 200 kt/yr for the EC as a whole.

Benzene extraction from reformates would be applied at most of the EC refineries in case of more severe restrictions; benzene production could be up to 2.2 Mt/yr if the maximum benzene content of gasoline should be kept at 1% vol. Addition of oxygenates would only marginally reduce the amount of extracted benzene. Large LDF demands from the petrochemical market might locally contribute to limit or even offset benzene extraction requirements but the refining industry as a whole would still have to deal with a benzene amount which could exceed the production capacity of all the existing hydrodealkylation units. The impact on the petrochemical industry is the subject of a separate study by the CEFIC Aromatic Sector Group.

4.7 COMPARISONS WITH PREVIOUS CONCAWE REPORT

When comparing previous CONCAWE results (1) with the findings of the present study, it can be noticed that the economic consequences of limiting benzene content do not differ significantly if calculations are based on a common set of product prices and investment costs for new process facilities. Details are reported hereafter for the case of meeting 1% vol benzene content with updated prices and costs in line with the basic assumptions of the recent study (see Sections 2.2.3 and 2.4.2.); a benzene price of 0.53 times that of gasoline was used to reflect the product heating value in a saturated market situation.

The penalty for the hydroskimming refineries is confirmed at about 20 USD/ton of gasoline if some differences of operations and octane requirements are taken into account. Also complex refineries show the same penalty of 11 to 12 USD/ton with the lower costs being mainly related to the 92 RON Clear specification assumed in the previous study.

Meeting 1% vol benzene content

Comparison between present and previous report

Data are reported for a typical 5 Mt/yr refinery; a common set of updated prices/costs has been used for crudes, products and investments in new process facilities. Economic consequences are in terms of USD per ton of gasoline.

Reference Report (1)		A	A	B	A	A	B	A
Type of crude								
- North Sea	(wt%)	100	100	80	30	30	20	-
- Middle East	(wt%)	-	-	20	70	70	80	100
Gasoline characteristics								
- RON		97	92	95	97	92	95	97
- Lead content	(g/l)	0.15	-	-	0.15	-	-	0.15
Hydroskimming refinery								
- Isomerization feed	(kt/yr)	-		210	148		175	178
- Benzene production	(kt/yr)	50		36	27		18	19
- Surplus/deficit	(USD/t)	8.8		5.4	5.3		4.1	7.4
- Benzene extraction	(USD/t)	5.6		5.7	5.2		5.8	6.3
- Isomerization	(USD/t)	-		8.7	7.2		9.5	9.1
- Total penalty	(USD/t)	14.4		19.8	17.7		19.4	22.8
Complex refinery								
- Isomerization feed	(kt/yr)	-	-	216	147	77	182	
- Benzene production	(kt/yr)	40	38	38	10	9	21	
- Surplus/deficit	(USD/t)	7.9	4.0	3.7	2.7	1.6	2.5	
- Benzene production	(USD/t)	4.1	3.7	3.5	2.8	2.6	3.2	
- Surplus/deficit	(USD/t)	-	-	5.1	6.8	4.3	5.1	
- Total penalty	(USD/t)	12.0	7.7	12.3	12.3	8.5	10.8	

Note(1): Ref. A is for previous report; Ref. B is for the present one.

5. REFERENCES

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3. CONCAWE (1987) Sulphur emissions from small stationary oil combustion plant and the availability of low sulphur fuel oil in the EC. Report No. 87/61. The Hague: CONCAWE

4. A forecast of the MTBE availability in Europe (private communication)

5. Chem Systems International (1987) Presentation at European Octane and Fuel Oxygenates Conference, Geneva - May 5-6, 1987

Table 1 Distribution of the benzene and total aromatics contents of European gasoline

(Data are reported as % volume)

COUNTRY	GASOLINE GRADE (2)	YEAR		LOWEST CONTENT	% of samples with less than reported cont. 10	20	30	40	50	60	70	80	90	HIGHEST CONTENT	NUMBER OF SAMPLES
Austria	LL PMS	1987	BENZ.	1.4	1.8	1.9	1.9	2.6	3.0	3.1	3.3	3.6	3.6	4.2	13
		1986/87	AROMAT.	-					38					40	2
	UL PMS (1)		BENZ.	2.5					3.5					4.3	5
			AROMAT.												N.A.
	UL RMS	1987	BENZ.	1.6	1.6	2.2	2.6	2.7	2.9	3.0	3.1	3.1	3.2	3.6	10
		1986/87	AROMAT.	-					27					31	2
Belgium	LL PMS	1987-5	BENZ.	-	-				1.2					2.0	2
		1987-5	AROMAT.	-					34					38	2
	UL PMS (1)	1987-5	BENZ.	-					1.4					2.8	2
		1987-5	AROMAT.	-					35					41	2
	LL RMS	1987-5	BENZ.	-					1.7					•	1
		1987-5	AROMAT.	-					20					-	1
Denmark	LL PMS	1986/87	BENZ.	2.7					3.6					5.0	9
		1986/87	AROMAT.	36					39					47	9
	UL PMS	1986/87	BENZ.	3.3					4.1					4.6	8
		1986/87	AROMAT.	37					42					51	8
	LL RMS	1986	BENZ.	1.8					3.5					4.3	5
		1986	AROMAT.	18					30					33	5
Finland	LL PMS	1986/87	BENZ.	1.6	1.8	1.8	1.9	1.9	2.0	2.2	2.4	2.7	2.9	2.9	12
		1986/87	AROMAT.	33	34	35	38	39	39	41	41	43	43	47	12
	UL PMS (1)	1987	BENZ.	1.5					2.2					2.6	6
		1987-6	AROMAT.	39					41					43	4
	LL RMS	1987	BENZ.	0.5					1.8					2.4	6
		1987	AROMAT.	21					21					26	6
France	L PMS	1987/88	BENZ.	0.7	1.1	1.4	1.6	1.9	2.0	2.2	2.6	3.5	4.3	8.6	64
		1987/88	AROMAT.	20	24	25	27	28	29	30	31	33	34	38	64
	UL PMS (1)	1987	BENZ.	1.8					2.5					4.4	12
		1987	AROMAT.	24					42					50	12
	L RMS	1987/88	BENZ.	1.3					1.5					2.0	3
		1987/88	AROMAT.	23					24					29	3
Greece	L PMS	1987	BENZ.						2.8						N.A.
		1987	AROMAT.						30						N.A.
	L RMS	1987	BENZ.						1.5						N.A.
		1987	AROMAT.						26						N.A.
Italy	L PMS	1987/88	BENZ.	0.5	1.3	1.8	2.0	2.4	2.6	2.7	3.0	3.4	4.0	4.4	148
		1987/88	AROMAT.	15	22	25	29	31	32	34	35	36	40	57	151
	UL PMS (1)	1987-6/7	BENZ.	2.0					3.0					3.5	7
		1987-6/7	AROMAT.	30					46					48	7
	L RMS	1987-6/7	BENZ.						2.4						1
		1987-6/7	AROMAT.						23						1
Netherlands	LL PMS	1987-5/7	BENZ.	0.5					2.7					4.7	7
		1987-5/7	AROMAT.	36					42					46	7
	UL PMS (1)	1987-5/7	BENZ.	1.9					3.0					3.6	6
		1987-5/7	AROMAT.	33					40					46	6
	UL RMS	1987-5/7	BENZ.	1.4					2.4					3.6	6
		1987-5/7	AROMAT.	26					32					35	6

Note (1): Date not representative in view of very low sales volume of unleaded gasoline

Note (2): The reported symbols identify the various grades as follows:
L = Leaded (0.4 g Pb/l); LL = Low-leaded (0.15 g Pb/l); UL = Unleaded (Eurosuper)
PMS = Premium Gasoline; RMS = Regular Gasoline

Table 1 (con't) Distribution of the benzene and total aromatics contents of European gasoline

(Data are reported as % volume)

COUNTRY	GASOLINE GRADE(2)	YEAR		LOWEST CONTENT	% of samples with less than reported cont. 10	20	30	40	50	60	70	80	90	HIGHEST CONTENT	NUMBER OF SAMPLES
Norway	LL PMS	1987/80	BENZ.	3.3					4.4					5.2	8
		1987/88	AROMAT.	32					41					47	8
	UL PMS	1987/88	BENZ.	3.5					4.4					5.4	8
		1987/88	AROMAT.	33					44					52	8
Portugal	L PMS	1987	BENZ.	1.9					3.1					5.8	7
		1987	AROMAT.	26					33					41	7
	L RMS	1986-4	BENZ.	-					2.0					2.4	2
		1986-4	AROMAT.	-					31					36	2
Spain	L PMS	1987	BENZ.	1.2	1.2	1.4	1.5	1.8	2.1	2.1	2.3	2.3	2.5	4.3	13
		1987	AROMAT.	27	27	30	31	32	33	34	37	37	40	42	13
	L RMS	1987	BENZ.	1.0					1.9					5.1	8
		1987	AROMAT.	17					22					35	8
Sweden	LL PMS	1986/87	BENZ.	1.8	1.9	2.2	3.2	3.8	3.9	4.0	4.3	4.6	4.6	5.0	10
		1986/87	AROMAT.	34	35	35	35	37	38	42	42	43	43	45	10
	UL PMS	1986/87	BENZ.	2.5					4.0					4.4	4
		1986/87	AROMAT.	44					45					46	4
	LL RMS	1986	BENZ.	2.8					3.3					4.4	6
		1986	AROMAT.	25					31					35	6
Switzerland	LL PMS	1986/87	BENZ.	2.3					2.6					3.5	4
		1986/87	AROMAT.	31					32					35	4
	UL PMS	1986/87	BENZ.	3.1					3.3					3.8	4
		1986/87	AROMAT.	32					33					37	4
U.K.	LL PMS	1986/88	BENZ.	0.7	1.4	1.8	2.2	2.5	2.8	2.9	3.5	3.8	4.0	5.7	32
		1986/88	AROMAT.	17	26	29	30	32	33	33	36	37	39	48	39
	UL PMS (1)	1987/88	BENZ.	0.7	3.3	3.5	3.8	4.4	5.2	5.3	5.6	5.7	5.7	5.7	10
		1987/88	AROMAT.	27					43					55	9
	LL RMS	1986	BENZ.	0.5					1.4					2.1	6
		1986	AROMAT.	22					31					36	6
West Germany	LL PMS	1987	BENZ.	1.4	1.8	2.3	2.5	2.7	2.8	3.0	3.2	3.5	4.0	8.0	146
		1987	AROMAT.	25	31	34	37	38	39	41	42	44	48	57	146
	UL PMS	1987	BENZ.	0.3	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.4	4.3	5.3	108
		1987	AROMAT.	29	34	36	38	40	41	42	43	44	46	54	108
	UL RMS	1987	BENZ.	0.3	1.2	1.5	1.7	2.0	2.1	2.5	2.7	3.0	3.4	4.7	108
		1987	AROMAT.	21	27	31	32	33	34	36	37	39	44	65	108
	LL RMS	1987	BENZ.	0.3	0.9	1.2	1.3	1.5	1.7	1.8	2.0	2.3	2.9	7.6	138
		1987	AROMAT.	14	21	24	25	26	27	29	30	32	36	58	139
Yugoslavia	L PMS	1987-8/9	BENZ.	1.3					2.4					3.4	4
		1987-8/9	AROMAT.	34					36					38	4
	UL PMS (1)	1987-8/9	BENZ.						3.3						1
		1987-8/9	AROMAT.						45						1
	L RMS	1987-8/9	BENZ.	-					0.7					1.3	2
		1987-8/9	AROMAT.	-					20					20	2
Average for above 16 Countries (3)	LL PMS	1986/80	BENZ.	0.5					2.8					8.0	243
		1986/88	AROMAT.	17					36					57	239
	L PMS	1986/88	BENZ.	0.5					2.3					8.6	236
		1986/88	AROMAT.	15					31					57	239
	UL PMS	1986/88	BENZ.	0.3					3.3					5.7	181
		1986/88	AROMAT.	24					41					55	173
	UL RMS	1987	BENZ.	0.3					2.4					4.7	124
		1986/87	AROMAT.	27					33					65	116
	LL RMS	1986/88	BENZ.	0.3					1.7					7.6	162
		1986/88	AROMAT.	14					26					58	163

Note (1): Data not representative in view of very low sales volume of unleaded gasoline

Note (2): The reported symbols identify the various grades as follows:
L = Leaded (0.4 g Pb/l); LL = Low-Leaded (0.15 g Pb/l); UL = Unleaded (Europsuper)
PMS = Premium Gasoline; RMS = Regular Gasoline

Note (3): Average weighted according to the estimated 1987 gasoline market of each country

Table 2 Individual refinery configurations

Effect of isomerization when meeting the unleaded Eurograde gasoline production - No oxygenate addition -

		Hydro Skimming		Thermal Conversion		Complex I		Complex II	
Isomerization feed	kt/yr	-	166	-	187	-	168	-	121
Crude feed (80 AL/20 B)									
- Brent	kt/yr	1000	1000	1000	1000	1000	1000	1000	1000
- Ar.Light	kt/yr	4000	4000	4000	4000	4000	4000	4000	4000
	kt/yr	5000	5000	5000	5000	5000	5000	5000	5000
Yields									
- Gasoline	% wt	14.0	18.0	17.9	19.4	23.9	27.0	24.6	30.6
- Naphtha	% wt	2.5	0.1	2.5	0.5	3.1	-	3.9	0.6
Gasoline characteristics									
- Density		.765	.746	.764	.745	.760	.748	.746	.738
- Benzene	% vol	4.0	2.6	3.6	2.9	2.9	2.7	2.6	2.3
- Aromatics	% vol	55	44	51	45	42	38	39	35
Isomerization feed	kt/yr	-	202	-	210	-	213	-	143
Crude feed (20 AL/80 B)									
- Brent	kt/yr	4000	4000	4000	4000	4000	4000	4000	4000
- Ar.Light	kt/yr	1000	1000	1000	1000	1000	1000	1000	1000
		5000	5000	5000	5000	5000	5000	5000	5000
Yields									
- Gasoline	% wt	18.1	22.0	21.8	23.3	27.1	31.1	28.4	33.8
- Naphtha	% wt	2.3	-	2.2	0.1	3.6	-	3.5	1.5
Gasoline characteristics									
- Density		.768	.751	.766	.750	.763	.751	.750	.743
- Benzene	% vol	5.1	3.8	5.0	4.2	4.3	3.3	3.5	2.4
- Aromatics	% vol	56	45	53	47	45	40	42	37

B = Brent
AL = Arabian Light

Table 3 Charactistics of unleaded Eurograde gasoline without oxygenates addition

Crude feed:		
- Arab Light % wt	80	20
- Brent % wt	20	80
- Density	0.749	0.754
- RON	95.8	95.8
- MON	85.2	85.2
- RVP kPa	80.7	80.0
- Benzene % vol	2.8	3.7
- Aromatics % vol	42	44

Table 4

Contribution of isomerization to reduce benzene and aromatics contents

Data refer to differences from base cases without isomerization; the assumed 5 Mt/yr capacity is available in the EC refining industry base case.

Ar.Light/ Brent feed ratio	Hydro skimming 80/20	80/20	Thermal conversion 80/20	80/20	Complex I 80/20	80/20	Complex II 80/20	80/20	EC ref. industry 57/43 (1)
Yields									
Gasoline wt%	+4.0	+3.9	+1.5	+1.5	+3.1	+4.0	+6.0	+5.4	+2.3
Naphtha wt%	-2.4	-2.3	-2.0	-2.1	-3.1	-3.6	-3.3	-2.0	-1.7
Gasoline characteristics									
Density	-0.019	-0.017	-0.019	-0.016	-0.012	-0.012	-0.008	-0.007	-0.006
Benzene % vol	-1.4	-1.3	-0.7	-0.8	-0.2	-1.0	-0.3	-1.1	-0.3
Aromatics % vol	-11	-11	-6	-6	-4	-5	-4	-5	-4

Note(1): Crude feed ratio as from basic assumption (see Section 2.2.2)

Table 5 Oxygenates limits set out in Directive 85/536/EEC (a)

	A (% vol)	B (% vol)
- Methanol, suitable stabilizing agents must be added (b)	3%	3%
- Ethanol, stabilizing agents may be necessary (b)	5%	5%
- Iso-propyl alcohol	5%	10%
- TBA	7%	7%
- Iso-butyl alcohol	7%	10%
- Ethers containing 5 or more carbon atoms per molecule (b)	10%	15%
- Other organic oxygenates defined in Section 1	7%	10%
- Mixture of any org.oxygenates (c) defined in Section 1	2.5% oxygen weight, not exceeding the individual limits fixed above for each component	3.7% oxygen weight, not exceeding the individual limits fixed above for each component

Notes:

(a) Not all countries permit levels exceeding those in column (A) even if the service station dispenser is labelled.

(b) In accordance with national specifications or, where these do not exist, Industry specifications

(c) Acetone is authorized up to 0.8% by volume when it is present as a by-product of the manufacture of certain organic oxygenate compounds

Table 6 MTBE availability trend in Europe (1)

		1988	1990	1995
Installed capacities				
- Ex Steam Crackers	(Mt/yr)	0.4	0.4	0.4
- Ex Catalytic Crackers	(Mt/yr)	0.3	0.5	0.5
- Combined	(Mt/yr)	0.5	0.6	0.6
Sub-Total	(Mt/yr)	1.2	1.5	1.5
TBA dehydration	(Mt/yr)	0.3	0.8	0.8
		1.5	2.3	2.3
Expected production	(Mt/yr)	1.1	1.8	1.8
Net import				
- From Saudi Arabia	(Mt/yr)	0.2	0.3	0.4
- From Venezuela	(Mt/yr)	-	-	0.2
- From USSR	(Mt/yr)	-	-	0.4
- From other countries	(Mt/yr)	0.1	-	-
Total	(Mt/yr)	0.3	0.3	1.0
Total availability	(Mt/yr)	1.4	2.1	2.8

Note (1): As from a 1987 forecast (4).

INDIVIDUAL REFINERY CONFIGURATIONS

Table 7

Submissions on cases without any restriction of benzene and aromatics contents

		Hydroskimming		Thermal conversion		COMPLEX I (1) With Isomerization		COMPLEX I (1) Without Isomerization		COMPLEX II	
INTAKE											
- Crude feed	kt/yr	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
- Ar. Light/Brent ratio		80/20	20/80	80/20	20/80	80/20	20/80	80/20	20/80	80/20	20/80
PRODUCTS											
- LPG	kt/yr	81.4	105.3	175.9	180.5	260.8	263.8	202.3	216.6	142.0	168.3
- LDF	kt/yr	4.8	-	26.8	3.9	-	-	153.9	181.5	28.1	74.1
- Gasoline	kt/yr	901.6	1098.6	968.1	1166.9	1349.0	1555.3	1186.2	1353.8	1527.7	1680.2
- Gasoils	kt/yr	1482.5	1565.7	2019.9	2151.3	1434.8	1574.7	1455.6	1588.4	1854.4	1928.4
- Other products (2)	kt/yr	2365.0	2074.3	1481.2	1173.9	1725.7	1377.0	1741.5	1407.0	1164.8	864.7
- Cons. & Loss	kt/yr	154.7	156.1	328.0	323.5	230.6	229.2	250.5	251.7	281.9	273.3
		5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
OPERATIONS											
- Reformer feed IBP	C	66	66	66	66	66	66	66	66	66	71
- Reformer severity	RONC	97.2	97.2	97.8	97.6	100	100	100.5	100.5	99.6	99.4
- LCN split./reforming	kt/yr	-	-	-	-	194.7	170.4	190	175	133.4	137.4
- Isomerization feed	kt/yr	165.6	202.1	187.1	209.5	169.2	214.1	-	-	121.4	143.1
GASOLINE CHARACTERISTICS											
- Density		0.746	0.751	0.745	0.750	0.748	0.751	0.760	0.763	0.738	0.743
- RVP	kPa	81.4	81.4	73.8	73.8	81.4	82.3	88.9	88.8	83.4	82.1
- Benzene content	% Vol	2.6	3.8	2.8	4.2	2.7	3.3	2.9	4.3	2.3	2.4
- Aromatics content	% Vol	43.5	45.3	45.2	47.0	37.7	40.1	42.4	44.8	35.1	37.3
- RON/MON		95/86	95/85.8	95/86.2	95/86.1	96/85	96/85	96.8/85	96.8/85	95.8/85	95.8/85
ISOMERIZATION COST (3)											
- Plant capital charge	M USD/yr	5.3	5.8	5.6	6.0	5.3	6.1	-	-	4.3	4.8
operating cost	M USD/yr	1.9	2.1	2.1	2.2	1.9	2.2	-	-	1.7	1.8
- Total cost	M USD/yr	7.2	8.0	7.7	8.2	7.2	8.3	-	-	6.0	6.6
- USD/ton of Gasoline		8.0	7.3	8.0	7.0	5.4	5.3	-	-	3.9	3.9
- Investment cost	M USD	23.8	26.8	25.6	27.4	24.1	27.7	-	-	19.7	21.8

Note (1): Cases with Isomerization as from one single contribution Note (2): Kerosine, Fuel Oil, Bitumen and Sulphur
Note (3): To be applied where Isomerization facilities should not be available to meet the reported performances

HYDROSKIMMING REFINERY

Table 8 Feed rate 5000 kt/yr - 80/20 Ar. Light/Brent ratio

Data are changes from Base Case derived from individual submissions

RESTRICTIONS					
- Benzene content % vol		3	1		1
- Aromatics content % vol		35	FREE		35
MTBE addition		Yes	No	Yes	Yes
ISOMERIZATION availability (175.4 kt/yr)		Yes	Yes	Yes	Yes
PRODUCTS					
- LPG	kt/yr	-4.2	+6.6	-8.7	-2.9
- LDF	kt/yr	+516.1	-0 1	-0 1	+501.4
- Gasoline	kt/yr	-404.4	-29 4	+55.5	-398 2
- Gasoil	kt/yr	-	+6.2	+6.6	-
- Fuel oil	kt/yr	-	-13.1	-16.0	-
- Cons. & Loss	kt/yr	-42.5	+11.4	+7.3	-41 1
- Benzene	kt/yr	-	+18.4	+16.6	+16.5
OPERATIONS					
- Reformer feed IBP	C	-	-	-	-
- Reformer severity	RON Clear	+0.4	+0.3	-2.5	+0.2
- LCN splitting/reforming	kt/yr	-	-	-	-
- Isomerization feed	kt/yr	-	-	-	-
- Benzene extraction feed	kt/yr	-	+490.6	+455.4	+212 3
- MTBE to the gasoline pool	kt/yr	+65 0	-	+61.2	+65.7
GASOLINE CHARACTERISTICS					
- Density		0.743	0.738	0.751	0.743
- RVP	kPa	74.5	73.8	73.8	74.5
- RON Clear/MON Clear		95/	95/	95/	95/
MON Clear		86 4	86.5	86	86.5
- Benzene content	% Vol	1.8	1.0	1.0	1.0
- Aromatics content	% Vol	34.2	43 6	37 5	34.2
- MTBE content	% Vol	10.0	-	7.1	10 0

HYDROSKIMMING REFINERY

Table 9 Feed rate 5000 kt/yr - 20/80 Ar. Light/Brent ratio

Data are changes from Base Case derived from individual submissions

RESTRICTIONS								
- Benzene content	% Vol	3			3	1		1
- Aromatics content	% Vol	free			35	free		35
MTBE addition		No	Yes	No	Yes	No	Yes	Yes
ISOMERIZATION avaiability (210.2 kt/yr)		Yes	Yes	Yes	Yes	Yes	Yes	Yes
PRODUCTS								
- LPG	kt/yr	-5.9	-22.3	+2.2	+12.2	+5.7	-9.3	+14.6
- LDF	kt/yr	+237.2	+144.3	-	+622.0	-	-	+599.4
- Gasoline	kt/yr	-198.4	+36.8	-17.2	-517.9	-44.8	+48.7	-513.3
- Gasoil	kt/yr	-20.5	-52.7	+1.0	-	+2.7	+2.7	-
- Fuel Oil	kt/yr	+4.3	+6.3	-5.4	-	-13.9	-15.0	-
- Cons. & loss	kt/yr	-16.7	-11.0	+14.4	-39.2	+14.4	+10.2	-37.2
- Benzene	kt/yr	-	-	+13.8	-	+35.9	+33.8	+14.1
OPERATIONS								
- Reformer feed IBP	C	+4	-	-	-	-	-	-
- Reformer severity	RON Clear	+0.3	-0.7	+0.2	+0.3	+0.3	-2.3	+0.5
- LCN splitting/reforming	kt/yr	-	-	-	-	-	-	-
- Isomerization feed	kt/yr	-	-	-	-	-	-	-
- Benzene extraction feed	kt/yr	-	-	+242.9	-	+631.0	+615.0	+330.3
- MTBE to the gasoline pool	kt/yr	-	+101.4	-	+77.1	-	+71.1	+77.6
GASOLINE CHARACTERISTICS								
- Density		0.751	0.740	0.745	0.746	0.743	0.736	0.746
- RVP	kPa	78.6	73.8	73.8	73.8	73.8	73.8	73.8
- RON Clear/		95/	95/	95/	95/	95/	95/	95/
MON Clear		86.1	85.8	86.3	86.3	86.4	85.9	86.3
- Benzene content	% Vol	3.0	3.0	3.0	2.5	1.0	1.0	1.0
- Aromatics content	% Vol	45.2	36.8	45.8	35.0	45.1	38.9	34.8
- MTBE content	% Vol	-	10.0	-	10.0	-	6.9	10.0

THERMAL CONVERSION REFINERY

Table 10 Feed rate 5000 kt/yr - 80/20 Ar. Light/Brent ratio

Data are changes from Base Case derived from individual submissions

RESTRICTIONS					
- Benzene content	% Vol	3	1		1
- Aromatics content	% Vol	35	FREE		35
MTBE addition		Yes	No	Yes	Yes
ISOMERIZATION availability (175.4 kt/yr)		Yes	Yes	Yes	Yes
PRODUCTS					
- LPG	kt/yr	-26.1	+7.4	-17.4	-22.6
- LDF	kt/yr	+188.0	-	-	-
- Gasoline	kt/yr	-24.4	-39.3	+89.5	+149.5
- Gasoil	kt/yr	-27.0	+9.1	+9.1	-28.2
- Fuel oil	kt/yr	+1.5	-11.8	-16.1	-13.6
- Cons. & Loss	kt/yr	-18.6	+13.4	+6.6	+8.5
- Benzene	kt/yr	-	+21.2	+18.8	+17.4
OPERATIONS					
- Reformer feed IBP	C	-	-	-	-
- Reformer severity	RON Clear	-3.2	+0.3	-3.1	-3.2
- LCN splitting/reforming	kt/yr	-	-	-	-
- Isomerization feed	kt/yr	-	-	-	-
- Benzene extraction feed	kt/yr	-	+559.2	+513.4	+519.6
- MTBE to the gasoline pool	kt/yr	+93.4	-	+90.5	+111.0
GASOLINE CHARACTERISTICS					
- Density		0.737	0.743	0.733	0.735
- RVP	kPa	73.8	73.8	73.8	73.8
- RON Clear/ MON Clear		95/ 85.5	85/ 86.3	95/ 85.7	95/ 85.6
- Benzene content	% Vol	1.9	1.0	1.0	1.0
- Aromatics content	% Vol	35.0	44.4	36.8	35.0
- MTBE content	% Vol	10.0	-	8.6	10.0

THERMAL CONVERSION REFINERY

Table 11 Feed rate 5000 kt/yr - 20/80 Ar. Light/Brent ratio

Data are changes from Base Case derived from individual submissions

RESTRICTIONS								
- Benzene content	% Vol		3		3	1		1
- Aromatics content	% Vol		free		35	free		35
MTBE addition		No	Yes	No	Yes	No	Yes	Yes
ISOMERIZATION avaiability (210.2 kt/yr)		Yes	Yes	Yes	Yes	Yes	Yes	Yes
PRODUCTS								
- LPG	kt/yr	-6.1	-26.1	+2.6	-40.7	+6.7	-9.2	-20.3
- LDF	kt/yr	+505.3	+147.0	-	+456.3	-	-	+213.8
- Gasoline	kt/yr	-421.2	+80.7	-20.0	-383.9	-52.0	+37.0	-82.3
- Gasoil	kt/yr	-28.9	-40.4	+0.9	-124.7	+2.5	+2.5	-12.8
- Fuel Oil	kt/yr	-18.8	-32.0	-6.7	+262.4	-17.5	-17.3	-11.7
- Cons. & loss	kt/yr	-29.9	-6.7	+7.1	-91.8	+13.4	+12.6	-8.3
- Benzene	kt/yr	-	-	+16.1	-	+41.9	+40.0	+29.5
OPERATIONS								
- Reformer feed IBP	C	+5	-	-	+4	-	-	-
- Reformer severity	RON Clear	+1.5	-1.8	-0.9	-0.3	+0.3	-1.8	+3.0
- LCN splitting/reforming	kt/yr	-	-	-	-	-	-	-
- Isomerization feed	kt/yr	-	-	-	-	-	-	-
- Benzene extraction feed	kt/yr	-	-	+288.5	-	+749.0	+726.0	+536.3
- MTBE to the gasoline pool	kt/yr	-	+122.5	-	+77.6	-	+65.6	+107.9
GASOLINE CHARACTERISTICS								
- Density		0.748	0.744	0.749	0.737	0.748	0.742	0.734
- RVP	kPa	73.8	73.8	73.8	66.9	73.8	73.8	73.8
- RON Clear/MON Clear		95/	95/	95/	95/	95/	95/	95/
MON Clear		86.5	85.6	86.1	85.8	86.2	85.8	86.7
- Benzene content	% Vol	3.0	3.0	3.0	2.8	1.0	1.0	1.0
- Aromatics content	% Vol	43.7	37.6	46.6	35.0	45.9	40.9	35.0
- MTBE content	% Vol	-	10.0	-	10.0	-	5.5	10.0

COMPLEX I REFINERY

Table 12 Feed rate 5000 kt/yr - 80/20 Ar. Light/Brent Ratio

Data are changes from Base Case derived from individual submissions

RESTRICTIONS								
- Benzene content	% Vol	3	3		1	1	1	
- Aromatics content	% Vol	35	30		Free	35	30	
MTBE addition		Yes	Yes	Yes	No	Yes	Yes	Yes
ISOMERIZATION avaiability (169.2 kt/yr)		No	Yes(1)	Yes(2)	No	No	Yes(1)	Yes(2)
PRODUCTS								
- LPG	kt/yr	+4.0	-1.2	+26.2	+5.7	+6.9	+0.1	+27.5
- LDF	kt/yr	+3.0	+189.5	+26.7	+3.0	-19.0	+323.6	+160.8
- Gasoline	kt/yr	+62.1	-72.6	+32.1	-50.0	+132.2	-309.4	-204.7
- Gasoil	kt/yr	+81.9	+50.7	+82.3	+12.7	+6.1	+50.7	+82.3
- Fuel Oil	kt/yr	-	-	-	-	-	-	-
- Cons. & loss	kt/yr	-11.8	-29.0	-28.9	-0.3	-5.0	-33.1	-33.0
- Benzene	kt/yr	-	-	-	+28.9	+25.4	+16.5	+16.5
OPERATIONS								
- Reformer feed IBP	C	-	-	-	-	-	-	-
- Reformer severity	RON C	-1.8	-3.0	-3.0	-	-0.6	-	-
- LCN splitting/reforming	kt/yr	-121.1	-10.7	-10.7	-	-95.3	-	-
- Isomerization feed	kt/yr	-	-	+169.2	-	-	-	+169.2
- Benzene extraction feed	kt/yr	-	-	-	+744.1	+607.0	+422.8	+422.8
- MTBE to the gasoline pool	kt/yr	+139.2	+138.4	+138.4	-	+146.6	+49.4	+49.4
GASOLINE CHARACTERISTICS								
- Density		0.759	0.745	0.745	0.759	0.759	0.741	0.741
- RVP	kPa	82.1	76.5	76.5	86.2	81.4	76.5	76.5
- RON Clear/MON Clear		96.6/	95.8/	95.8/	96.7/	96.7/	95.9/	95.9/
MON Clear		85	85	85	85	85	85	85
- Benzene content	% Vol	2.6	2.3	2.3	1.0	1.0	1.0	1.0
- Aromatics content	% Vol	35.0	30.0	30.0	41.9	35.0	30.0	30.0
- MTBE content	% Vol	10.0	10.0	10.0	-	10.0	4.4	4.4

Note (1): Available in the Base Case

Note (2): Not available in the Base Case concawe

COMPLEX I REFINERY

Table 13 Feed rate 5000 kt/yr 20/80 Ar. Light/Brent ratio

Data are changes from Base Case derived from individual submissions

RESTRICTIONS								
- Benzene content % Vol	3	3	3		1	1	1	
- Aromatics content % Vol	FREE	35	30		FREE	35	30	
MTBE addition	No	Yes	Yes	Yes	No	Yes	Yes	Yes
ISOMERIZATION avaiability (214.1 kt/yr)	No	No	Yes(1)	Yes(2)	No	No	Yes(1)	Yes(2)
PRODUCTS								
- LPG kt/yr	-6.6	+4.5	+1.5	+26.1	+0.7	-5.3	+15.6	+40.2
- LDF kt/yr	+50.8	+467.2	+366.3	+187.4	+38.0	+555.1	+465.3	+286.4
- Gasoline kt/yr	-37.1	-320.6	-189.1	-33.5	-73.3	-401.6	-487.6	-332.0
- Gasoil kt/yr	-	-	-	-	-	-	+75.8	+75.8
- Fuel Oil kt/yr	-	-	-	-	-	-	-	-
- Cons. & loss kt/yr	-7.1	-36.7	-31.0	-32.3	-3.8	-46.7	-36.8	-38.1
- Benzene kt/yr	-	-	-	-	+38.4	+4.1	+21.7	+21.7
OPERATIONS								
- Reformer feed IBP C	+5	-	-	-	-	+16	-	-
- Reformer severity RON Clear	-	-	-	-	-	-	-	-
- LCN splitting/reforming kt/yr	-	-	-61.0	-70.0	-	-	+9.0	-
- Isomerization feed kt/yr	-	-	-	+214.1	-	-	-	+214.1
- Benzene extraction feed kt/yr	-	-	-	-	+902.3	+187.9	+451.9	+451.9
- MTBE to the gasol. pool kt/yr		+114.4	+147.7	+147.7	-	+105.6	+54.0	+54.0
GASOLINE CHARACTERISTICS								
- Density	0.766	0.762	0.748	0.748	0.765	0.764	0.740	0.740
- RVP kPa	86.2	80.7	76.5	76.5	86.2	80.7	75.2	75.2
- RON Clear/MON Clear	96.8/	96.8/	95.9/	95.9/	96.8/	96.9/	95.7/	95.7/
MON Clear	85	85	85	85	85	85	85	85
- Benzene content % Vol	3.0	2.8	2.4	2.4	1.0	1.0	1.0	1.0
- Aromatics content % Vol	45.8	35.0	30.0	30.0	45.0	35.0	30.0	30.0
- MTBE content % Vol	-	10.0	10.0	10.0	-	10.0	4.6	4.6

Note (1): Available in the Base Case

Note (2): Not available in the Base Case

COMPLEX II REFINERY

Table 14 Feed rate 5000 kt/yr - 80/20 Ar. Light/Brent ratio

Data are changes from Base Case derived from individual submissions

RESTRICTIONS								
- Benzene content	% Vol	3	3		1		1	
- Aromatics content	% Vol	35	30		free		30	
MTBE addition		No	No	Yes	No	Yes	No	Yes
ISOMERIZATION avaiability (182.1 kt/yr)		Yes	Yes	Yes	Yes	Yes	Yes	Yes
PRODUCTS								
- LPG	kt/yr	-	+4.3	-6.4	+4.3	-0.5	+8.4	-2.2
- LDF	kt/yr	-	+190.1	-0.1	-0.1	+0.1	+148.2	-
- Gasoline	kt/yr	-	-167.8	+77.7	-25.7	+15.4	-143.5	+50.7
- Gasoil	kt/yr	-	-18.1	-1.5	-1.2	-21.4	-29.0	-12.7
- Fuel Oil	kt/yr	-	-10.1	+0.4	-12.2	-3.4	-15.5	-9.4
- Cons. & Loss	kt/yr	-	+1.6	-4.7	+13.5	+8.2	+15.2	+9.2
- Benzene	kt/yr	-	-	-	+21.4	+17.2	+16.2	+19.1
OPERATIONS								
- Reformer feed IBP	C	-	-	-	-	-	-	-
- Reformer severity	RON Clear	-	+0.4	-0.4	+0.2	-0.1	+0.3	-0.2
- LCN splitting/reforming	kt/yr	-	+29.0	-77.3	+3.9	-28.1	+28.3	-67.0
- Isomerization feed	kt/yr	-	-	-	-	-	-	-
- Benzene extraction feed	kt/yr	-	-	-	+514.4	+445.1	+411.8	+466.4
- MTBE to the gasoline pool	kt/yr	-	-	+65.4	-	+15.6	-	+54.7
GASOLINE CHARACTERISTICS								
- Density		0.735	0.732	0.734	0.733	0.730	0.732	0.734
- RVP	kPa	78.6	77.9	77.9	78.6	73.8	77.9	77.9
- RON Clear/MON Clear		95.3/85	95.3/85	95.3/85	95.3/85.1	95/85	95.3/85	95.6/85
- Benzene content	% Vol	2.2	1.9	2.0	1.0	1.0	1.0	1.0
- Aromatics content	% Vol	32.7	30.0	30.0	32.1	31.8	30.0	30.0
- MTBE content	% Vol	-	-	4.1	-	4.1	-	3.5

COMPLEX II REFINERY

Table 15 Feed rate 5000 kt/yr - 20/80 Ar. Light/Brent ratio

Data are changes from Base Case derived from individual submissions

RESTRICTIONS							
- Benzene content % Vol	3	3		1		1	
- Aromatics content % Vol	35	30		free		30	
MTBE addition	No	No	Yes	No	Yes	No	Yes
ISOMERIZATION availability (215.6 kt/yr)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PRODUCTS							
- LPG kt/yr	-	+11.6	-10.1	+5.8	-0.5	+16.7	-4.4
- LDF kt/yr	-	+398.6	+56.7	-0.9	-	+347.3	+21.6
- Gasoline kt/yr	-	-434.0	+72.2	-49.1	-31.0	-423.0	+56.8
- Gasoil kt/yr	-	+49.3	+15.9	+4.5	+23.0	+54.6	+11.0
- Fuel Oil kt/yr	-	-46.3	-9.1	-17.0	-13.3	-54.4	-20.4
- Cons. & loss kt/yr	-	+20.8	-2.9	+19.1	+9.2	+32.8	+12.4
- Benzene kt/yr	-	-	-	+37.6	+34.2	+26.0	+33.5
OPERATIONS							
- Reformer feed IBP C	-	-	-	-	-	-	-
- Reformer severity RON Clear	-	+1.3	-1.2	+0.2	-0.4	+1.3	-0.9
- LCN splitting/reforming kt/yr	-	-	-111.2	-30.9	-6.4	-	-111.2
- Isomerization feed kt/yr	-	-	-	-	-	-	-
- Benzene extraction feed kt/yr	-	-	-	+682.9	+592.1	+499.8	+612.2
- MTBE to the gasol. pool kt/yr	-	-	+122.7	-	+21.6	-	+110.5
GASOLINE CHARACTERISTICS							
- Density (15/4 C)	0.741	0.735	0.736	0.737	0.733	0.734	0.736
- RVP kPa	78.6	80.7	77.9	78.6	73.8	80.7	77.9
- RON Clear/MON Clear	95.3/	95.6/	95.6/	95.3/	95/	95.6/	95.5/
MON Clear	85.1	85.4	85	85.1	85	85.4	85
- Benzene content % Vol	3.0	2.5	2.5	1.0	1.0	1.0	1.0
- Aromatics content % Vol	35.6	30.0	30.0	34.1	33.3	30.0	30.0
- MTBE content % Vol	-	-	6.8	-	1.4	-	6.2

INDIVIDUAL REFINERY CONFIGURATION

Table 16 Economic consequences of meeting:
3% vol Benzene content
No MTBE addition
Free Aromatics content

Data are changes from Base Case derived from individual submissions

REFINERY CONFIGURATION		HYDROSKIMMING		THERMAL CONVERSION		COMPLEX I		COMPLEX II	
Ar.Light/Brent feed ratio		(1) 20/80	20/80	(1) 20/80	20/80	80/20	20/80	80/20	20/80
- Surplus/Deficit	M USD/yr	0.4	2.2	0.6	4.2	-	0.4	-	-
- MTBE cost	M USD/yr	-	-	-	-	-	-	-	-
- Plant capital charge	M USD/yr	1.4	-	1.6	-	-	-	-	-
operating cost	M USD/yr	1.3	-	1.5	-	-	-	-	-
- Total cost	M USD/yr	3.1	2.2	3.7	4.2	-	0.4	-	-
- USD/ton of gasoline		3.2	2.4	3.2	5.6		0.3		
- Investment cost	M USD	6.5	-	7.2	-	-	-	-	-
SENSITIVITIES									
- 1.5 MTBE/gasol. price ratio	M USD/yr	-	-	-	-	-	-	-	-
- 45 USD/t gasol.-LDF price difference	M USD/yr	-	+4.7	-	+10.1	-	+1.0	-	-
- 0.53 Benzene/Gasoline price ratio	M USD/yr	-	-	-	-	-	-	-	-
- Isomerization (2)									
capital charge	M USD/yr	+6.0	+6.0	+6.0	+6.0	-	-	+4.3	+4.8
operating cost	M USD/yr	+2.2	+2.2	+2.2	+2.2	-	-	+1.7	+1.8
- Total cost	M USD/yr	11.3	15.1	11.9	22.5	-	1.4	6.0	6.6
- USD/ton of gasoline		11.6	16.6	10.4	30.0		1.0	3.9	3.9
- Investment cost	M USD	33.9	27.4	34.6	27.4	-	-	19.7	21.8

Note (1): Cases with benzene extraction reformates
Note (2): Costs to be added at those refineries where isomerization is not available but needed to meet Base Case requirements

INDIVIDUAL REFINERY CONFIGURATION

Table 17 Economic consequences of meeting:
3% vol Benzene content
MTBE addition
Free Aromatics content

Data are changes from Base Case derived from individual submissions

REFINERY CONFIGURATION		HYDROSKIMMING		THERMAL CONVERSION		COMPLEX I		COMPLEX II	
Ar.Light/Brent feed ratio		80/20	20/80	80/20	20/80	80/20	20/80	80/20	20/80
- Surplus/Deficit	M USD/yr	-	-20.0	-	-26.2	-	-	-	-
- MTBE cost	M USD/yr	-	25.0	-	30.0	-	-	-	-
- Plant capital charge	M USD/yr	-	-	-	-	-	-	-	-
operating cost	M USD/yr	-	-	-	-	-	-	-	-
- Total cost	M USD/yr	-	5.0	-	4.1	-	-	-	-
- USD/ton of gasoline		-	4.9		3.3	-	-	-	-
- Investment cost	M USD	-	-	-	-	-	-	-	-
SENSITIVITIES									
- 1.5 MTBE/gasol. price ratio	M USD/yr	-	+3.9	-	+4.7	-	-	-	-
- 45 USD/t gasoline-LDF price difference	M USD/yr	-	+2.9	-	+2.9	-	-	-	-
- 0.53 Benzene/Gasoline price ratio	M USD/yr	-	-	-	-	-	-	-	-
- Isomerization (1)									
capital charge	M USD/yr	+5.3	+6.0	+5.6	+6.0	-	-	+4.3	+4.8
operating cost	M USD/yr	+1.9	+2.2	+2.1	+2.2	-	-	+1.7	+1.8
- Total cost	M USD/yr	7.2	20.0	7.7	19.9	-	-	6.0	6.6
- USD/ton of gasoline		8.0	19.5	8.0	16.0			3.9	3.9
- Investment cost	M USD	23.8	27.4	25.6	27.4	-	-	19.7	21.8

Note (1): - Costs to be added at those refineries where isomerization is not available but needed to meet Base Case requirements
- Simple cracking refinery is reported without isomerization

INDIVIDUAL REFINERY CONFIGURATION

Table 18 Economic consequences of meeting:
3% vol Benzene content
MTBE addition
35% vol Aromatics content

Data are changes from Base Case derived from individual submissions

REFINERY CONFIGURATION		HYDROSKIMMING		THERMAL CONVERSION		COMPLEX I		COMPLEX II	
Ar.Light/Brent feed ratio		80/20	20/80	80/20	20/80	80/20	20/80	80/20	20/80
- Surplus/Deficit	M USD/yr	-7.8	-5.9	-18.7	-3.0	-25.9	-16.8	-	-
- MTBE cost	M USD/yr	16.1	19.0	23.1	19.2	34.4	28.3	-	-
- Plant capital charge	M USD/yr	-	-	-	-	-	-	-	-
operating cost	M USD/yr	-	-	-	-	-	-	-	-
- Total cost	M USD/yr	8.3	13.1	4.4	16.2	8.5	11.5	-	-
- USD/ton of gasoline		13.9	18.4	4.7	20.7	6.5	10.7		
- Investment cost	M USD	-	-	-	-	-	-	-	-
SENSITIVITIES									
- 1.5 MTBE/gasol. price ratio	M USD/yr	+2.5	+2.9	+3.5	+2.9	+5.3	+4.3	-	-
- 45 USD/t gasol.-LDF price difference	M USD/yr	+10.3	+12.4	+3.8	+9.1	+0.1	+9.3	-	-
- 0.53 Benzene/Gasoline price ratio	M USD/yr	-	-	-	-	-	-	-	-
- Isomerization (1)									
capital charge	M USD/yr	+5.4	+6.0	+5.6	+6.0	-	-	+5.5	+6.1
operating cost	M USD/yr	+2.0	+2.2	+2.1	+2.2	-	-	+2.0	+2.2
- Total cost	M USD/yr	+28.5	36.6	19.4	36.4	13.9	25.1	7.5	8.3
- USD/ton of gasoline		47.6	51.4	20.6	46.5	10.6	23.3	5.7	6.8
- Investment cost	M USD	24.6	27.4	25.6	27.4	-	-	25.2	27.8

Note (1): - Costs to be added at those refineries where the Isomerization is not available but needed to meet the Base Case requirements
- Simple cracking refinery is reported without Isomerization

INDIVIDUAL REFINERY CONFIGURATION

Table 19 Economic consequences of meeting:
3% vol Benzene content
30% vol Aromatics content

Data are changes from Base Case derived from individual submissions

REFINERY CONFIGURATION		COMPLEX I				COMPLEX II			
		(1)		(2)		(4)		(5)	
Ar.Light/Brent feed ratio		80/20	20/80	80/20	20/80	80/20	20/80	80/20	20/80
- Surplus/Deficit	M USD/yr	-25.4	-24.7	-27.2	-28.1	-13.7	-23.3	3.8	11.9
- MTBE cost	M USD/yr	34.2	36.5	34.2	36.5	16.2	30.3	-	-
- Plant capital charge	M USD/yr	-	-	5.3	6.1	-	-	-	-
operating cost	M USD/yr	-	-	1.9	2.2	-	-	-	-
- Total cost	M USD/yr	8.8	11.8	14.2	16.7	2.5	7.0	3.8	11.9
- USD/ton of Gasoline		6.9	8.6	11.1	12.2	1.6	4.0	2.9	10.2
- Investment cost	M USD	-	-	24.1	27.7	-	-	-	-
SENSITIVITIES									
- 1.5 MTBE/gasol. price ratio	M USD/yr	+5.3	+5.6	+5.3	+5.6	+2.5	+4.7	-	-
- 45 USD/t gasol.-LDF price difference	M USD/yr	+3.8	+7.3	+0.5	+3.7	-	+1.1	+3.8	+8.0
- 0.53 Benzene/Gasoline price ratio	M USD/yr	-	-	-	-	-	-	-	-
- Isomerization (3)									
capital charge	M USD/yr	+5.3	+6.1	-	-	+5.5	+6.1	+5.5	+6.1
operating cost	M USD/yr	+1.9	+2.2	-	-	+2.0	+2.2	+2.0	+2.2
- Total cost	M USD/yr	25.1	33.0	20.0	26.0	12.5	21.1	15.1	28.2
- USD/ton of gasoline		19.7	24.2	15.7	19.0	8.0	12.2	11.5	24.2
- Investment cost	M USD	24.1	27.7	24.1	27.7	25.2	27.8	25.2	27.8

Note (1): - Isomerization unit is available in the Base Case
Note (2): - Isomerization unit is not available in the Base Case
Note (3): - Costs to be added at those refineries where isomerization is not available but needed to meet Base Case requirements
Note (4): - With MTBE addition
Note (5): - Without MTBE addition

INDIVIDUAL REFINERY CONFIGURATION

Table 20 Economic consequences of meeting:
1% vol Benzene content
No MTBE addition
Free Aromatics content

Data are changes from Base Case derived from individual submissions

REFINERY CONFIGURATION		HYDROSKIMMING		THERMAL CONVERSION		COMPLEX 1		COMPLEX 11	
Ar.Light/Brent feed ratio		80/20	20/80	80/20	20/80	80/20	20/80	80/20	20/80
- Surplus/Deficit	M USD/yr	1.1	1.1	1.7	1.4	0.1	-0.6	1.2	1.7
- MTBE cost	M USD/yr	-	-	-	-	-	-	-	-
- Plant capital charge	M USD/yr	2.2	2.5	2.3	2.8	2.8	3.1	2.2	2.6
operating cost	M USD/yr	2.3	2.9	2.6	3.3	3.3	3.9	2.4	3.1
- Total cost	M USD/yr	5.6	6.5	6.6	7.5	6.2	6.4	5.8	7.4
- USD/ton of Gasoline		7.2	6.7	7.1	6.7	5.2	4.8	4.0	4.6
- Investment cost	M USD	9.8	11.4	10.6	12.7	12.6	14.2	10.1	12.0
SENSITIVITIES									
- 1.5 MTBE/gasol. price ratio	M USD/yr	-	-	-	-	-	-	-	-
- 45 USD/t gasol.-LDF price difference	M USD/yr	-	-	-	-	0.1	+0.8	-	-
- 0.53 Benzene/gasoline price ratio	M USD/yr	+2.1	+4.0	+2.4	+4.7	3.2	+4.3	+2.4	+4.2
- Isomerization (1)									
capital charge	M USD/yr	+5.4	+6.0	+5.6	+6.0	-	-	+5.5	+6.1
operating cost	M USD/yr	+2.0	+2.2	+2.1	+2.2	-	-	+2.0	+2.2
- Total cost	M USD/yr	+15.1	18.7	16.7	20.4	9.5	11.5	15.7	19.9
- USD/ton of Gasoline		19.4	19.8	18.0	18.3	8.0	8.7	10.8	12.3
- Investment cost	M USD	34.4	38.8	36.2	40.1	12.6	14.2	35.3	39.8

Note (1): - Costs to be added at those refineries where isomerization is not available but needed to meet Base Case requirements
- Simple cracking refinery is reported without Isomerization

INDIVIDUAL REFINERY CONFIGURATION

Table 21 Economic consequences of meeting:
1% vol Benzene content
MTBE addition
Free Aromatics content

Data are changes from Base Case derived from individual submissions

REFINERY CONFIGURATION		HYDROSKIMMING		THERMAL CONVERSION		COMPLEX II	
Ar.Light/Brent feed ratio		80/20	20/80	80/20	20/80	80/20	20/80
- Surplus/Deficit	M USD/yr	-12.3	-14.1	-18.5	-13.0	-2.8	-3.7
- MTBE cost	M USD/yr	11.6	13.5	17.2	12.5	3.9	5.3
- Plant capital charge	M USD/yr	2.1	2.5	2.2	2.7	2.0	2.4
operating cost	M USD/yr	2.2	2.8	2.4	3.2	2.1	2.7
- Total cost	M USD/yr	3.6	4.7	3.3	5.4	5.2	6.7
- USD/ton of Gasoline		4.2	4.5	3.1	4.5	3.7	4.3
- Investment cost	M USD	9.4	11.3	10.1	12.4	9.3	11.0
SENSITIVITIES							
- 1.5 MTBE/gasol. price ratio	M USD/yr	+2.3	+2.7	+3.4	+2.5	+0.6	+0.8
- 45 USD/t gasol.-LDF price difference	M USD/yr	-	-	-	-	-	-
- 0.53 Benzene/Gasoline price ratio	M USD/yr	+1.9	+3.8	+2.1	+4.5	+1.9	+3.8
- Isomerization (2)							
capital charge	M USD/yr	+5.4	+6.0	+5.6	+6.0	+5.5	+6.1
operating cost	M USD/yr	+2.0	+2.2	+2.1	+2.2	+2.0	+2.2
- Total cost	M USD/yr	+15.2	19.4	16.5	20.6	15.2	19.6
- USD/ton of gasoline		17.6	18.7	15.6	17.1	10.8	12.5
- Investment cost	M USD	34.0	38.7	35.7	39.8	34.5	38.8

Note (1): - Costs to be added at those refineries where isomerization is not available but needed to meet the Base Case requirements

INDIVIDUAL REFINERY CONFIGURATION

Table 22 Economic consequences of meeting:
1% vol Benzene content
MTBE addition
35% vol Aromatics content

Data are changes from Base Case derived from individual submissions

REFINERY CONFIGURATION		HYDROSKIMMING		THERMAL CONVERSION		COMPLEX I		COMPLEX II	
Ar.Light/Brent feed ratio		80/20	20/80	80/20	20/80	80/20	20/80	80/20	20/80
- Surplus/Deficit	M USD/yr	-8.1	-6.3	-23.2	-20.0	-29.3	-15.4	-2.8	-3.7
- MTBE cost	M USD/yr	16.2	19.2	27.4	26.7	36.2	26.1	3.9	5.3
- Plant capital charge	M USD/yr	1.3	1.7	2.2	2.3	2.5	1.2	2.0	2.4
operating cost	M USD/yr	1.1	1.6	2.4	2.5	2.8	1.0	2.1	2.7
- Total cost	M USD/yr	10.5	16.2	8.8	11.5	12.2	12.9	5.2	6.7
- USD/ton of Gasoline		17.4	22.6	7.9	10.6	8.9	12.9	3.7	4.3
- Investment cost	M USD	6.0	7.6	10.2	10.4	11.2	5.5	9.3	11.0
SENSITIVITIES									
- 1.5 MTBE/gasol. prict ratio	M USD/yr	+2.5	+2.9	+4.2	+4.1	+5.6	+4.0	+0.6	+0.8
- 45 USD/t gasol.-LDF price difference	M USD/yr	+10.0	+12.0	-	+4.3	-0.4	+11.1	-	-
- 0.53 Benzene/Gasoline price ratio	M USD/yr	+0.7	+1.6	+2.0	+3.3	+2.8	+0.5	+1.9	+3.8
- Isomerization (1)									
capital charge	M USD/yr	+5.4	+6.0	+5.6	+6.0	-	-	+5.5	+6.1
operating cost	M USD/yr	+2.0	+2.2	+2.1	+2.2	-	-	+2.0	+2.2
- Total cost	M USD/yr	31.1	40.9	22.7	31.4	20.2	28.5	15.2	19.6
- USD/ton of Gasoline		51.5	57.1	20.3	29.0	14.7	28.6	10.8	12.5
- Investment cost	M USD	30.6	35.0	35.8	37.8	11.2	5.5	34.5	38.9

Note (1): - Costs to be added at those refineries where isomerization is not available but needed to meet the Base Case requirements
- Simple cracking refinery is reported without Isomerization

INDIVIDUAL REFINERY CONFIGURATION

Table 23 Economic consequences of meeting:
1% vol Benzene content
30% vol Aromatics content

Data are changes from Base Case derived from individual submissions

REFINERY CONFIGURATION		COMPLEX I				COMPLEX II			
		(1)		(2)		(4)		(5)	
Ar.Light/Brent feed ratio		80/20	20/80	80/20	20/80	80/20	20/80	80/20	20/80
- Surplus/Deficit	M USD/yr	-6.2	-3.0	- 8.0	- 6.3	-10.4	-20.6	4.4	11.9
- MTBE cost	M USD/yr	12.2	13.3	12.2	13.3	13.5	27.3	-	-
- Plant capital charge	M USD/yr	2.0	2.1	+7.3	+8.2	2.1	2.5	1.9	2.2
operating cost	M USD/yr	2.0	2.1	+3.9	+4.3	2.2	2.8	2.0	2.3
- Total cost	M USD/yr	10.0	14.5	15.4	19.5	7.4	12.0	8.3	16.4
- USD/ton of Gasoline		9.6	13.6	14.8	18.3	4.8	7.0	6.2	10.3
- Investment cost	M USD	9.0	9.4	33.1	37.1	9.5	11.2	8.9	9.9
SENSITIVITIES									
- 1.5 MTBE/Gasol. price ratio	M USD/yr	+1.9	+2.1	+1.9	+2.1	+2.1	+4.2	-	-
- 45 USD/t gasol.-LDF price difference	M USD/yr	+6.5	+9.3	+3.2	+5.7	-	+0.4	+3.0	+6.9
- 0.53 Benzene/Gasoline price ratio	M USD/yr	+1.8	+2.4	+1.8	+2.4	+2.1	+3.8	+1.8	+2.9
- Isomerization (3)									
capital charge	M USD/yr	+5.3	+6.1	-	-	+5.5	+6.1	+5.5	+6.1
operating cost	M USD/yr	+1.9	+2.2	-	-	+2.0	+2.2	+2.0	+2.2
- Total cost	M USD/yr	27.4	36.6	22.3	29.7	19.1	28.7	20.6	34.5
- USD/ton of Gasoline		26.4	34.3	21.5	27.8	12.5	16.7	15.4	21.6
- Investment cost	M USD	33.1	37.1	33.1	37.1	34.7	39.1	34.1	37.8

Note (1): - Isomerization unit is available in the Base Case
Note (2): - Isomerization unit is not available in the Base Case
Note (3): - Costs to be added at those refineries where isomerization is not available but needed to meet the Base Case requirements
Note (4): - with MTBE addition
Note (5): - without MTBE addition

EC-12 REFINING SYSTEM

Table 24 Alternatives of operations to limit benzene and aromatics content (1)

Benzene content % Vol		Free	Free	3	3	3	3	1	1	1	1
Aromatics content % Vol		Free	Free	Free	Free	35	35	Free	Free	35	35
Additional "Iso" capacity (2)	Mt/yr	4.6	9.2	4.6	4.6	6.4	11.3	5.1	4.8	6.1	11.8
MTBE addition	Mt/yr	-	-	-	1.0	5.5	5.6	-	2.2	6.1	4.3
Feed (3)											
- High sulphur crude	Mt/yr	199.2	190.4	200.2	198.7	219.1	210.3	206.6	188.2	209.2	217.3
- Low sulphur crude	Mt/yr	150.7	144.0	151.4	150.3	165.7	159.1	156.3	150.7	158.3	164.4
- MTBE	Mt/yr	-	-	-	1.0	5.5	5.6	-	2.2	6.1	4.3
		349.9	334.4	351.6	350.0	390.3	375.0	362.9	352.1	373.6	386.0
Products											
- LPG	Mt/yr	12.2	12.9	12.5	11.9	13.0	13.7	13.0	12.0	12.5	14.6
- LOF	Mt/yr	4.5	0.4	4.9	6.2	18.5	16.5	5.1	4.8	15.5	16.4
- Gasoline	Mt/yr	89.0	89.0	89.0	89.0	89.0	89.0	89.0	89.0	89.0	89.0
- Kerosine	Mt/yr	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
- Gasoils	Mt/yr	123.1	117.3	124.0	121.2	136.1	131.4	127.3	121.6	128.4	137.9
- F.O. & other products	Mt/yr	79.7	74.7	79.5	80.4	91.1	84.3	83.5	80.7	84.9	85.0
- Cons. & Loss	Mt/yr	19.4	18.1	19.5	19.3	19.6	18.1	20.8	18.8	19.8	19.6
- Extracted benzene	Mt/yr	-	-	0.2	-	-	-	2.2	1.9	1.5	1.5
		349.9	334.4	351.6	350.0	390.3	375.0	362.9	352.1	373.6	386.0
Operations											
- Reformer severity	RON Clear	99.2	99.1	99.1	99.1	98.4	98.1	99.4	97.9	98.3	98.2
- Isomerization feed	Mt/yr	8.8	12.7	8.8	8.8	9.7	14.1	9.2	8.8	9.3	14.5
- Benzene extraction feed	Mt/yr	-	-	2.5	-	-	-	48.3	44.0	33.9	34.9
- LCN splitting/reforming	Mt/yr	7.1	6.8	7.1	7.0	7.8	5.9	7.1	6.6	5.5	5.3
Gasoline characteristics											
- Density		0.748	0.744	0.748	0.747	0.745	0.741	0.746	0.743	0.742	0.736
- RVP	kPa	81.4	79.6	80.8	80.5	78.1	76.4	80.0	77.9	75.8	74.5
- RON		95.7	95.5	95.5	95.7	95.7	95.4	95.7	95.5	95.6	95.2
- MON		85.3	85.3	85.1	85.3	85.2	85.2	85.3	85.2	85.3	85.3
- MTBE content	% Vol	-	-	-	1.2	6.3	6.4	-	2.5	7.0	4.9
- Benzene content	% Vol	3.1	2.9	2.8	2.8	2.6	2.4	1.0	1.0	1.0	1.0
- Aromatics content	% Vol	40.2	38.6	40.3	39.2	34.5	32.7	39.5	37.5	33.9	32.4

Note (1): Each reported case is a weighted average of individual configurations data and covers wide differences of actual situations.
Note (2): Reference is made to the basic assumption of a future 5 Mt/yr availability; data are in terms of installed capacity
Note (3): High sulphur/low sulphur crude feed ratio as from basic assumption (Section 2.2.3)

EC-12 REFINING SYSTEM

Table 25 Alternatives of operations to limit benzene and aromatics content (1)

Benzene content % vol		Free	Free	3	3	3	3	1	1	1	1
Aromatics content % vol		Free	Free	Free	Free	35	35	Free	Free	35	35
Additional "Iso" capacity (2)	Mt/yr	4.6	9.2	4.6	4.6	6.4	11.3	5.1	4.8	6.1	11.8
MTBE addition	Mt/yr	-	-	-	1.0	5.5	5.6	-	2.2	6.1	4.3
Surplus/Deficit	M USD/yr	-	-72.8	-42.0	-130.7	-1114.5	-1344.2	489.2	65.3	-856.8	-894.5
MTBE cost	M USD/yr	-	-	-	247.0	1358.5	1383.2	-	543.4	1506.7	1062.1
Plant capital charge		177.6	306.3	245.5	176.7	195.3	331.5	394.0	382.6	350.8	508.4
operating cost		66.7	115.7	82.8	66.4	72.8	122.2	291.0	273.9	236.9	294.9
Total cost	M USD/yr	244.3	349.2	296.3	359.4	512.1	432.7	1174.2	1265.2	1237.6	970.9
USD/ton of Gasoline		2.7	3.9	3.3	4.0	5.8	5.5	13.2	14.2	13.9	10.9
Investment cost	M USD	807	1392	1116	803	888	1507	1791	1739	1585	2311
Sensitivities											
1.5 MTBE/Gasoline price ratio	M USD/yr			-	38.0	209.0	212.8	-	83.6	231.8	153.4
45 USD/t Gasoline - LDF price difference	M USD/yr			-	34.0	300.0	240.0	-	-	220.0	238.0
0.53 Benzene/Gasol. price ratio	M USD/yr			-	-	-	-	246.6	213.0	168.2	168.2
Total cost		244.3	349.2	296.3	431.4	1021.1	945.5	1420.8	1561.8	1857.6	1540.5
USD/ton of Gasoline		2.7	3.8	3.3	4.8	11.5	10.6	16.0	17.5	20.9	17.3

Note (1): Each reported case is a weighted average of individual configurations data and covers wide difference of actual situations

Note (2): Reference is made to the basic assumption of a future 5 Mt/yr availability; data are in terms of installed capacity

COST OF LIGHT NAPHTHA ISOMERIZATION WITH "NORMALS RECYCLING"

The following data represent the average figures of five individual participant's estimates, which take into account different feed qualities and process solutions. The estimates have been pro-rated for a plant size which would be suitable for a 5000 kt/yr refinery; a utilization factor of 89% and an average European crude oil feed composition have been used for the calculations.

- Average size of the unit (installed capacity)	6000 BPSD
- Utilized capacity	184.5 kt/yr
- CAPITAL COST OF THE UNIT	25.4 million USD '87
- (off-sites, royalties and contingencies included)	
- OPERATION COSTS (per year)	
- Utilities	see note (1)
- Other variable charges	260 thousand USD '87
- Plant charges and overheads	1770 thousand USD '87
- Depreciation 10%	2537 thousand USD '87
- R.O.C. 12%	3044 thousand USD '87
FULL COST + RETURN	7611
- TOTAL COST PER TON OF FEED	41 USD '87

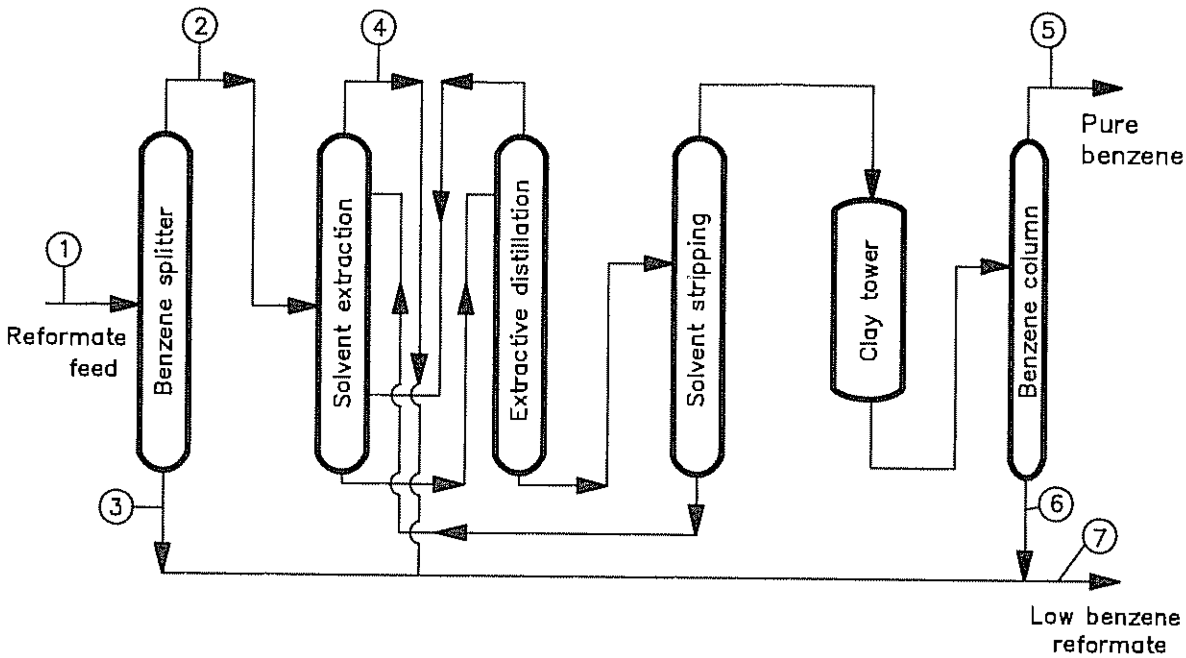
Note (1): The utilities consumptions have been already taken into account in each single elaboration of the study cases and are included in the resulting Consumption & Losses figures.

COST OF BENZENE EXTRACTION FROM REFORMATES

- EC-12 overall Catalytic Reforming capacity as from 1st January 1987		1 745 800 B/CD
- Number of operating units		84
- Average size of the operating units		20 783 B/CD
		904 kt/yr
		113 t/hr
- Catalytic Reformate to each extraction unit		83 t/hr
- Extractable benzene		3.5 t/hr
- CAPITAL COST OF EACH UNIT (off-sites, royalities and contingencies included)		11 million USD '87
- OPERATING COSTS (per year)		
- Variable charges	1789	thousand USD '87
- Plant charges	640	thousand USD '87
- Overheads	275	thousand USD '87
- Depreciation 10%	1100	thousand USD '87
- R.O.C. 12%	1320	thousand USD '87
FULL COST + RETURN	5124	
- TOTAL COST PER TON OF EXTRACTED BENZENE (1)		206 USD '87

Note (1): Based on 89% plant utilization and 5% vol benzene content in the feed

SCHEME FOR BENZENE EXTRACTION



Stream Flows Assumed:							
Stream No.	1	2	3	4	5	6	7
Non-Aromatics kl/hr	30.0	17.0	13.0	17.0	-	-	30.0
Benzene "	5.0	4.0	1.0	-	4.0	-	1.0
Other Aromatics "	65.0	0.1	64.9	-	-	0.1	65.0
Totals "	100.0	21.1	78.9	17.0	4.0	0.1	96.0
Benzene % vol	5.0	18.9	1.3	-	100.0	-	1.0
Total Aromatics %vol	70.0	19.4	83.5	-	100.0	100.0	68.8
Non-Aromatics t/hr	21.9	12.4	9.5	12.4	-	-	21.9
Benzene "	4.4	3.5	0.9	-	3.5	-	0.9
Other Aromatics "	56.5	0.1	56.4	-	-	0.1	56.5
Totals "	82.8	16.0	66.8	12.4	3.5	0.1	79.3
Benzene % wt	5.3	21.9	1.4	-	100.0	-	1.1
Total Aromatics %wt	73.5	22.5	85.4	-	100.0	100.0	72.3